
From: GBHint@aol.com [mailto:GBHint@aol.com]
Sent: Sunday, September 07, 2008 9:42 PM
To: zzMSHA-Standards - Comments to Fed Reg Group
Cc: Verakis, Harry C - MSHA
Subject: "RIN 1219–AB59" GBH comments

Dear sir/madam:

I attach comments by Marcelo M. Hirschler (GBH International) to the "RIN 1219–AB59" call for comments.

I attach the basic comments to this e-mail. It will be followed by 28 e-mails with attachments, named GBH Attachment 1 through GBH Attachment 28.

Yours sincerely.

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Comment by GBH International on Mine Belt Flammability Regulation

Background

I understand that the Technical Study Panel on the Utilization of Belt Air and the Composition and Fire Retardant Properties of Belt Materials in Underground Coal Mining, created under Section 11 of the Mine Improvement and New Emergency Response Act of 2006 (MINER Act)(Public Law 109-236), and chartered under the provisions of the Federal Advisory Committee Act (FACA) has issued a report, namely: The Final Report of the Technical Study Panel on the Utilization of Belt Air and the Composition and Fire Retardant Properties of Belt Materials in Underground Coal Mining, authored by J.M. Mutmansky, J.F. Brune, F. Calizaya, T.P. Mucho, J.C. Tien and J.L. Weeks, published in December 2007 (http://www.cdc.gov/niosh/mining/mineract/pdfs/BeltAirFinalReport122007.pdf).
Among other issues, the Panel's charge was to prepare and submit this report concerning the composition and fire retardant properties of belt materials in underground coal mining to the Secretary of Labor, the Secretary of Health and Human Services, the Committee on Health, Education, Labor, and Pensions of the Senate, and the Committee on Education and the Workforce of the House of Representatives. I also understand that the panel recommended to use as a fire test for conveyor mine belts, the BELT test for regulatory purposes, replacing the Bunsen burner test currently in 30 CFR §18.65, which was based on ASTM D 635 (or UL 94 HB). I also understand that the BELT test was developed by the US Bureau of Mines and is conducted in a 1.7 m (5.5 ft) long by 0.2 m^2) (1.5 ft^2) ventilated tunnel. The belt material sample size is 1.5 m (5 ft) long by 230 mm (9 in.) wide. The sample is ignited by applying a gas burner to the front edge of the belt sample with the flames distributed equally on the top and bottom surfaces of the sample. After five minutes, the burner is removed, and the belt sample allowed to burn until the flames are out. A belt passes the BELT if, in three separate trials, there remains a portion of the conveyor mine belt sample that is undamaged across its entire width. If, in any of the three trials, fire damage extends to the end of the sample, the conveyor belt formulation fails the test. Comparison testing showed excellent agreement for 19 of the belts between the pass/fail results of the large-scale fire gallery test and of the BELT. Agreement has been reached that this will be implemented.

It is also my understanding that, on June 19, 2008, the Mine Safety and Health Administration (MSHA) published in the Federal Register a Request for Information (http://www.msha.gov/REGS/FEDREG/RFI/E8-13633.pdf), with comments due by September 8, as to whether tests exist that can be used for assessing conveyor belt combustion toxicity and smoke density. Comments need to be identified with "RIN 1219-AB60" and sent to MSHA. The information collected will result in developing fire test requirements for conveyor mine belts.

Recommendations:

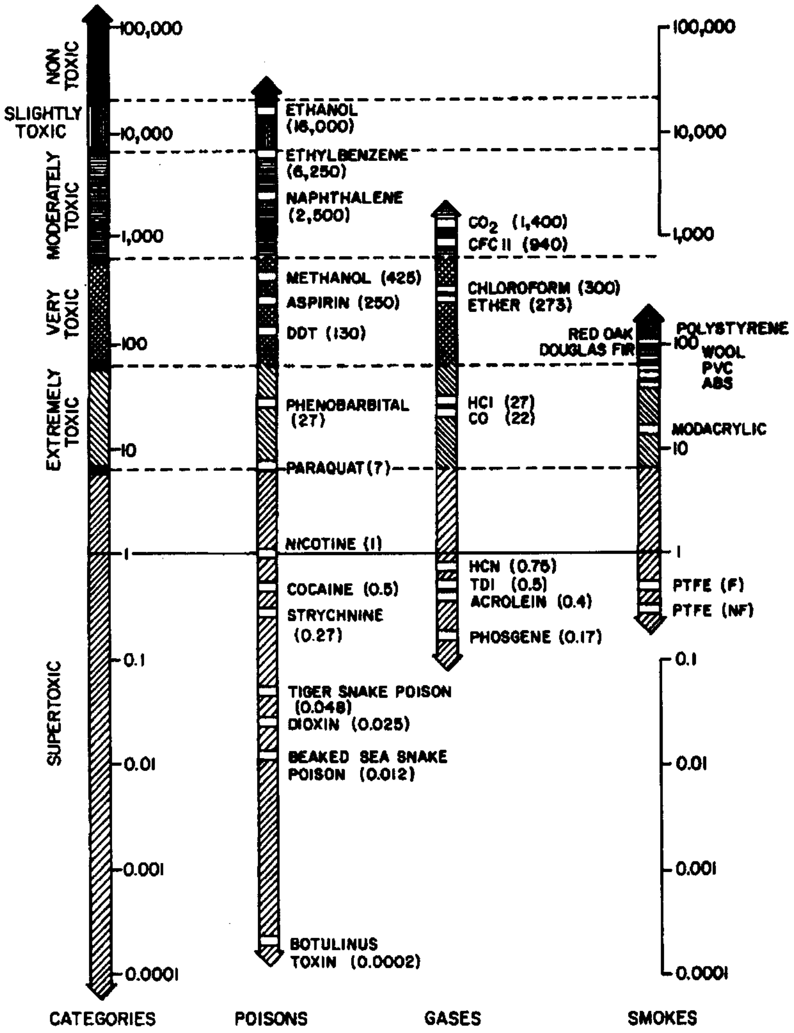
1. It is now essential that new fire safety regulation be put in place for mine conveyor belts that requires a suitable fire test, since clearly the Bunsen burner test currently in 30 CFR §18.65 is inadequate. Such a test must provide a higher level of thermal insult (for example incident heat flux or flame source intensity) than the Bunsen burner test. It is also important to use a single fire test that can be used to assess all the problems associated with fires on conveyor belts in the confined spaces of a mine.

2. It is now well known that the key issue in a fire is heat release. Heat release rate is the key factor in determining the fire hazard of upholstered furniture and is a much more important factor in fire safety than is ignitability. The attached paper by V. Babrauskas and R. Peacock, explains why heat release rate is the most important fire safety issue. As explained by Babrauskas and Peacock, the effect of doubling the heat release rate of one product in a standard compartment is that the survival time is reduced by a factor of more than three times (from > 600 seconds to just 180 seconds). On the other hand, if the time required for ignition of the product is doubled it has virtually no effect on survival time. It has been shown by a significant amount of work that some products can release enough heat to get a compartment to flashover. Flashover is "a stage in the development of a contained fire in which all exposed surfaces reach ignition temperatures more or less simultaneously and fire spreads rapidly throughout the space." As explained by NFPA 555, Guide on Methods for Evaluating Potential for Room Flashover, flashover occurs when the surface temperatures of combustible contents rise, producing pyrolysis gases, and the room heat flux becomes sufficient to heat all such gases to their ignition temperatures. Therefore it is best to use a heat release test for assessing the flammability of mine conveyor belt materials.

3. In terms of smoke release, the question has been posed: is it necessary to test for smoke release if a material shows excellent fire performance in a heat release or flame spread test, or is it enough to just develop low heat release products? Recent work [Hirschler 2004, attached] shows that of five series of tests conducted in room-corner tests (2 of them in Europe and 3 in the US), with a total of 84 materials tested, systematically some 10% of the materials (in fact 10 of the 84) give low heat release but very high smoke release. Therefore, it is important to also assess smoke release of materials, especially in a relatively secluded environment such as a mine. In the US, all codes require smoke release criteria for approval of interior finish materials, even if they meet the heat release and flashover criteria from the NFPA 286 room-corner test. The code requirements, total smoke release (TSR) of 1,000 m^2 in the NFPA 286 room corner test, is roughly equivalent to the 450 smoke developed index

(SDI) criterion used for the Steiner tunnel test. Therefore it is essential to assess smoke release from mine conveyor belts.

4. Smoke toxicity is of minimal consequence in fires, since the smoke toxicity of virtually all normal combustible materials is very similar. The toxicity of smoke in a fire is a function of four factors; the amount of materials burnt; the distribution of combustion products within the smoke; the individual toxic potencies of each combustion product found in the vapor phase; and the duration of exposure. Clearly, the greater the amount of material burnt the greater the toxicity of the smoke. In fact although roughly two-thirds of fire victims die from the effects of smoke inhalation, it is extremely rare for the root cause of their deaths to be that the smoke comes from a specific very toxic material. Fire fatalities are usually the result of inhaling too much smoke of average toxicity. More than 83 percent of fire deaths in building fires in the United States occur in fires that have become very large so that they extend beyond the room of origin, and thus generate too much toxic smoke [Hirschler 2006, attached]. This means that very few people actually die in fires that are small and that fire deaths are rarely due to burning or heat effects, even in small fires. All combustible materials release carbon monoxide (CO) when they burn. Once a fire has reached flashover – the moment when every combustible in the fire area is burning and the temperature exceeds 500°C – roughly 20 percent of the mass lost from the combination of any material has been converted into carbon monoxide (CO). This is almost irrespective of fuel composition or ventilation [Debanne et al., 1992, Hirschler 1994, both attached]. Most fire fatalities occur only after flashover. Thus, the smoke from fires that have reached flashover contains a baseline toxicity from carbon monoxide. The smoke toxicity from fire effluents other than CO is of little consequence, since there is enough smoke toxicity from carbon monoxide to cause fatalities. Under conditions where flashover is not achieved, smoke toxicity is calculated (with the N-gas model) by adding the contributions to overall smoke toxicity from each individual toxicant found in the smoke (or in the vapor phase). In a simplified approach, the overall smoke toxicity can be calculated under the general assumption that all smokes are similar in toxicity. This means that the overall smoke toxicity of most materials or products is very similar, and not that every component in smoke has the same toxic potency. With this approach, it is sufficient to assess an overall mass loss, and the criterion for the concentration time product (Ct) for lethality can then be considered to be 900 g min/m^3. This is consistent with various calculations that have been made by summing up abundant data from multiple sources. In general, the values of toxic potency of smoke have been found to range between 15 and 30 g/m^3, leading to Ct products of 450 to 900 g min/m^3 (for a 30 minute exposure, which is typically used in smoke toxicity tests). With the lesser toxicity (i.e. higher value) criterion in a normal size room that has a volume of about 36 m^3, lethality results following an exposure to the smoke resulting from burning no more than some 10 kg in just over 3 minutes (actually, a mass loss of exactly 10.8 kg over the 3 minutes). Therefore testing specifically for smoke toxicity is unnecessary and would deviate from a real effort to improve fire safety. See smoke toxicity scale figure below.



5. If the mass loss approach is not used, the overall smoke toxicity can also be calculated in more detail as a fractional effective dose (FED) using the formula shown in Equation 1. In Equation 1, $\sum_1$ (from 1 to n), corresponds to the summation of the effects of each one of n toxic gases, $\sum_2$ (from t_1 to t_2), corresponds to the summation of the relative concentration-time effects of the toxicants at each individual time increment (usually 1 min). C_i is the average concentration (in ppm) of the toxic gas "i" over the chosen time increment Δt and $(C\ t)_i$ are the specific lethal exposure dose (concentration-time product, in ppm•min). Fractional Effective Doses (FEDs) can be determined for each toxic gas (from 1 to n) at each discrete increment of time. The time at which their accumulated sum exceeds the lethal toxic dose represents the time available until lethality sets in with the actual concentrations measured. With this analysis, smoke toxicity depends both on the concentrations of toxic gases and on the intrinsic toxic potency of each component of smoke. This analysis is also based on the concept that the effects of both asphyxiant gases and irritant gases are a function of their dose (i.e. concentration and duration of exposure) and not simply of their concentration (as shown in studies of baboons and rats).

Abundant work has shown that the N-gas model should not be limited to asphyxiants and that the effect of irritants is also dose-related and should be added to the FED equation, including work by the FAA, by NIST and by SwRI [Hirschler 1990, 1991, 1994, 1995, 1999, 2000, 2006, Kaplan et al. 1989, Hirschler and Grand 1993, all attached].

$$FED = \sum_1 \sum_2 [C_i * \Delta t] / (C\ t)_i \qquad \{\text{Equation 1}\}$$

Typical lethal toxic potencies (in volumetric units of parts per million, ppm, for 30 minute exposures) for the major toxicants are:

LC_{50} CO:	4,000-5,100	Units: ppm
LC_{50} HCN:	150-200	Units: ppm
LC_{50} HCl:	3,700	Units: ppm
LC_{50} HBr:	3,000	Units: ppm
LC_{50} HF	2,500-2,900	Units: ppm
LC_{50} Acrolein:	90-200	Units: ppm
LC_{50} O_2 (oxygen depletion):	- 54,000	Units: ppm

This information can be used if desired, but it is not necessary for regulation.

6. An analysis of irritant gases shows that the scare about them has no foundation. The issue of smoke toxicity of individual toxicants is some times incorrectly addressed by separating asphyxiants from irritants. Asphyxiants are always properly addressed by using the N-gas model, whereby the fractional effective dose (or FED) for toxicity by asphyxiants is the summation of the exposure dose of the individual toxic gases, based on their individual concentration at each time period, just as in Equation 1. However, some people assume that irritant gases have no effect on FED for asphyxiants, a statement which is patently incorrect and is not based on any published scientific work. Thus, they assess the effects of irritants based on the bizarre concept of "incapacitating concentration" for dealing with irritants. This concept eliminates exposure time considerations, so that incapacitation occurs only after adding the effects of exposure to a toxic concentration at every time period. This means that as soon as a critical concentration of an irritant is reached, the victim is instantly incapacitated. This approach is reminiscent of denigrated concepts in use many years ago when people talked about "instant clampdown" resulting from PVC [poly(vinyl chloride)] smoke and developed "correction" factors when dealing with the toxicity of PVC smoke to make it look worse. The concept of "incapacitating concentration" is particularly unrealistic for people who have worked in a chemical research laboratory, where it is not uncommon for emissions of irritant gases (e.g. hydrogen chloride) to occur. However, there is no evidence that incapacitated researchers are found throughout chemical laboratories. It is worthwhile remembering also that human exposures to various toxic gases (especially including irritants) have been

conducted in Europe, in the late 19th century and early 20th century [Hirschler 2006, attached]. All of that work was summarized in a modern publication [Hinderer and Hirschler 1990, attached]; it clearly showed how researchers were able to continue being active and alert during exposure to high concentrations of irritants. Some of the experimental results of that work on humans are worth repeating:

* Lehmann 1886: A 30 year old man was exposed for 12 minutes to 600 ppm min of HCl. He had available a gas mask which he could use to breathe if conditions became intolerable. He found working in the room absolutely impossible after 12 min, part of which was spent outside. He had some irritation of the respiratory system (nose, larynx), irregular respiration solely through his nose, chest pains (needle-like sensation), shortness of breath, no eye irritation and no acid taste.

* Matt 1889: Three experiments were conducted, designed to address safe work-place concentrations of HCl and did not involve concentration which were incapacitating or lethal. On 12/13/1888 three men were exposed to 100 ppm min of HCl for 10 min. They experienced cold and acid sensation in nose, mouth and throat, no effect on their eyes, a slight discomfort in their larynx, trachea and lung, as well as some secretion and coughing. One man had slight head and chest pains. All men recovered immediately on leaving the HCl atmosphere. On 12/18/1888 one man was exposed to 1,050 ppm min of HCl for 15 min. He experienced little eye irritation, some irritation on breathing through the mouth, somewhat artificial respiration, irritation in the nose, throat, larynx, trachea and sternum, including "scratching" feelings and coughing. he had to exit the room because of chest pains. He experienced slight headache on termination of the experiment, which disappeared very rapidly. On 12/13/1888 one man was exposed to 1,500 ppm min of HCl for 15 min. He experienced slight irritation in his eyes, abundant tear secretion, a strong feeling of coldness and irritation in the nose, mouth, throat, larynx and trachea. His respiration was enhanced and his salivation increased. He experienced strong coughing and a sensation of heat in the head, forcing him to exit the room. On reentry, he experienced abundant coughing and catarrh. After the experiment he felt a slight headache and catarrh, which disappeared soon. As a result, the author recommended the following work-place limits for HCl:

10 ppm	Work unhindered
10-50 ppm	Work possible but uncomfortable
50-100 ppm	Work impossible

* Lehmann et al. 1908: A man (one of the authors, Dr. J. Yamada) breathed from a bottle containing progressively higher concentrations of HCl for periods of 20, 20 and 5 min respectively, and exhaled into another bottle. The inhaled doses were 4,021 ppm min, 4,107 ppm min and 5,170 ppm min. There were no ill effects whatsoever on the subject.

* In more recent times, it has been shown that irritants (such as HCl or acrolein) do not cause incapacitation of baboons (primates very similar to humans) or of rats at

dose levels so high that the victim eventually dies of inhalation toxicity after the exposure. This is a complex concept, but is critical: when animals have been exposed to doses of irritants at levels where they died a few days after exposure, they were still capable of performing the necessary avoidance responses to escape the exposure, thus not being incapacitated. Interestingly, it has also been found that incapacitation from asphyxiants occurs at levels very similar to those leading to lethality, and not at levels an order of magnitude lower.

* Thus, the type of statement frequently made regarding the inexistence of data on human exposure (or primate exposure) to irritants is misleading. This should not be used as excuse for presenting other concepts that have not been validated by experiments. Moreover, the pungent odor of most irritant gases (and their low odor detection level, often in the order of 1 ppm) means the warning appears at levels much lower than those at which any effect occurs. This is usually not being considered.

In consequence, irritant gases, such as hydrogen chloride, are of similar concern from the point of view of smoke toxicity as other gases and require no special concern.

7. Acid gases, such as hydrogen chloride, there is another issue that makes them less of a fire hazard problem: decay. Hydrogen chloride decays so that the airborne concentration is much lower after a short travel distance than it was when it was released. This has been discussed extensively and has been incorporated into fire hazard models [Galloway and Hirschler 1991, 1992, attached]. What this means is that there will be very little hydrogen chloride left to breathe at a short distance away from the fire.

8. I understand that the BELT test has been around for many years and that there is a significant amount of experience regarding its use with conveyor mine belt materials. However, the test is a fairly simplistic test that probably cannot be modified in order to be used to make smoke obscuration measurements.

9. A number of fire tests exist that can be used to assess smoke obscuration, including the NBS smoke chamber (ASTM E 662), the ISO smoke chamber (ISO 5659-2, ASTM E 1995) and small scale or large scale heat release tests [Hirschler 1990, 1991, 1993, all attached]. The ASTM E 662 and the ISO 5659-2/ASTM E 1995 tests are closed chambers which do not have recirculating air. They are perfectly reasonable as sources of data on materials but the data cannot be correlated with real-scale data, for two reasons: (1) if a material does not burn much but releases a lot of smoke per unit mass burnt the closed smoke chambers (either of them) will give the impression that it releases a lot of smoke but it probably will not release much actual smoke in real fires, and (2) the data from the closed chamber smoke chambers is not well correlated with data from large scale/real scale fires [Hirschler 1990, 1991, all attached]. Moreover, the smoke chambers cannot be modified to measure heat release or flame spread in addition to smoke obscuration.

10. It is very important to measure smoke in a manner that can be used to assess realistic fire hazard. There are several tests that can do that. In a small scale, the tests are the cone calorimeter (ASTM E 1354), the Ohio State University calorimeter (OSU, ASTM E 906) and the FM Fire Propagation Apparatus (FM FPA, ASTM E 2058). All three of these tests are excellent for assessing ignitability and both heat release and smoke release on the same sample. The data can also be used to extrapolate to full scale heat and smoke release. In fact all of them are being used for regulatory purposes at present. For example the cone calorimeter is being used to assess a variety of materials in codes, including children's playgrounds materials (at an incident heat flux of 50 kW/m^2), waste containers(at an incident heat flux of 50 kW/m^2), cleanroom materials and train interior materials (at an incident heat flux of 50 kW/m^2) and is the most widely used fire hazard fire test instrument in the world today, and is available to many (if not most) manufacturers of plastic materials and additives [Hirschler 2007, 2008, both attached]. The OSU calorimeter is being used for virtually all interior materials in aircraft (at an incident heat flux of 35 kW/m^2), by the Federal Aviation Administration (FAA) and the FM FPA is being used for cleanroom materials and cables (at 40% oxygen {compared to ca. 21% oxygen in air} and an incident heat flux of 50 kW/m^2). The use of high oxygen content is equivalent to increasing the heat flux significantly. All three instruments are available commercially from fire test instrument manufacturers.

11. All three instruments described above can be used at a variety of incident heat fluxes, which makes it possible to assess the fire hazard associated with more than one fire scenario. Thus, for example, it would be advisable to use the cone calorimeter at two incident heat fluxes, ranging from 35 kW/m^2 to 70 kW/m^2, which would cover a broad enough range of heat insult that is significantly higher than the one in the present regulatory test (recommended heat fluxes are 35 and 50 kW/m^2). The OSU should be used under the same conditions as the FAA uses it, at an incident heat flux of 35 kW/m^2, because aircraft built to that requirement have a proven fire safety record. The FM FPA apparatus should be used under conditions that are not as severe as the way the apparatus is used for cleanroom materials, since the materials for conveyor belts are not exposed to the extreme conditions (e.g. cleanliness) as in a cleanroom and the fire hazard is not as severe. The best recommendation is probably the use of the cone calorimeter, at two incident heat fluxes, 35 and 50 kW/m^2, with measurement of parameters for ignitability, heat release and smoke release that have been shown to be associated with low hazard.

/Marcelo M Hirschler

Dr Marcelo M. Hirschler

September 7, 2008

Attachments

GBH Attachment 1: Babrauskas and Peacock Paper
GBH Attachment 2: Curriculum Vitae of Marcelo M. Hirschler (CV)
GBH Attachment 3: Paper # 137 from CV
GBH Attachment 4: Paper # 166 from CV
GBH Attachment 5: Paper # 168 from CV
GBH Attachment 6: Paper # 185 from CV
GBH Attachment 7: Paper # 214 from CV
GBH Attachment 8: Paper # 236 from CV
GBH Attachment 9: Paper # 270 from CV
GBH Attachment 10: Paper # 347 from CV
GBH Attachment 11: Paper # 246 from CV
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GBH Attachment 25: Paper # 374 from CV
GBH Attachment 26: Paper # 206 from CV
GBH Attachment 27: Paper # 220 from CV
GBH Attachment 28: Paper # 247 from CV

GBH Attachment 1

AB59-COMM-7-1

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Heat Release Rate: The Single Most Important Variable in Fire Hazard*

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ABSTRACT

Heat release rate measurements are sometimes seen by manufacturers and product users as just another piece of data to gather. It is the purpose of this paper to explain why heat release rate is, in fact, the single most important variable in characterizing the 'flammability' of products and their consequent fire hazard. Examples of typical fire histories are given which illustrate that even though fire deaths are primarily caused by toxic gases, the heat release rate is the best predictor of fire hazard. Conversely, the relative toxicity of the combustion gases plays a smaller role. The delays in ignition time, as measured by various Bunsen burner type tests, also have only a minor effect on the development of fire hazard.

INTRODUCTION

The 1988 edition of the compilation of fire tests[1] by the American Society for Testing and Materials (ASTM) alone lists some 77 tests. ASTM is only one of many US and international organizations publishing fire test standards; thus, the actual number of fire tests in use is at least in the hundreds.[2] It is customary to divide the actual fire test standards into two broad categories: (1) reaction-to-fire, or flammability, and (2) fire endurance, or fire resistance.

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* This paper is a contribution of the National Institute of Standards and Technology and is not subject to copyright.

The paper is based on a talk presented at the 1990 Fall meeting of the Fire Retardant Chemical Association, Ponte Vedra Beach, Florida.

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Reaction-to-fire is how a material or product responds to heating or to a fire. This includes ignitability, flame spread, heat release, and the production of various—toxic, obscuring, corrosive, etc., products of combustion. Reaction-to-fire largely concerns the emission of undesired things, e.g. how much heat is emitted, how much smoke, or how fast does the first emission start (ignitability). A reaction-to-fire test is typically performed on *combustibles.*

Fire endurance, by contrast, asks the questions: how well does a product prevent the spread of fire beyond the confines of the room? And, how well does it continue to bear load during the fire? Such a test is performed on *barriers to fire* and *load-bearing elements,* such as walls, floors, ceilings, doors, windows and related items.

The scope of the present paper is restricted to reaction-to-fire tests only.

Manufacturers of resins, fire retardants, and plastic products are accustomed to describing reaction-to-fire performance according to two tests: the UL 94 vertical Bunsen burner test[3] and the limiting oxygen index (LOI) test.[4] The LOI test determines under how low an oxygen fraction a test specimen can continue burning in a candle-like configuration. It has never been correlated to any aspect of full-scale fires. The UL 94 test was developed to determine the resistance to ignition of small plastic parts, such as may be found inside electric switches. For this purpose, it is an accurate simulation of a real fire source. A problem arises when UL 94 data are used, as they often are, to imply how large surfaces or objects made of a particular material might perform. For such situations, when the product is larger than the very small objects envisioned by UL 94, we wish to ask what the proper approach is to evaluating the fire performance.

In this paper, we will provide a brief historical overview of bench-scale reaction-to-fire tests and the relation to hazard in fires. We will then turn to the meaning of heat release in a fire. We will show that although bench-scale heat release rate tests were developed quite early, they could not be put to widespread use without the parallel capability for making heat release rate measurements in full-scale room fires, as a basis for validating the bench-scale tests. We will then provide several examples illustrating the development of fire hazard in full-scale room fires and demonstrate that the heat release rate is, in fact, the most essential variable controlling the rate at which untenable conditions occur. Finally, we will illustrate, by example, the process of combining bench-scale testing and computational techniques to predict successfully the full-scale development of fire hazard.

HISTORICAL BACKGROUND

Early reaction to fire tests

Early reaction-to–fire tests were not developed for general fire protection use. Instead, the development of tests was first done for very narrow, specialized product categories. The earliest standard reaction-to-fire test of which we have a record was for the performance of fire-retarded wood. In 1902, the pioneering Columbia University professor Ira H. Woolson started working with the US Navy to develop a standard test for the burning behavior of fire retardant wood.[5] This test (Fig. 1) was called the 'timber test' and was used for a number of years. Later, additional specialized test methods were devised for that purpose[6] in the 1920s.

The next reaction-to-fire test of which we have a record was from 1905. After a series of disastrous theater fires, the famed American engineer John R. Freeman developed a 'stovepipe' test for flammable fabrics.[7] In this test, strips of test cloth were hung inside a 2-ft-high chimney, and lighted by excelsior kindling at the bottom. Since this was not a readily portable test, he also commissioned the development of an

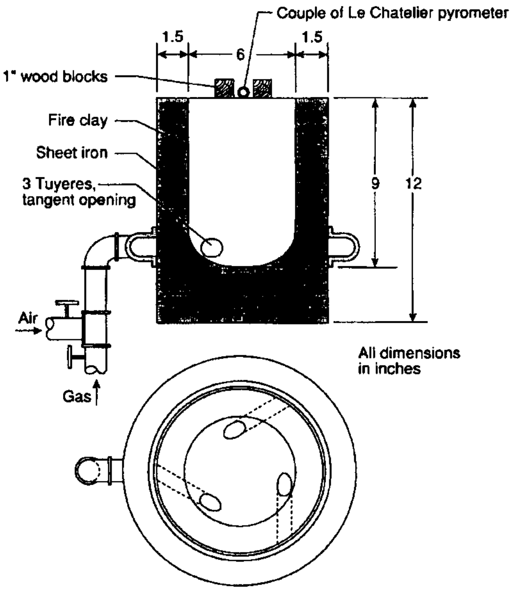

Fig. 1. The first-ever standard reaction-to-fire test method, the 'timber test'.

alcohol-lamp field test. This was known as the Whipple–Fay test, after the names of the two persons hired by Freeman to develop the test. Neither of these became a standard test. The first standard tests for the flammability of textiles arose in England with the alcohol-cup test of the British Standards Institution in 1936,[8] and in the USA with the first version of the current NFPA 701 Bunsen-burner test, proposed by the National Fire Protection Association in 1938.[9]

Flammable fabrics, however, pose a very specialized fire hazard. These can cause injury if they are garments which are ignited on the wearer. In addition, in public spaces, curtains and decorative fabrics can spread fire at a very high speed. Such fires, however, typically burn only a very short time and are not likely to be directly hazardous to those not intimately involved with them. The more serious danger comes from the fact that other combustible materials can be ignited by such textiles. Thus, for materials such as textiles, which are thin and have little combustible mass, the main fire hazard that must be recognized and measured is rapid flame spread. For most other combustibles, the situation, as we shall see, is different.

The need to measure the flammability of additional categories of combustibles was seen during the late 1930s. This resulted in the first Bunsen burner tests for plastics being developed in 1940.[10] In the same period, A. J. Steiner, of Underwriters Laboratories, also developed the Steiner Tunnel Test.[11] This was intended primarily for testing flame spread along cellulosic products, and has since become the main reaction-to-fire test used in US building codes. The method also incorporated a smoke measurement and a 'fuel contributed' measurement, which can be taken to be a crude form of heat release rate. In recent years, this 'fuel contributed' measurement has been de-emphasized, and the current ASTM procedure no longer requires that a specific classification be derived from it.[12]

Quantifying hazard in fire

During the 1970s it came to be felt that knowledge about the toxicity of materials was the 'missing link' in understanding fire hazard. Thus, a number of tests were developed and proposed in this area, although none have yet been accepted by US or UK standards organizations or by ISO. Nonetheless, methods for measuring the toxic potency of materials (e.g. the NBS Cup Furnace Method[13]) started being widely used in the 1980s. Yet, the data from them could not be treated in a useful engineering way, since a suitably comprehensive analysis methodology was lacking.

One of the earliest milestones in the search for methods to quantitatively evaluate the fire hazard in buildings was a 2-day workshop on 'Practical Approaches for Smoke Toxicity Hazard Assessment',[14] sponsored by the National Fire Protection Association in February 1984. This workshop convened groups of leading toxicologists, fire protection engineers, fire scientists, fire modelers, and code and fire service representatives to study the problem. Later in 1984, the Toxicity Advisory Committee of NFPA proposed a simple four-step procedure[15] derived from the workshop's efforts. As the project progressed, papers were published which discussed the evolving philosophy and structure of the hazard assessment methodology.[16,17] These papers, and the growing questions regarding combustion product toxicity, stimulated some early hazard analyses using both hand-calculated estimates and some of the available fire models.

In May of 1984, the Toxicity Advisory Committee of the National Fire Protection Association published a procedure for providing 'order of magnitude estimates' of the toxic hazards of smoke for specified situations.[18] In this report, Bukowski based the estimating procedure on a series of algebraic equations, which could be solved on a hand calculator. Individual equations were provided to estimate steady-state values for such parameters as upper layer temperature, smoke density, and toxicity; and graphical solutions were provided for room filling time. This work was followed by the more extensive compilation of such equations for use by the US Navy in assessing fire hazards on ships.[19] Subsequently, the Toxicity Advisory Committee was asked by the National Electrical Code Committee for assistance in addressing a toxicity hazard question regarding polytetrafluoroethylene (PTFE) plenum cables. In providing that help, a hand-calculated analysis was performed.[20] This paper concluded for a single, specified scenario, that the size of room fire needed to cause the decomposition of the cable insulation would itself cause a toxicity hazard in an adjacent space before the cable would become involved.

Several systematized procedures for evaluating the fire hazard in buildings by means of 'hand-crank' computations have been put forth.[21,22] Such computations are simple to perform and can be suitable for estimating. However, the algebraic equations used are limited to steady-state analyses, and cannot deal consistently with the transient aspects of fire behavior. A more complete answer requires a computer to solve the differential equations which describe these transient phenomena. This is the role of computer fire models.

The computer models currently available vary considerably in scope, complexity, and purpose. Simple 'room filling' models such as the

Available Safe Egress Time (ASET) model[23] run quickly on almost any computer, and provide good estimates of a limited number of parameters of interest for a fire in a single compartment. A special purpose model can provide a single function, e.g. COMPF2[24] calculates post-flashover room temperatures. And, very detailed models like the HARVARD V code[25] predict the burning behavior of multiple items in a room, along with the time-dependent conditions therein. In addition to the single-room models mentioned above, there are a smaller number of multi-room models which have been developed. These include the BRI (or Tanaka) transport model[26] which served as a basis for the FAST model included as part of HAZARD I, and the HARVARD VI code[27] a multi-room version of HARVARD V. All of these models are of the zone (or control volume) type. They assume that the buoyancy of the hot gases causes them to stratify into two layers; a hot, smokey upper layer and a cooler lower layer. Experiments have shown this to be a relatively good approximation. While none of these models were written specifically for the purpose of hazard analysis, any of them could be used within the hazard framework to provide required predictions. Their applicability depends upon the problem and the degree of detail needed in the result.

Over the past few years, models began to be used within a hazard analysis framework to address questions of interest. In 1984, Nelson published a 'hazard analysis' of a US Park Service facility which used a combination of models (including ASET) and hand calculations.[28] The calculations were used to determine the impact of various proposed fire protection additions (smoke detectors sprinklers, lighting, and smoke removal) on the number of occupants who could safely exit the building during a specified fire incident.

In 1985, Bukowski conducted a parametric study of the hazard of upholstered furniture using the FAST model.[29] Here, the model was used to explore the impact of changes in the burning properties of furniture items (burning rate, smoke production, heat of combustion, and toxicity) on occupant hazard relative to the random variations of the different houses in which the item might be placed. These latter variables were room dimensions, wall materials, and the effect of closed doors. The conclusion was that reducing the burning rate by a factor of two produced a significantly greater increase in time to hazard than any other variable examined. So much so that the benefit would be seen regardless of any other parameter variation. Results such as this can show a manufacturer where the greatest safety benefit can be achieved for a given investment in redesign of his product.

A more recent example of a hazard analysis application is the elegant work of Emmons on the MGM Grand Hotel fire of 1980. This work, conducted during the litigation of this fire was only recently published.[30] Using the HARVARD V model, Professor Emmons analyzed the relative contributions of the booth seating, ceiling tiles and decorative beams, and the HVAC system, all in the room of origin, on the outcome of the fire. A report issued by the National Academy of Sciences[31] provides two hazard analysis case studies—one making use of the HARVARD V model and the other using experimental data. The cases deal with upholstered furniture and a combustible pipe within a wall, respectively.

It is fairly obvious that one of the first questions a person might wish to ask about the hazard of a building fire is 'How big is the fire?' Thus, it is exceedingly curious, in hindsight, that until fairly recently there was no quantitative way of asking or answering this question. Nowadays, we know that, in quantitative terms, this means, 'Tell me the heat release rate of the fire.' We also know that the heat release rate is measured in kilowatts (kW), or some multiple, e.g. megawatts. We further realize that this is not the same thing as asking what is the flame spread rate of the fire. Thus, neither the E 84 flame spread test nor the Bunsen burner ignitability tests will help us answer this question. It is clear that knowledge of underlying variables related to burning rate is the key to understanding and quantifying the hazard in unwanted fires. Measurement of the heat release rate provides this understanding.

MEASUREMENT OF HEAT RELEASE

Small-scale tests

The fuel-contributed measurement done in E 84 does not qualify as a *measurement* of heat release rate since it is not in the physically correct units of kW. The first apparatus in which heat release rate was measured quantitatively, in correct (albeit, British) units was the FM Construction Materials Calorimeter. It was developed by Thompson and Cousins at the Factory Mutual Research Laboratories in 1959.[32] This was a medium-scale test, with a specimen size of 1·22 by 1·22 m. The method was cumbersome to run and has only been used by the FM system. It is still in use at FM today as part of an approval standard for steel deck roofs.[33]

Progress in heat release rate was still not being made, once the FM test was available, for two reasons: (1) the method was only intended for testing roof decks; and (2) it was a medium-scale test, and there was no room-scale test yet available. If we assume the purpose of a bench-scale test is to reproduce room-scale fire behavior, it becomes clear that little progress in developing bench-scale test methods could be made until heat release rate could be satisfactorily measured in room fires. During the 1970s the small-scale HRR test which came into the widest use was the Ohio State University apparatus (ASTM E 906).[34] This was accompanied by a room fire model[35] which used the bench-scale HRR data to predict large-scale product performance. The OSU HRR apparatus was appealing for its simplicity even though substantial systematic errors accompanied the measurement; thus, it became rather well-known and used in the era prior to when the profession shifted over to using oxygen consumption based methods. The OSU room fire model, however, was based on physics approximations which were not well accepted and, thus, did not play a significant role in hazard quantification.

During the 1970s Parker[36] and Sensenig[37] pioneered the use of oxygen consumption calorimetry as a way of making HRR measurements substantially freer of systematic error. The technique for doing it has been described by Parker[38] and forms the basis for all subsequent HRR measuring apparatuses, both bench-scale and room-scale. As an example, the FMRC Flammability Apparatus[39] was developed using the oxygen consumption technique, but it did not become a standardized HRR test. In fact, during the late 1970s and early 1980s interest in bench-scale HRR testing remained rather small. We now realize that the proper fire hazard assessment role for a bench-scale test is to predict the full-scale fire behavior.[40] However, correlations establishing the successful prediction of the full-scale fire behavior could not be established until adequate capability was available to measure the heat release rate in the full scale.

Having established some of the major historical milestones in this area, we shall examine the current situation in a later section.

Room-scale tests

The first attempt to develop some technique for measuring rate of heat release in full scale was in 1978, by Warren Fitzgerald, at Monsanto Chemical.[41] The Monsanto Calorimeter involved measurements of temperatures at numerous thermocouple locations, from which a heat release rate was computed. This method, because of its uncertain computational premises and its limited measurement capacity, did not obtain acceptance.

The first room-scale test for heat release rate to win widespread acceptance was the 1982 draft ASTM room fire test.[42] This method forms the basis of all current-day room fire tests, which are only different in minor details from the 1982 draft method. Peacock & Babrauskas have reviewed the history of room fire tests in greater detail;[49] again, we will return to the current situation later in this paper.

EXAMPLES OF THE IMPORTANCE OF HEAT RELEASE RATE

To determine what is most important to consider in building fires, we first restrict ourselves to 'typical' building fires. This means we exclude as special those fires which are associated with gas or dust explosions, or where the victims are injured by direct burns from flammable clothing or faulty appliances. Instead, we consider the typical fire where occupant death or injury occurs from an ignition source not in immediate contact with this person, the fire spreads, grows, and then does or does not result in death or injury. Such fires can be broken down into their constituent phenomena:[40,44]

ignition;
flame spread;
heat release rate and, closely related, the mass loss rate;
release rates for smoke, toxic gases, and corrosive products.

The real-scale fire hazard can be assessed by tracking incapacitation or mortality of building occupants during the course of the fire. Increased hazard is identified with earlier incapacitation/mortality or with greater total numbers of victims. We now wish to determine which of the above fire phenomena, and, specifically, which variables, are most strongly associated with increased fire hazard. To examine the relative importance of these phenomena, we will consider two examples.

Example I—A single upholstered chair burning in a room

The first example will be a simple case where we consider variations on a scenario of a single upholstered chair burning in a room with a single doorway opening. The procedures detailed for HAZARD I by Bukowski *et al.*[45] and Peacock & Bukowski[46] were used to calculate the hazard for the scenarios. Fire performance data for the burning chair in the base case were taken directly from the fire properties data base included with HAZARD I. To assess the relative importance of several factors, the following variations were studied:

base case, single burning chair in room;
double heat release rate of chair;
double toxicity of materials;
halve ignition delay of burning chair from 70 to 35 s.

The general development of these fires is shown in Fig. 2, where the predicted temperatures and CO_2 levels in the upper layer of the room are given. Although other gas species could be chosen as indicators of toxicity, the CO_2 concentration is representative of the type (and shape) of curves for other gases. As expected, changing the heat release rate has a much greater effect than the change in ignition time. (Although we note that improved ignition performance can also, in some cases, *prevent* a fire from occurring. The analysis of product performance which includes both fires that occur and fires that are prevented falls into the category of risk analysis, and is outside the scope of the present paper.) The relative effect of changes in the toxicity can be seen in Table 1, as calculated from the simulations illustrated in Fig. 2.

Comparing the results for the four scenarios, it is apparent from the predicted time to death that changing the heat release rate has by far the greatest effect on the tenability of the space, reducing the time to death from greater than 600 s (the total simulation time) to about the same time as the time to incapacitation for all other scenarios.

In this simple example we have treated the burning product as if its characteristics were completely uncorrelated, that is, that we could, for example, change the ignition delay time without altering at all the heat release rate characteristics. In practice, there is very likely to be some

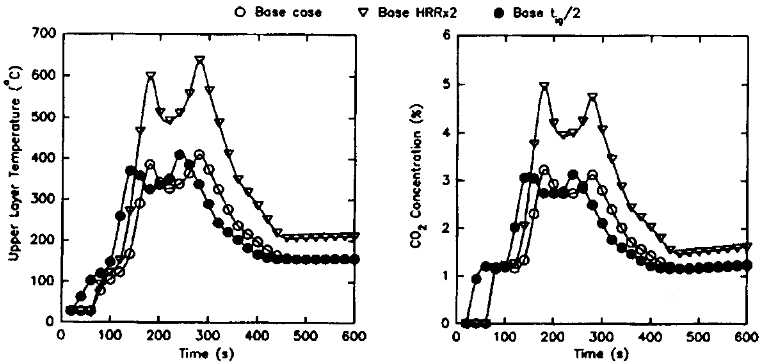

Fig. 2. Results of simulations with HAZARD I: Example I.

TABLE 1
Results for Example 1.

Scenario	*Time to incapacitation (s)*	*Time to death (s)*
Base case	180	>600
Double heat release rate	160	180
Double material toxicity	180	>600
Halve ignition delay	140	>600

degree of correlation amongst various of the reaction-to-fire properties of a product. Thus, it is also of interest, next, to look at the behavior of some actual tested products.

Example II—Multiply furnished rooms

In the previous example, only the burning in a room of a single item is considered. For a more realistic, albeit more complex example, we can turn to the study done by NIST for the Fire Retardant Chemicals Association (FRCA).[47] In the FRCA study, five different categories of products were assembled and tested in full-scale room fires. In one series, all five products were fire retardant, whereas in the other series the same base polymers were used, but without fire retardant agents. The products included upholstered chairs, business machine housings, television housings, electric cable, and electronic circuit board laminates. These products were studied thoroughly in full-scale fires, in bench-scale tests, and by computer modeling. For present purposes, however, we wish to concentrate on one aspect, the identification of the most important physical variable in these tests which is a predictor of the fire hazard.

To do this, we can consider the results in Table 2.

In this test series, the two most important measures of fire hazard were the time to reach untenable conditions (reflecting hazard to nearby occupants), and the total toxicity, expressed as CO-equivalent kilograms (reflecting hazard to far-removed occupants). The differences between the performance of the FR and non-FR product series were striking. (Within each series, the different tests conducted indicate replicates or slight scenario variations.) One might conjecture that the fire hazard performance could be predicted by the yields of CO observed for these two series. Clearly, Table 2 shows that such is not the case. Other variables, such as toxic potencies (LC_{50} values), derived

TABLE 2
Results for Example 2.

Products	*Test no.*	*Fire hazard condition*		*Predictive variable*	
		Total toxicity, expressed as (CO-equiv. kg)	*Time to reach untenable conditions in burn room (s)*	*CO yield (kg/kg)*	*Peak heat release rate (kW)*
non-FR	N1	21	110	0·22	1 590
non-FR	NX0	17	112	0·18	1 540
non-FR	NX1	16	116	0·14	1 790
FR	F1	2·6	∞	0·22	220
FR	FX0	5·5	1 939	0·23	370
FR	FX1	6·1	2 288	0·23	350
FR	FX1a	5·6	1 140	0·23	450

from the individual products tested, although more difficult to evaluate, show the same non-prediction. Likewise, time-to-ignition data for the five products in the two series show ignition time differences ranging from negligible to about two-fold. Thus, ignition behavior is also clearly unable to predict the much superior fire hazard performance exhibited by the FR products. By contrast, the peak heat release rates, shown in the last column, delineate quite clearly the difference between the two series.

The two examples presented above are only several possible illustrations of an infinite number of possible scenarios; a few may exhibit different trends. Nonetheless, these above results are consistent with numerous other studies, such as Ref. 29, and with the detailed understanding of the physics of room fires.[48]

PREDICTION OF REAL-SCALE FIRE HAZARD FROM BENCH-SCALE TESTS

Basically, the same variables—ignition, flame spread, heat release rate, and release rates for other products of combustion—can be measured in real-scale fires and in bench-scale fire tests. The ability to measure these quantities in bench-scale tests has improved enormously since the first efforts of 1959. It has become accepted practice that *all* heat release rate testing—in bench scale, in room scale, and in intermediate scale

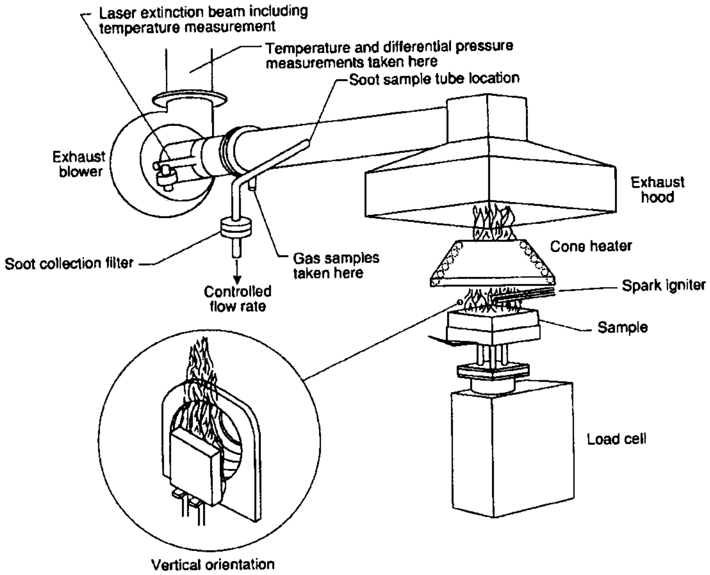

Fig. 3. A schematic view of the cone calorimeter.

(furniture calorimeters)—is done in apparatuses which are based on the oxygen consumption technique. The most widely accepted are the ones standardized by the International Organization for Standardization (ISO). ISO has adopted the Cone Calorimeter as its bench-scale method (ISO DIS 5660) for measuring HRR.[49] The same method has also been issued by ASTM as E 1354.[50] The Cone Calorimeter (Fig. 3) has been designed to measure simultaneously, not just the heat release rate, but also ignitability, smoke production, and the production of a number of toxic gas species.[51] For room-scale testing, the ISO room corner test (ISO DIS 9705) is used.[52] For testing products at an intermediate scale, open-air hood systems, again using the oxygen consumption technique, are employed. ISO has not yet worked on standardizing such 'furniture calorimeter,' but the standard most commonly specified is the one published by NORDTEST.[53] The above, then, comprise the modern toolkit for measuring HRR; while scale and appearance is different they are unified by using a common measurement technique for making the fundamental HRR measurement.

Even though the very same phenomena are measured in real-scale fires and in bench-scale tests, it does not mean that there is necessarily a simple, direct relationship between the two. In very simple cases, this can be true. For instance, if small-flame ignition is to be assessed, a bench-scale small-flame ignition test represents identically the situation occurring in the real-scale fire.

As we have seen, however, ignition variations compose but a small component of expected fire hazard. Our primary focus, instead, must be in predicting the real-scale heat release rate. Since peak hazard is associated with peak heat release rate, it is then the peak value that we wish to predict. The first successful example of such prediction has been for upholstered furniture. In an extensive NIST study on fires with residential upholstered furniture, it was found that the peak real-scale heat release rate can, indeed, be predicted from bench-scale Cone Calorimeter measurements.[59] However the relationship is not

peak real-scale HRR versus peak bench-scale HRR

but, rather,

peak real-scale HRR versus 180 s average bench-scale HRR.

An average, rather than the peak HRR is needed from the bench scale due to the physics of burning: at the time the peak HRR is being registered in the room fire, not every portion of the burning item is undergoing its peak burning—some portions are already decaying, while others are barely getting involved. Statistical considerations then lead to 180 s as a useful length of the averaging period.[54]

Another example where a more complicated relationship has to be sought is for combustible wall linings. Wickström & Göransson[55] found that, for predicting room fires caused by combustible wall linings, the heat release rate in the real-scale fires was predicted not by bench-scale heat release rate measurements alone, but by a combination of heat release rate and ignition measurements, as determined in the Cone Calorimeter. The ignition time, here, is not used to describe the ignition event. Instead, it is known that radiant ignition and flame spread are both governed by the same material properties (thermal inertia and ignition temperature) of the specimen. Thus, in the Wickström/Göransson method, use of the ignition time data allows the entire prediction to be made from the use of Cone Calorimeter data, without needing to introduce a second test for obtaining flame spread parameters. More complex models are also available[56,57] which do require input from additional tests.

SUMMARY

Reaction-to-fire tests have been in use since the early 1900s. Those most commonly used for plastics—UL 94 and the LOI test—do not predict the development of hazard in room fires. Fire deaths are most commonly the result of toxic products of combustion. The actual hazard produced depends on many factors, including the rapidity of ignition and the toxic potency of the gases. Nonetheless, it is illustrated that the *most significant predictor of fire hazard is the heat release rate.* Our ability to predict this most important aspect of fires is relatively very recent, since the first standard method for quantitatively measuring heat release rate in room fires was not available until 1982. During the 1980s, bench-scale techniques for making measurements which can predict the real-scale heat release rate were defined and put into place. Thus, all the needed tools are now at hand to enable the correct, quantitative computation of room fire hazard, based on correctly designed bench-scale tests.

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GBH Attachment 2

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* December 1986 - February 1991
R & D Manager - Fire Sciences
BFGoodrich Co. - Geon Vinyl Division, Avon Lake, Ohio

* June 1986 - December 1986
Sr. R & D Associate - Flammability
BFGoodrich Co. - Geon Vinyl Division, Avon Lake, Ohio

* August 1984 - June 1986
R & D Associate - Flammability
BFGoodrich Co. - Chemical Group, Avon Lake, Ohio

* October 1977 - July 1984
Temporary Lecturer (Physical Chemistry)
Department of Chemistry - The City University, London, England

* October 1975 - October 1977
Post Doctoral Research Fellow
School of Molecular Sciences - University of Sussex, Brighton, E. Sussex, England

* June 1975 - October 1975
Researcher - Physical Chemistry of Carbons
R & D Department - ALUAR Aluminio Argentino, Buenos Aires, Argentina

* March 1971 - June 1975
Post-graduate Research Assistant, Department of Physical Chemistry
School of Pharmacy and Biochemistry - University of Buenos Aires
Buenos Aires, Argentina

* March 1970 - December 1971
Undergraduate Teaching Assistant, Department of Physical Chemistry
School of Exact and Natural Sciences - University of Buenos Aires
Buenos Aires, Argentina

MEMBERSHIP PROFESSIONAL SOCIETIES

- Amer. Soc. for Testing and Materials (ASTM): Subcommittees: E-5 (Fire Standards), C-16 (Thermal Insulation), D-9 (Electrical Materials), D-11 (Rubber), D-13 (Textiles), D-20 (Plastics), E-34 (Occupational Health & Safety), F-7 (Aerospace), F-8 (Sports Equipment and Facilities), F-15 (Consumer Products), F-23 (Protective Clothing), F-25 (Shipbuilding) and F-33 (Correctional Facilities)
- Canadian Standards Association (CSA)
- Combustion Institute (Western States Section)
- Institution of Electrical and Electronic Engineers (IEEE)
- Int. Assoc. for Fire Safety Science
- Int. Assoc. Of Plumbing and Mechanical Officials (IAPMO)
- Int. Heat Release Association
- National Fire Protection Association (NFPA) (Various Sections)
- Royal Society of Chemistry (M.R.S.C., C. Chem.)
- International Code Council (ICC)

LANGUAGES

English, German, Spanish, French

SOME AWARDS

- Interflam Trophy (UK): 1988
- ASTM E-5 Certificate of Appreciation: 1989
- Wire Association International: Best Electrical Paper 1989.
- ASTM Society Frank W. Reinhardt Award for Fire Terminology: 1990.
- ASTM E-5 Award of Recognition: 1995
- ASTM E-5 Award of Recognition: 1998
- Canadian Standards Association: Award of Merit: 1999
- ASTM D-9 Award of Appreciation: 2001
- ASTM E-5 Wayne Ellis Award from Society Chairman: June 2002
- ASTM E-5 Award of Appreciation: 2005
- ASTM E-5 Award of Special Recognition: 2006
- ASTM D-20 Award of Appreciation: 2006
- ASTM E-5 Award of Appreciation: 2007

ACTIVITIES

Marcelo Hirschler Provides Technical Expertise in Fire Safety Including:

- **Product Liability Expert Witness**
- **Codes and Standards**
- **Fire Safety Research and Testing Projects**

WORK ACCOMPLISHED

■ Consultancy

Product Liability: Expert Witness on Fire Safety Subjects

- Fire safety of mattresses
- Fire safety of upholstered furniture
- Flammability of textiles, including apparel and protective clothing
- Fire safety in transportation, including especially automobiles and trains
- Fire properties and fire testing of plastics
- Fire properties and fire testing of cables
- Smoke toxicity
- Smoke corrosivity
- Fire hazard
- Codes and standards

Fire Research (Public Activities)

- Manager Program for Interlaboratory Precision of Intermediate Scale Calorimeter Test Method (ASTM E1623) (1997-1998)
- Technical Coordinator, Fire Protection Research Foundation (NFPA, FPRF) Research Advisory Council on Transportation Vehicles (2002-06)
- Member of NIBS Smotox Steering Committee (1987-91)
- Member of NFPRF Risk Assessment Advisory Committee (1987-91)
- Session chairman at many fire conferences, including: Fire and Materials (1992 -), Materials for Increased Fire Safety at Int. Conf. Fire Safety (Dr. C.J. Hilado) (1987-98), BCC Flame Retardancy (1990-2005), Int. Assoc. Fire Safety Science, Combustion Institute, American Chemical Society Fire & Polymers, Fire Retardant Chemicals Association.

Editorial

- Associate Editor, Fire and Materials Journal (1991-)
- Editor: Flame Retardancy News (2005)
- Editor: Fire Safety & Technology Bulletin (2006 -)
- Member Editorial Board Journal Fire Sciences, Fire Safety Journal, Fire & Flammability Bulletin (1995 to 2003), Journal of Testing and Evaluation.

Codes and standards:

- **ASTM E05:**

* Chairman ASTM E-5.15: Subcommittee on Fire and Interior Furnishings and Contents (1990-95)
* Chairman ASTM E-5.31: Subcommittee on Fire Terminology and Editorial (2000-5)
* Chairman ASTM E-5.21: Subcommittee on Smoke and Combustion Products (2004-)
* Recording Secretary ASTM E05: Committee on Fire Standards (2000-5)
Member-at-large of executive subcommittee of ASTM E05 (2006 - 07)
* Membership Secretary ASTM E05 (2008-)

- Recording Secretary ASTM E-5.15:Subcommittee on Fire and Interior Furnishings and Contents (1988-90 and 1996-)
- Recording Secretary ASTM E-5.91: Subcommittee on Planning and Review of Fire Standards (1990-1999 and 2000-)
- Recording Secretary ASTM E-5.17: Subcommittee on Fire and Transportation (2003-)
- Chairman ASTM E-5.22.02: Task Group on ASTM E 84 Steiner Tunnel Mounting Methods (2002-). Developed practices ASTM E 2231 and ASTM E 2404.
- Chairman ASTM E-5.13.1: Task Group on ASTM E603, Standard Guide for Room Fire Experiments (1992-).
- Chairman ASTM E-5.13.8: Task Group on New Practice for Large Scale Heat Release Tests (1997-). Developed test method ASTM E 2257.
- Chairman ASTM E-5.15.3: Task Group on Fire Hazard Assessment of Floor Coverings (1987-92)
- Chairman ASTM E-5.15.8: Task Group on Full Scale Fire Testing of Upholstered Furniture (1989-). Developed test methods ASTM E1537, ASTM E1590 and ASTM E1822.
- Chairman ASTM E-5.15.12: Task Group on Vandalized Mattresses for Correctional Institutions (1991-93)
- Chairman ASTM E-5.15.13: Task Group on Fire Hazard Assessment of Upholstered Furniture (1994-). Developed ASTM E 2280, Standard guide on fire hazard assessment for health care occupancies.
- Chairman ASTM E-5.17.94: Task Group on Fire Hazard Assessment of Rail Transportation Vehicles (1991-). Developed ASTM E2061, new guide on fire hazard assessment of passenger rail vehicles.
- Chairman ASTM E-5.21.13: Task Group on Smoke Toxicity for Flashover Fires (1993-)
- Chairman ASTM E-5.21.33: Task Group on ASTM E906 (Ohio State University Rate of Heat Release Apparatus) (1994-2004). Developed new version of standard.
- Chairman ASTM E-5.21.34: Task Group on Intermediate Scale Calorimeter (1997-2004). Managed interlaboratory round robin for ASTM E 1623 and updated standard.
- Chairman ASTM E-5.21.35: Task Group on Rate of Heat Release Apparatus by Thermopile Method) (1995-). Developed new test method ASTM E 2102.
- Chairman ASTM E-5.21.3: Task Group on ISO (5659-2) Smoke Chamber (1995-2004) and NBS Smoke Chamber. Developed new test method ASTM E1995 & updated ASTM E 662.
- Chairman ASTM E5.31/91 Task Group on Uncertainty (2002-)
- Chairman ASTM E-5.32.2: Task Group on 1990 Symposium on Fire Hazard and Fire Risk Assessment (1988-1992). Editor of ASTM STP 1150 (Fire Hazard & Fire Risk Assessment)
- Chairman ASTM E-5.35.2: Task Group on Examples of Fire Hazard Assessment Standards (1989-91)

- **NFPA**

- Chairman NFPA Technical Committee on Hazard and Risk of Contents and Furnishings (2001-)
- Chairman NFPA Technical Committee on Glossary of Terms (2007 -)
- Member NFPA Life Safety Technical Committee on Furnishings and Contents (1991-)
- Member NFPA Technical Committee on Hazard and Risk of Contents and Furnishings (1991-)
- Member NFPA National Electrical Code CMP 15: National Electrical Code Panel on Places of Assembly (1993-2001)
- Member NFPA Technical Committee on Fire Tests: (1996-)
- Member NFPA Technical Committee on Merchant Vessels: (1998-)
- Member (Alternate, for Society of the Plastics Industry) of NFPA Technical Committee on Fixed Guideway Transit Systems [Trains]: (2001)

* Member (for American Fire Safety Council/Plenum Cable Association) of NFPA Technical Committee on Air Conditioning [NFPA 90A-B]: (2002-)

- **ASTM D09**

* Chairman ASTM D-9.94: Subcommittee on Terminology and Editorial (2008-)
* Secretary ASTM D-9.94: Subcommittee on Terminology and Editorial for Electrical Insulation Materials (1994-2008)
* Chairman ASTM D-9.21.3: Task Group on Smoke Obscuration on Burning of Electrical Cables (1987-). Developed ASTM D5424.
* Chairman ASTM D-9.21.7: Task Group on Rate of Heat Release from Electrical Cables (1992-). Developed ASTM D5537 and ASTM D6113.
* Chairman ASTM D-9.21.1: Task Group on Fire Hazard Assessment of Electrotechnical Products (1995-). Developed Guide ASTM D5425.
* Chairman ASTM D-9.97-1: Task Group on March1999 "90th Anniversary Symposium on Electrical Insulating Materials: International Issues" (1997-1999). Editor of ASTM STP 1376 (1999).
* Chairman ASTM D-9.97 Task Group on ASTM D9 Symposium on Electrical Materials and Fire October 2004.

- **ASTM F33**

* Chairman ASTM F33.05 Task Group on Furnishings within Detention Occupancies (1997-). Developed new test methods ASTM F 1534 and F 1550 and new guide ASTM F 1870.

- **ASTM D20, ASTM F15. ASTM F08 and other ASTM committees:**

Task group chair and member various task groups.

- **CSA (Canadian Standards Association)**

* Chairman Task Group on Circuit Integrity for CSA C22.2 No. 0.3 (1997-2000)
* Member Committee CSA C22.2 No. 0.3 Wiring Test Methods (1992 -)
* Member Committee CSA C22.2 No. 239 Control & Instrumentation Cables (1995 -)

- **IEEE (Institution of Electrical and Electronic Engineers)**

* Member IEEE Technical Committee on Electrical Installations in Ships (IEEE 45) (1999-2007)
* Member IEEE Technical Committee on Shipboard Wire and Cable (IEEE 1580) (2000-07)

- **International Code Council**

* Member International Building Code Fire Safety Code Committee (2006-7 and 2008-9)
* Proponent of code changes for IBC, IFC, IMC and IRC on various cycles

Fire Safety Industrial Consultant (Public Information)

- Consultant to the Vinyl Institute on fire and PVC (1991-96)
- Consultant to the Fire Retardant Chemicals Association/American Fire Safety Council on codes and standards (1997 -)
- Consultant to the National Cotton Council on code issues (2003 -05)
- Expert on various fire issues, for a variety of industrial clients

EMPLOYMENT RESPONSIBILITIES IN PREVIOUS WORK

■ BFGoodrich - Geon Vinyl Division (Fire Sciences Manager)

- Head of BFGoodrich fire testing laboratory: routine small-scale tests.
- Head of BFGoodrich fire research: smoke toxicity and fire hazard assessment; combustion and thermal analysis of poly(vinyl chloride) and other polymers; generation, transport and decay of hydrogen chloride; smoke corrosivity; analytical techniques for measuring combustion products. Provided a presence at national and international fire conferences: participation and presentation of scientific work. Carried out full scale fire demonstrations, for research and public relations purposes. Support of line groups in the development of new commercial compounds.
- Technical consultant for BFGoodrich on litigation and other external affairs regarding fire and combustion toxicity.
- Standards activities representing BFGoodrich: e.g. ASTM, NFPA, Canadian Standards Association.
- Vinyl industry spokesperson.
- Chairman Technical Fire Sciences Subcommittee, Coordinating Committee for Fire Safety, Society of the Plastics Industry. Main spokesperson on fire activities for the plastics industry. Liaison with Center for Fire Research (National Bureau of Standards), NFPA, NIBS, etc.
- Technical Monitor SPI Carbon Monoxide and Fire Fatalities Project, etc. (1987-91)
- Chairman Combustibility Subcommittee, Vinyl Institute Technical Committee. Technical monitor of projects at Center for Fire Research (NBS), Southwest Research Institute.
- Chairman ASTM E-5.15: Subcommittee on Fire and Interior Furnishings and Contents
- Secretary ASTM E-5.91: Subcommittee on Planning and Review of Fire Standards
- Chairman ASTM E-5.15.3: Task Group on Fire Hazard Assessment of Floor Coverings
- Chairman ASTM E-5.15.8: Task Group on Full Scale Fire Testing of Upholstered Furniture
- Chairman ASTM E-5.31.3: Task Group on Smoke Toxicity Definitions
- Chairman ASTM E-5.32.2: Task Group on 1990 Symposium on Fire Hazard and Fire Risk Assessment
- Chairman ASTM E-5.35.2: Task Group on Examples of Fire Hazard Assessment Standards
- Chairman ASTM D-9.21.3: Task Group on Smoke Obscuration on Burning of Electrical Cables
- Member of NIBS Smotox Steering Committee (1987-91)
- Member of NFPRF Risk Assessment Advisory Committee (1987-91)
- Session chairman on Materials for Increased Fire Safety at Int. Conf. Fire Safety (Dr. C.J. Hilado) (1987-91)
- Session chairman at Combustion Institute Eastern Section meetings
- Session Chairman at Fire Retardant Chem. Assoc. meetings

- Member of ASTM Task Groups E-5.21.70 and D-9.21-4 (smoke corrosivity test development), ASTM E-5.21.02 and E-5.21.03 (smoke obscuration test development), and E5-21.11 (quick toxic fire hazard assessment)

■ **BFGoodrich - Chemical Group & Geon Vinyl Division**

- As subsequent job, at a lower level of responsibility.

■ **Department of Chemistry - The City University**

- Supervision of post-graduate and undergraduate research students.
- Research in combustion and air pollution: medium and high molecular weight hydrocarbons, liquid fuels (gasoline, diesel efficiency and effects of additives), polymers (thermal decomposition, flammability and flame retardance: efficiency and mechanism), cellulosic materials (cellulose, cotton, cigarette paper: mechanisms and means of decreasing emissions), emission processes of gaseous pollutants, etc.
- Consultant to the "Unit for Oxidation and Combustion Technology": Ministry of Defense and industrial contract research organization.
- Consultant to the OECD (Organization for Economic Cooperation and Development; Paris, France): industrial and automotive pollution issues.

■ **School of Molecular Sciences - University of Sussex**

- Research in physical organic chemistry: syntheses and kinetics of radioactive decay by protiodetritiation of polycyclic aromatic hydrocarbons.

■ **R & D Department - ALUAR Aluminio Argentino**

- Planning for setting up a laboratory and literature search.

■ **Department of Physical Chemistry - School of Pharmacy and Biochemistry - University of Buenos Aires**

- Research into polymerization mechanisms, leading to Ph.D.

PUBLICATIONS

Books:

1) "The Combustion of Organic Polymers", C.F. Cullis and M.M. Hirschler, Oxford University Press, Oxford, 1981.

2) "Oxidation of Organic Compounds. Solvent Effects in Radical Reactions", N.M. Emanuel', G.E. Zaikov and Z.K. Maizus, translators: A.K. Henn and I.G. Evans, translation editor: M.M. Hirschler, Pergamon Press, Oxford, 1984.

3) "Fire hazard and fire risk assessment", ASTM STP 1150, Amer. Soc. Testing and Materials, Philadelphia, PA, Editor: M.M. Hirschler, (1992).

228) "Carbon monoxide and human lethality: Fire and non fire studies", Editor in Chief: M.M. Hirschler, Associate Editors: S.M. Debanne, J.B. Larsen and G.L. Nelson, Elsevier, 1993.

274) "Fire Calorimetry", Editors: M.M. Hirschler and R.E. Lyon, DOT/FAA/CT-95-46, NTIS, 1995.

345) "Electrical Insulating Materials - International Issues", ASTM STP 1376, Amer. Soc. Testing and Materials, West Conshohocken, PA, Editor: M.M. Hirschler (2000).

Other Scientific Publications and Presentations:

1974

4) "Free radical polymerization of methyl methacrylate in the presence of benzoquinone and triethyl aluminium", J. Grotewold and M.M. Hirschler, Int. Symp. on Macromolecules, Rio de Janeiro, Brazil, July 26-31, 1974.

5) "Formation of a methyl methacrylate oligomer by combining triethyl aluminium and azobisisobutyronitrile", J. Grotewold and M.M. Hirschler, Kinetics and Photochemistry Symposium, Rio Cuarto (Argentina), August 6-10, 1974.

1975

6) "Mechanism of polymerization of methyl methacrylate in the presence of triethyl aluminium together with a typical free radical inhibitor or an initiator", Doctoral Dissertation, University of Buenos Aires.

7) "Report on carbons, carbonization, additives (oxidative and reductive) and polycyclic aromatic hydrocarbons", M.M. Hirschler, Internal Publication, ALUAR Aluminio Argentino, 1975.

1977

8) "Stoichiometric formation of methyl methacrylate oligomer by triethyl aluminium in the presence of azobisisobutyronitrile", J. Grotewold and M.M. Hirschler, J. Polymer Sci., A-1 (Polymer Chemistry), <u>15</u>, 383-91 (1977).

9) "Triethyl aluminium as a concentration-dependent coinitiator and chain-transfer agent of free radical polymerization of methyl methacrylate in the presence of benzoquinone", J. Grotewold and M.M. Hirschler, J. Polymer Sci., A-1 (Polymer Chemistry), <u>15</u>, 393-404 (1977).

10) "Electrophilic aromatic substitution. Part 18. Protiodetritiation of anthracene, coronene and triphenylene in anhydrous trifluoroacetic acid", H.V. Ansell, M.M. Hirschler and R. Taylor, J. Chem. Soc., Perkin II, 353-5 (1977).

1978

11) "The formation and destruction of pentenes during the combustion of pentane", C.F. Cullis and M.M. Hirschler, Proc. Royal Soc. (London) A 364, 75-88 (1978).

12) "Isotopic tracer studies of the further reactions of pentenes in the combustion of pentane", C.F. Cullis and M.M. Hirschler, Proc. Royal Soc. (London) A 364, 309-29 (1978).

1979

13) "Sulphur emissions into the atmosphere", C.F. Cullis and M.M. Hirschler, Int. Symp. on Sulphur Emissions and the Environment, London (U.K.), May 8-10, Soc. Chem. Industry, pp. 1-23 (1979).

1980

14) "Atmospheric cycles of some common elements: II. Man's activities", C.F. Cullis and M.M. Hirschler, Educ. Chem. 17, 40-3 (1980).

15) "Sulphur emissions, the environment and chemical industry", M.M. Hirschler, Introductory Lecture, Int. Symp. on Sulphur Emissions and the Environment, London (U.K.), May 8-10, 1979, Soc. Chem. Industry, pp. 445-55 (Discussion Volume) (1980).

16) "Atmospheric sulphur: natural and man-made sources", C.F. Cullis and M.M. Hirschler, Atmos. Environ., 14, 1263-78 (1980).

17) "Ignition of Kynar oxygen valve material", M.M. Hirschler, Report for Health and Safety Executive, U.K., Contract No. 1186-46.04, November 1980.

18) "The effect of atropisomerism upon electrophilic aromatic reactivity: detritiation of hexa- and tetra-o-phenylene", M.M. Hirschler and R. Taylor, J. Chem. Soc., Chem. Comm., 967-9 (1980).

1981

19) "Man's emission of carbon dioxide into the atmosphere", M.M. Hirschler, Atmos. Environ., 15, 719-27 (1981).

20) "Smoking and air pollution", C.F. Cullis and M.M. Hirschler, Seventh Int. Clean Air Conf., Clean Air Soc. Australia and New Zealand, Adelaide (Australia), August 21-27, pp. 115-29 (1981).

21) "Biogenic sulphur emissions", M.M. Hirschler, Atmos. Environ. 15, 1336 (1981).

22) "The oxidative thermal stability of plastic propellants", A.W. Benbow and M.M. Hirschler, Report for Procurement Executive, Propellants, Explosives and Rockets Motor Establishment, Ministry of Defence, U.K., Contract No. D/RM 1/11/240, February 1981.

23) "The combined action of aluminium oxides and halogen compounds as flame retardants", F.K. Antia, C.F. Cullis and M.M. Hirschler, Europ. Polymer J., 17, 451-5, (1981).

24) "The inhibition of polymer combustion by metal oxides", F.K. Antia, C.F. Cullis and M.M. Hirschler, First Specialists' Mtg Combustion Institute, Bordeaux (France), July 20-25, pp. 602-7 (1981).

25) "Experimental techniques for the combustion of fuels of low volatility and high reactivity", C.F. Cullis, M.M. Hirschler and R.L. Rogers, 18th. Symp. (Int.) on Combustion, pp. 1575-82, The Combustion Institute, Pittsburgh, 1981.

26) "The oxidation of decane in the gaseous and liquid phases", C.F. Cullis, M.M. Hirschler and R.L. Rogers, Proc. Royal Soc. (London), A 375, 543-63 (1981).

1) "The Combustion of Organic Polymers", C.F. Cullis and M.M. Hirschler, Oxford University Press, Oxford, 1981.

1982

27) "The cool-flame combustion of decane", C.F. Cullis, M.M. Hirschler and R.L. Rogers, Proc. Royal Soc. (London), A 382, 429-40 (1982).

28) "Recent developments in flame-retardant mechanisms", M.M. Hirschler, in "Developments in Polymer Stabilisation, Vol. 5", Ed. G. Scott, pp. 107-52, Applied Science Publ., London, 1982.

29) "Binary mixtures of metal compounds as flame retardants for organic polymers", F.K. Antia, C.F. Cullis and M.M. Hirschler, Europ. Polymer J., 18, 95-107 (1982).

30) "Comprehensive study of the effect of composition on the flame-retardant activity of antimony oxide and halogenated hydrocarbons in thermoplastic polymers", F.K. Antia, P.J. Baldry and M.M. Hirschler, Europ. Polymer J., 18, 167-74 (1982).

31) "Effect of oxygen on the thermal decomposition of poly(vinylidene fluoride)", M.M. Hirschler, Europ. Polymer J. 18, 463-7, (1982).

32) "Relation between the thermal behaviour and flame-retardant effectiveness of metal oxides in halogen-containing thermoplastics", M.M. Hirschler, Sixth European Conf. on Flammability and Fire Retardants, Alena Enterprises of Canada, June 24-25, Nice (France), 1982.

33) "Thermal stability and flammability of organic polymers", C.F. Cullis and M.M. Hirschler, I.U.P.A.C. Macro '82, Polymer Degradation and Stabilisation, July 12-16, Amherst (U.S.), p. 286, 1982.

1983

34) "The role of specific elements in flame-retardant mechanisms", M.M. Hirschler, Polymer Flammability: Mechanistic and Practical Aspects, P.D.D.G. Conf., Macro Group U.K.(Royal Soc. Chemistry), September 2-3, Cambridge (U.K.), 1983 (Industrial Chemistry Bulletin, 2, 52 (1983)).

35) "The pyrolysis of cellulose under conditions of rapid heating", C.F. Cullis, M.M. Hirschler, R.P. Townsend and V. Visanuvimol, Combust. Flame 49, 235-48 (1983).

36) "The combustion of cellulose under conditions of rapid heating", C.F. Cullis, M.M. Hirschler, R.P. Townsend and V. Visanuvimol, Combust. Flame 49, 249-54 (1983).

37) "Flame retardance and smoke suppression by tin (IV) oxide phases and decabromobiphenyl", J.D. Donaldson, J. Donbavand and M.M. Hirschler, Europ. Polymer J. 19, 33-41 (1983).

38) "Thermal analysis and flammability of polymers: Effect of halogen-metal additive systems", M.M. Hirschler, Europ. Polymer J. 19, 121-9 (1983).

39) "The effect of combinations of aluminium (III) oxides and decabromobiphenyl on the flammability of and smoke production from acrylonitrile-butadiene-styrene terpolymer", M.M. Hirschler and O. Tsika, Europ. Polymer J., 19, 375-80 (1983).

40) "Mechanism of action of pyrogenic silica as a smoke suppressant for polystyrene", R. Chalabi, C.F. Cullis and M.M. Hirschler, Europ. Polymer J., 19, 461-8 (1983).

41) "The significance of thermoanalytical measurements in the assessment of polymer flammability", C.F. Cullis and M.M. Hirschler, Polymer, 24, 834-40 (1983).

42) "The influence of metal chelates on the oxidative degradation of polypropylene", C.F. Cullis and M.M. Hirschler, in Proc. Fifth Ann. Int. Conf. Advances in the Stabilisation and Controlled Degradation of Polymers, Zurich (Switzerland), June 1-3, pp. 195-207 (1983).

43) "Metal oxides as flame retardants-smoke suppressants: recent developments", M.M. Hirschler, Seventh Europ. Conf. on Flammability and Fire Retardants, Alena Enterprises of Canada, London (U.K.), June 9-10, 1983.

44) "A novel dilution tunnel-flame burner system for studying the effects of automotive diesel fuels on air quality", C.F. Cullis, M.M. Hirschler and M.A.M. Stroud, Sixth World Congress on Air Quality, Paris (France), May 16-20, Int. Union Air Pollution Prevention Assocns, Vol. 4, pp. 265-72 (1983).

45) "Effects of organic sulphur compounds on the ignition of unleaded and leaded hydrocarbon fuels", C.F. Cullis, M.M. Hirschler and G.O.G. Okorodudu, 19th. Symp. (Int.) on Combustion, pp. 1475-86, The Combustion Institute, Pittsburgh, 1983.

46) "The effects on alkane combustion of added sulphur compounds", C.F. Cullis, M.M. Hirschler, G.O.G. Okorodudu and H.A.G. Okuns, Combust. Flame 54, 209-24 (1983).

1984

47) "Char formation from polyolefins: correlations with low-temperature oxygen uptake and with flammability in the presence of metal-halogen systems", C.F. Cullis and M.M. Hirschler, Europ. Polymer J. 20, 53-60 (1984).

48) "Reduction of smoke formation from and of flammability of thermoplastic polymers by metal oxides", M.M. Hirschler, Polymer 25, 405-11 (1984).

49) "Degradation of polystyrene in the presence of magnesium compounds", M.M. Hirschler and T.R. Thevaranjan, Pre-prints, Polymer Div., Amer. Chem. Soc., 189th. Ann. Mtg., pp 91-2 (1984).

50) "Effect of dispersing and binding agents on the flammability of, and smoke production from, thermoplastic polymers", J.D. Donaldson, J. Donbavand and M.M. Hirschler, Europ. Polymer J., 20, 323-7 (1984).

51) "The flame retardance of a natural polymer by a sulphur-aluminium-bromine system", C.F. Cullis, M.M. Hirschler and M.A.A.M. Khattab, Europ. Polymer J. 20, 559-62 (1984).

52) "The flame-retardant and smoke-suppressant activity of molybdenum (VI) oxide and other metal oxides", C.F. Cullis, M.M. Hirschler and T.R. Thevaranjan, Eighth Europ. Conf. on Flammability and Fire Retardants, Alena Enterprises of Canada, Amsterdam (Holland), June 8-9, 1984.

53) "Combustion of cigarette paper under conditions similar to those during smoking", C.F. Cullis, D. Goring and M.M. Hirschler, Cellucon '84 (Macro Group U.K.), Wrexham (Wales), Chapter 35, pp. 401-10, July 16-20, Ellis Horwood, Chichester, 1984.

54) "Heat transfer from fires", M.M. Hirschler, Report for BFGoodrich Chemical Co., July 1984.

55) "Metal chelates as flame retardants and smoke suppressants for thermoplastic polymers", C.F. Cullis, A.M.M. Gad and M.M. Hirschler, Europ. Polymer J., 20, 707-11 (1984).

56) "Combinations of titanium (IV) oxide, iron (III) oxide and molybdenum (VI) oxide as flame retardants and smoke suppressants for thermoplastic polymers", C.F. Cullis, M.M. Hirschler and T.R. Thevaranjan, Europ. Polymer J. 20, 841-7 (1984).

57) "Red phosphorus as a flame retardant for a thermoplastic nitrogen-containing polymer", J.R.A. Broadbent and M.M. Hirschler, Europ. Polymer J. 20, 1087-93 (1984).

58) "The role of diffusion in the rapid combustion of cellulose", M.M. Hirschler and R.P. Townsend, Proc. Royal Soc. (London), A 396, 119-30 (1984).

59) "Carbon monoxide from cigarette paper combustion", M.M. Hirschler and Y.R. Shashoua, Chemical and Physical Processes in Combustion, Eastern Section Combustion Inst., 1984 Fall Tech. Mtg, Clearwater Beach (FL, U.S.), p. 104/1-4, Dec. 3-5 1984.

60) "A novel engine-free dilution tunnel for the collection of particulate matter formed during combustion", C.F. Cullis, M.M. Hirschler and M.A.M. Stroud, J. Phys. E: Sci. Instrum., 17, 317-22, (1984).

61) "The combustion of deuterium-labelled decane", D. Herron and M.M. Hirschler, Oxidation Communications, 7, 321-32 (1984).

62) "Environmental implications of energy strategies (Transportation) Chapter 5: Diesel engines and Fuels", C.F. Cullis and M.M. Hirschler, O.E.C.D., Paris, 1984.

63) "Environmental implications of energy strategies (Transportation) Chapter 6: Two-stroke engines", M.M. Hirschler, O.E.C.D., Paris, 1984.

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Some of the Main Subjects of Publications

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4. Fire and Furniture or Furnishings, including Mattresses
5. Fire and Electrical Cables
6. Fabric Flammability
7. Fire and Transportation Vehicles, especially Automobiles
8. Smoke Toxicity
9. Smoke Corrosivity
10. Poly(vinyl chloride) Issues
11. Hydrogen Chloride Decay
12. Atmospheric Pollution
13. Cigarette Combustion

GBH Attachment 3

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EVALUATION OF SMOKE TOXIC POTENCY TEST METHODS: COMPARISON OF THE NBS CUP FURNACE, THE RADIANT FURNACE AND THE UPITT TESTS

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ABSTRACT

A number of smoke toxicity screening tests are being used, and some have been proposed for regulatory purposes. These methods differ markedly in the combustion device, the combustion conditions, the exposure conditions and even the test animal. However, virtually all use an LC_{50} value, or some lethality determination, as the principal or sole measure of toxicity. In this study, lethal potencies were determined by the NBS Cup Furnace, the Radiant Furnace and the UPITT test methods for one nylon- and four PVC-based materials. These results were correlated with analytical data to identify the major toxicants responsible for the lethalities. This study shows that, while all of these methods have deficiencies, the UPITT method has more serious limitations. The use of this method to determine LC_{50} values for screening materials may lead to erroneous assessments of the toxic hazards of these materials to humans.

INTRODUCTION

During the past 20 years, considerable time, effort an funds have been expended in research on fire and life safety. Significant achievements and advancements have been made, leading to a better understanding of the hazards of fire and of procedures for its assessment. In order to understand the contribution of of smoke toxicity to these hazards, a number of test methods were developed during the 1970's and 1980's, to measure the toxicity of smoke produced from burning materials[1-5]. These methods differ in a variety of respects, including the combustion device, the combustion conditions and even the test animal. However, virtually all of the methods use a median lethal concentration value, or LC_{50} (or another measure of lethality) as the principal or sole index of toxic potency.

The use of an LC_{50} value alone in these tests is not an adequate or meaningful measure of the toxicity of smoke or of any atmosphere to man[6-8]. Furthermore, the various test methods generate different rankings for materials when LC_{50} values alone are used for comparison. Thus, in a study of 14 materials by two methods[9], the material deemed most toxic by one method appeared to be the least toxic by the other method. In another study in which LD_{50} values were repeatedly determined for 26 chemicals[10], the values for one chemical varied by a factor of as much as three. Because of this variability, the relative toxicity rankings of these chemicals obviously also varied markedly depending on the value chosen. This demonstrates that a comparison of LC_{50} values determined by different test methods is of little meaning without an understanding of the toxicants responsible for the lethalities and other toxic effects. These toxicants may contribute to the toxicity of smoke atmospheres, even though carbon monoxide (CO) has been shown to be the major cause of smoke inhalation fatalities in real fires, as shown by various authors, e.g. [11]. Furthermore, it is important to point out that small-scale toxicity test methods are biased in favor of non-CO species[12].

Nevertheless, some of these lethal potency test methods have been, or are being, proposed as toxicity screening tests for regulatory purposes. Thus, the objective of this study was to make a thorough comparison of three of the test methods used to determine the lethal potency of smoke generated by combustion of materials. In order to carry out this comparison, LC_{50} values were determined for five materials with the three test methods. In addition, the concentrations of those gases suspected, a priori, to be the major toxicants were measured in the combustion atmospheres. The mechanisms of the observed lethality were investigated by evaluating the correlation of LC_{50} values with the analytical data.

METHODOLOGY

Test Methods

The three test methods that were evaluated in this study were: the National Bureau of Standards (NBS, today the National Institute for Standards and Technology) Cup Furnace Test Method[1,5], the Radiant Furnace Test Method[4,5] and the University of Pittsburgh (UPITT) Test Method[3].

NBS Cup Furnace Test Method. The apparatus of the NBS Cup Furnace Test Method (Figure with a volume of ca. 200 L. The furnace is operated at a fixed temperature, at 25°C below or above the pre-determined autoignition temperature, to produce either non-flaming or flaming combustion, respectively. In each experiment, six male rats are exposed, in the head-only mode, for 30 min to the combustion atmosphere. A series of experiments with varying amounts of a material are conducted to establish a concentration-response lethality relationship and to derive an LC_{50} value by standard methods[13,14] for each of the two combustion modes. The LC_{50} value is an estimate of the quantity of material that causes death of 50% of the animals during the 30 min exposure and a 14 day post-exposure period. This mass of material is divided by the chamber volume and the LC_{50} is expressed in units of mg/L.

With some of the test materials (and with Douglas fir wood) additional experiments were conducted in which male mice were used as the test animal, with the NBS cup furnace test method. From these experiments, LC_{50} values were obtained to allow a comparison of the sensitivity of mice and rats to the combustion atmospheres produced by these materials.

Radiant Furnace Test Method. The apparatus of the Radiant Furnace Test Method (Figure 2) uses the same exposure chamber as the NBS Cup Furnace, but a radiant heater system is used to thermally decompose the material, for a period of 10 min. The radiant heater system consists of four tubular quartz tungsten-filament lamps mounted in parabolic reflectors. The system delivers a heat flux of 5 W/cm^2 (+/- 20%) over a 7.5 x 15 cm sample area and, with the assistance of a hot wire, promotes flaming combustion of a material. The protocols for the animal exposures and derivation of LC_{50} values are the same as those for the cup furnace method.

University of Pittsburgh (UPITT) Test Method. The apparatus of the UPITT method (Figure 3) consists of a muffle furnace connected to a glass animal exposure chamber by means of a quartz tube. Weighed samples of material are thermally decomposed in the furnace, the temperature of which is increased at a constant rate of 20°C/min. The products are carried through the furnace by an air stream and diluted and cooled with additional air before entering the exposure chamber. In each experiment four male mice are exposed, in the head-only mode, to the combustion atmosphere for 30 min, starting from the time of a 1.0% weight loss of the material. At least four experiments are conducted in order to derive an LC_{50} value by the Weil method[15]. The LC_{50} is an estimate of the amount of material required to cause death of 50% of the animals during the 30 min exposure and 10 min recovery period,

Materials

All five test materials are wire and cable coating compounds: four are poly(vinyl chloride) (PVC)-based (BFGoodrich proprietary materials) and one is nylon-based. Two of the four PVC compounds (SI and SJ) are standard, commercially available compounds while the other two are experimental compounds. The standard insulation (SI) is a 105°C rated compound used for the insulation of building wire; it contains moderate amounts of flame retardants. The standard jacket (SJ) is a 60°C rated compound used as a jacket material for building wire and does not contain added flame retardants. Experimental B (EX B) is a modification of the SI compound, formulated in order to achieve a reduced amount of HCl emission per unit mass burnt. Experimental C (EX C) is a more advanced modification of SI, formulated for even less HCl emission. The nylon (NR) is a standard nylon 6,6 compound, used in the manufacture of THHN and THWN wires for use in cables (Allied 8222).

Analyses

During the majority of the experiments, measurements were made continuously of CO, carbon dioxide (CO_2) and oxygen, with a closed loop sampling system. Concentrations of the carbon oxides were determined with Beckman 865 non-dispersive infrared analyzers and oxygen was measured with a Beckman OM-11 paramagnetic analyzer. Prior to each experiment, every analyzer was calibrated with appropriate calibration gases. In selected experiments, the combustion atmospheres were also analyzed for HCl or HCN. Analyses for HCl were accomplished either by means of a continuous silver nitrate titration analyzer, based on a modified French standard[16,17], or by the use of an ion selective electrode on atmospheric samples withdrawn periodically into a syringe containing a small amount of deionized water[18]. Dry soda-lime absorption tubes were used to collect samples of atmospheres containing HCN, for later extraction and analysis by a pyridine-pyrazolone method[19].

The weight percent of HCl emitted by the PVC samples was measured by means of the coil test method[20,21]. This method heats a sample to destruction and collects the soluble effluents into deionized water, for subsequent titration of chloride content by using an ion selective electrode. The percent of available Cl emitted can then be calculated from the formulation of the PVC compound. The results are shown in Table 1.

RESULTS

Emission of Hydrogen Chloride

The results in Table 1 show that, the SI PVC emits virtually its entire Cl content as HCl and that the SJ PVC also emits a very large proportion of its Cl as HCl. On the other hand, the experimental compounds emit a very low fraction of their Cl contents as HCl: the HCl is retained in the solid residue. The fraction emitted by EX C is roughly half of that emitted by EX B. Since HCl is one of the two main toxicants in PVC compounds, together with CO, it was of interest, therefore, to investigate whether this decrease in HCl emission would lead also to a decrease in toxic potency.

Lethal Potencies of the Materials

The LC_{50} values, and the appropriate confidence limits, for the five materials, as determined by all test methods, are shown in Table 2. Examination of the relative ranking of these materials, as they would be evidenced purely by the LC_{50} values obtained with each method shows that the rankings are different for the three methods.

A comparison of the lethal potencies of the two experimental PVC compounds with those of the standard compounds shows that all three test methods yielded LC_{50} values for EX B that are approximately 2-2.5 times greater than the value for either SI or SJ. Also, with all test methods (except for the non-flaming mode of the NBS cup furnace test), the LC_{50} values for EX C are ca. 3-5 times greater than the values for either of the two standard materials and approximately twice as large as the values for EX B.

The LC_{50} values for the various materials, as determined by all test methods were compared statistically[14]. Thus, while the differences in LC_{50} values between SI or SJ and EX B are statistically significant ($p<0.05$) for the NBS cup furnace test (both in the flaming and non-flaming modes) and for the radiant furnace test, the differences are not sufficient to demonstrate statistical significance in the UPITT test method ($p>0.05$). Similarly, the differences in LC_{50} values between EX B and EX C are statistically significant in the NBS cup furnace (flaming) and the radiant furnace but not the UPITT method (nor the NBS cup furnace non-flaming). The differences in LC_{50} values between SI and SJ are

With the nylon compound, a sample charge of up to 100 mg/L was insufficient to kill test animals in the non-flaming mode of the NBS cup furnace test, and so no LC$_{50}$ was determined for this mode. One reason for this result is that the nylon material bursts into flame easily at a temperature very close to the autoignition temperature, making the non-flaming test invalid. In the flaming mode of the NBS cup furnace and in the radiant furnace the LC$_{50}$ of nylon differed significantly from the values of the experimental PVC compounds but not of the standard compounds. In the UPITT test, the LC$_{50}$ of nylon differed statistically only from that of EX C.

In order to investigate one of the potential reasons for this lack of discrimination by the UPITT test method, the LC$_{50}$ values of three test materials and of Douglas fir, were determined using one of the NBS cup furnace protocols, but replacing the rats by mice. The results, in Table 3, show that the LC$_{50}$ value with mice was consistently lower than the value obtained for rats, with the differences ranging from a factor of ca. 2.5 to a factor of as much as almost 8.

CORRELATION OF ANALYTICAL AND TOXICOLOGICAL RESULTS

Analytical data for CO, HCl and HCN from selected experiments were used to evaluate which toxicants were primarily responsible for the lethal effects of the combustion atmospheres. These evaluations were made by comparing pure gas lethal concentration-exposure time values for lethality (i.e. LC$_{50}$t values) with analytical data.

Analytical data for the four PVC-based compounds, when combusted in the NBS cup furnace test (non-flaming mode) are shown in Figure 4. The amounts of HCl emitted were consistent with what was known about the compounds (e.g. Table 1), namely that the experimental compounds release considerably less HCl than the standard ones and that EX C releases much less HCl than EX B. In the case of the standard compounds HCl was clearly the major toxicant (since its LC$_{50}$t ranges between 111,000 and 150,000 ppm min[11,22,23]), representing a fractional effective dose of well over 0.5. There may well be a contribution to lethality by some other combustion products. In particular, CO (with an LC$_{50}$t range of ca. 138,000-192,000 ppm min[11]) has a fractional effective dose of well over 0.1. With EX B and EX C, even the high sample charges required to cause lethalities did not generate sufficient HCl to result in rat deaths. When large quantities of these materials were combusted, sufficient concentrations of overall smoke (i.e. gases and particulates other than HCl) were produced to consider cause lethality with an important contribution by irritants. In the case of the NR, very small amounts of material were decomposed with this protocol, so that the concentration of smoke was very low. Consequently charges of up to 100 mg/L generated low concentrations of CO and undetectable amounts of HCN and did not cause any lethalities.

The analytical data for the four PVC-based compounds, when burnt in the NBS cup furnace test (flaming mode) are shown in Figure 5. The amounts of HCl emitted were again consistent with what was known about the compounds (e.g. Table 1), namely that the experimental compounds release considerably less HCl than the standard ones and that EX C releases much less HCl than EX B. In the case of the standard compounds both HCl and CO were clearly major toxicants, with similar contributions from each in terms of the fractional effective dose. The two experimental compounds generated much less CO than equivalent sample charges of the experimental compounds, as well as generating much less HCl. It is interesting, however, that with EX B and EX C, the major toxicant was CO. this was confirmed by the high blood COHb levels in the animals dying during exposure. the considerably reduced emissions of CO and HCl by the experimental compounds were reflected, too, in the statistically significantly lower toxic potency for EX B and EX C as compared to SI or SJ, and a much greater LC$_{50}$ for EX C than for EX B.

With the Radiant Furnace Method (Figure 6) also much less HCl and CO are generated by the two experimental compounds when compared with equivalent weights of the standard compounds, and by EX C in comparison with EX B. However, with all four PVC compounds much less HCl was produced than in the NBS cup furnace method (in either mode) and the HCl generated decayed much more rapidly. The Figure shows how the descending slope of the HCl/time curve is much steeper than in the cup furnace protocols. Both the consistently high concentrations of CO (and CO ct products) measured and the COHb levels found in the animals suggest that the major toxicant in all these atmospheres generated by the radiant combustion of flexible PVC compounds was CO, and not HCl. Differences in the quantity of CO generated by the compounds were reflected in statistically significant increases in LC$_{50}$ values for EX B and EX C in comparison with SI or SJ and in a significantly greater LC$_{50}$ value for EX C than EX B.

The analytical data obtained for the four PVC compounds after being subjected to the UPITT test method (Figure 7) are markedly different than those obtained with any of the other three methods. In ascending slopes of the concentration-time curves). This means that they were carried through the exposure chamber over a short period of time, so that the test animals (mice) were exposed to high concentrations of these gases for a fraction of the 30 min exposure period only. The descending slopes are, of course, related in this test method simply to the flow-through character of this dynamic test and not to decay. The analytical data show that exposure of animals to toxicologically significant concentrations of CO ranged from 3 to 7 min (except in the case of SJ, where they were slightly longer). Similarly, exposures to significant HCl concentrations were of even shorter duration.

As with the other methods, in the UPITT method again EX B and EX C generated much less HCl than equivalent weights of SI or SJ, as did EX C when compared to EX B. However, the ratios of HCl generated by the various materials are much smaller than would have been predicted from the results in Table 1 or from the results with the other methods.

Based on the results of pure gas studies on mice exposed to CO and HCl, the major toxicants in the combustion atmospheres produced by all 4 PVC compounds were determined to be CO and HCl. In the case of EX C, the contribution of HCl to lethalities would appear to be minimal from the analytical data; pure gas studies with HCl have shown that mice are extremely sensitive to HCl, and even low concentrations of this gas markedly increase the sensitivity of mice to CO[24]. The LC_{50} values of the two experimental compounds were larger than those of the two standard compounds; however, the differences in values between EX B and SI or SJ and between EX B and EX C were not sufficient to demonstrate statistical significance ($p>0.05$).

The analytical data for the nylon compound with three of the test methods are shown in Figure 8. The moderate quantities of CO and HCN generated in the NBS Cup Furnace method (flaming mode) were insufficient to have caused animal lethality on their own. The LC_{50} of HCN in rats, over a 30 min exposure is ca. 160 ppm[11]. Thus, the HCN represents a fractional effective dose of 0.23, while the CO represents a fractional effective dose of up to 0.3, approximately. Furthermore, the majority of the lethalities were found post-exposure. This indicates that other toxicants, probably irritants, among which it is likely that there are nitrogen oxides, NO_x, were present in the combustion atmospheres and were responsible for the lethality. In contrast, with the Radiant Furnace and with the UPITT test methods, the nylon material generated sufficiently high concentrations of CO and HCN to account for the observed lethalities. Virtually all deaths from the Radiant Furnace method occurred during (flaming). With the UPITT method the peak concentrations of CO and HCN were extremely high (see Figure 8), but the toxicologically significant exposure was probably only ca. 2 min long.

DISCUSSION

The results obtained in this study demonstrate that the three test methods differ markedly in the thermal decomposition characteristics and in the nature and rate of evolution of decomposition products. The results also show that all three methods have limitations in evaluating the toxic potency of smoke. One limitation is the lack of correlation between sample weight combusted and the quantity of gases evolved in the case of some materials. This limitation is particularly evident with the UPITT test method and is illustrated by the analytical data obtained in experiments with EX B (Table 4) and EX C (Table 5). In these examples the large deviations from linearity between the evolution of some combustion products and the amount of sample charged contributed to wide variability in the LC_{50} values of the materials. It may be indicative also of inhomogeneous burning of materials, as also suggested by the recent finding that the UPITT method can give multiple LC_{50} values for the same material[25].

Another difference between the three test methods that may severely limit the relevance and utility of the LC_{50} values obtained from them is the type of exposure system. The use of a static exposure system in both the NBS Cup Furnace and in the Radiant Furnace test methods provided for exposure of the test animals to the thermal decomposition products of a material over most, if not all, of the 30 min exposure period. In contrast, with the UPITT test method, the use of a dynamic exposure system, together with a programmed heating rate, resulted in exposure of test animals to high concentrations of toxicants, particularly HCl and HCN, for brief periods of time. This type of exposure is generally much more toxicologically severe than exposure to the same ct product of a gas over a longer time. Furthermore, this type of exposure is of questionable relevance to most fire scenarios, except possibly for locations near the fire itself at the time of flashover. In the latter situation, the toxicity of combustion products is generally considered to be of minimal significance in comparison to other hazards.

The analytical data showed a marked difference between the NBS Cup Furnace and the Radiant Furnace methods, even though both of them use a static exposure system. This was particularly

The amount of HCl generated in the Radiant Furnace method was much lower than in the NBS Cup Furnace method and, furthermore, the decay of HCl also appeared to be more rapid in the same test. This may be explained by the more complete combustion in the Radiant Furnace method, which leads to the generation of much more water vapor, which, in turn, reacts rapidly with HCl.

Of the several differences between test methods, however, the one that has the greatest impact on the LC_{50} value is the test animal. Whereas the NBS Cup Furnace and the Radiant Furnace methods use the rat as a test animal, the UPITT method uses the mouse, a species much more sensitive to the lethal effects of HCl, and probably to those of all irritant gases[26,27]. A comparison of lethal potencies of four materials determined in mice and rats by the NBS Cup Furnace test method (Table 3) shows that the sensitivity of the mouse to the combustion atmospheres produced by these materials was greater than that of the rat by a factor which ranged from approximately 2.5 to as much as almost 8. It is important to stress that, under the conditions tested, all these four materials generate smoke which contains a very large proportion of irritants, so that it is to be expected that the difference in sensitivity found for mouse and rat is likely to be associated with the presence of irritants primarily. Furthermore, it has been shown that mice and rats have similar sensitivity to CO. In terms of the sensitivity to HCl itself, LC_{50} values for a 5 min exposure (and 7 day post-exposure) were reported by Darmer et al.[26] to be 13,745 ppm for the mouse and 40,989 ppm for the rat, indicating a three-fold greater sensitivity of the mouse to this gas compared to the rat. A comparison of the lowest lethal concentrations (LLC) data for the two species (Table 6) indicates an even greater difference in sensitivity between the mouse and the rat: the mouse is almost eight times more sensitive.

The baboon is a non-human primate regarded as a good surrogate of man because its respiratory response to irritants, its upper airways and its general physiology are all very similar to those of humans, in particular young children[28]. Available data, although limited, have shown that the baboon can survive short exposures to very high concentrations of HCl[29]. Studies have shown that a 15 min exposure to 10,000 ppm, a 10 min exposure to 15,000 ppm or even a 5 min exposure to 30,000 ppm (all exposure doses of 150,000 ppm min) of HCl does not cause lethality of this animal[23]. Studies with baboons and rats have also shown that concentrations which resulted in eventual deaths (18 and 76 days after exposure) of two animals exposed for 5 min to HCl are similar to those which caused lethality in rats exposed for 5 min[29]. Thus, the sensitivity of the baboon to the lethal effects of HCl is much more comparable to that of the rat than to that of the mouse. The mouse is much more sensitive to the lethal

Because of this hypersensitivity of the mouse, LC_{50} values as determined by the UPITT method may overestimate the relative toxic hazard to man of materials that generate HCl or other irritant gases and underestimate those of materials, such as nylon or Douglas fir, which generate mainly asphyxiant gases (CO or HCN) under UPITT test conditions. This seems to be the explanation for the lack of differentiation between SI or SJ and EX B by the UPITT method, even though much less CO and HCl are produced by EX B than by SI or SJ. This limitation is particularly serious in the lack of differentiation between nylon and EX B, despite the generation by the former compound of a combustion atmosphere in the UPITT test method which appears to be immediately and extremely hazardous to man.

CONCLUSIONS

The results demonstrate that neither toxicity nor toxic hazard can be measured adequately by simple determinations of lethal potency via small-scale toxic potency tests. The toxic hazard associated with the combustion of a material is best determined by an assessment based on the degree and type of toxic effects produced and by an identification of the toxicants responsible, in conjunction with the determination of other relevant fire parameters.

Furthermore, fire safety will best be improved by programs designed to develop fire hazard and fire risk assessment techniques rather than by concentrating on lethal potency tests. Fire hazard and fire risk assessment must incorporate a consideration of all essential fire parameters, including ignitability, flame spread, heat release, smoke toxicity and transport, together with the probability of fire occurrence and with the effects on people and the environment.

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Table 1. Emission of HCl and available chlorine by PVC compounds.

	SI	SJ	EX B	EX
Weight Percent HCl Emitted*	33.5	26.0	10.2	4
Percent of Available Cl Emitted	95.3	87.8	38.1	19

*Measured by Coil Test Method [20,21].

Table 2. Lethal potencies (LC$_{50}$ values) of PVC compounds determined by three test methods.[a]

NBS Cup Furnace (Non Flaming) (mg/L)		NBS Cup Furnace (Flaming) (mg/L)	
SI	25.0	SI	35.0
	(20.0–32.4)		(31.3–39.2)
SJ	31.6	SJ	29.6
	(27.8–36.1)		(22.7–37.4)
EX B	55.7	EX B	60.8
	(44.5–66.0)		(53.0–70.0)
EX C	59.9	EX C	159.0
	(52.5–64.9)		(127.0–199.0)
NR	No Deaths[b]	NR	49.0
	> 100 mg/L		(42.2–57.0)

Radiant Furnace (mg/L)		UPITT (g)	
SI	33.4	SI	5.6
	(29.5–56.1)[c]		(3.9–8.2)
SJ	53.1	SJ	5.5
	(49.6–55.9)		(4.2–7.1)
EX B	86.2	EX B	10.0
	(79.0–93.5)		(5.1–19.4)
EX C	149.0	EX C	21.6
	(122.0–184.0)		(11.1–42.0)
NR	36.7	NR	5.3
	(21.6–45.4)		(4.7–6.0)

[a] Values are LC$_{50}$ values and 95% confidence limits, calculated from initial sample weights. UPITT values were determined using a standard 2.3 L exposure chamber. Units are in g for the UPITT test method and in mg/L for the others.

[b] No deaths with sample charges up to 100 mg/L, LC$_{50}$ value not determined.

[c] Calculated from three experiments: 25 mg/L: 0/6; 30 mg/L: 1/6; and 35 mg/L: 4/6.

Table 3. Lethal potencies (LC_{50} values) of SJ, EX C, NR and Douglas fir determined by the NBS cup furnace test method with rats and mice.

	NBS-NF[a] Rats	NBS-NF[a] Mice	NBS-F[b] Rats	NBS-F[b] Mice
SJ	31.6 (27.8–36.1)	4.2 (2.5–6.7)		
EX C	59.9 (52.5–64.9)	13.9 (7.7–20.8)		
			49.0 (42.2–57.0)	20.2 (14.3–30.4)
DF[c]	32.8 (29.3–36.7)	8.9 (6.5–11.8)	37.6 (33.2–44.6)	

*Values are sample changes in mg/L units.
[a] NBS nonflaming mode.
[b] NBS flaming mode.
[c] DF = Douglas fir.

Table 4. Analytical and lethality data in determination of LC_{50} for EX B by UPITT method.

Sample Mass (g)	CO Ct (ppm-min)	HCl Ct (ppm-min)	No. of Deaths
6.94	18,592	12,800	2/4
8.33	18,811	2,880	1/4
10.00	22,126	14,550	2/4
12.00	25,576	12,930	3/4

LC_{50}: 10.0 (5.1–19.4) g.

Table 5. Analytical and lethality data in determination of LC_{50} for EX C by UPITT method.

Sample Mass (g)	CO Ct (ppm-min)	HCl Ct (ppm-min)	No. of Deaths
12.00	19,354	420	0/4
15.73	22,897	330	0/4
16.83	NA*	NA*	4/4
18.00	22,649	9,660	3/4
19.27	25,367	10,290	3/4

*NA: Not analyzed.
LC_{50}: 21.6 (11.1–42.0) g.

Table 6. Lowest lethal concentrations (LLC) of HCl in the mouse and the rat.

	Mouse	Rat
LLC (ppm) (5-min exposure + 1-day post exposure)	3,200[a]	32,255[a]
LLC (ppm) (within 5-minute exposure)	11,482[b]	87,660[c]

[a] From Darmer, et al. [16].
[b] Kaplan, et al. [12].
[c] Kaplan, et al. [17].

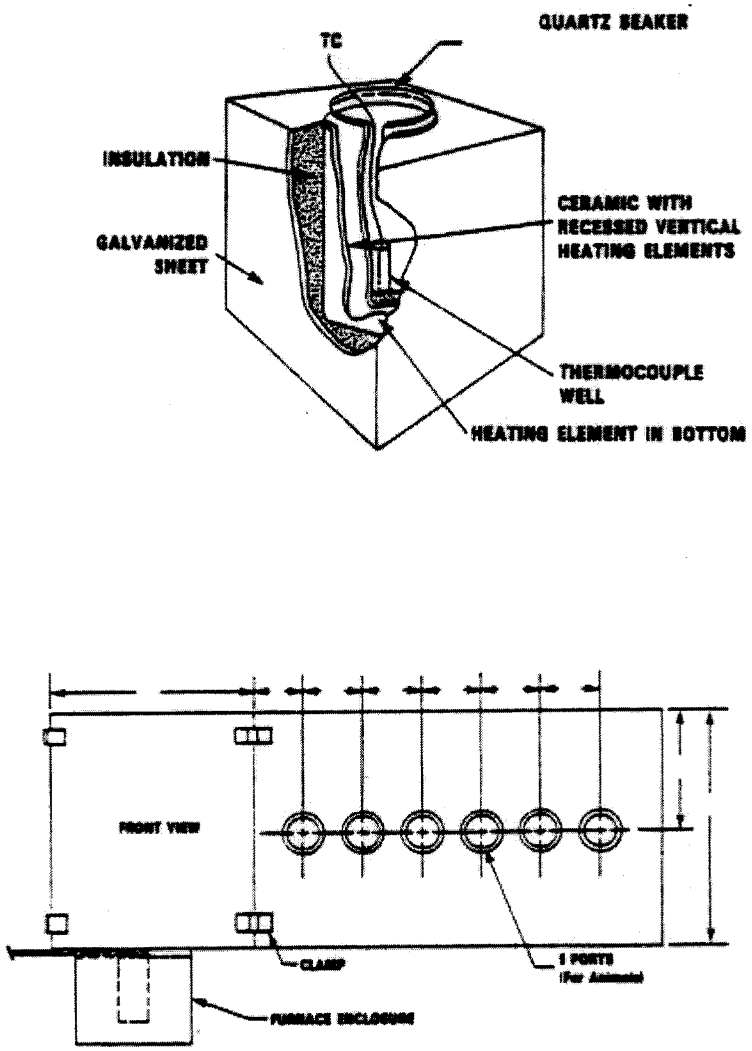

QUARTZ BEAKER
TC
INSULATION
GALVANIZED SHEET
CERAMIC WITH RECESSED VERTICAL HEATING ELEMENTS
THERMOCOUPLE WELL
HEATING ELEMENT IN BOTTOM
FRONT VIEW
CLAMP
6 PORTS (For Animals)
FURNACE ENCLOSURE

Figure 1.

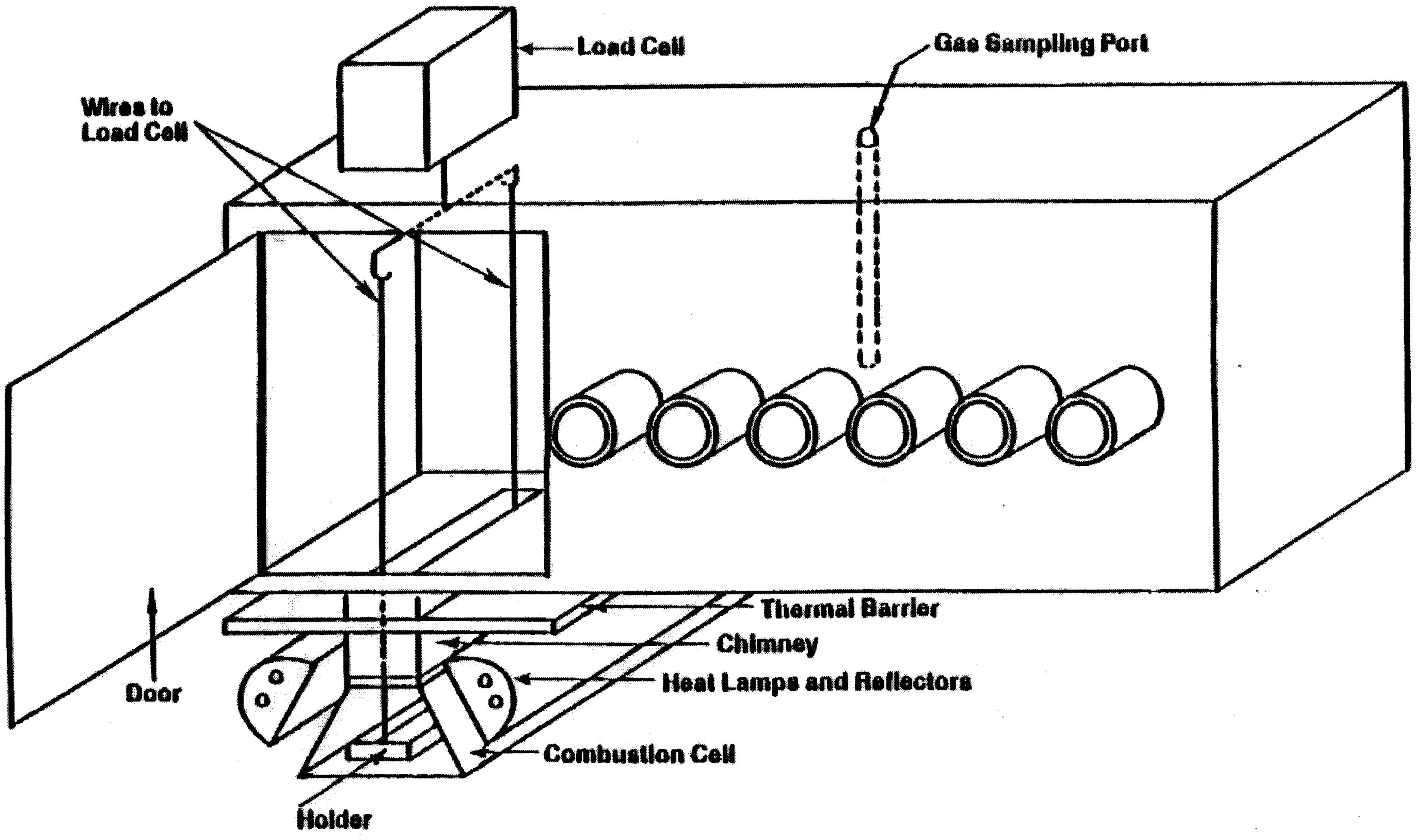

Load Cell
Gas Sampling Port
Wires to Load Cell
Thermal Barrier
Chimney
Heat Lamps and Reflectors
Door
Combustion Cell
Holder

Figure 2.

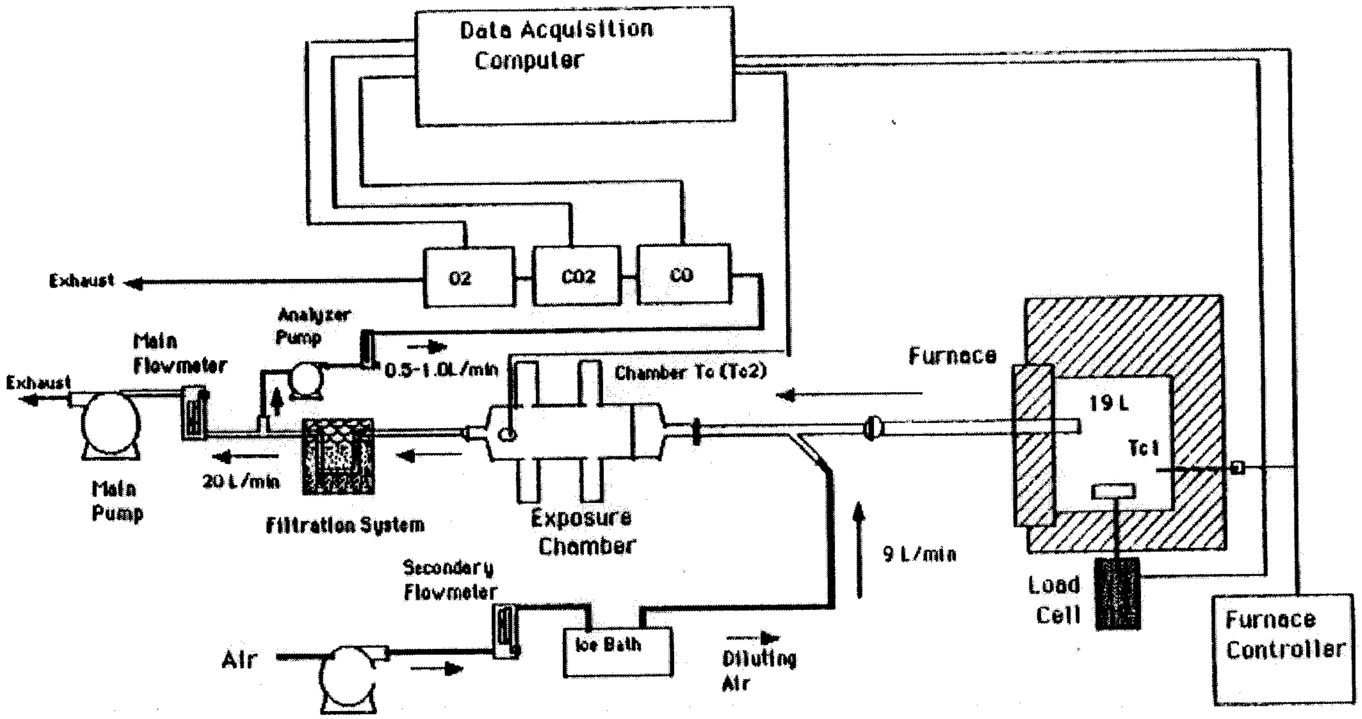

Data Acquisition Computer
Exhaust
O2
CO2
CO
Analyzer Pump
Main Flowmeter
Exhaust
0.5-1.0L/min
Chamber Tc (Tc2)
Furnace
19 L
Tc1
Main Pump
20 L/min
Filtration System
Exposure Chamber
9 L/min
Load Cell
Secondary Flowmeter
Air
Ice Bath
Diluting Air
Furnace Controller

Figure 3.

Fig 4

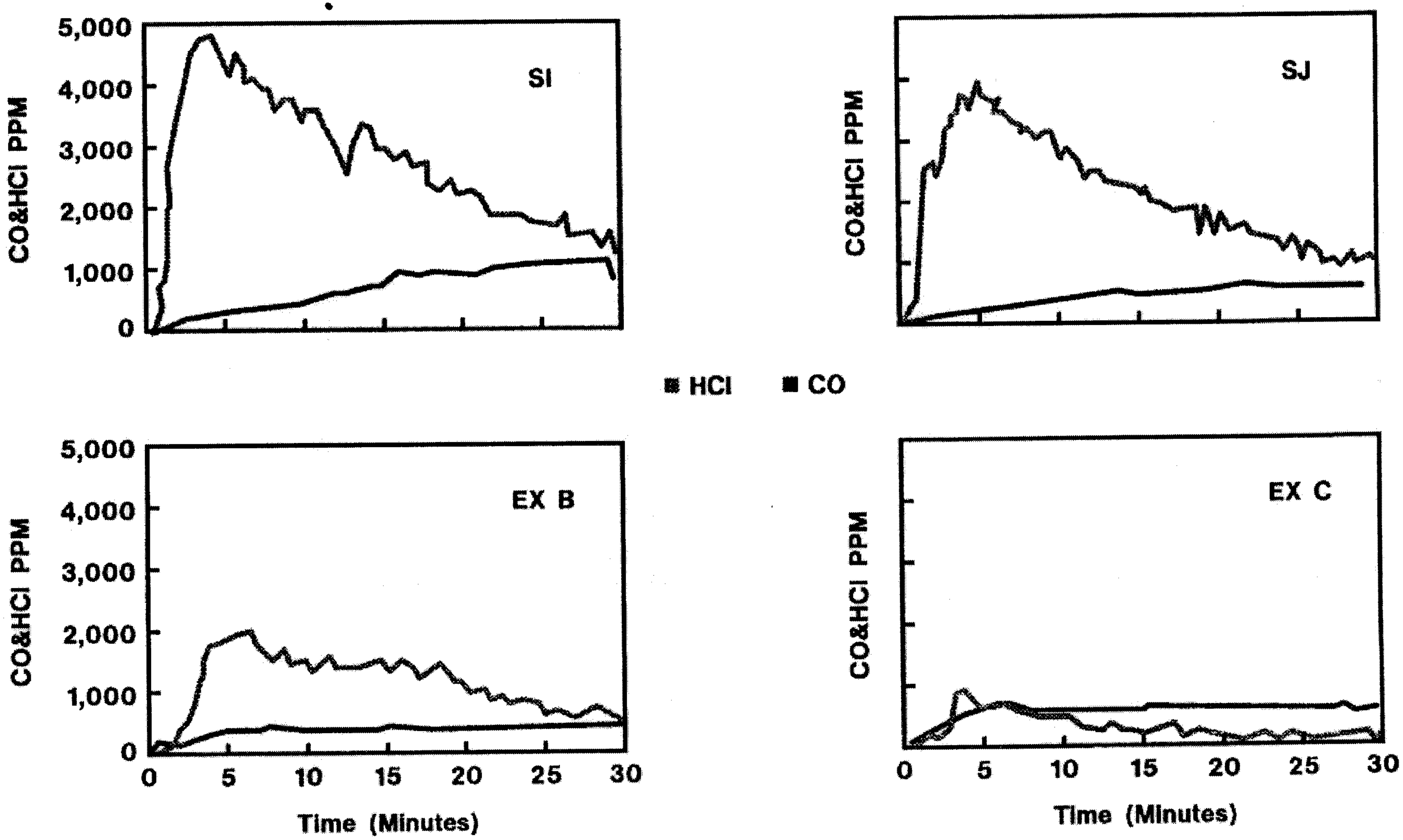

SI
SJ
EX B
EX C
CO&HCl PPM
5,000
4,000
3,000
2,000
1,000
0
Time (Minutes)
0
5
10
15
20
25
30
▨ HCl
■ CO

Fig 5

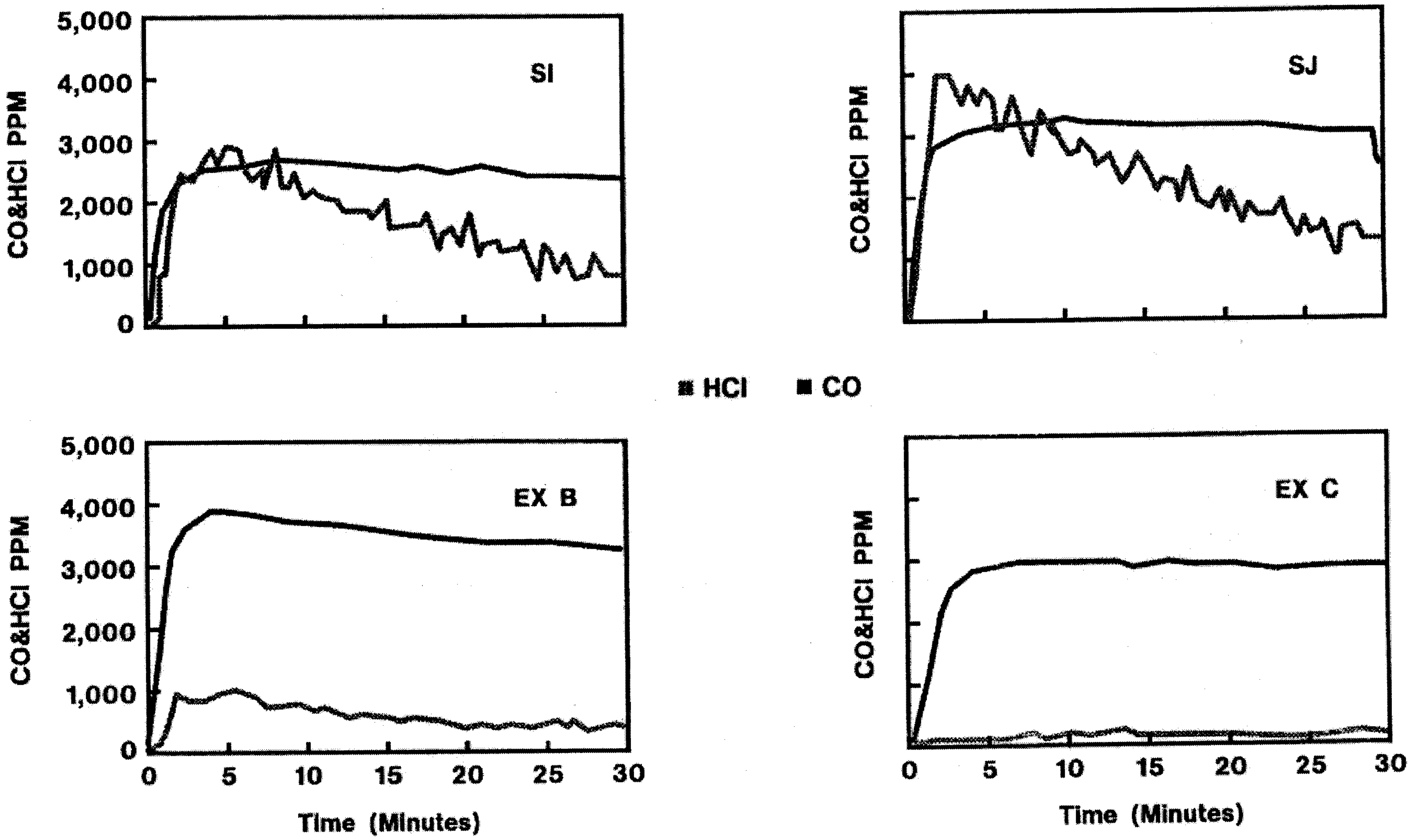
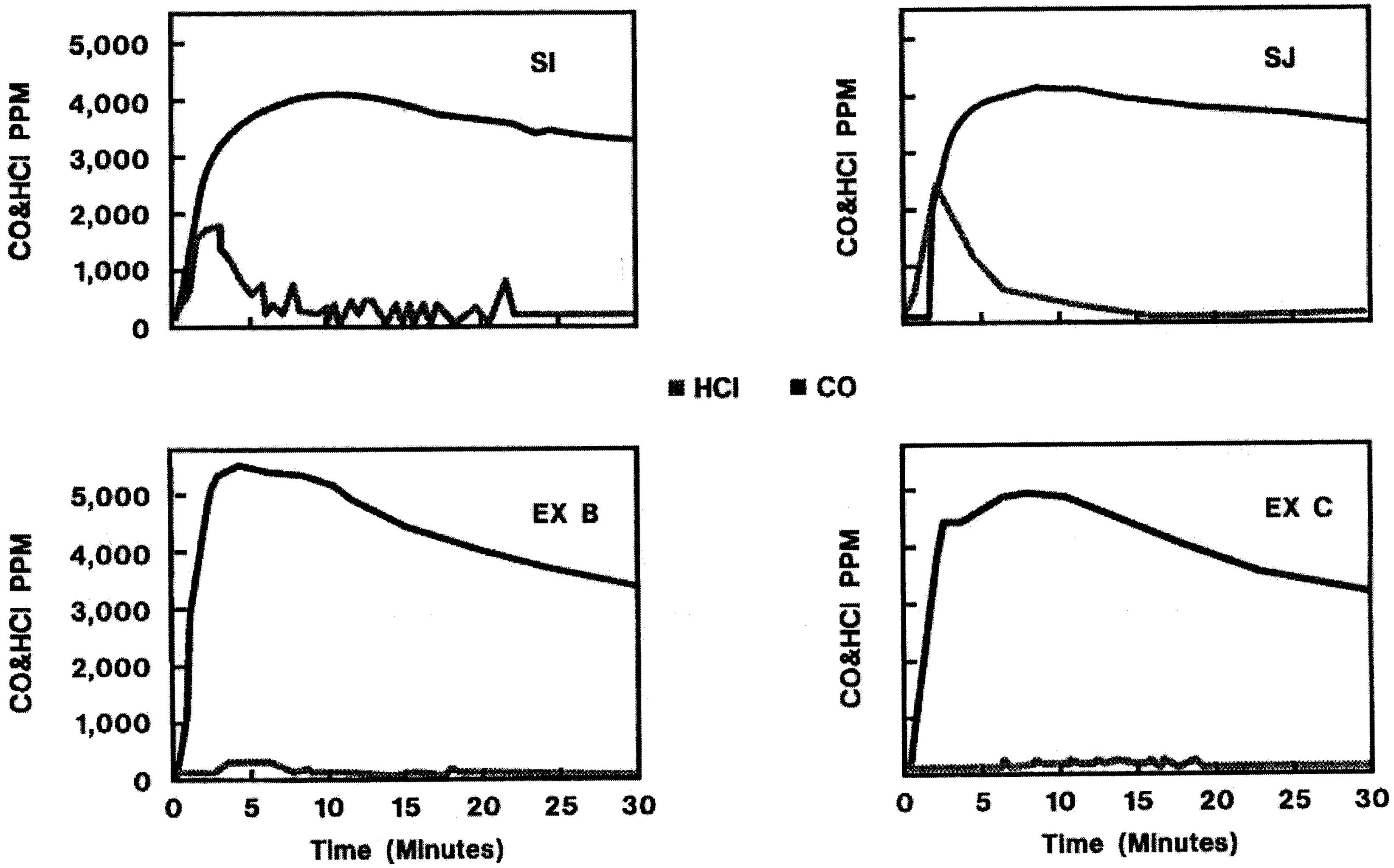

SI
SJ
EX B
EX C
CO&HCl PPM
5,000
4,000
3,000
2,000
1,000
0
0
5
10
15
20
25
30
Time (Minutes)
▨ HCl
■ CO

Fig 6



SI
SJ
EX B
EX C
CO&HCl PPM
5,000
4,000
3,000
2,000
1,000
0
■ HCl
■ CO
0
5
10
15
20
25
30
Time (Minutes)

Fig 7

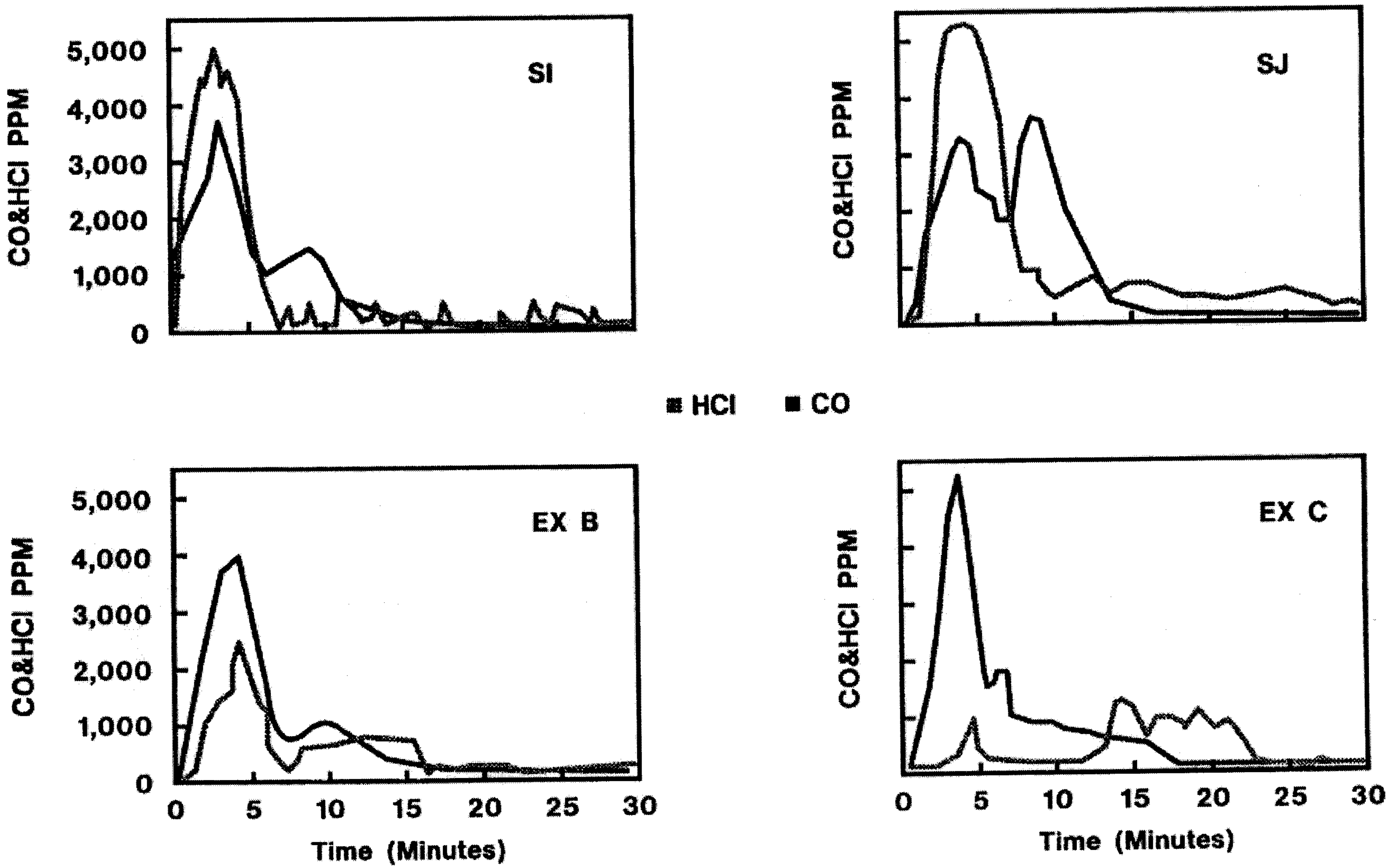

SI
SJ
EX B
EX C
CO&HCl PPM
5,000
4,000
3,000
2,000
1,000
0
0
5
10
15
20
25
30
Time (Minutes)
▪ HCl
■ CO

Fig 8

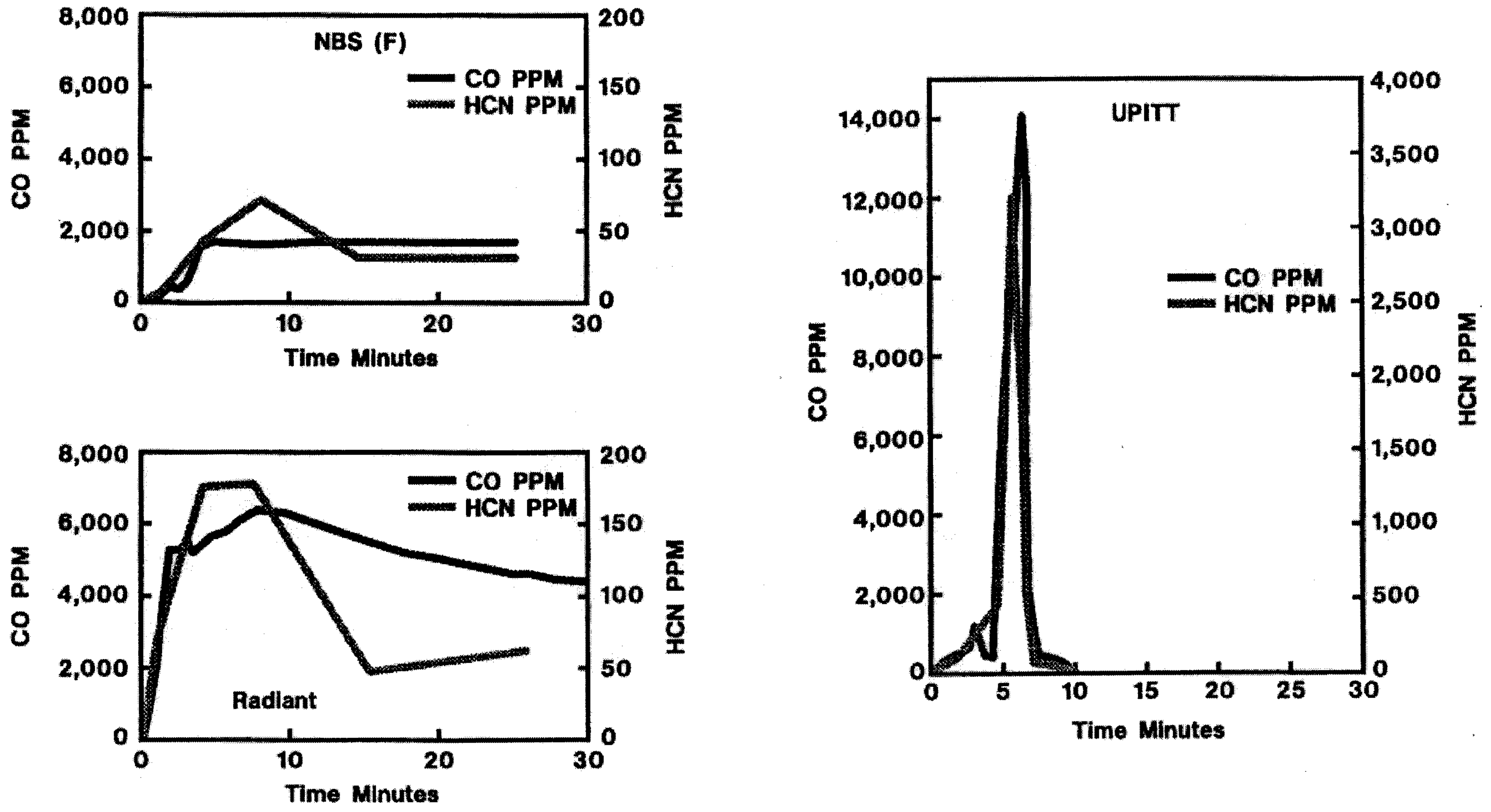

NBS (F)
CO PPM
HCN PPM
CO PPM
HCN PPM
8,000
6,000
4,000
2,000
0
200
150
100
50
0
0
10
20
30
Time Minutes
Radiant
CO PPM
HCN PPM
CO PPM
HCN PPM
8,000
6,000
4,000
2,000
0
200
150
100
50
0
0
10
20
30
Time Minutes
UPITT
CO PPM
HCN PPM
CO PPM
HCN PPM
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
5
10
15
20
25
30
Time Minutes

Figure Legends

Figure 1: Diagrams of the NBS Cup Furnace Test Method Apparatus.

Figure 2: Diagram of the Radiant Furnace Test Method Apparatus.

Figure 3: Diagram of the UPITT Test Method Apparatus.

Figure 4: Generation of CO and HCl by PVC compounds in the NBS Cup Furnace Test Method (Non-flaming mode).

SI: LC_{50}: 22.4 mg/L
Sample conc: 25 mg/L
CO Ct: 23,280 ppm min
HCl Ct: 81,780 ppm min

SJ: LC_{50}: 31.6 mg/L
Sample conc: 35 mg/L
CO Ct: 21,600 ppm min
HCl Ct: 70,800 ppm min

EX B: LC_{50}: 55.7 mg/L
Sample conc: 50 mg/L
CO Ct: 13,950 ppm min
HCl Ct: 34,890 ppm min

Ex C: LC_{50}: 59.9 mg/L
Sample conc: 60 mg/L
CO Ct: 13,980 ppm min
HCl Ct: 7,050 ppm min

Figure 5: Generation of CO and HCl by PVC compounds in the NBS Cup Furnace Test Method (Flaming mode).

SI: LC_{50}: 35.0 mg/L
Sample conc: 25 mg/L
CO Ct: 75,540 ppm min
HCl Ct: 51,270 ppm min

SJ: LC_{50}: 29.6 mg/L
Sample conc: 35 mg/L
CO Ct: 86,550 ppm min
HCl Ct: 65,430 ppm min

EX B: LC_{50}: 60.8 mg/L
Sample conc: 70.0 mg/L
CO Ct: 102,090 ppm min
HCl Ct: 16,500 ppm min

Ex C: LC_{50}: 159.0 mg/L
Sample conc: 140 mg/L
CO Ct: 96,960 ppm min
HCl Ct: 660 ppm min

-Figure Legends (cont.)-

Figure 6: Generation of CO and HCl by PVC compounds in the Radiant Furnace Test Method.

SI:
LC_{50}: 33.4 mg/L
Sample conc: 30 mg/L
CO Ct: 109,650 ppm min
HCl Ct: 5,940 ppm min

SJ:
LC_{50}: 53.1 mg/L
Sample conc: 55 mg/L
CO Ct: 128,220 ppm min
HCl Ct: 7,200 ppm min

EX B:
LC_{50}: 86.2 mg/L
Sample conc: 100 mg/L
CO Ct: 137,300 ppm min
HCl Ct: 1,500 ppm min

Ex C:
LC_{50}: 149.0 mg/L
Sample conc: 140 mg/L
CO Ct: 119,250 ppm min
HCl Ct: negligible

Figure 7: Generation of CO and HCl by PVC compounds in the UPITT Test Method.

SI:
LC_{50}: 5.6 g
Sample mass: 6.3 g
CO Ct: 22,000 ppm min
HCl Ct: 20,280 ppm min

SJ:
LC_{50}: 5.5 g
Sample mass: 7.1 g
CO Ct: 31,000 ppm min
HCl Ct: 45,000 ppm min

EX B:
LC_{50}: 10.0 g
Sample mass: 10.0 g
CO Ct: 22,130 ppm min
HCl Ct: 14,550 ppm min

Ex C:
LC_{50}: 21.6 g
Sample mass: 18.0 g
CO Ct: 22,650 ppm min
HCl Ct: 9,660 ppm min

Figure 8: Generation of CO and HCN by Nylon in the NBS Cup Furnace (Flaming), Radiant Furnace and UPITT Test Methods.

NBS (F):
LC_{50}: 49.0 mg/L
Sample conc: 50 mg/L
CO Ct: 43,980 ppm min
HCN Ct: 1,080 ppm min

Radiant:
LC_{50}: 36.7 mg/L
Sample conc: 70 mg/L
CO Ct: 150,870 ppm min
HCN Ct: 2,529 ppm min

UPITT:
LC_{50}: 5.3 g
Sample mass: 8.0 g
CO Ct: 26,600 ppm min
HCl Ct: 5,853 ppm min

GBH Attachment 4

AB59-COMM-7-4

SMOKE IN FIRES: OBSCURATION AND TOXICITY

Marcelo M. Hirschler
B. F. Goodrich

Smoke in Fires: Obscuration and Toxicity

"Smoke in fires: obscuration and toxicity", M.M. Hirschler, Plenary Lecture, Business Communications Company Conference on Recent Advances in Flame Retardancy of Polymeric Materials, May 15-17, 1990, Stamford, CT, Eds. G.S. Kirshenbaum and M. Lewin, p. 70-82, Norwalk, CT, 1990.

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BFGoodrich
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ABSTRACT

One serious fire hazard can be smoke generation, which causes decrease in visibility and increase in toxicity. Such parameters should be determined in ways that represent full scale fires; this paper surveys existing measurement methods. Smoke obscuration is best measured, in small scale tests, by using RHR instruments and compensating for total sample burning, since products with good fire performance are usually not fully consumed in fires. Smoke toxicity should also be determined in such a way that no unrealistic "rankings" are made based on minor differences in small scale tests, since those tests cannot predict concentrations of CO, the major toxicant in fires.

INTRODUCTION

There are three main ways in which fire, whatever the products involved, can cause harm to people, property or operations. These are, in decreasing order of their importance to fire hazard: (a) effects of heat or flames spreading from the item first ignited to other products, potentially resulting in thermal injury to people, destruction of property or loss of operation, (b) production of smoke which obscures vision and can inhibit both the escape of trapped victims and the action of fire fighters and (c) generation of toxic products (gases and particulates in smoke) which can be inhaled by victims and injure them.

For clarification purposes, the definition of smoke given by the ASTM Fire Standards Committee (in ASTM E176) is used in this paper. It states "smoke is the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis and combustion".

SMOKE OBSCURATION

The test methods used to measure smoke obscuration accompanying a fire can be classified into five categories:

(I) Static small scale smoke obscuration tests on materials
(II) Dynamic small scale smoke obscuration tests on materials
(III) Traditional full scale smoke obscuration tests on products
(IV) Full scale tests measuring heat release and smoke release
(V) Small scale tests measuring heat release and smoke release

This paper will briefly discuss these different types of methods in turn, while giving a few examples of tests in each category. The description will involve mostly general features which are common to most methods in a particular category.

In the first category are the single most widely used smoke test, i.e. the NBS smoke chamber, and an earlier version: the Rohm and Haas chamber (Table I). These tests are similar in design; the main difference is the light beam direction. It has been shown that results from these tests do not usually represent the smoke emission to be expected in full scale fires. A large amount of information has been published on NBS smoke chamber deficiencies [1-4]; they will not be discussed in depth here, beyond presenting a table of recognised deficiencies (Table II). These tests have some, limited, usefulness as laboratory tools to observe effects of changing a base formulation. Effects must still be confirmed by a reliable fire test.

There have been two proposals to remedy one of the main objections to the NBS smoke chamber: the inadequate representation of melting and dripping materials: the use of a dual burner, which can be set against a horizontal or vertical sample or the use of a conical burner.

Most of the tests in the second category measure smoke obscuration together with another property, although this was rarely an original objective of the test designers (Table III). such a use recognises, implicitly, the fact that smoke obscuration is not an isolated phenomenon, but is always a result of the fire itself.

The radiant panel flame spread test apparatus can be used to measure smoke obscuration by means of a filter in the exhaust stream. The Michigan chamber [e.g. 5] has been widely used as a tool for investigating effects of flame retardants and smoke suppressants on specific polymer systems. It consists of a box through which the smoke from the exhaust of a limiting oxygen index test apparatus is drawn. Smoke obscuration is measured photometrically; in order to ensure some burning uniformity, oxygen in the LOI tester is often set at LOI + 1. The Arapahoe smoke chamber offers a standard procedure for gravimetric soot measurements of smoke but uses a poor fire model, unrepresentative of real fires: the test is thus of limited use. The Dutch Vlamoverslag test exposes building materials vertically in a chamber to radiant heat combined with a pilot flame until flashover occurs; smoke obscuration is measured horizontally in a chimney above the chamber flue, together with the energy required for flashover at 5 or 15 min. Conceptually similar tests exist in the Nordic countries (Nordtest NT Fire 004) and Germany (Brandschacht test: DIN 4102 part 1).

Table I Static Small Scale Smoke Obscuration Tests on Materials

Examples: ASTM D2843 - Rohm & Haas Test (XP-2 Chamber)
ASTM E662/NFPA 258/BS 6401 - NBS Smoke Density Chamber

Details of Tests

Sample is Heated to Destruction in Sealed Cabinet
Smoke Obscuration is Measured Photometrically
Static Test
Single Measurement

Specifics of the Individual Tests

Rohm & Haas Test: Horizontal Optical Density
NBS Chamber: Vertical Optical Density

Table II Deficiencies in the NBS Smoke Chamber

Results do not correlate with full-scale fires.
Vertical orientation leads to melt and drip
Time dependency of results cannot be established
No means of weighing sample during test.
Maximum incident radiant flux is 25 kW/m^2
Fire self-extinguishes if oxygen level becomes <14 %
Therefore, composites often give misleading results
Wall losses are significant
Soot gets deposited on optics
Light source is polychromatic
Rational units of m^2/kg are not available

Table III Dynamic Small Scale Smoke Obscuration Tests on Materials

Examples:	ASTM E162 - Radiant Panel Flame Spread Test
	Arapahoe Chamber (ASTM D4100)
	Dutch Vlamoverslag Test (NEN 3883)
	Michigan Chamber
	BFGoodrich Smoke-Char Test

Details of Tests

Sample is Heated to Destruction
Smoke Obscuration is Measured Together With Another Property
Dynamic Test
Single Measurement of Smoke Obscuration

Characteristics of the Individual Tests

Radiant Panel: Soot - Measured with Vertical Flame Spread
Arapahoe: Soot - Measured after Burning Horizontal Sample
Vlam Overslag: Horizontal Optical Density -
Michigan Chamber: Horizontal Optical Density - Measured with LOI
Smoke-Char: Horizontal Optical Density - Measured with Char

The BFGoodrich smoke-char tester [6] is based on an interesting concept: simultaneous measurement of obscuration and of mass of residue. It was one of the first attempts at quantifying (albeit very imperfectly) a very important fire safety issue: materials which burn more extensively will, usually, give off more smoke simply by virtue of the larger amount of mass burnt. A very small sample is placed on a holder sited above the flame of an LOI tester and burnt for 30 s in air. A horizontal light beam and detector measure decrease in light transmission and the mass of residue is determined gravimetrically. It too has a poor fire model and no provision for the effects of high heat fluxes. However, there is still some interest in this approach, mainly because of its potential for mechanistic studies. The carbon contained in organic materials will result in three type of products: (a) gaseous compounds (mainly organic hydrocarbons and carbonyls and inorganic carbon oxides), (b) solid residue (principally char, remaining in the condensed phase) and (c) soot (suspension in air of solid particles, mainly carbonaceous, often with adsorbed polycyclic aromatic hydrocarbons, which get transported into the gas phase and cause obscuration of light). If a carbon mass balance is attempted, this method will give indications of the relative contributions of (b) and (c), rather than addressing only (c) like most other smoke tests do. It does not distinguish, unfortunately, between the carbonaceous (char) and the inorganic (ash) portion of the residue. Results from the smoke char test have been used to identify additives which operate by an intumescent mechanism [6] and to get information on whether smoke suppression was achieved by simple dilution via inorganic fillers [7].

Many full scale tests have been proposed for products and the most important ones are described in Table IV. They have little in common, other than that the original tests were usually designed in response to a specific need and they have often outlived their utility. They were not designed to measure heat release, but often for flame spread. Smoke obscuration was usually added later, almost as an afterthought. These tests are important because the product is allowed to "do its own thing" and, thus, a material (or product with good fire performance) is not necessarily burnt to completion. Moreover, smoke obscuration is always measured continuously, together with some other fire property. The results of these tests have however, as a rule, not been shown to correlate with the results of tests in more realistic scenarios.

This class of tests includes the Steiner tunnel test (first standardised by ASTM in 1950) and its several variations applicable to individual products (e.g. cable, UL 910 or sprinkler pipe, UL 1887), which has been used to regulate the amount of flame spread (and, often, the smoke developed) by materials for various applications with stringent fire performance requirements. Although its deficiencies are well known it is a popular procedure, because of widespread regulatory applications: sheet, cable, pipe, wall lining, sprinkler pipe, etc. It should be pointed out that it can yield misleading results, because materials have been developed "to pass the test", rather than for good fire performance. The test has been shown to misrepresent the fire performance of wall linings and floor coverings. One problem with wall linings is the test sample orientation (horizontal) which can lead to a less severe exposure than a vertical orientation, for partial sample burning. Another problem is that, since the sample is sited on the ceiling of the tunnel, some products tend to drip or melt away from the flame source and thus not propagate the fire. Moreover, unfortunately test results cannot be used as input for fire hazard assessment models.

The flooring radiant panel test was designed, in the early 1970's to solve the problem of carpets spreading fire outside the room of fire origin. Consequently, virtually none of the commercial carpets sold in the US in the late 1980's and 1990's is likely to cause such a problem. The maximum incident flux to this test is, however, much too small (10 kW/m^2) for it to adequately address the flooring product contribution to fire hazard, if the fire reaches significant intensity.

The 3 m cube test is a large static smoke chamber, used mainly for measuring the smoke developed from cables. Unfortunately its fire model is a very intense liquid hydrocarbon pool which is sufficient, often, to consume completely the combustible portion of the cables, due to the geometrical arrangement. Thus, the test suffers from most of the same defects that plague small scale static smoke chamber tests.

The ultimate measure of fire performance of a material or product is, of course, the way in which the end product reacts in a real fire. The best approximation to this fire performance will be found with room size fire tests where products can be tested in end use configurations, or as close as possible. The single most important fire property is the rate of heat release, since its peak value will determine the peak intensity of a fire [8-9]. The fire science community has understood this concept only relatively recently. Table V lists several such tests, which measure smoke obscuration together with heat release.

An empirical "rule" discovered in the 1970's has helped to show the way ahead: the rate of heat release of the majority of combustibles is proportional to the level of consumption of oxygen (the proportionality constant is 13.1 ± 0.3 kJ O_2/kg fuel) [10-11]. This was accompanied by an improvement in oxygen measurement techniques, so that O_2 can be determined with paramagnetic analysers at an accuracy of 0.001% O_2. Thus, the almost insurmountable problem of ensuring adiabaticity is now replaced by a much simpler problem: ensuring complete capture of the fire effluents of the fire (or of a known representative fraction).

Table IV Full Scale Tests for Smoke Obscuration but Not Heat Release

Examples: ASTM E84/NFPA 255/UL 723 - Steiner Tunnel Test
UL 910 - Cable Tunnel Test
London Underground - 3 m Cube Chamber
ASTM E648 Modified - Carpet Critical Radiant Flux

Details of Tests

- Sample is Not Heated to Destruction
- Smoke Obscuration is Measured Together With Flame Spread
- Continuous Measurements

Characteristics of the Individual Tests

Steiner Tunnel:
- Sheet/Cable/Pipe is Burned Horizontally
- Smoke Obscuration is Measured Vertically
- Results are Very Erratic
- Dynamic Test

3 m Cube:
- Cable is Burnt Horizontally
- Smoke Obscuration is Measured Horizontally
- Almost Full Length of Sample is Consumed
- Static Test

Flooring Panel:
- Carpet is Burnt Horizontally
- Smoke Obscuration is Measured Horizontally
- Other Fire Properties are also Measured
- Dynamic Test

Table V Full Scale Tests Measuring Heat Release and Smoke Release

Examples ASTM E603 - Standard Room
UL 1581 (Modified) - Cable Tray Test

Details of Tests

Sample is Not Heated to Destruction
Smoke Obscuration is Measured Together With Other Properties
Heat Release is Measured
Continuous Measurements
Dynamic Test
Gas Release can be Measured Simultaneously

Characteristics of the Individual Tests

ASTM Room:
Sheet is Burned Vertically
Smoke Obscuration is Measured Horizontally

UL 1581:
Cable is Burnt Vertically
Smoke Obscuration is Measured Horizontally

In the late 1970's and 1980's several tests were developed in which products are burnt in a simulated end-use environment and in which heat release is measured together with other properties, including smoke obscuration. These are dynamic tests, involve continuous measurements and give a realistic appraisal of the fire performance of the product. Among the tests worth mentioning are a lined room (ASTM E603, Nordtest NT Fire 025), vertical cable tray tests (IEEE 383, UL 1581, ICEA 529 or CSA FT-4, all of them modified to measure heat and smoke release), and furniture tests (UL 1056, furniture calorimeter, Nordtest NT Fire 032).

There remains, however, a problem with such tests: their cost. It is desirable to find smaller scale tests the results of which can serve as reasonable predictors of real fire performance and which can be used as inputs into fire models for assessment of fire hazard or fire risk.

In view of these issues, smoke obscuration should be measured with small scale tests which can fulfill four basic criteria, as follows:

(1) Such tests must measure fire properties so that they can be used for purposes other than simple rankings or pass/fail criteria.

(2) Such tests should measure fire properties of considerable fire hazard interest, principally, the rate of heat release.

(3) Such tests must have been proven to give results that are representative of the corresponding property in a full scale scenario.

(4) Such tests must allow calculations to compensate for complete sample consumption, characteristic of small scale tests.

Probably the only tests in existence to fulfill these requirements are based on heat release (RHR) calorimetry. They are the cone calorimeter (cone) [12-13], the Ohio State University (OSU) RHR calorimeter [14] and the Factory Mutual RHR calorimeter [15] (Table 6).

The first two have been used extensively by many investigators and are very well known. There are eight main differences, viz.:

(a) The cone uses the oxygen consumption principle. It is not adiabatic but allows easy observation of the burning process. The OSU was designed as adiabatic, and sample burning visibility is minimal. The apparatus can be modified to allow heat release measurement by O_2 consumption. Apparatus geometry cannot be changed easily, however.

(b) The cone is normally used with horizontal samples, while the OSU is normally used with vertical samples. Samples can be burnt in the cone vertically and horizontally in the OSU; the latter leads to larger irreproducibility because of makeshift radiation reflection.

(c) The radiant source in the OSU is a set of four glow bars, sited directly across from the horizontal sample. Soot particles and smoke must make their way through a "chimney" between the burning sample and the heat source, causing afterburn. There is a truncated conical radiant heater in the cone; this generates a uniform energy distribution; smoke is captured with minimal losses or afterburn.

(d) The OSU has a flame igniter and the cone a spark igniter. Thus, the OSU ignition source is more powerful and more localised. The flux on the actual sample is larger in the OSU than the cone, if both radiant heaters are calibrated to the same value. Therefore, samples may ignite in the OSU but not in the cone. Fire models are more likely to require data without "hot spots", but the OSU is better at modelling impinging flames. This can easily be altered for either instrument.

(e) The cone has a load cell to measure mass continuously, but the OSU does not. This is very important, to calculate fire properties on a per mass lost basis. Attempts have been made to make an OSU apparatus with a load cell, which appear promising.

(f) The cone uses a laser for measuring smoke obscuration while the OSU uses a white light. Results from both measuring systems are virtually equivalent, if scanning times are small ($\leq$ 3 s [16-17]). The white light is more similar to what the human eye sees, but it needs more maintenance (very infrequent cleaning is needed in the laser). Alternative obscuration sensors can be installed in either apparatus.

(g) The sample size is somewhat different: ca. 10 x 10 cm^2 in the cone and ca. 15 x 15 cm^2 in the OSU. This will make no major difference to the results and is simply a consequence of the geometry.

(h) The incident air flow rate is much higher in the OSU than in the cone, because of the geometric apparatus design.

In both apparatuses the incident air composition can be changed to simulate the vitiated atmospheres prevalent in intense fires; the nitrogen content of the air can be increased relatively easily. High incident air flow rates make it inconvenient (although not impossible, in the cone) to increase the oxygen content of the atmosphere. The Factory Mutual RHR calorimeter can operate at high oxygen levels. This is of interest with products destined for use in outer space. It has been proposed also that higher atmospheric oxygen contents may simulate reradiation due to the burning sample [18]. This is an interesting idea which remains to be confirmed, since, unfortunately, only a single laboratory has, as yet, had extensive experience with this apparatus.

Smoke obscuration is normally reported in the OSU by calculating rate of smoke release and integrating this parameter to obtain total smoke released. In the cone, the normal way of reporting obscuration is the average extinction area, which measures obscuration per unit mass. Both ways of reporting smoke obscuration can be interconverted.

In order to compensate for the complete consumption of the sample, it is possible to calculate derived magnitudes of smoke obscuration, which can be determined directly in small scale RHR apparatuses. Two have recently been used often: smoke parameter [2] and smoke factor [19]. Smoke parameter is the product of average extinction area and peak RHR, while smoke factor is the product of total smoke released and peak RHR. Both are measured continuously and often reported at 5 min.

An attempt has been made to compare NBS smoke chamber results with those of full scale tests and RHR test smoke obscuration results: cone and OSU [19]. The results indicate a lack of correlation between the NBS smoke chamber and any of the other three tests. Moreover, results also showed that the cone smoke factor and smoke parameter correlated very well indeed with the OSU smoke factor, for a total of 17 plastic materials covering a wide gamut of fire performance. Recent work has shown that the cone calorimeter RHR can be used to predict the results of full scale fire tests of cables in vertical trays [20]. A model was developed to predict full scale RHR from small scale results. More interesting however, is the fact that the total amount of smoke obscuration measured in the full scale tests correlated very well with the smoke factor measured in the cone calorimeter, for the cables. In the same work [20], the materials used to make the cables were burnt in the cone and in the OSU. Predictably, heat release results in both instruments correlated well with one another. More unexpectedly, smoke factors for both instruments correlated wonderfully with each other as did smoke factors in each instrument at two different incident fluxes. Other work has also shown good correlations between small scale results in the cone calorimeter and full scale fire test results, in the room-corner test, both in terms of heat and of smoke release.

All this suggests clearly that, at present, the best way of measuring smoke obscuration in a meaningful way for full scale fires is the use of a small scale rate of heat release test, such as the cone calorimeter (or the OSU calorimeter) and compensate for incomplete burning of fire retardant materials by using the smoke factor concept.

SMOKE TOXICITY

Toxic potency of smoke is a quantitative expression relating smoke concentration and exposure time to adverse effects, usually lethality, on a test animal. It has to be stressed that toxic potency of smoke is heavily dependent on the conditions of smoke generation, which affect both quality and quantity of smoke.

During the 1970's and early 1980's many smoke toxic potency test methods were developed;

the ones most widely used are in refs. 21-24. These tests differ in many respects, including: fire model, being static or dynamic, use of animals or analytical tools, animal model for bioassay and end point. Due to all these differences the tests lead to tremendous ranking variations for the smoke of various materials. A case in point was illustrated in a study of the toxic potency of 14 materials by two methods [25] (Table VII). It showed that the material ranked most toxic by one protocol was ranked least toxic by the other protocol! Neither of those protocols is in common use now, but the work illustrates some of the shortcomings inevitable with small scale toxic potency of smoke tests.

Toxicity of smoke is a function of composition, which depends both on what is burnt and on how it is burnt. Thus, the composition of the smoke generated by any material in different tests varies broadly, so will its toxic potency. In fact, the toxic potency of the smoke of most ordinary materials (whether natural or synthetic) is very similar (see Figure 1 [26]). The difference between the smoke toxic potencies of almost all combustible materials is less than 1 order of magnitude. Thus, relative toxicity rankings are heavily dependent on the exact composition of the smoke being tested, i.e. on the test protocol, and are of little interest from the viewpoint of fire hazard assessment.

The main direct cause of death in fires has always been toxicity of combustion products, as already discussed in the NFPA Quarterly in 1933 [27]. However, fire victims are often incapacitated by heat effects before being killed by smoke inhalation. Smoke contains mainly 2 types of toxic gases: asphyxiants and irritants, but the individual toxic gas associated with the largest fire hazard is carbon monoxide (CO).

CO is a combustion product present in all fires, because it results from the combustion of any organic material. Its physiological result is the formation of carboxyhemoglobin (COHb) in blood. The exact COHb lethal level depends heavily on the individual affected, but any value > 20% can lead to death [28]. Even with the ultraconservative (and incorrect) estimate that 50% COHb is the lethal threshold, CO alone accounts for 60% of fire deaths, while > 91% of fire victims have COHb levels > 20%. Many factors can lead to lower CO tolerance, even with no other toxic gases: heart disease, blood alcohol, burns and age. It is fascinating to note the great similarity found between the blood COHb level distributions in two studies, one involving the 1980 MGM Grand Hotel fire and the other involving CO deaths from gas heaters [4]. This indicates that deaths in fires and deaths from CO poisoning (in non-fires) correlate well. Statistical studies of data on > 2,000 fatalities (CO from fire and non-fire sources) [29] have shown that, once the controlling factors of age, disease and blood alcohol are separated, COHb distribution in fire and non-fire deaths are similar.

Table VI Small scale tests Measuring Heat Release and Smoke Release
Rate of Heat Release Calorimeter Tests

Examples: ASTM E906 - OSU RHR Calorimeter
ASTM P190 - NBS Cone Calorimeter
Factory Mutual Calorimeter

Details of Tests

Sample is Heated to Destruction
Heat Release is Measured
Smoke Obscuration is Measured Together With Other Properties
Dynamic Test
Continuous Measurements
Combined Smoke/Fire Hazard Properties can be Measured
Gas Release can be Measured Simultaneously

Characteristics of the Individual Tests

OSU Calorimeter:
Sample is Burnt Vertically
No Mass Loss is Measured
There are Heat Losses
Light Source is Polychromatic

Cone Calorimeter:
Sample is Burnt Horizontally
Mass Loss is Measured Continuously
There are No Heat Losses
Light Source is Monochromatic
Best Known Combustion Model
Measures All Fire Hazard Parameters

Table VII Comparative Mortality Data of Combustion Products of Polymers

	STATIC CHAMBER		DYNAMIC CHAMBER	
LC_{50} g	Sample	Toxicity Ranking (Toxicity Increases Upwards)	Sample	LC_{50} g
9	Red Oak	1	Wool	0.4
10	Cotton	2	Polypropylene	0.9
21	ABS (FR)	3	Polypropylene (FR)	1.2
23	SAN	4	Polyurethane foam (FR)	1.3
25	Polypropylene (FR)	5	Poly(vinyl Chloride)	1.4
28	Polypropylene	6	Polyurethane foam	1.7
31	Polystyrene	7	SAN	2.0
33	ABS	8	ABS	2.2
37	Nylon 6,6	9	ABS (FR)	2.3
37	Nylon 6,6 (FR)	10	Nylon 6,6	2.7
47	Polyurethane foam (FR)	11	Cotton	2.7
50	Polyurethane foam	12	Nylon 6,6 (FR)	3.2
50	Poly(vinyl Chloride)	13	Red Oak	3.6
60	Wool	14	Polystyrene	6.0

Many gases other than CO are given off in fires, but CO is the overwhelming hazardous toxicant in a fire. Peak concentrations [4] of various gases found by fire fighters equipped with gas sensors were: 7,450 ppm CO, 100 ppm acrolein, 280 ppm HCl and 10 ppm HCN, while the corresponding lethal doses are: 90,000-138,000 ppm min CO, 2,500-5,000 ppm min acrolein, 112,000 - 159,000 ppm min HCl and 4,800 ppm min HCN.

As regards HCl, it is relevant to point out that its airborne concentration only remains at a peak value for a short period before decaying [4]. This decay of HCl is particularly fast in the presence of sorptive surfaces such as most ordinary construction materials [30].

Many studies have been made of combinations of individual toxic gases. Most of them show that have simply additive effects. This is the case for CO and HCN and for CO and HCl, although the mechanisms of action are different. These results can be interpreted as each toxicant taking its toll and acting on a weakened system. The CO-carbon dioxide combination has been claimed to be synergistic.

The fire scenarios where fire hazard is greatest are those with full room involvement, or flashover. In such fires, there is excess of fuel to oxidant, and, generally, low ventilation. CO concentration in those fires depends heavily on fire load (i.e. how much material is burning, per unit volume) and on geometrical arrangements, including ventilation, while its dependence on materials is of a lower order. This secondary effect of materials is illustrated in a recent study [31], in which attempts were made to correlate CO concentrations measured in small scale and full scale fire tests. The small scale equipment (cone calorimeter) predicted adequately all important full scale fire properties except full scale CO concentrations. The latter concentrations were controlled by the geometry of the full-scale fire, the ventilation/oxygen content and the mass loading, and were little affected by the chemical composition of the burning materials. Small scale tests predict CO yields (or carbon monoxide to carbon dioxide ratios) which are much lower than those found in intense fires. Small scale toxicity tests can predict reasonably well yields of non CO, thus overpredicting the relative toxicity of materials (or products) which are heavy emitters of such compounds.

This discussion suggests that measuring smoke toxic potency can, at best, only give a small portion of the toxicity picture. Such data are of no use in isolation. Toxic potency screening tests may point to materials (or products) with toxic potency outside the range of most products. These are very rare and generally result from very small concentrations of gases not usually measured directly. Thus, extreme toxic potencies can only be found with a bioassay (animal model), and should then be dealt with by a full fire hazard assessment.

A quick screening method to choose materials for more intense scrutiny of toxic hazard is to calculate [4] the ratio of their toxic potency and their mass loss rate parameter. Mass loss rate parameter is the ratio of an average mass loss rate and time to ignition. If the mass loss rate parameter differs by more than an order of magnitude from that of ordinary materials the material in question should be investigated more thoroughly. The choice of a factor of 10 is typical of the difference between toxicity categories, in classical toxicology.

A recent study has looked critically at the more common smoke toxic potency screening tests [32]. It found serious problems with all, but mostly with the UPITT test [22]. Its animal model (the mouse) is very poor, because the mouse is a poor predictor of human lethality [35].

If a toxic potency test shows no unusual toxicity, the data needed for fire hazard assessment can be obtained by analytical experiments. One potential way of solving the underprediction of CO yields by small scale tests would then be an independent estimation of CO yields from the appropriate full scale scenario (where the fuel chemistry has little effect). The toxic potency could then be calculated based on that CO yield and the small scale yields of other combustion products.

CONCLUSIONS

Adequate means exist to determine the smoke obscuration resulting from real fires. The best way of doing that in small scale is by using RHR calorimeters and compensating for the fact that products with good fire performance will not fully burnt up in a fire. That is done well with the smoke factor, a combination of smoke obscuration and rate of heat release. Smoke toxicity in fires is a consequence principally of the CO concentration, which is determined by geometric arrangements, ventilation and fire load. Small scale tests cannot reproduce the high fuel/air ratio and high heats of intense fires and, thus, underpredict the effect of CO and overpredict the effects of other fire gases. In fact, the smoke from most materials has very similar toxic potency; so the role of toxic potency tests is just to identify the, few, outliers.

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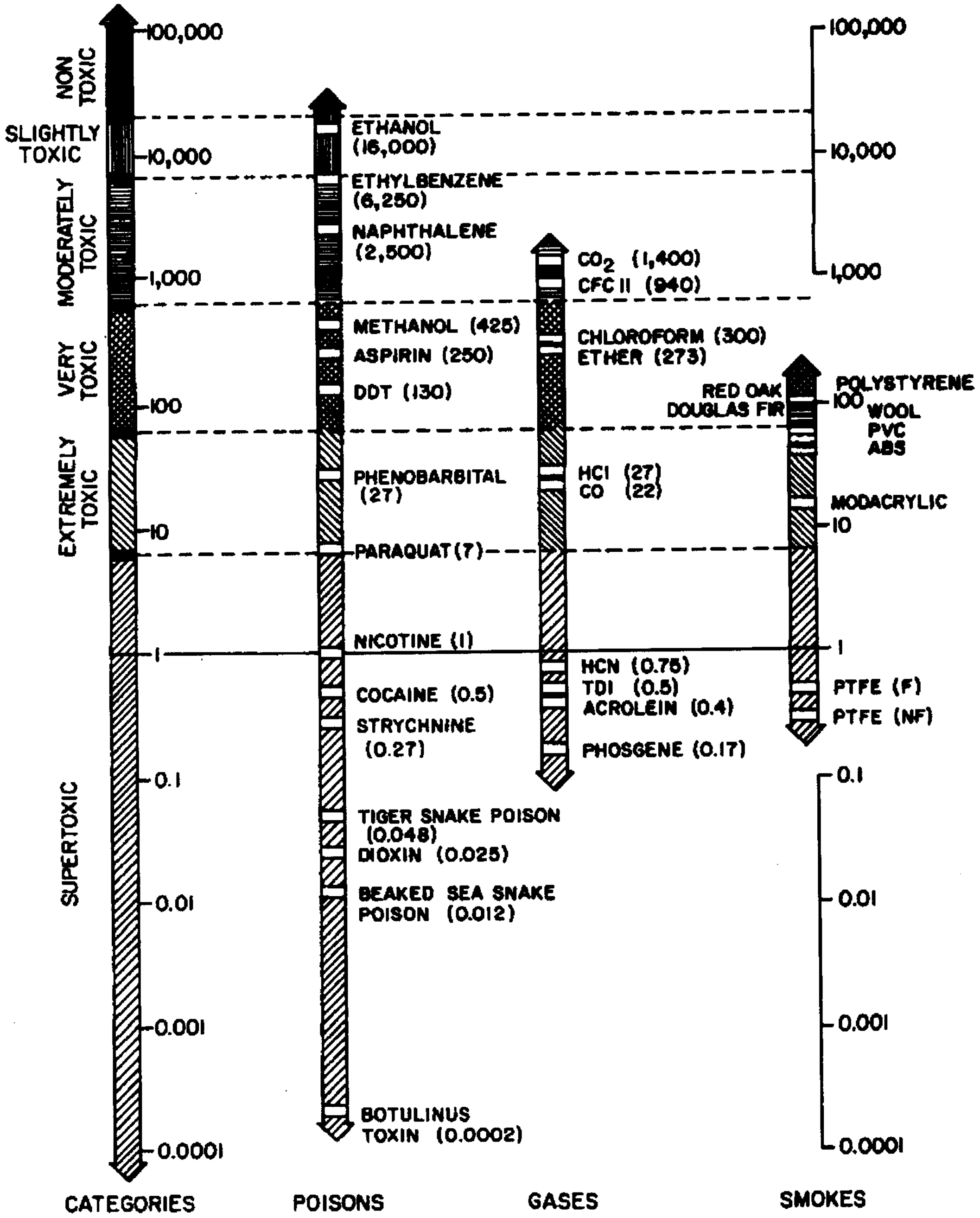
Figure 1: Toxic Potency (LD_{50} in mg/kg) of various substances and of smoke



GBH Attachment 5

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Chapter 28

General Principles of Fire Hazard and the Role of Smoke Toxicity

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Fire hazard is a combination of several properties, including ignitability, flammability, flame spread, amount of heat released, rate of heat release, smoke obscuration and smoke toxicity.

A large number of procedures are now available for measuring fire properties, but many of them are of little interest since they represent outdated technologies. Thus, in order to obtain a realistic estimate of fire hazard for a scenario it is essential to measure relevant fire properties. Furthermore, the appropriate instruments have to be used, viz. those yielding results known to correlate with full scale fire test results.

True fire hazard can be determined only in a specific scenario. Therefore, it is necessary to determine which fire properties are most relevant to the scenario in question. These fire properties will then have to be measured and combined in order to obtain an overall index of fire hazard. As a general rule, it is clear that the most important individual property that governs levels of fire hazard is the rate of heat release: the peak rate of heat release is proportional to the maximum intensity a fire will reach.

A large number of small-scale tests have been designed to measure the toxic potency of the smoke of materials. These tests differ in many respects; the consequence of this is that the relative toxic potencies of smoke resulting from these various tests are different. The tests are not useful,

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> therefore, to rank materials in terms of their toxicity. The tests are useful, however, in selecting those, very few, materials with a much higher toxic potency than the common materials in everyday use.
>
> Fire safety can be improved by decreasing fire hazard, but is unlikely to be affected by small changes in toxic potency of smoke, since the toxic potency of most materials is very similar.

In order to understand the various concepts associated with fire safety it is essential for all major terms to be defined adequately.

Fire hazard can be defined as the potential for harm associated with fire: it addresses threats to people, property, or operations, resulting from a particular fire scenario. A fire scenario involves those conditions relevant to the initiation, development, or harm caused by a fire. Fire risk is a combination of three elements: (a) fire hazard, (b) probability of fire occurrence in the scenario in question and (c) probability of the material or product in question being present in the fire scenario. Toxic potency (of smoke) is a quantitative expression relating concentration and exposure time to a certain adverse effect, on exposure of a test animal; the effect is usually lethality. It is necessary to stress that the toxic potency of smoke is also heavily dependent on the conditions under which the smoke has been generated, since the mode of generation will affect both the quality and the quantity of smoke. Smoke is interpreted here as the sum total of the gaseous, liquid and solid airborne products of combustion. Exposure dose is an integration of the toxic insult, as calculated from the smoke concentration vs. time curve. If the insult results from an exposure to a single toxicant, and its concentration is constant, the exposure dose is simply the product of concentration and time of exposure. Time to effect can be very different from time of exposure, since many toxicants act with a delayed effect, so that the test animal (or the victim) may die long after the exposure.

Stages of a Fire and Fire Hazard

A major fire follows several stages:

1. Ignition (onset of fire)
2. Development of fire within original compartment
3. Involvement of other products
4. Full room involvement (or flashover)

5. Transport of fire to other compartments
6. Decay

The intensity of the fire will determine which stages the fire will traverse on its way from ignition to decay. The National Fire Protection Association (NFPA) stores statistical data collected from the fire marshalls' reports. It classifies [1] fires as:

(i) restricted to the object of origin
(ii) restricted to the area of origin
(iii) restricted to the room of origin and
(iv) extending beyond the room of origin.

It is clear that fires of type (i) will not go through stages 3-5, fires of type (ii) will skip stages 4 and 5, and fires of type (iii) will not reach stage 5, before decaying. These considerations are important because they will be an essential tool in deciding the properties to be measured for estimating fire risk or fire hazard.

As far as fire hazard to humans is concerned, the main aspects to be considered are:

* Heat effects
* Toxicity of smoke
* Lack of visibility

These phenomena all depend both on time and location. Thus, it is important to consider the following two aspects for all of them:

* Transport of smoke
* Decay of smoke components

The fire properties most relevant to each stage of a fire are:

1.* Ease of ignition of product first ignited
  * Ease of extinction of product first ignited
2.* Rate of heat release of product first ignited
  * Amount of heat released by product first ignited
  * Flame spread characteristics of product first ignited
  * Mass loss rate of product first ignited
  * Smoke factor of product first ignited
  * Rate of fire growth
  * Presence of fire suppression devices (e.g. sprinklers)
  * Toxicity of smoke
3-4.* Ease of ignition of other products
  * Rate of heat release of other products
  * Amount of heat released by other products
  * Flame spread characteristics of other products
  * Mass loss rate of other products

- * Smoke factor of other products
- * Rate of fire growth
- * Presence of fire suppression devices
- * Toxicity of smoke

5-6.* Fire performance of products in original compartment

- * Fire endurance of structural components of original compartment
- * Ease of ignition of products in other compartments
- * Same issues as in earlier stages, for new compartments
- * Overall fuel and oxygen supply
- * Geometric scenario considerations
- * Transport and decay of smoke
- * Fire protection measures:
  - Compartmentalisation
  - Sprinklers
  - Smoke detectors
  - Extinction capabilities
- * Effects of conditions on fire fighters
  - Visibility
  - Heat
  - Toxicity of smoke

Some of the fire properties mentioned have been measured and well understood for a long time, but others are relatively new concepts. The most important fire properties and proposed measurement methods will thus be discussed in the following sections.

Rate of Heat Release and Associated Fire Properties

It has now become clear that the single property which most clearly defines the magnitude of a fire is the maximum rate of heat release [2, 3]. The peak rate of heat release is an indication of the peak intensity of a fire. The rate of heat release (RHR) can, thus, be used as a small scale substitute for the burning rate of the full scale fire. This property (RHR) governs not only the burning rate (and mass loss rate) of the product being consumed but also the amounts of other items which will be burnt. The rate of heat release will also therefore govern the overall amount of smoke and combustion products being generated in the fire, since other products will be ignited only if enough heat reaches them at sufficient speed. The rate of fire growth can be represented by the rate of rise of the heat release rate.

Much research has been done to identify the relationship between the properties of materials as measured in small scale tests and the performance of products made from them under real fire conditions [4, 5]. The best approach is to estimate the rate of growth of a real fire (or perhaps the time available before flashover) based on measuring, in a small scale test, the peak rate of heat release for those materials used to manufacture the burning product. The rate of burning of a real fire can be expressed in terms of the rate of mass loss. Yield factors can be measured in small scale tests to give the amounts of heat, smoke and toxic gases generated per unit mass burnt. They can then be coupled with the burning rate of the real fire to estimate the potential build up of heat, smoke and toxic gases in the real fire [6]. Rate of heat release can be measured in instruments called rate of heat release (or RHR) calorimeters [7-10]. The data measured from one of these instruments (the cone calorimeter, developed at the National Institute for Standards and Technology, NIST) has been shown, repeatedly, to correlate well with those found in full scale fires [11-13]. The data from another RHR calorimeter (the Ohio State University instrument) has been shown to correlate with those from the cone calorimeter [14] and from full scale aircraft tests [15]. It is already being used to regulate aircraft interior materials [16]. A third RHR calorimeter (the Factory Mutual instrument) is being used to assign insurance risk to cables in non-combustible environments [17].

Rate of heat calorimeters can be used to measure a number of the most important fire hazard parameters, including the peak rate of heat release, the total heat release, the time to ignition and smoke factor (a smoke hazard measure combining the total smoke released and the peak RHR [14, 18-20]). The smoke factor will give an indication of the total amount of smoke emitted in a full scale fire.

In summary, thus, if RHR calorimeters are fitted with the appropriate instrumentation they can be used to measure:

Rate of heat release
Total heat released
Ease of ignition
Mass loss rate
Smoke factor

Other Fire Properties Useful for Aspects of Fire Hazard

Some of the other properties of interest for fire hazard assessment cannot be measured with RHR calorimeters. They include flame spread, limiting oxygen index (LOI, or simply oxygen index, OI: both names have been used, but the author's preferred nomenclature is the one used here) and fire endurance.

It is outside the realm of this paper to discuss the instruments used for these tests in any detail. It is only worth mentioning a few general principles.

If a material does not ignite, it will not endanger lives or contribute to fire hazard. Most organic materials do, however, ignite; the hazard will, thus, be greater the lower the ignition temperature or the shorter the time to ignition. Some of the most common ignitability tests, other than RHR instruments, are:

* ISO 5657:	Measures sample ignitability, with a conical combustion module. Normal sample orientation: horizontal.
* IEC 695-2:	This contains two ignitability tests: one uses a glowing wire and one a needle flame.
* ASTM D1929:	Setchkin ignition apparatus. Measures flash ignition and spontaneous ignition temperatures. Normal sample orientation: horizontal.

Once a material has ignited, the hazard associated with it will increase if its flammability is greater; one of the most reliable quantitative small scale flammability tests is the limiting oxygen index test (ASTM D2863). This test measures the limiting oxygen concentration in the atmosphere necessary for sustained combustion. It is not a good predictor of full scale fire performance, but can give an indication of ease of burning or ease of extinction. Tables of typical results have been published (e.g. refs. 21-23).

The LOI test cannot be used to predict full-scale fire performance. However, if a material has, as a rule of thumb, an LOI value above 25-27 it will, generally, only burn under extreme conditions (high applied heat). It has been shown that the LOI does not, in fact, correlate well with other fire tests, not even a small-scale flammability test such as UL 94 [24]. It has, further, been suggested that there may be some advantage in using a modification that uses bottom ignition [25]. It is important to keep in perspective the utility of this test for ease of extinction: it can (a) give a first approximation to suggest whether a material is very flammable or not; (b) show whether changes in a base formulation have improved flammability characteristics and (c) be used as a quality control tool.

The next property of interest is flame spread, which can be measured by a variety of standard test methods, depending on the angle at which the flame impinges on the material. The two most widely used tests are ASTM E162 and ASTM E84. In ASTM E162 a radiant panel ignites a 15 cm by 45 cm sample at an angle of 30° to the right of the vertical. A variant of this test is the IMO (or Lateral Ignition and Flame Spread Test, LIFT) apparatus. In ASTM E84 (Steiner tunnel test) a pair of gas burners ignite a horizontal 7.5 m long sample from below. A variety of other flame spread tests exist, but they are generally associated with specific applications or scenarios (e.g. cable tests, floor covering tests, etc.).

Fire endurance properties are always measured directly on finished products, and are specific for a particular application.

Smoke Obscuration

Another important property of materials is their tendency to decrease visibility. The most common method for measuring this property is the NBS smoke chamber in the vertical configuration at 25 kW/m^2 (ASTM E662). This instrument has now been shown to be associated with a variety of deficiencies, the most important of which is its lack of correlation with the results of full scale fires [26-28]. A variety of other devices are also used for measuring smoke obscuration, and details are beyond the scope of this paper. Suffice it to mention that, in order to obtain results meaningful for fire hazard assessment it is necessary either to avoid full sample consumption or to compensate for it in some way, for those materials or products which do not burn up completely in a fire. Furthermore, when samples are exposed vertically to flame they may melt or drip and, thus, avoid being consumed by letting the material artificially escape the action of the flame. The best methods for assessing smoke obscuration are those that combine smoke and heat release measurements.

Toxic Potency of Smoke

During the 1970's and early 1980's a large number of test methods were developed to measure the toxic potency of the smoke produced from burning materials. The ones most widely used are in refs. 29-32. These tests differ in several respects: the conditions under which the material is burnt, the characteristics of the air flow (i.e. static or dynamic), the type of method used to evaluate smoke toxicity (i.e. analytical or bioassay), the animal model used for bioassay tests, and the end point determined. As a consequence of all these differences the tests result in a tremendous variation of ranking for the smoke of various materials. A case in point was made in a study of the toxic potency of 14 materials by two methods [33]. It showed (Table I) that the material ranked most toxic by one of the protocols used was ranked least toxic by the other protocol! Although neither of these protocols is in common use in the late 1980's, it illustrates some of the shortcomings associated with small scale toxic potency of smoke tests.

Smoke is not a uniform substance and its composition depends on the exact conditions under which it was generated. Therefore, the composition of the smoke generated from the same material in different tests can vary broadly and, consequently, so will its toxicity.

Table I. Comparative Mortality Data of Combustion Products of Polymers

LC_{50} g	STATIC CHAMBER Sample	Toxicity Ranking (Toxicity Increases Upwards)	DYNAMIC CHAMBER Sample	LC_{50} g
9	Red Oak	1	Wool	0.4
10	Cotton	2	Polypropylene	0.9
21	ABS (FR)	3	Polypropylene (FR)	1.2
23	SAN	4	Polyurethane foam (FR)	1.3
25	Polypropylene (FR)	5	Poly(vinyl Chloride)	1.4
28	Polypropylene	6	Polyurethane foam	1.7
31	Polystyrene	7	SAN	2.0
33	ABS	8	ABS	2.2
37	Nylon 6,6	9	ABS (FR)	2.3
37	Nylon 6,6 (FR)	10	Nylon 6,6	2.7
47	Polyurethane foam (FR)	11	Cotton	2.7
50	Polyurethane foam	12	Nylon 6,6 (FR)	3.2
50	Poly(vinyl Chloride)	13	Red Oak	3.6
60	Wool	14	Polystyrene	6.0

The toxic potency of the smoke of most common materials (natural or synthetic) is very similar (see Figure 1). In fact, the difference between the toxic potency of almost all combustible materials is less than one order of magnitude. Therefore, the relative rankings of materials are heavily dependent on the exact composition of the smoke being tested, i.e. on the combustion procedure being used.

The fact that the main direct cause of death in fires has always been the toxicity of combustion products was already discussed in the National Fire Protection Association (NFPA) Quarterly in 1933 [34]. Smoke contains mainly two types of toxic gases: asphyxiants and irritants, but the individual toxic gas associated with the largest fire hazard is carbon monoxide (CO).

Toxic Gases in Fires

CO is present in all fires, because it is a combustion product of any organic material, and it causes the formation of carboxyhemoglobin (COHb) in blood. Although the exact lethal level of COHb is heavily dependent on the individual affected, any value above 20% can lead to death [35]. Even if a very conservative estimate is taken of the lethal level of COHb (viz. 50%), it alone accounts for 60% of all fire deaths, while over 91% of fire victims have levels above 20% COHb [36]. Other factors can lead to a lower tolerance towards CO, even in the absence of other toxic gases: typically heart disease, blood alcohol level, burns and age [35]. However, it is interesting to note the great similarity found between the blood COHb level distributions in two studies, one involving the notorious 1980 MGM Grand Hotel fire [37] and the other one involving deaths from CO evolution due to malfunctioning gas heaters [38]. This indicates that deaths in fires correlate well with deaths from carbon monoxide poisoning. A recent statistical analysis of a data base of of over 2,000 fatalities involving carbon monoxide from fire and non-fire sources [35] has shown that, once the controlling factors of age, disease and blood alcohol level have been accounted for, the COHb distribution from fire and non-fire fatalities are very similar [39].

A variety of other gases are also given off by burning materials: In two studies fire fighters went to address actual buildings on fire, equipped with combustion product monitors [40, 41]. Both studies had the same conclusions: the overwhelming hazardous toxicant in a fire is carbon monoxide.

These studies also pointed out that a potentially very dangerous gas in fires is acrolein, because the ratio of its concentration, as measured in the atmosphere of real fires, to its lethal exposure dose (LED) is higher than for many other common fire gases. The ratios of concentrations

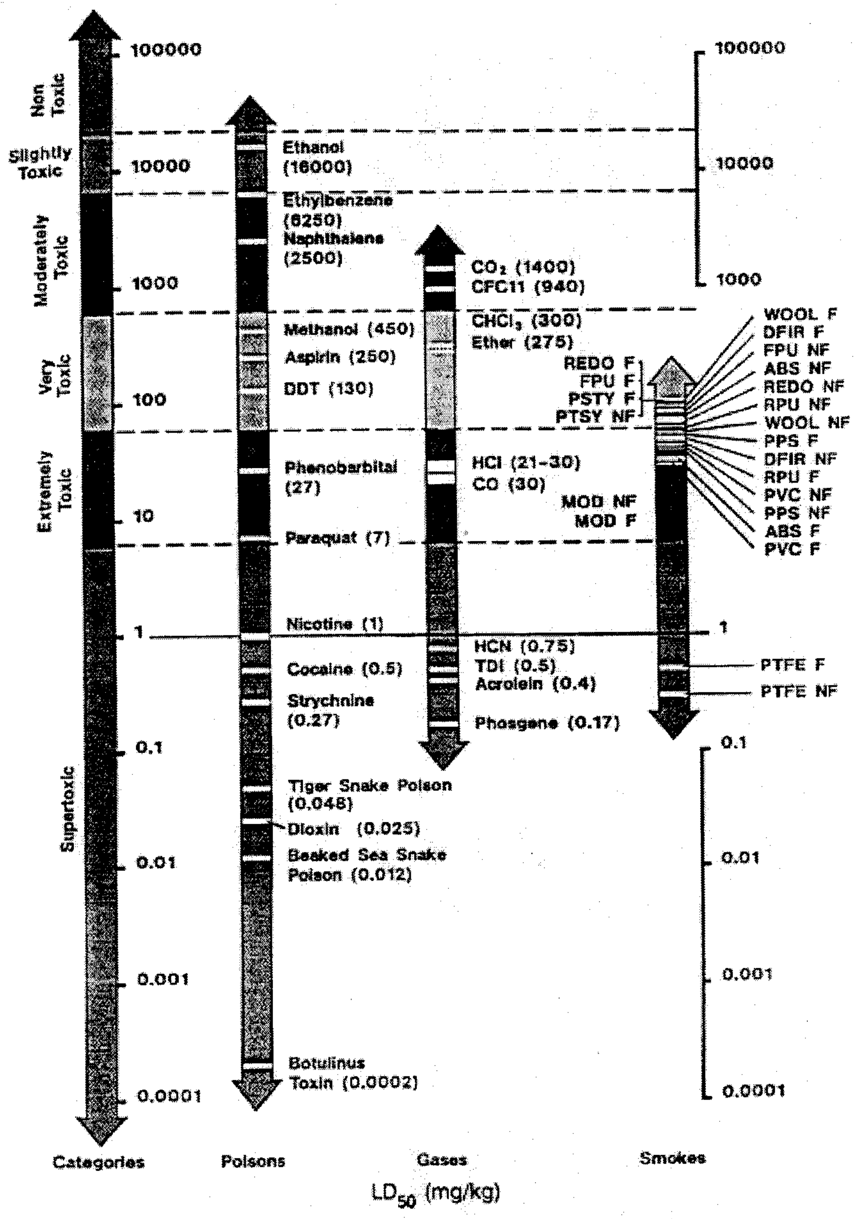

Figure 1. Categories of toxicity and lethal doses of various poisons and of the smoke from polymeric materials according to the NBS Cup Furnace Smoke Toxicity Protocol.

to LED found for two other common toxic combustion products, hydrogen chloride (HCl) and hydrogen cyanide (HCN), were much lower.

This discussion does not address the mechanism of action of these toxicants, i.e. whether the toxicant is an asphyxiant (as CO or HCN) or an irritant (as acrolein or HCl). Table II shows the highest concentration found in these studies for the 4 most common fire gases, together with their lethal levels and their odor detection levels [42-47]. The peak concentrations found were 7,450 ppm of CO, 100 ppm of acrolein, 280 ppm of HCl and 10 ppm of HCN. As regards HCl, it is relevant to point out that its airborne concentration remains at a peak value for a short period only before decaying [48]. The decay of HCl is particularly fast in the presence of sorptive surfaces such as most ordinary construction materials [49, 50]. The rate of HCl decay can be fast enough so that within 30 min its airborne concentration may have fallen to virtually nothing. The majority of other common fire gases (CO, carbon dioxide, hydrocarbons) are virtually unreactive and do not decay [51]. The gases that can decay either do so at a much lower rate than HCl (e.g. HCN) or are much less frequently present in fires (e.g. hydrogen fluoride, because less fluorinated polymers are in use).

A number of studies have been made of combinations of individual toxic gases. Most of these studies show that the effects of these combinations of toxic gases are simply additive. This has been found empirically for CO and HCl [52] and for CO and HCN [44], although the mechanisms of action are different. These results can be interpreted as each toxicant taking its toll and acting on a weakened system. The CO-carbon dioxide combination has been claimed to be synergistic [53].

Fire Hazard and Smoke Toxicity

It has already been stated that the principal toxicant in a fire scenario is carbon monoxide, generated when all carbonaceous materials burn. Moreover, the carbon monoxide concentration in full scale fire scenarios depends heavily on fire load (i.e. how much material is burning, per unit volume) and on geometrical arrangements, including ventilation, while the dependence on materials is of a lower order.

This secondary effect of materials is illustrated by the difficulties encountered, in a recent study [54], when attempts were made to correlate CO concentrations measured in small scale and full scale fire tests. The same small scale equipment (typically the cone calorimeter rate of heat release test) could predict adequately a number of very important full scale fire properties, including ignitability, rate of heat release, amount of heat release and smoke obscuration. It could not, however, be used to

Table II. Toxicity of Combustion Gases

	Lethal exposure dose ppm min	Animal -	ODL ppm	Peak in Fire ppm
Carbon monoxide[a]	138,000	rats	-	7,450
Carbon monoxide[b]	90,000	mice	-	7,450
Acrolein[c]	2,500 - 5,000	baboons	0.16	98
Hydrogen cyanide[d]	4,800	rats	0.58	9
Hydrogen chloride[e]	112,000 - 169,000	rats	0.77	280
Hydrogen chloride[f]	ca.150,000	baboons	0.77	280
Hydrogen chloride[g]	38,250	mice	0.77	280

ODL: Odor detection level. Ref. 38.

[a]: Ref. 39, 30 min exposure, within exposure deaths.

[b]: Ref. 40, 30 min exposure, within exposure deaths.

[c]: Ref. 41, 5 min exposure, post-exposure deaths.

[d]: Ref. 40, 30 min exposure, within exposure deaths.

[e]: Ref. 42, 30-60 min exposures, post-exposure deaths.

[f]: Ref. 41, 5-15 min exposures, no deaths.

[g]: Ref. 43, 15 min exposure, incapacitation and death.

predict full-scale CO concentrations. The latter concentrations were controlled by the geometry of the full-scale fire, the ventilation/oxygen content and the mass loading, and were little affected by the chemical composition of the burning materials.

Thus, smoke toxicity is often very closely associated simply with the mass loss rate, since the toxicity in a fire scenario will be primarily a function of the mass ofsmoke per unit volume and per unit time being emitted into the ambient atmosphere.

This discussion indicates that toxic potency measurements are a small portion of the overall toxicity picture. They may serve a useful purpose only in identifying those materials (or products) with a toxic potency outside that of the majority of other products. Such materials (or products) may well have to be looked at somewhat more closely.

One method for quick screening of the toxic hazard of materials is to calculate the ratio of their toxic potency and their mass loss rate parameter. The mass loss rate parameter is the ratio of the average mass loss rate and the time to ignition [55], and thus represents the product of mass loss rate and flame spread rate. If the mass loss rate parameter differs by more than an order of magnitude from that of ordinary materials the material in question should be investigated more thoroughly [55, 56]. The choice of a factor of 10 is typical of the difference, in classical toxicology, between toxicity categories [57].

Fire Hazard Assessment

Probably the best way of assessing fire hazard is by calculations via mathematical fire growth and transport models, such as HAZARD I [58], FAST [59], HARVARD [60] or OSU [61]. These models predict times to reach untenable situations. They are often combined with fire escape models and will, then, yield times to escape.

It is possible, however, to estimate effects on fire hazard in a particular scenario by simpler means. In some cases, an adequate choice of fire properties can be made. Then, the combination of test results into a matrix form, or into a single parameter, can indicate, even if only semi-quantitatively, the effect of varying a particular material or fire protection measure on fire hazard.

Full scale tests are particularly valuable to obtain information on fire hazard. They can be used to validate small scale tests, and to validate mathematical fire models. The most important additional dimension full scale tests add are effects, e.g. radiation from the fire itself, which are difficult to simulate in a smaller scale. Full scale tests are very expensive and time consuming. It is essential, thus, to design them in such a way as to (a) make them most relevant (b) minimize their number and (c) help replace them by appropriate small scale tests and fire models.

Fire risk assessment is made in order to determine the overall value of decreasing fire hazard in a particular scenario. The level of fire risk that is acceptable for a situation is, normally, a societal, and not a technical, decision. Therefore, fire hazard assessments are generally more common than fire risk assessments. The NFPA Research Foundation has undertaken a project to develop a methodology for fire risk assessment. It has done this by studying four cases in detail: upholstered furniture in residential environments, wire and cable in concealed spaces in hotels and motels, floor coverings in offices and wall coverings in restaurants.

Conclusions

Fire safety in a particular scenario is improved by decreasing the corresponding level of fire risk or of fire hazard. Technical studies will, more commonly, address fire hazard assessment. Fire hazard is the result of a combination of several fire properties, including ignitability, flammability, flame spread, amount of heat released, rate of heat release, smoke obscuration and smoke toxicity.

The most important fire property associated with fire hazard is the rate of heat release: the peak rate of heat release is an indication of the maximum intensity of a fire.

Categories of toxicity are classically distinguished by differences in orders of magnitude. The toxic potency of the smoke of most common materials is very similar, and thus, the toxicity of smoke is usually governed simply by the amount of material burnt per unit time.

Toxic potency of smoke data can be used as one of the inputs in fire hazard assessment. In particular, they can be combined with average mass loss rates and times to ignition to obtain a quick estimate of toxic fire hazard.

In order to improve fire safety for each scenario, the most relevant fire properties for that scenario have to be measured, with the appropriate instruments.

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GBH Attachment 6

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HOW TO MEASURE SMOKE OBSCURATION IN A MANNER RELEVANT TO FIRE HAZARD ASSESSMENT: USE OF HEAT RELEASE CALORIMETRY TEST EQUIPMENT

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ABSTRACT

In the first section of this paper smoke obscuration measurement tests are being classified according to the type of equipment used (static or dynamic), the scale and the other properties measured. The conclusion of this section is that the most adequate means to measure smoke obscuration, so as to have results useful for fire hazard assessment, is by determining a combination of heat release and smoke release, e.g. with the cone or OSU calorimeter.

In view of this conclusion the other sections of this paper deal with measurements done in the cone calorimeter, found to be one of the best tools.

The second section of this paper discusses a few examples of cases where the cone calorimeter (and in particular the smoke factor) was used to predict adequately the fire and smoke performance of products, e.g. cables and upholstered furniture and its possible correlations with other fire tests.

The third section of this paper presents data and puts into perspective the heat and smoke release from a total of 35 materials, all but one of them plastics (the exception being a wood sample), with the cone calorimeter, at three incident heat fluxes: 20, 40 and 70 kW/m^2. The materials tested cover a wide range of materials and are representative of commercial materials available in the 1990's and cover a very wide range in fire performance. The peak heat release rates range from values within the experimental error range of the equipment to values of almost 3000 kW/m^2. Those materials with the best fire performance tend also to have low smoke release.

The final, short, section of this paper discusses the importance of testing products (or combinations of materials) rather than materials alone, in order to get optimal predictions of real fire performance.

INTRODUCTION

Once ignition has occurred, there are three main ways in which fire, whatever the products involved, can cause harm to people, property or operations. These are, in decreasing order of their importance to fire hazard: (a) the effects of heat or flames spreading from the item first ignited to other items, potentially resulting in thermal injury to people, destruction of property or loss of operation, (b) the production of smoke, which obscures vision and can inhibit both the escape of trapped victims and the action of fire fighters and (c) the generation of toxic products (gases and particulates in smoke), which can be inhaled by victims and injure them.

For clarification purposes, the definition of smoke given by the ASTM Fire Standards Committee (in ASTM E176) is used in this paper. It states "smoke is the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis and combustion".

This paper comprises four sections:

1. Discussion and classification of smoke tests.

2. Discussion of a few product tests carried out using full scale tests and a preferred small scale test (cone calorimeter) and of some test correlations attempted (with emphasis on smoke measurements).

3. Testing of representative modern materials using the same small scale test.

4. Comparison of testing of products and of materials.

Section 1

SMOKE OBSCURATION

Test methods used to measure smoke obscuration accompanying a fire can be classified into five categories:

(I)	Static small scale smoke obscuration tests on materials
(II)	Dynamic small scale smoke obscuration tests on materials
(III)	Traditional large scale smoke obscuration tests on products
(IV)	Full scale tests measuring heat release and smoke release
(V)	Small scale tests measuring heat release and smoke release

This paper will present first a brief discussion of these different types of methods in turn, while giving a few examples of tests in each category. The description will involve mostly general features which are common to most methods in a particular category.

Category (I) includes the single most widely used smoke test, i.e. the NBS smoke chamber (ASTM E662), and an earlier version: the Rohm and Haas chamber (Table 1). Both these tests are similar in design; the main difference between them is the light beam direction. The results from these tests do not, normally, do an adequate job of representing the smoke emission to be expected in full scale fires. A large amount of information has been published on the deficiencies of the NBS smoke chamber test (Table 2) [1-4]. Tests in this category do have some, limited, utility as laboratory tools for quality control and to observe effects of changing a base formulation. Favourable effects must still, however, be confirmed by a reliable fire test.

The tests in category (II) can all measure smoke obscuration together with another property, although this was rarely an original objective of the test designers (Table 3). This is important, since such developments recognise, implicitly, the fact that smoke obscuration is not an isolated property, but is always a result of the fire itself.

The radiant panel flame spread test apparatus (ASTM E162) can be used to measure smoke obscuration by using a filter in the exhaust stream. The Michigan chamber [e.g. 5] has been widely used as a tool for investigating effects of flame retardants and smoke suppressants on specific polymer systems. It consists of a box through which the smoke from the exhaust of a limiting oxygen index test apparatus is drawn. Smoke obscuration is measured photometrically; in order to ensure some burning uniformity, oxygen in the LOI tester is often set at LOI + 1. The Arapahoe smoke chamber (ASTM D4100) offers a standard procedure for gravimetric soot measurements of smoke but uses a poor fire model, unrepresentative of real fires: the test is thus of limited use. Conceptually similar tests exist in the Netherlands (Vlam Overslag), the Nordic countries (Nordtest NT Fire 004) and Germany (Brandschacht test: DIN 4102 part 1)

The BFGoodrich smoke-char tester [6] is based on an interesting concept: simultaneous measurement of smoke obscuration and mass of residue. It was an early attempt at quantifying (albeit very poorly) a very important fire safety issue: materials which burn more extensively will, usually, give off more smoke just because of the larger amount of mass burnt. A very small sample is put on a holder above the flame of an LOI tester and burnt for 30 s in air. A horizontal light beam and detector measure light transmission and gravimetric measurements are made of the mass of residue. It too has a poor fire model and no provision for the effects of high heat fluxes. However, there is still some interest in this approach, mainly because of its potential for mechanistic studies. The carbon from organic materials results in three type of products: (a) gaseous compounds, (b) solid residue and (c) soot. This method gives indications of the relative contributions of (b) and (c) to the carbon mass balance, rather than addressing only (c) like most smoke tests do. It does not distinguish, however, between the carbonaceous (char) and inorganic (ash) portions of the residue. Results from the smoke char test have been used to identify additives which operate by an intumescent mechanism [6] and to get information on whether smoke suppression was achieved by simple dilution via inorganic fillers [7].

Many large scale fire/smoke tests (category (III)) have been proposed for products; some of the most important ones are in Table 4. They have little in common, other than that they were originally designed in response to a specific need and have often outlived their utility. They were not designed to measure heat release, but were often meant for flame spread and smoke obscuration was usually added later. These tests are important because the product is allowed to "do its own thing". This means that a material (or product) with good fire performance is not necessarily burnt to completion. Moreover, smoke obscuration is always measured continuously, together with some other fire property, and often in a flow-through system. The results of these tests have however, as a rule, not been shown to correlate with the results of tests in more realistic scenarios.

This class of tests includes the Steiner tunnel test (first standardised by ASTM in 1950) and its several variations applicable to individual products (e.g. cable, UL 910 or sprinkler pipe, UL 1887), which are used to regulate the amount of flame spread (and, often, smoke developed) by materials for applications with stringent fire performance requirements. The deficiencies of this test are well known. However, it is a popular procedure, used for: sheet, cable, pipe, wall lining, sprinkler pipe, etc. The test can yield misleading results, because materials are sometimes developed "to pass the test" rather than for good fire performance. The principal examples where the test can misrepresent fire performance are wall linings [8] and floor coverings. One problem with wall linings is that the test sample orientation is horizontal, and this tends to be a less severe exposure than a vertical orientation, especially for partial sample burning. Another problem is sample location: some products can drip or melt away from the flame source (since the sample is located higher than the flame) and thus not propagate the fire. A final problem is the fact that thin materials sometimes do not spread flame in the test simply because the fuel has been consumed. Furthermore, unfortunately, test results cannot be used in fire hazard assessment models.

The flooring radiant panel test was designed, in the early 1970's to solve a problem with carpets, when they spread fire outside the room of fire origin. As a consequence, virtually no commercial carpets sold in the US today is likely to cause such a problem. The maximum incident flux to this test is, however, much too small (10 kW/m_2) for it to adequately address the flooring product contribution to fire hazard, if the fire reaches a significant intensity.

The 3 m cube smoke test consists of a large static chamber, used principally for measuring the smoke developed from electrical cables. Its fire model is a very large liquid hydrocarbon pool which is often sufficient to burn the entire combustible portion of the cables tested, due to the fact that the length of cable tested is comparable to the size of the burner. Thus, the test suffers from most of the same defects as smaller scale static smoke chamber tests.

The ultimate measure of fire performance of a material or product is, of course, how the end product reacts in a real fire. The best approximation to such fire performance can be measured when products are tested in room size fire tests and in end use configurations, or as close to them as possible. The single most important fire property is the rate of heat release, since its peak value will determine the peak intensity of a fire [9-10]. The fire science community has understood this concept only relatively recently. The exponential growth in the interest in heat release rate happened when it became possible to measure this magnitude directly and adequately.

An empirical discovery, made in the 1970's, that the rate of heat release of the vast majority of combustibles is proportional to the oxygen consumption level (the proportionality constant is 13.1 ± 0.3 kJ O_2/kg fuel) [11-12] was a crucial milestone. Moreover, oxygen measurement techniques, now allow O_2 concentration to be determined with paramagnetic analysers at an accuracy of 0.001 vol% O_2. Thus, the almost insurmountable problem of ensuring adiabaticity is now replaced by a much simpler problem: ensuring total capture of the fire effluents (or at least of a known representative fraction).

Table 5 lists several such full scale tests, i.e. Category (IV) tests, which measure smoke obscuration together with heat release.

In recent years several tests were developed in which products are burnt in a simulated end-use environment and in which heat release is measured together with other properties, including smoke obscuration. These tests are dynamic tests and involve continuous measurements. They give realistic appraisals of the fire performance of a product. Among the tests worth mentioning are a lined room (ASTM E603, Nordtest NT Fire 025), vertical cable tray tests (IEEE 383, UL 1581, ICEA 529 or CSA FT-4, all of them modified to measure heat and smoke release), furniture tests (UL 1056, furniture calorimeter, Nordtest NT Fire 032) and mattress tests (UL 1092).

However, the cost of conducting such tests is one of the remaining problems to them being used for all cases. It is desirable to find smaller scale tests, but only if their results can (a) serve as reasonable predictors of real fire performance and (b) be used as inputs into models for assessment of fire hazard or fire risk.

Thus, smoke obscuration in a dynamic mode is best measured by means of small scale tests (Category (V)), if these can fulfill four basic criteria, as follows.

(1) Measure fire properties in such a way that they can be used for purposes other than simple rankings or pass/fail criteria.
(2) Measure smoke obscuration together with those fire properties of considerable fire hazard interest, principally, the rate of heat release.
(3) Have been proven to give results that are representative of the corresponding property in a full scale scenario.
(4) Allow for calculations to compensate for complete sample consumption, characteristic of small scale tests.

Probably the only tests in existence to fulfill these requirements are based on heat release (RHR) calorimetry. They are the cone calorimeter (cone, ASTM E1354) [13-14], the Ohio State University (OSU, ASTM E906) RHR calorimeter [15] and the Factory Mutual RHR calorimeter [16] (Table 6).

The first two tests (viz. ASTM E1354 and ASTM E906) have been used extensively by many investigators and are well known. However, these very useful tools are relatively modern and thus not as well understood as they should be. Therefore, their differences will be discussed in detail. The tests will be referred to by their common abbreviations "cone" and "OSU". There are eight main differences, viz.:

(a) The cone uses the oxygen consumption principle. It is not adiabatic but allows easy observation of the burning process. The OSU was designed as adiabatic, and sample burning visibility is minimal. The apparatus can be modified to allow heat release measurement by O_2 consumption. Apparatus geometry cannot be changed easily, however.

(b) The cone is normally used with horizontal samples, while the OSU is normally used with vertical samples. Samples can be burnt in the cone vertically and horizontally in the OSU; the latter leads to larger irreproducibility because of the makeshift radiation reflector and the former leads to serious ignitability problems.

(c) The radiant source in the OSU is a set of four glow bars, sited directly across from the horizontal sample. Soot particles and smoke must make their way through a "chimney" between the burning sample and the heat source, causing afterburn. There is a truncated conical radiant heater in the cone; this generates a uniform energy distribution; smoke is captured with minimal losses and there is little afterburn caused by the radiant heater, once the smoke has evolved.

(d) The OSU has a flame igniter and the cone a spark igniter. Thus, the OSU ignition source is more powerful and more localised. The flux on the actual sample is larger in the OSU than the cone, if both radiant heaters are calibrated to the same value. Therefore, samples may ignite in the OSU but not in the cone. Fire models are more likely to require data without "hot spots", but the OSU is better at modelling impinging flames. This can easily be altered for either instrument.

(e) The cone has a load cell to measure mass continuously, but the OSU does not. This is very important, to calculate fire properties on a per mass lost basis. Attempts have been made to make an OSU apparatus with a load cell, which appear promising.

(f) The cone uses a laser to measure smoke obscuration while the OSU uses a white light. Results from both measuring systems are virtually equivalent, for small scanning times (≤ 3 s [17-18]). The white light is more similar to what the human eye sees, but it needs more maintenance. Alternative obscuration sensors can be installed in either apparatus.

(g) The sample size is somewhat different: ca. 0.10 m x 0.10 m in the cone and ca. 0.15 m x 0.15 m in the OSU. This will make no major difference to the results and is simply a consequence of the geometry.

(h) The incident air flow rate is much higher in the OSU than in the cone, because of the geometric apparatus design.

In both calorimeters the incident air composition can be changed by increasing the nitrogen content, to simulate the vitiated atmospheres prevalent in intense fires. This is experimentally much easier to accomplish in the OSU than in the cone. High incident air flow rates means that it is inconvenient (although, in the cone, not impossible) to increase the oxygen content of the atmosphere. The Factory Mutual RHR calorimeter can easily operate at high oxygen levels. This is of interest when testing products destined for use in outer space. It has been proposed also that higher atmospheric oxygen contents may simulate reradiation from the burning sample [19]. This is an interesting idea which needs confirmation, since, unfortunately, only a single laboratory has, as yet, had extensive experience with this calorimeter.

Smoke obscuration in the OSU is normally reported by calculating smoke release rate and integrating it to obtain total smoke released. In the cone, smoke obscuration is normally reported by average extinction area, i.e. obscuration per unit mass. Both ways of reporting smoke obscuration can be interconverted.

The complete consumption of the sample can be compensated for, in these calorimeters, by calculating derived magnitudes of smoke obscuration, which can be determined directly in small scale RHR apparatuses. Two such empirical parameters have recently been used often: smoke parameter [2] and smoke factor [20]. Smoke parameter is the product of the average extinction area and the peak RHR, while smoke factor is the product of the total smoke released and the peak RHR. Both are measured continuously and reported most often at 5 min. Section 2 will discuss these magnitudes in more detail and show examples of how they have been found useful in some specific cases.

In conclusion, section 1 showed that, although a variety of tests exist to determine smoke obscuration, the most adequate ones are those that can measure smoke obscuration in the small scale, together with heat release, in a way that can predict real full scale smoke obscuration.

Section 2

CORRELATIONS AND PRODUCT TESTING

Full scale fire tests, which, as has been stated, are most desirable in order to obtain the fullest information on a particular fire, can, realistically, only be carried out to a limited extent. Moreover, they are most relevant when carried out with a full complement of products present. It is, thus, somewhat more difficult to separate the effect of a single material or product on the fire performance of the system. However, a number of recent sets of tests have shown that there is good predictability from heat release rate equipment test results to full scale test results [14, 21-24]. This is particularly true for wall coverings [25-27], upholstered furniture [22-23, 28-31] and electrical cables [32-35].

The smoke obscuration magnitude most often reported from the cone calorimeter is the average specific extinction area, which is calculated from the extinction coefficient and the mass loss rate. The smoke parameter, originally defined by Babrauskas [2] is calculated by multiplying this value by the peak RHR. Unfortunately, this parameter carries the experimental errors involved with mass measurements.

It is, also, possible to measure smoke obscuration in RHR calorimeters in the same way it is done in full scale tests, by determinations of optical density (or extinction coefficient) and without involving mass. This is the concept that is used for the smoke factor.

The rate of smoke release is calculated in different ways for the two small scale calorimeters, for historical reasons.

OSU RSR = (V * OD)/Light Path Length

Cone: RSR = (V * OD * ln10)/ (Sample area * Light Path Length)

where V is the volumetric flow rate (in m^3/s, corrected for the relative locations of the flow measurement device and the light measurement device and for the elevated temperature in the duct), OD is the optical density, the Light Path Length is 0.1095 m (cone) or 0.134 m (OSU) and the sample area is 0.0100 m^2 in the cone and 0.0213 m^2 in the OSU. The units are 1/s in the cone and m^2/s in the OSU.

The total smoke released is calculated as the time integral of the rate of smoke release after 15 min, which is non-dimensional in the OSU and has units of m^2 in the cone. The smoke factor is the product of the total smoke released and the peak RHR.

In full scale tests the rate of smoke release is measured just like in the OSU, as explained before.

An attempt has recently been made to compare NBS smoke chamber (ASTM E662) results with those of full scale room corner burn tests and RHR (cone and OSU) test smoke obscuration results [20]. Results from the NBS smoke chamber did not correlate with those of any of the other tests (Tables 7 and 8). On the other hand, cone smoke factor and cone smoke parameter correlated very well indeed both among themselves and with the OSU smoke factor, for a total of 17 plastic materials covering a wide gamut of fire performance. Table with correlation results are shown in Table 8.

In another series of experiments, a number of vinyl wire and cable compounds, all of them with fair to good fire performance, were tested in the cone and OSU, and it was found that the results correlated very well with each other [32]. In particular, there was almost perfect linear correlation not only between the smoke factors in both instruments but also between the smoke factors in each instrument at two different fluxes, viz. 20 and 40 kW/m^2. Table 9 shows the corelations found between smoke factors with these two instruments.

Recent work has also shown that testing of cables in the cone calorimeter RHR can be used to predict the results of full scale fire tests of cables in vertical trays [32]. An empirical model was developed to predict these full scale RHR from small scale results. More interesting however, is the fact that the total amount of smoke obscuration measured in the full scale tests correlated very well with the smoke factor measured in the cone calorimeter, for the cables. Some results can be seen in Table 10.

The full scale tests carried out for that work were run in an established cable tray facility at Underwriters' Laboratory, using a traditional white light system for measuring smoke obscuration. Subsequent full scale tray tests were run at another facility, the BFGoodrich fire testing laboratory. In this case, a novel laser system for measuring smoke obscuration, manufactured commercially (Fire Testing Technology Ltd.) was used, because it has been found that the use of laser systems instead of white light has virtually no effect on the results, but helps in reducing maintenance time. In the case of white light systems the optics become soiled with smoke particles and require frequent cleaning. Laser systems, because of the positive pressure applied, require much less frequent manual cleaning. Both systems correlated well with each other and with the cone calorimeter tests on cables [35].

In conclusion from this section, smoke obscuration results from the cone calorimeter and from the OSU calorimeter correlate well with each other and with the results of full scale tests, for various products.

Section 3

TESTING OF MATERIALS IN THE CONE CALORIMETER

In practice, materials are virtually never used in the form of a pure polymer, but always contain additives. In this work a total of 35 materials were tested, all of them under the same conditions, viz. 20, 40 and 70 kW/m^2, in a horizontal orientation in the cone calorimeter.

Most of the materials used were commercial samples and, thus, their composition is not disclosed by the manufacturer. Some of the samples, mainly among the vinyls, are experimental materials and are not commercially available. Virtually all the samples contain some additives, and many will, probably contain flame retardants. The materials illustrate a broad spectrum of the materials available in the late 1980's and early 1990's. Three materials were chosen because they have been used extensively for other testing programs and their fire performance can be used, thus, as an indicator for that of the other materials: Douglas fir wood, PMMA (1 in thick, plus cardboard) and "standard flexible PVC" (FL PVC PVC).

The standard flexible PVC has been used for several other applications, including smoke corrosivity testing [36, 37], smoke toxicity testing [38] and the cone calorimeter ASTM round robin [39].

Table 11 contains a description of the non vinyl materials, while Table 12 describes the vinyl materials. All samples are at 6 mm thickness, except as indicated. The numbers following the description of each material in these Tables are those used throughout the remainder of the paper for Tables and Figures. They originate in the decreasing order of peak heat release rate at the lowest incident flux used, viz. 20 kW/m^2 (see Figure 1).

Results Presented

The results presented will include 6 properties for each material. These will be:

TTI:	Time to ignition, at each flux, in s. If no ignition was observed, after 1 h of exposure, time to ignition was recorded as 10,000 s.
Pk RHR:	Peak value of the heat release rate vs. time curve, in kW/m^2, of the sample.
Ht Comb:	Effective heat of combustion, in MJ/kg. The value reported is the average for the entire test.
SmkFct:	Smoke factor, measured at 5 min into the test, in MW/m^2.
TTI/RHR:	Ratio of the time to ignition to the peak heat release rate (in s m^2/kW). This parameter has been shown to give an indication of propensity to flashover, because it relates to the time to flashover [25, 27, 40, 41].
Min Flux:	Minimum flux required to cause ignition within 600 s (in kW/m^2).

Since it is clear, from the discussion in the preceding sections, that increased smoke release in real fires is associated with poorer fire performance, the results presented here cover the most important parameters necessary for determining both the fire performance and the smoke release from materials. Further details on the same materials can be found elsewhere [42].

Tables 13-15 contain the data to be presented, at each incident flux. The materials are listed in order of ascending peak heat release rate at an incident flux of 20 kW/m^2. These Tables, and Figures 1-3, show that rankings based on peak heat release rates can change depending on incident flux. Table 16 lists the predicted limiting flux necessary for ignition after an exposure of 10 min.

Tables 13-15 also contain the average and median values of every magnitude, to give an indication of overall fire performance of the type of materials available in the world of the 1990's. This is useful since the selection of materials is a representative sample. Average and mean values can be compared to the values for Douglas fir, showing that values for new materials are, on average, not too different from values for wood.

Figures 4-13 contain the rate of heat release vs time curves for ten materials at all three incident fluxes: PTFE, VTE 3, CPVC, PVC CIM, PPO/PS, ABS FR, DFIR, PU. PMMA and PP, as examples of the general fire performance.

The materials chosen cover a very wide range of fire performance:

Peak RHR: values cover three orders of magnitude.

Heat Comb: values cover one order of magnitude.

TTI: values cover over 2 orders of magnitude.

TTI/RHR: values cover over 4 orders of magnitude.

SmkFct: values cover 3-4 orders of magnitude.

Lim Flux: values range from < 15 to 86 kW/m^2

The amount of smoke released in a full scale fire depends on both the smoke production tendency of the product and the amount of material burnt. Thus, the smoke factor provides, usually, a good guideline to improvements made in fire behaviour. The smoke factor is more useful as a predictive tool as the fire performance of a product improves than the total smoke released or the average extinction area, which address purely the specific smoke production tendency of the material. The reason for this is that, as a product becomes less flammable it will burn less readily in a full scale scenario. Thus, while in a small scale test the entire sample being tested is completely burnt up, in full scale fires some products often do not burn up totally. Another factor which may be important in smoke generation in fires is ventilation, but this is not addressed by the present work.

An overall view of other fire properties can be found in Figures 14-17, which show, respectively, the logarithm of the smoke factor and of the flashover parameter at an incident flux of 40 kW/m^2, the average heat of combustion (over all three incident fluxes) and the flux required for a time to ignition of 100 s. Clearly, although fire performance is not identical for all materials independent of property, the better performers are the same throughout.

It is interesting that some fire performance predictions that could have been made based on the chemical composition make sense. For example, the inclusion of heteroatoms, particularly halogens, does, indeed, improves fire performance, as could be expected from the general effect of halogens [43]. This can be seen by the fact that PTFE, rigid PVC and CPVC, with high contents of fluorine and chlorine respectively in their formulations, are among the top performers. However, another one of the top performers is a compound based on polycarbonate, a polymer containing only C, H and O in its base formulation.

Polymers containing no heteroatoms (other than oxygen) and abundant hydrogen in the base formulation tend to be the poorest performers, as made clear by the results of the PE, PP, PET PBT and PS tests.

Moreover, composition can make a significant difference. When fire retarded and non fire retarded versions of the same base polymer were tested, the fire performance improved in the presence of fire retardants. This is seen in several series: ABS and ABS FR or ABS FV, PS and PS FR, PE and XLPE, PMMA and Kydex, or PVC WC, PVC WC SM and PVC WC FR. However, other changes can be made, on a base polymer, which affect fire performance. This is exemplified by comparing the two polycarbonates, the polyphenylene oxide polystyrene formulations or the foamed polyurethane and the thermoplastic polyurethane.

Vinyl compounds need to be distinguished between flexibles (plasticised) and rigids, with the latter having much better fire performance, generally. The poorest fire performance for vinyls is found on a material (FL PVC) heavily loaded with plasticisers and containing no other flame retardant additives. On the other extreme, some vinyl thermoplastic elastomers are among the best fire performers in the entire database. Rigid vinyls also vary in fire performance, but the differences are smaller, since the fraction of additives tends to be much lower.

Another interesting aspect is a comparison of CPVC and rigid PVC. As already discussed, it would be expected that the addition of chlorine to a structure would improve fire performance [43], e.g. as measured by heat release. This is indeed the case for rigid PVC and CPVC.

An apparently less predictable result, is the fact that the resulting smoke obscuration values also tend to be lower. This can be explained on the basis of the mechanism of smoke formation from vinyl compounds [44]. Vinyl compounds break down by chain stripping and yield HCl and a carbonaceous char. The dehydrochlorination of PVC yields a polacetylene (-CH=CH-) while that of polyvinylidene chloride (repeating unit -CHCl-CHCl-) yields a purely carbonaceous char, (-C≡C-), with an almost graphitic structure. Since CPVC is partially chlorinated PVC, it yields chars that somewhere in between. The chars generated by chain stripping will continue breaking down by chain scission, provided there are sufficient hydrogen atoms present. Thus, the fragments will tend to cyclise into aromatic structures and these, in turn, generate significant amounts of soot per unit mass when burnt. As the hydrogen atom concentration is decreased, the probability of forming aromatic structures, and thus soot, becomes lower.

Classification of Fire Performance

In view of the wide range of results obtained it is useful to attempt to make up some five overall categories of material fire performance. These categories have been chosen in order to get an overall view of material performance. In three of the cases logarithmic scales were chosen, because they allow a better visualisation of results, particularly in the Figures.

A classification based on heat release rate could give five categories of material performance:

Pk RHR < 60 (kW/m^2)
60 < Pk RHR < 100 (kW/m^2)
100 < Pk RHR < 200 (kW/m^2)
200 < Pk RHR < 300 (kW/m^2)
300 < Pk RHR (kW/m^2)

In terms of ignitability another set of five categories can be set out:

2.5 < Log (TTI) (s)
1.5 < Log (TTI) < 2.5 (s)
1.0 < Log (TTI) < 1.5 (s)
0.5 < Log (TTI) < 1.0 (s)
Log (TTI) < 0.5 (s)

Thirdly, in terms of propensity to flashover, the following set of five categories can be set out:

1.0 < Log (TTI/RHR) (s m^2/kW)
0.0 < Log (TTI/RHR) < 1.0 (s m^2/kW)
-1.0 < Log (TTI/RHR) < 0.0 (s m^2/kW)
-2.0 < Log (TTI/RHR) <-1.0 (s m^2/kW)
Log (TTI/RHR) <-2.0 (s m^2/kW)

Finally, in terms of smoke factor, relevant categories appear to be:

$1.5 > \text{Log (SmkFct)}$ (MW/m^2)
$2.0 > \text{Log (SmkFct)} > 1.5$ (MW/m^2)
$2.5 > \text{Log (SmkFct)} > 2.0$ (MW/m^2)
$3.0 > \text{Log (SmkFct)} > 2.5$ (MW/m^2)
$\text{Log (SmkFct)} > 3.0$ (MW/m^2)

Figures 18-21 show the materials falling into each category for all the four properties. The better performing materials in terms of heat release rate, heat of combustion and smoke release are mostly the same. In fact, five materials are in the top category in each of the four classifications: 1, 2, 3, 4 and 7. Curiously, no material appears in the lowest category in all four classifications. This suggests, once again, that smoke obscuration, in full scale fires, is heavily dependent on fire performance and that those materials that have the best fire performance will also tend to generate less smoke.

Section 4

PRODUCT FIRE PERFORMANCE

A caveat needs to be presented before ending the discussion on fire performance. The fire performance of materials is of little consequence outside of the entire system within which the material is made into a product. It has been shown extensively that the fire performance of products results from the interaction between the materials contained in the product. These interactions can result in: (I) one material dominates the product fire performance, (II) product geometry overwhelms material composition, (III) fire performance of the system is better than that of each component material or (IV) fire performance of the system is worse than that of any component material.

Two sets of products have been analysed more extensively than others: upholstered furniture and electrical cables. In both cases it appears that, all else being equal, the outer layer of combustibles is more important than the inner layer. A typical example of this is given by the fire performance of fabric foam combinations, as they would appear in an item of upholstered furniture. The fire performance of the fabric (first line of attack of the fire) is more important than that of the foam. The combination of very poor foams with very good fabrics can yield excellent systems. These conclusions depend on maintaining the initial integrity of the fabric (i.e. not exposing the foam directly to the fire), which is one of the reasons why the fire performance of the interior materials cannot be neglected. On the other hand, the combination of an excellent foam with a very poor fabric will lead to a poor system [36].

In the case of electrical cables, if the fire performance of the jacket (layer surrounding individually coated conductors) is adequate, the fire performance of the insulation (the layer that coats the conductors directly) is of secondary importance. However, if the insulation material has very poor fire performance, it will dominate, depending on cable construction.

CONCLUSIONS

Smoke obscuration in fires has been measured, and continues to be determined, by using techniques which are totally inadequate. It is now clear that the measurements of smoke obscuration made in small scale tests need to be carefully monitored to ensure that they are relevant to the full scale scenario of interest.

This paper shows that, at present, the best way of measuring smoke obscuration in a way that is meaningful for full scale fires is by using a small scale rate of heat release test, such as the cone calorimeter (or the OSU calorimeter) and compensating for incomplete burning of fire retardant materials by using the smoke factor concept. Such results have been correlated with those of several full scale tests.

The results of cone calorimeter testing on 35 materials show that the materials with the best fire performance and the materials with the lowest smoke factors tend to be the same ones. This suggests, once again, that smoke obscuration is a consequence of fire development, since a bigger fire "pumps" heat into more materials and thus more smoke into the atmosphere.

Another important consequence to be drawn from this work is that fire performance of materials is important but that any final choice should only be made after testing products, or at least systems simulating the final product by containing all the materials involved, in the appropriate combinations. Product fire performance predictions should only come from material fire test results if it has previously been shown that the products perform in a way that can be predicted from a combination of the fire performance of the materials in the tests used.

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Table 1
Static Small Scale
Smoke Obscuration Tests on Materials

Examples

ASTM D2843 - Rohm & Haas Test (XP-2 Chamber)
ASTM E662/NFPA 258/BS 6401 - NBS Smoke Density Chamber

Details of Tests

Sample is Heated to Destruction in Sealed Cabinet
Smoke Obscuration is Measured Photometrically
Static Test
Single Measurement

Specifics of the Individual Tests

Rohm & Haas Test: Horizontal Optical Density
NBS Chamber: Vertical Optical Density

Table 2
Deficiencies in the NBS smoke chamber

Results do not correlate with full-scale fires.
Vertical orientation leads to melt and drip
Time dependency of results cannot be established
No means of weighing sample during test.
Maximum incident radiant flux is 25 kW/m^2
Fire self-extinguishes if oxygen level goes <14 %
Thus, composites often give misleading results
Wall losses are significant
Soot gets deposited on optics
Light source is polychromatic
Rational units of m^2/kg are not available

Table 3
Dynamic Small Scale
Smoke Obscuration Tests on Materials

Examples

- ASTM E162 - Radiant Panel Flame Spread Test
- Arapahoe Chamber (ASTM D4100)
- Dutch Vlamoverslag Test (NEN 3883)
- Michigan Chamber
- BFGoodrich Smoke-Char Test
- Nordic Nordtest NT Fire 004
- German Brandschacht test (DIN 4102 part 1)

Details of Tests

- Sample is Heated to Destruction
- Smoke Obscuration is Measured Together With Another Property
- Dynamic Test
- Single Measurement of Smoke Obscuration

Characteristics of the Individual Tests

Radiant Panel: Soot - Measured with Vertical Flame Spread
Arapahoe: Soot - Measured after Burning Horizontal Sample
Vlam Overslag: Horizontal Optical Density -
Michigan Chamber: Horizontal Optical Density - Measured with LOI
Smoke-Char: Horizontal Optical Density - Measured with Char
Nordtest: Horizontal Optical Density - Measured with Flame Spread
Brandschacht: Horizontal Optical Density - Measured with Flame Spread

Table 4
large Scale Tests
for Smoke Obscuration but Not Heat Release

Examples

ASTM E84/NFPA 255/UL 723 - Steiner Tunnel Test
UL 910 - Cable Tunnel Test
London Underground - 3 m Cube Chamber
ASTM E648 Modified - Carpet Critical Radiant Flux

Details of Tests

Sample is Not Heated to Destruction
Smoke Obscuration is Measured Together With Flame Spread
Continuous Measurements

Characteristics of the Individual Tests

Steiner Tunnel:
- Sheet/Cable/Pipe is Burned Horizontally
- Smoke Obscuration is Measured Vertically
- Results are Very Erratic
- Dynamic Test

3 m Cube:
- Cable is Burnt Horizontally
- Smoke Obscuration is Measured Horizontally
- Almost Full Length of Sample is Consumed
- Static Test

Flooring Panel:
- Carpet is Burnt Horizontally
- Smoke Obscuration is Measured Horizontally
- Other Fire Properties are also Measured
- Dynamic Test

Table 5
Full Scale Tests
Measuring Heat Release and Smoke Release

Examples	ASTM E603 - Standard Room UL 1581 (Modified) - Cable Tray Test

Details of Tests

Sample is Not Heated to Destruction
Smoke Obscuration is Measured Together With Other Properties
Heat Release is Measured
Continuous Measurements
Dynamic Test
Gas Release can be Measured Simultaneously

Characteristics of the Individual Tests

ASTM Room:
Sheet is Burned Vertically
Smoke Obscuration is Measured Horizontally

UL 1581/CSA FT-4:
Cable is Burnt Vertically
Smoke Obscuration is Measured Horizontally

Table 6
Small scale tests
Measuring Heat Release and Smoke Release
Rate of Heat Release Calorimeter Tests

Examples:	ASTM E906 - OSU RHR Calorimeter
	ASTM E1354 - NIST Cone Calorimeter
	Factory Mutual Calorimeter

Details of Tests

Sample is Heated to Destruction
Heat Release is Measured
Smoke Obscuration is Measured Together With Other Properties
Dynamic Test
Continuous Measurements
Combined Smoke/Fire Hazard Properties can be Measured
Gas Release can be Measured Simultaneously

Characteristics of the Individual Tests

OSU Calorimeter:
Sample is Burnt Vertically
No Mass Loss is Measured
There are Heat Losses
Light Source is Polychromatic

Cone Calorimeter:
Sample is Burnt Horizontally
Mass Loss is Measured Continuously
There are No Heat Losses
Light Source is Monochromatic
Best Known Combustion Model
Measures All Fire Hazard Parameters

Table 7.
Smoke Generation in a Room Corner Burn Test and in the NBS Smoke Chamber

Material	Thick. cm	Max. Smoke OD/m	Soot g	NBS Smoke (F) D_m
No sample	-	1.6	106	-
Polycarbonate	0.24	>15.1	>2900	247
FR ABS	0.23	>15.1	>1460	900
Oak Panel	0.58	9.6	750	106
FR Acrylic	0.24	7.7	398	435
Generic PVC	0.23	8.3	384	780
Low Smoke PVC	0.12	1.5	93	94
CPVC	0.12	1.5	75	53

A 6.3 kg wood crib was used in all room corner burn experiments; total panel area: 6.6 m^2. The PVC materials used in these experiments were all rigid, i.e. unplasticised.

Table 8
Statistical Analysis of Linear Correlations* Between Various Measures of Smoke Obscuration

Flux kW/m^2	Slope	Intercept	Corr. Coeff. %
		OSU Smoke Factor vs. Cone Smoke Parameter	
20	0.129	18.2	76
40	0.059	20.8	88
70	0.028	16.6	78
		OSU Smoke Factor vs. Cone Smoke Factor	
20	0.023	31.0	74
40	0.009	32.0	77
70	0.004	22.0	79
		Cone Smoke Factor vs. Cone Smoke Parameter	
20	5.1	- 371.2	85
40	6.1	- 763.1	88
70	7.0	-1225.1	92
		NBS Smoke Chamber (F) Specific D_m vs Cone Smoke Parameter (25 kW/m^2) (20 kW/m^2)	
	0.114	111.3	1

Model used: y = Slope * x + Intercept

Table 9
Correlations Involving Smoke Factors for Cone and OSU

Correlation between Cone and OSU

Flux 20 kW/m^2		Flux 40 kW/m^2	
Corr. Coeff.	86 %	Corr. Coeff.	97 %
Intercept	20.12	Constant	16.20
Slope	0.606	X Coefficient(s)	0.689

Correlation between incident fluxes

Cone: 20-40 kW/m^2		OSU: 20-40 kW/m^2	
Corr. Coeff.	84 %	Corr. Coeff.	84 %
Intercept	174.50	Intercept	94.61
Slope	2.405	Slope	2.588

Table 10
Correlation Between the Cone Calorimeter and a Cable Tray Test

Property	Flux	Corr. coeff. R^2 %	Adj Corr Coeff Adj R^2 %	Slope	Intercept
			UL 1581		
Peak RSR	20	70	62	0.62	-1.3
Peak RSR	40	75	68	0.43	-2.7
SmkFct	20	93	92	9.00	383.0
SmkFct	40	86	83	2.44	61.4
			CSA FT-4		
Peak RSR	20	68	57	1.98	-9.2
Peak RSR	40	19	-	0.38	0.5
SmkFct	20	93	91	11.778	1406.3
SmkFct	40	71	62	2.47	1805.2
			ICEA T-29		
Peak RSR	20	85	82	0.91	0.9
Peak RSR	40	57	50	0.40	0.2
SmkFct	20	66	60	5.13	1346.6
SmkFct	40	72	67	1.34	1110.3
SmkFct	70	65	60	0.61	1136.0

Table 11

Description of Non Vinyl Materials Used

ABS:	Cycolac CTB acrylonitrile butadiene styrene terpolymer (Borg Warner) (# 29)
ABS FR:	Cycolac KJT acrylonitrile butadiene styrene terpolymer fire retarded with bromine compounds (Borg Warner) (# 20)
ABS FV:	Polymeric system containing acrylonitrile butadiene styrene and some poly(vinyl chloride) as additive
ACET:	Polyacetal: polyformaldehyde (Delrin, Commercial Plastics) (# 24)
DFIR:	Douglas fir wood board (# 22)
EPDM:	Copolymer of ethylene propylene diene rubber (EPDM) and styrene acrylonitrile (SAN) (Rovel 701) (# 31)
KYDEX:	Kydex: fire retarded acrylic panelling, blue, (samples were 4 sheets at 1.5 mm thickness each, Kleerdex) (# 15)
PCARB:	Polycarbonate sheeting (Lexan 141-111, General Electric) (# 5)
PCARB B:	Commercial polycarbonate sheeting (Commercial Plastics) (# 16)
NYLON:	Nylon 6,6 compound (Zytel 103 HSL, Du Pont) (# 28)
PBT:	Polybutylene terephthalate sheet (Celanex 2000-2 polyester, Hoechst Celanese) (# 32)
PE:	Polyethylene (Marlex HXM 50100) (# 34)
PET:	Polyethylene terephthalate soft drink bottle compound (# 33)
PMMA:	Poly(methyl methacrylate) (25 mm thick, lined with cardboard, standard RHR sample) (# 26)
PP:	Polypropylene (Dypro 8938) (# 35)
PPO/PS:	Blend of polyphenylene oxide and polystyrene (Noryl N190, General Electric) (# 18)
PPO GLAS:	Blend of polyphenylene oxide and polystyrene containing 30% fiberglass (Noryl GFN-3-70, General Electric) (# 17)
PS:	Polystyrene, Huntsman 333 (Huntsman) (# 30)
PS FR:	Fire retarded polystyrene, Huntsman 351 (Huntsman) (# 23)
PTFE:	Polytetrafluoroethylene sheet (samples were two sheets at 3 mm thickness each, Du Pont) (# 1)
PU:	Polyurethane flexible foam, non fire retarded (Jo-Ann Fabrics) (# 25)
THM PU:	Thermoplastic polyurethane containing fire retardants (estane, BFGoodrich) (# 27)
XLPE:	Black non-halogen flame retardant, irradiation crosslinkable, polyethylene copolymer cable jacket compound (DEQD-1388, Union Carbide) (# 11)

Table 12
Description of Vinyl Materials Used

A. Rigid Vinyls:

PVC EXT:	Poly(vinyl chloride) rigid weatherable extrusion compound with minimal additives (BFGoodrich) (# 13)
PVC LS:	Poly(vinyl chloride) rigid experimental sheet extrusion compound with smoke suppressant additives (BFGoodrich) (# 10)
PVC CIM:	Poly(vinyl chloride) general purpose rigid custom injection moulding compound with impact modifier additives (BFGoodrich) (# 8)
CPVC:	Chlorinated poly(vinyl chloride) sheet compound (BFGoodrich) (# 7)

B. Flexible PVC's

FL PVC:	Standard flexible poly(vinyl chloride) compound (non-commercial; similar to a wire and cable compound) used for various sets of testing (including Cone Calorimeter RHR ASTM round robin; it contains PVC resin 100 phr; diisodecyl phthalate 65 phr; tribasic lead sulphate 5 phr; calcium carbonate 40 phr; stearic acid 0.25 phr (# 21)
PVC WC:	Flexible wire and cable poly(vinyl chloride) compound (non fire retarded) (BFGoodrich) (# 14)
PVC WC SM:	Flexible wire and cable poly(vinyl chloride) compound (containing minimal amounts of fire retardants) (BFGoodrich) (# 12)
PVC WC FR:	Flexible wire and cable poly(vinyl chloride) compound (containing fire retardants) (BFGoodrich) (# 9)

C. Advanced Flexible Vinyls:

VTE 1:	Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of the first of several families of VTE alloys (# 6)
VTE 2:	Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of the second of several families of VTE alloys (# 3)
VTE 3:	Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of the third of several families of VTE alloys (# 2)
VTE 4:	Semi flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of a family of VTE alloys containing CPVC (# 4)

Table 13. Heat release rate results at a flux of 20 kW/m^2.

# Material	Pk RHR	TTI	SmkFct	TTI/RHR	Ht Comb
1. PTFE	3	10,000	0.4	6780	3.6
2. VTE 3	4	10,000	0.4	2850	1.5
3. VTE 2	9	10,000	0.6	1301	0.9
4. VTE 4	14	10,000	1.1	1027	3.0
5. PCARB	16	10,000	0.1	5173	4.5
6. VTE 1	19	10,000	4.3	591	2.2
7. CPVC	25	10,000	1.3	392	2.4
8. PVC CIM	40	5159	13.7	1343	1.4
9. PVC WC FR	72	236	27.7	3.49	7.0
10. PVC LS	75	5171	9.3	72.4	2.0
11. XLPE	88	750	1.5	8.08	22.4
12. PVC WC SM	90	176	77.6	1.96	8.5
13. PVC EXT	102	3591	24.3	31.4	7.3
14. PVC WC	116	117	100.4	1.00	10.5
15. KYDEX	117	200	65.0	1.70	5.4
16. PCARB B	144	6400	2.7	474	13.1
17. PPO GLAS	154	465	1.8	3.03	59.0
18. PPO/PS	219	479	25.9	2.45	52.5
19. ABS FV	224	5198	22.3	66.3	17.0
20. ABS FR	224	212	456.2	0.93	12.5
21. FL PVC	233	102	481.6	0.44	19.3
22. DFIR	237	254	30.4	1.10	13.1
23. PS FR	277	244	290.1	0.90	15.0
24. ACET	290	259	13.0	0.90	13.0
25. PU	290	12	33.1	0.04	18.4
26. PMMA	409	176	51.6	0.43	23.5
27. THM PU	424	302	216.3	0.72	23.5
28. NYLON	517	1923	2.7	3.85	23.3
29. ABS	614	236	793.3	0.38	56.7
30. PS	723	417	44.6	0.58	40.7
31. EPDM/SAN	737	486	28.6	0.66	37.5
32. PBT	850	609	1.4	0.75	16.1
33. PET	881	718	2.8	0.82	16.2
34. PE	913	403	29.9	0.44	41.1
35. PP	1170	218	536.0	0.19	72.0
Average	295	2986	96.9	575.3	19.0
Median	219	479	24.3	2.0	13.1

Table 14. Heat release rate results at a flux of 40 kW/m^2.

# Material	Pk RHR	TTI	SmkFct	TTI/RHR	Ht Comb
1. PTFE	13	10,000	0.3	839	3.5
2. VTE 3	43	1212	13.5	36.4	5.3
3. VTE 2	64	1253	24.9	21.4	8.5
4. VTE 4	87	10,000	35.9	115	4.5
5. PCARB	429	182	733.2	0.43	22.3
6. VTE 1	77	1271	76.1	16.7	5.7
7. CPVC	84	621	3.8	7.44	5.4
8. PVC CIM	175	73	298.2	0.42	5.1
9. PVC WC FR	92	47	104.6	0.50	9.5
10 PVC LS	111	187	78.6	1.65	17.0
11. XLPE	192	105	24.0	0.55	24.2
12. PVC WC SM	142	36	473.0	0.25	11.5
13. PVC EXT	183	85	459.6	0.46	13.3
14. PVC WC	167	27	503.5	0.16	15.5
15. KYDEX	176	38	535.0	0.22	11.0
16. PCARB B	420	144	616.0	0.34	24.4
17. PPO GLAS	276	45	853.8	0.16	27.0
18. PPO/PS	265	87	1143.3	0.33	23.3
19. ABS FV	291	61	1499.2	0.21	17.4
20. ABS FR	402	66	3740.9	0.16	12.4
21. FL PVC	237	21	914.5	0.09	15.7
22. DFIR	221	34	42.9	0.15	17.6
23. PS FR	334	90	3461.7	0.27	14.6
24. ACET	360	74	17.5	0.20	12.7
25. PU	710	1	134.4	0.0014	45.3
26. PMMA	665	36	429.0	0.05	23.3
27. THM PU	221	60	367.6	0.28	17.4
28. NYLON	1313	65	887.9	0.05	31.0
29. ABS	944	69	4457.4	0.07	30.8
30. PS	1101	97	6791.5	0.09	38.0
31. EPDM/SAN	956	68	5785.4	0.07	28.8
32. PBT	1313	113	4711.2	0.09	21.1
33. PET	534	116	1207.9	0.22	11.6
34. PE	1408	159	1822.0	0.06	46.6
35. PP	1509	86	3416.5	0.06	42.1
Average	443	761	1304.7	29.8	19.0
Median	265	85	503.5	0.22	17.0

Table 15. Heat release rate results at a flux of 70 kW/m².

# Material	Pk RHR	TTI	SmkFct	TTI/RHR	Ht Comb
1. PTFE	161	252	4.4	1.56	4.6
2. VTE 3	70	17	42.4	0.24	7.7
3. VTE 2	100	424	80.3	6.01	6.8
4. VTE 4	66	1583	25.7	24.3	7.2
5. PCARB	342	75	728.4	0.22	21.4
6. VTE 1	120	60	239.1	0.49	7.1
7. CPVC	93	372	7.9	4.06	6.1
8. PVC CIM	191	45	701.8	0.24	12.7
9. PVC WC FR	134	12	283.9	0.09	10.4
10. PVC LS	126	43	148.6	0.34	12.0
11. XLPE	268	35	133.8	0.13	24.7
12. PVC WC SM	186	14	872.6	0.07	10.7
13. PVC EXT	190	48	1143.8	0.25	10.8
14. PVC WC	232	11	969.7	0.05	15.2
15. KYDEX	242	12	1368.9	0.05	9.4
16. PCARB B	535	45	1124.1	0.08	20.7
17. PPO GLAS	386	35	1830.5	0.09	23.8
18. PPO/PS	301	39	1519.0	0.13	22.9
19. ABS FV	409	39	2561.8	0.10	18.5
20. ABS FR	419	39	3438.2	0.09	10.3
21. FL PVC	252	15	1277.0	0.06	14.2
22. DFIR	196	12	59.7	0.06	13.5
23. PS FR	445	51	4490.1	0.11	11.9
24. ACET	566	24	103.3	0.04	14.6
25. PU	1221	1	239.9	0.0008	37.5
26. PMMA	988	11	1012.1	0.01	25.9
27. THM PU	319	38	746.1	0.12	17.9
28. NYLON	2019	31	4003.4	0.02	29.3
29. ABS	1311	48	5035.5	0.04	28.0
30. PS	1555	50	9152.8	0.03	28.8
31. EPDM/SAN	1215	36	10,376	0.03	29.2
32. PBT	1984	59	9656.5	0.09	25.6
33. PET	616	42	2355.9	0.07	15.2
34. PE	2735	47	3975.8	0.02	42.6
35. PP	2421	41	5509.4	0.02	43.1
Average	640	106	2149.1	1.1	18.3
Median	319	39	1012.1	0.09	15.2

Table 16. Predicted limiting flux (in kW/m²) for times to ignition of 10 min.

Materials	Lim Flux 600
1. PTFE	63
2. VTE 3	45
3. VTE 2	60
4. VTE 4	86
5. PCARB	34
6. VTE 1	47
7. CPVC	42
8. PVC CIM	30
9. PVC WC FR	≤15
10. PVC LS	33
11. XLPE	22
12. PVC WC SM	≤15
13. PVC EXT	30
14. PVC WC	≤15
15. KYDEX	≤15
16. PCARB B	32
17. PPO PS FGLAS	18
18. PPO PS	17
19. ABS FV	30
20. ABS FR	≤15
21. FL PVC	≤15
22. DFIR	≤15
23. PS FR	≤15
24. ACET	≤15
25. PU	≤15
26. PMMA	≤15
27. THMPLAS PU	≤15
28. NYLON	27
29. ABS	≤15
30. PS	≤15
31. EPDM SAN	18
32. PBT	20
33. PET	22
34. PE	≤15
35. PP	≤15

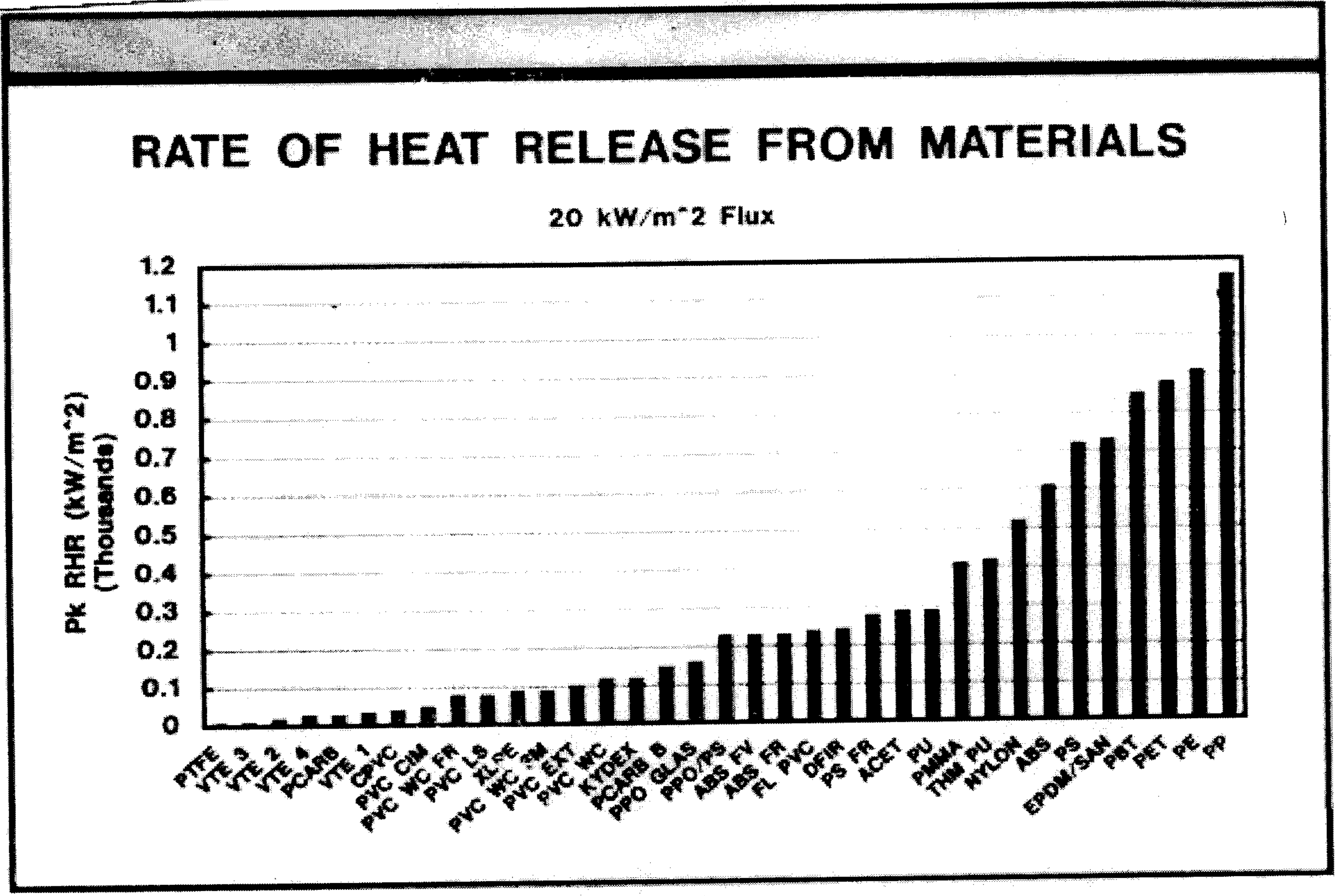


Figure 1. Peak rate of heat release from materials, in the cone calorimeter, at an incident flux of 20 kW/m².

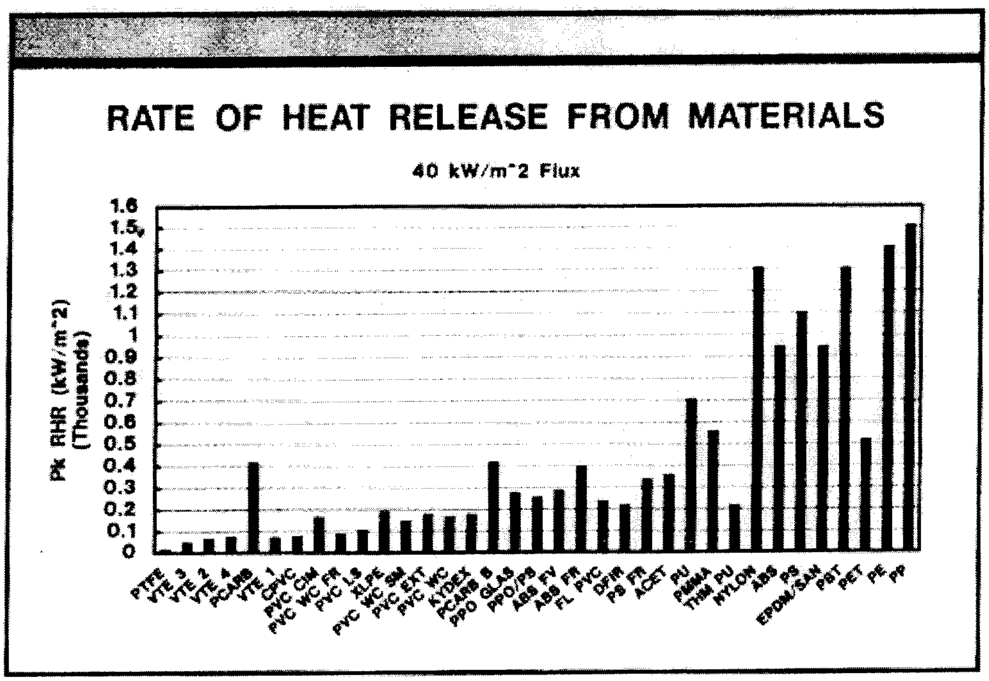


Figure 2. Peak rate of heat release from materials, in the cone calorimeter, at an incident flux of 40 kW/m².

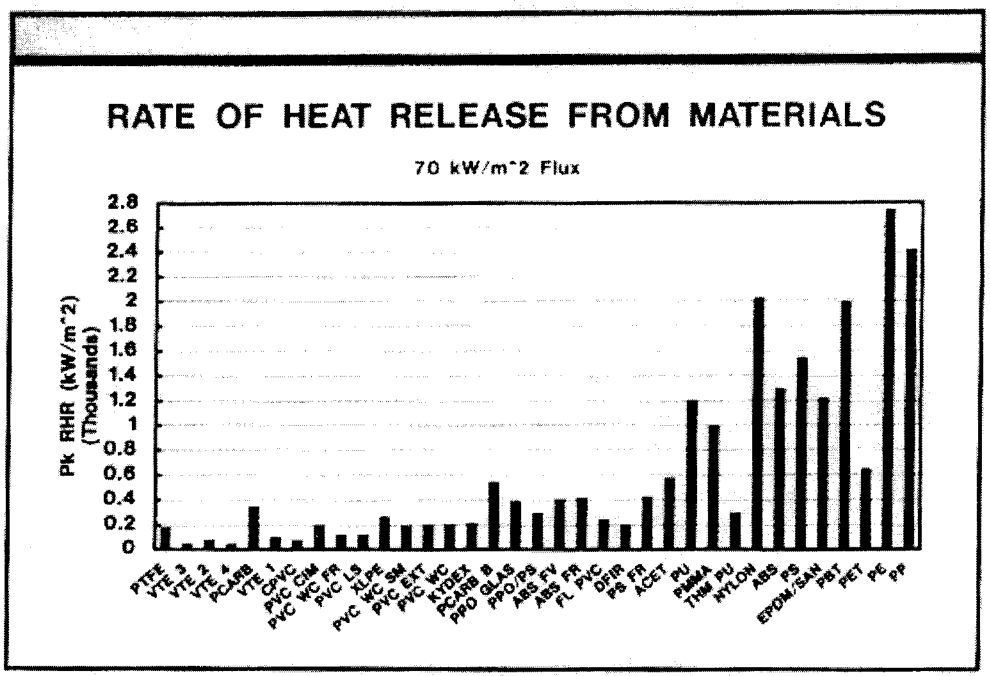


Figure 3. Peak rate of heat release from materials, in the cone calorimeter, at an incident flux of 70 kW/m².

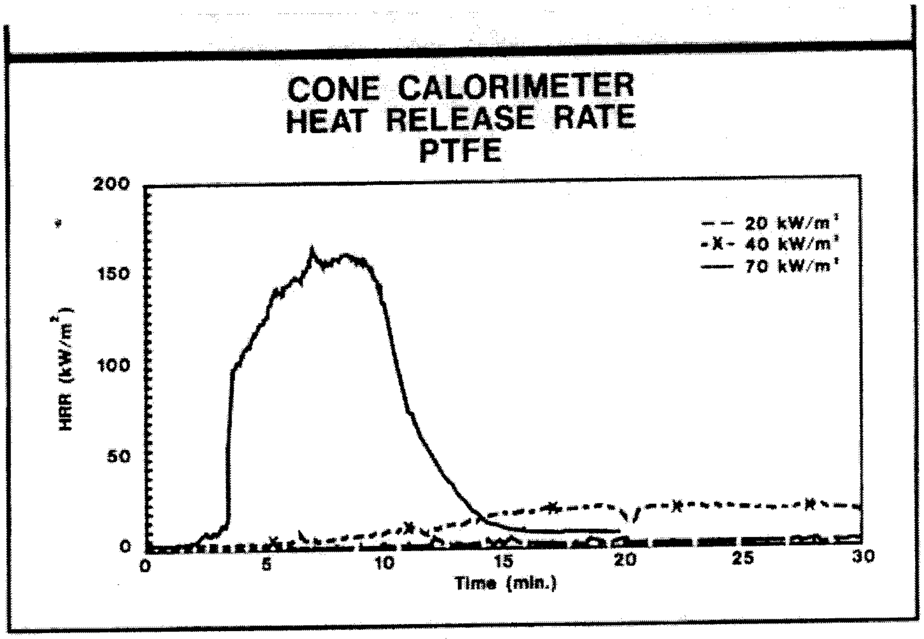


Figure 4. Rate of heat release vs. time curve for PTFE in the cone calorimeter at in dent fluxes of 20, 40 and 70 kW/m².

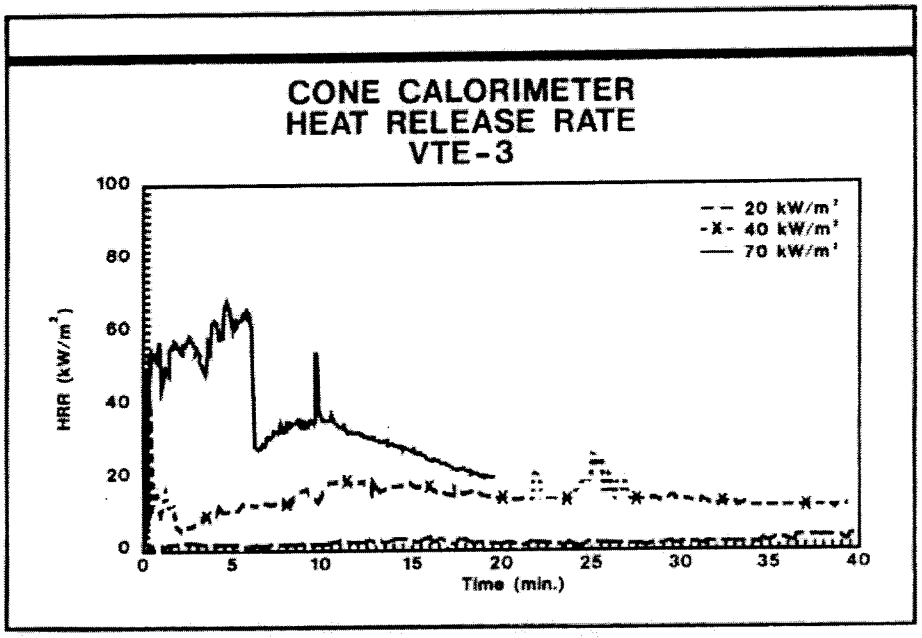


Figure 5. Rate of heat release vs. time curve for VTE-3 in the cone calorimeter at cident fluxes of 20, 40 and 70 kW/m².

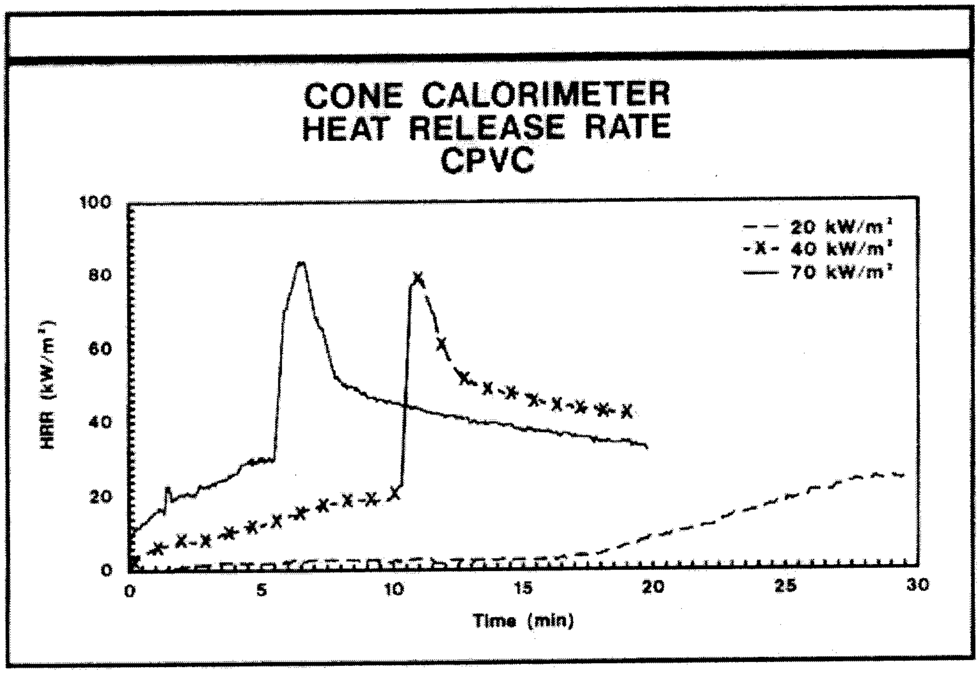


Figure 6. Rate of heat release vs. time curve for CPVC in the cone calorimeter at incident fluxes of 20, 40 and 70 kW/m².

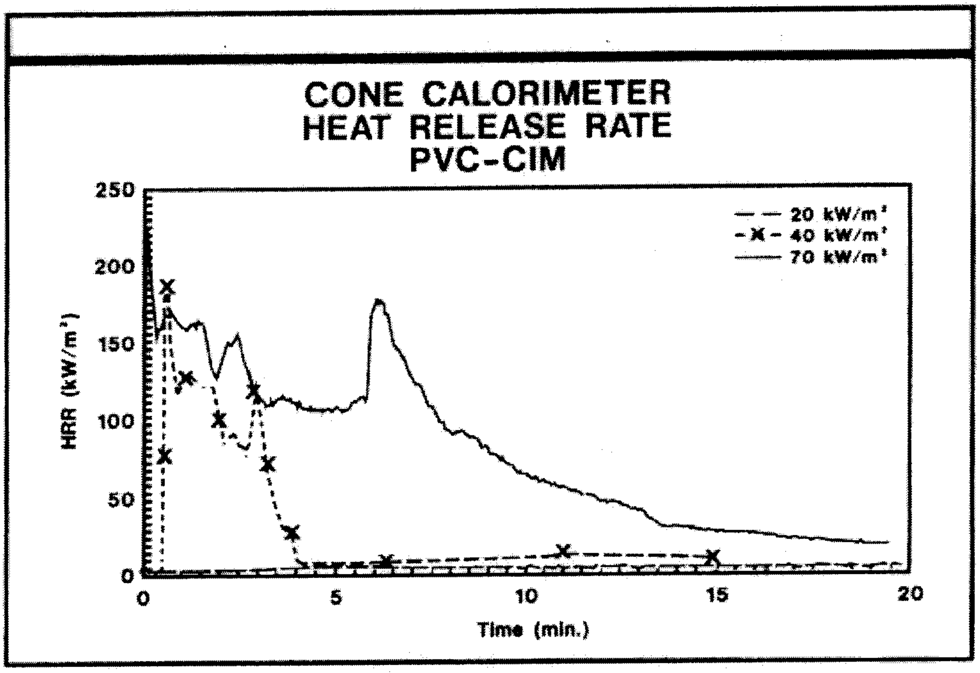


Figure 7. Rate of heat release vs. time curve for PVC-CIM in the cone calorimeter at incident fluxes of 20, 40 and 70 kW/m².

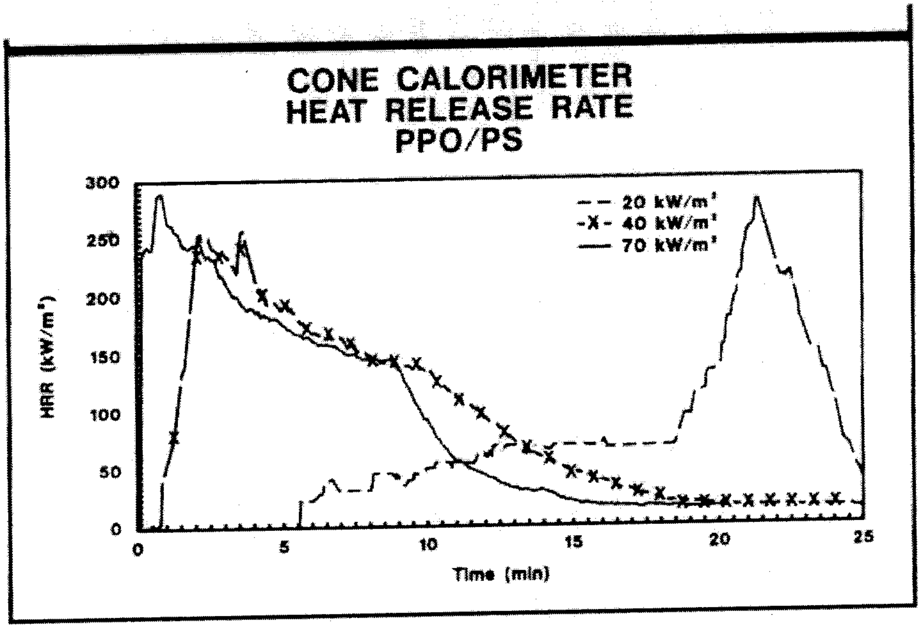


Figure 8. Rate of heat release vs. time curve for PPO/PS in the cone calorimeter at incident fluxes of 20, 40 and 70 kW/m².

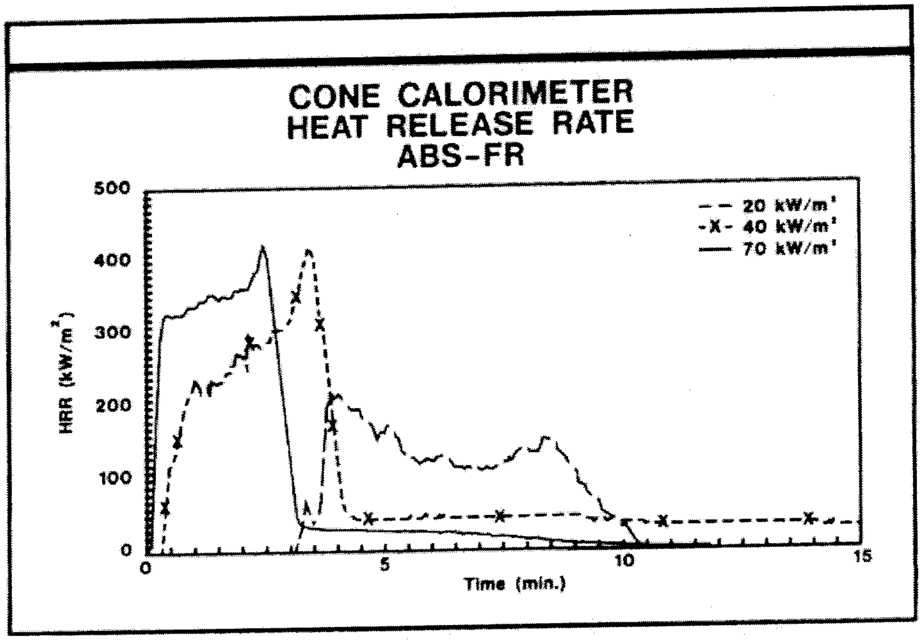


Figure 9. Rate of heat release vs. time curve for ABS-FR in the cone calorimeter at incident fluxes of 20, 40 and 70 kW/m².

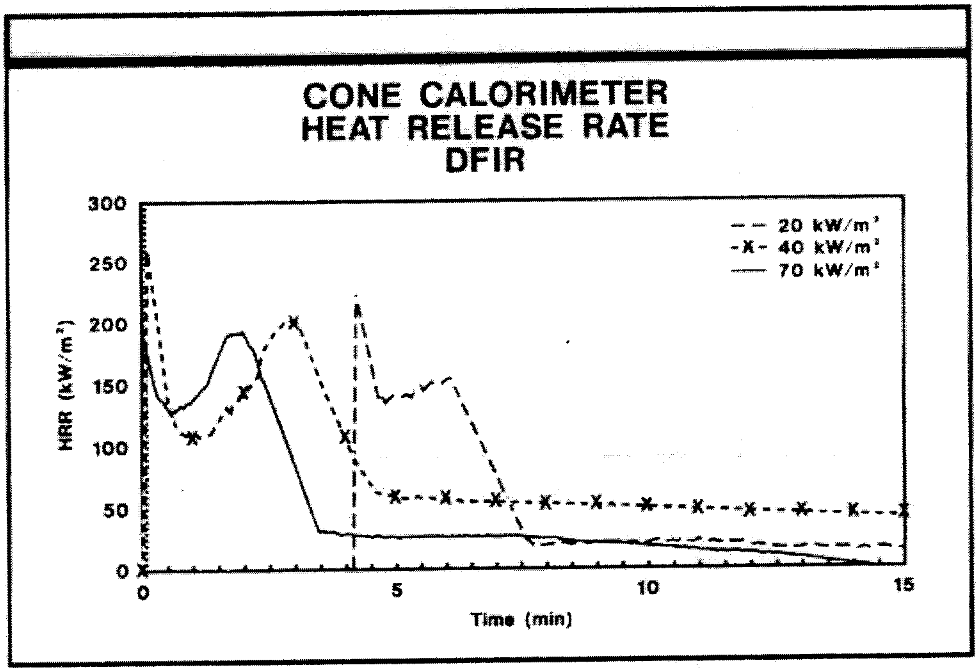


Figure 10. *Rate of heat release vs. time curve for DFIR in the cone calorimeter at incident fluxes of 20, 40 and 70 kW/m²*.

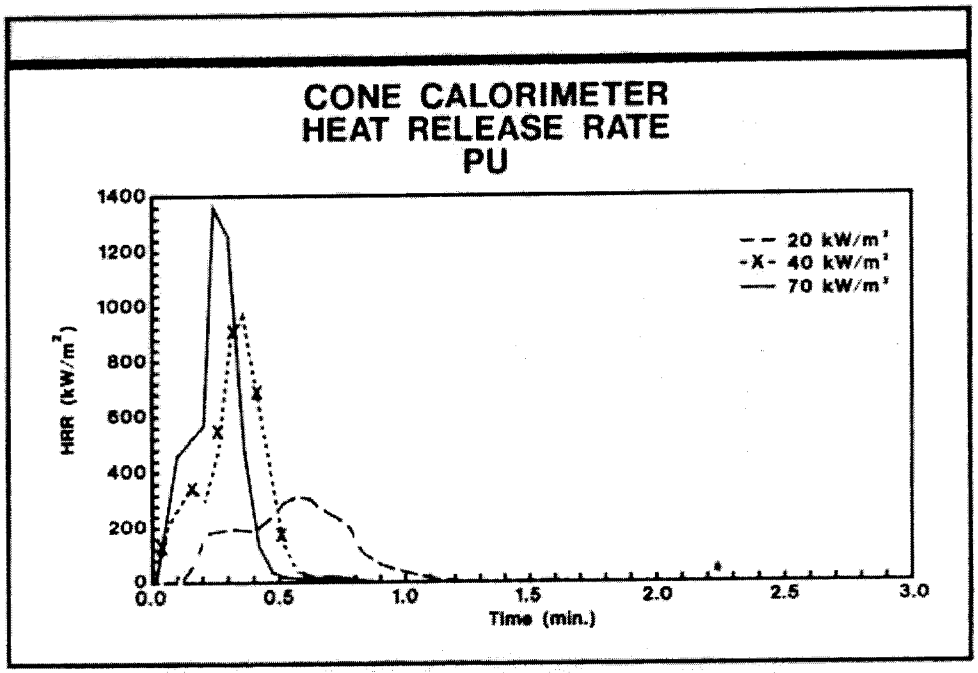


Figure 11. *Rate of heat release vs. time curve for PU in the cone calorimeter at incident fluxes of 20, 40 and 70 kW/m²*.

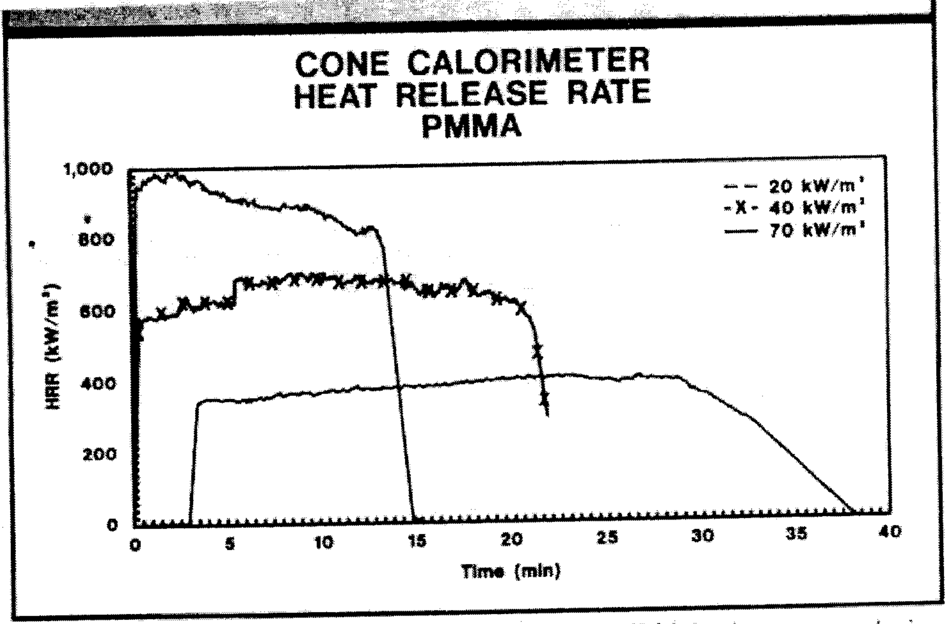


Figure 12. Rate of heat release vs. time curve for PMMA in the cone calorimeter at incident fluxes of 20, 40 and 70 kW/m².

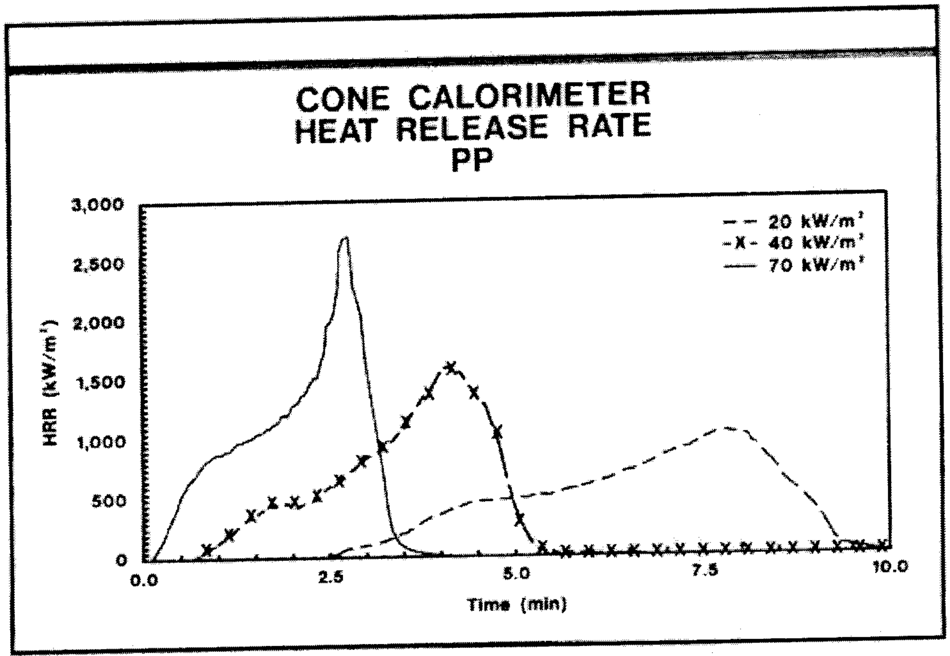


Figure 13. Rate of heat release vs. time curve for PP in the cone calorimeter at incident fluxes of 20, 40 and 70 kW/m².

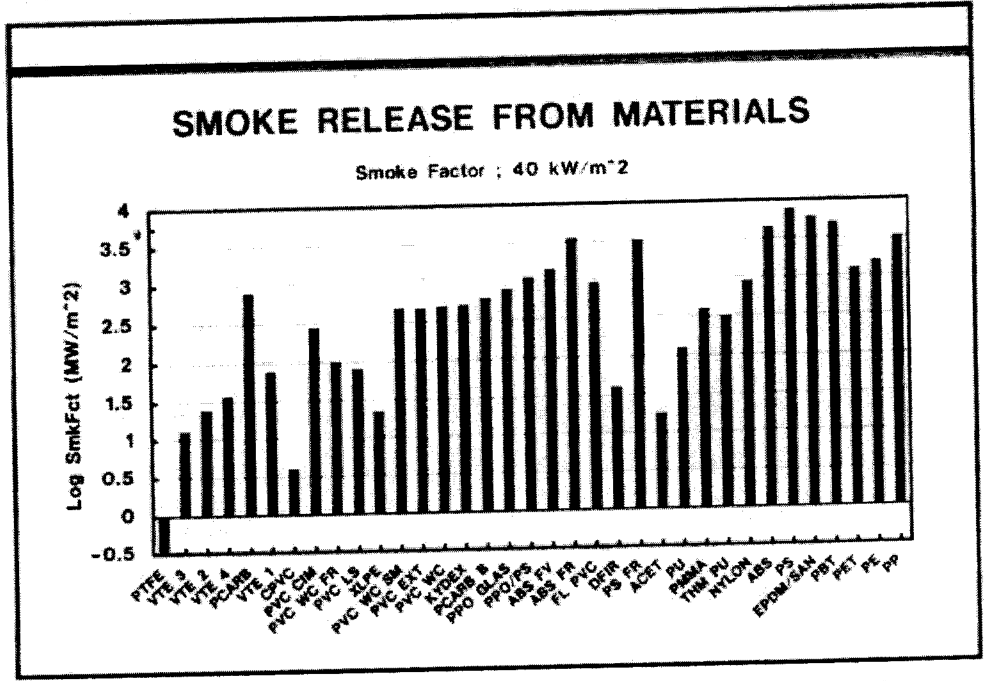


Figure 14. Smoke release from materials: smoke factor measured in the cone calorimeter at an incident flux of 40 kW/m².

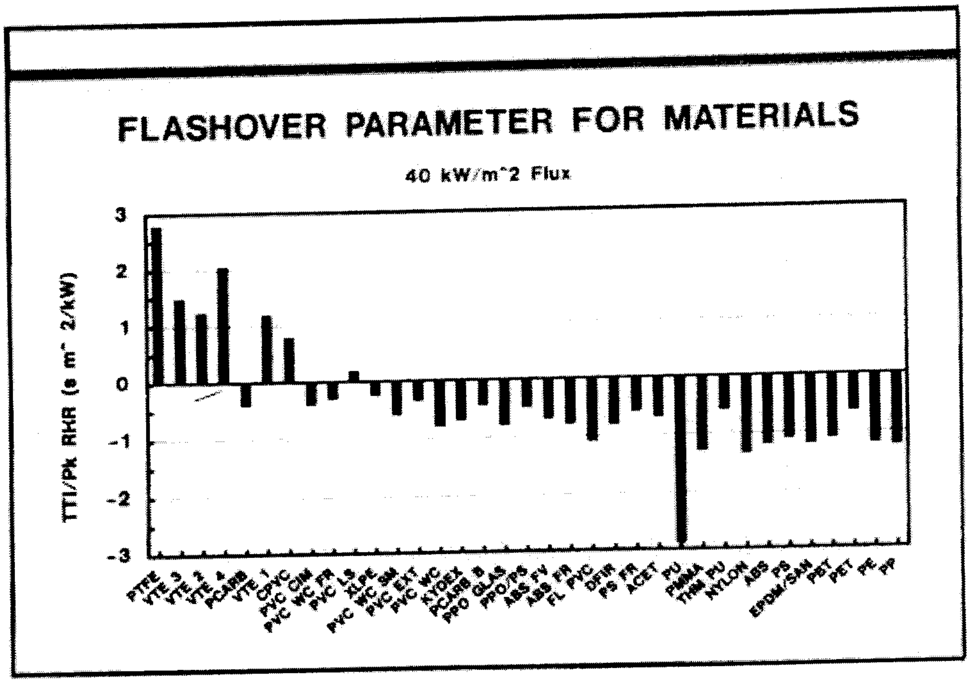


Figure 15. Flashover parameter from materials: ratio of time to ignition to peak rate of heat release measured in the cone calorimeter at an incident flux of 40 kW/m².

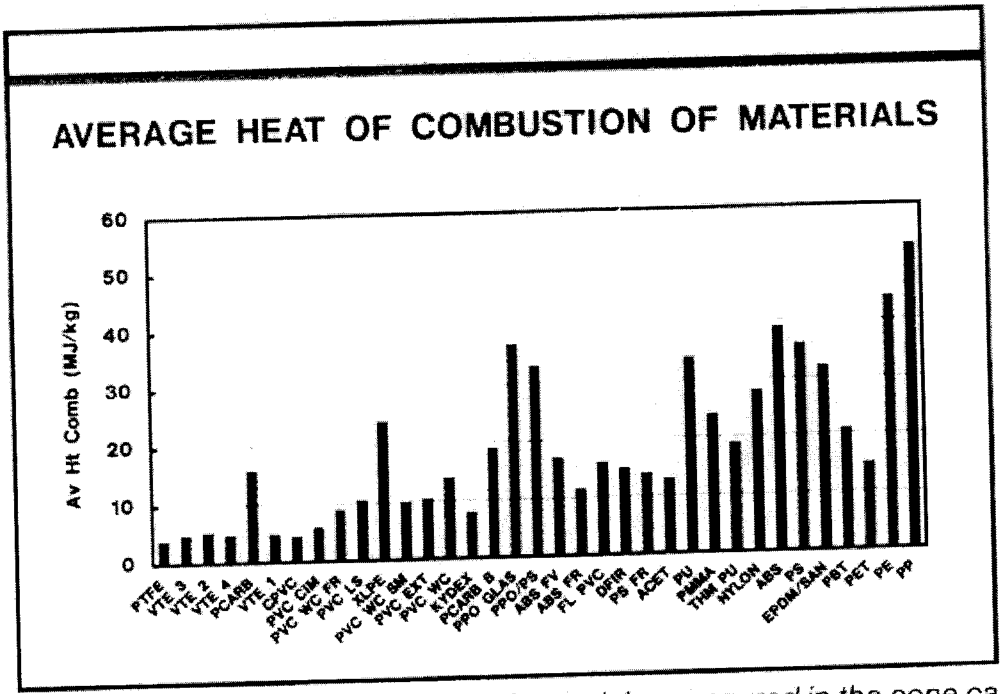


Figure 16. Average heat of combustion of materials, measured in the cone calorimeter at incident fluxes of 20, 40 and 70 kW/m^2.

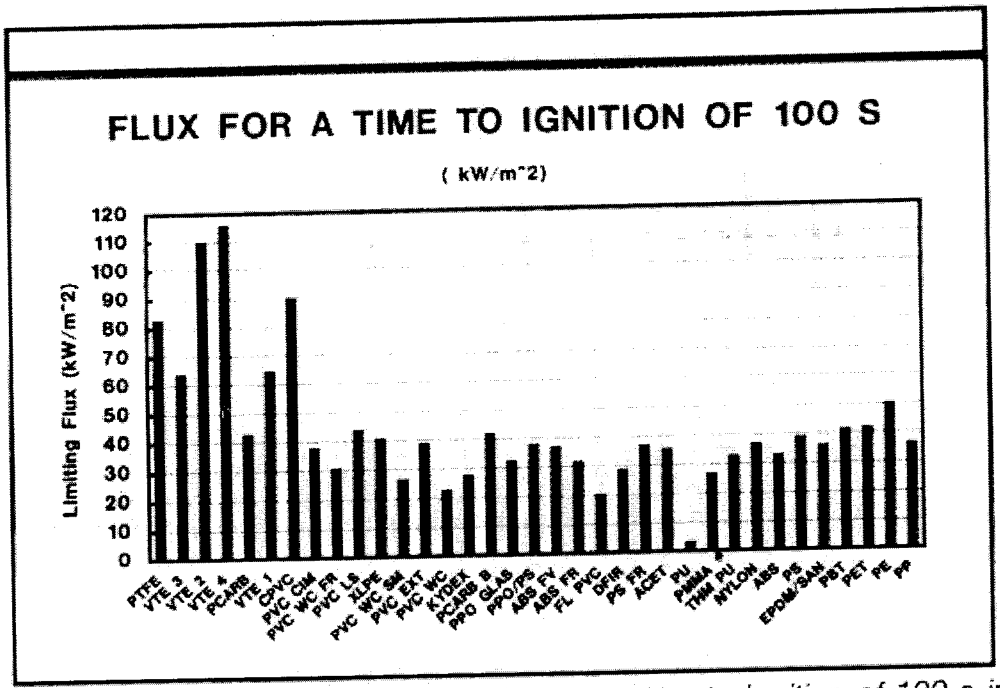
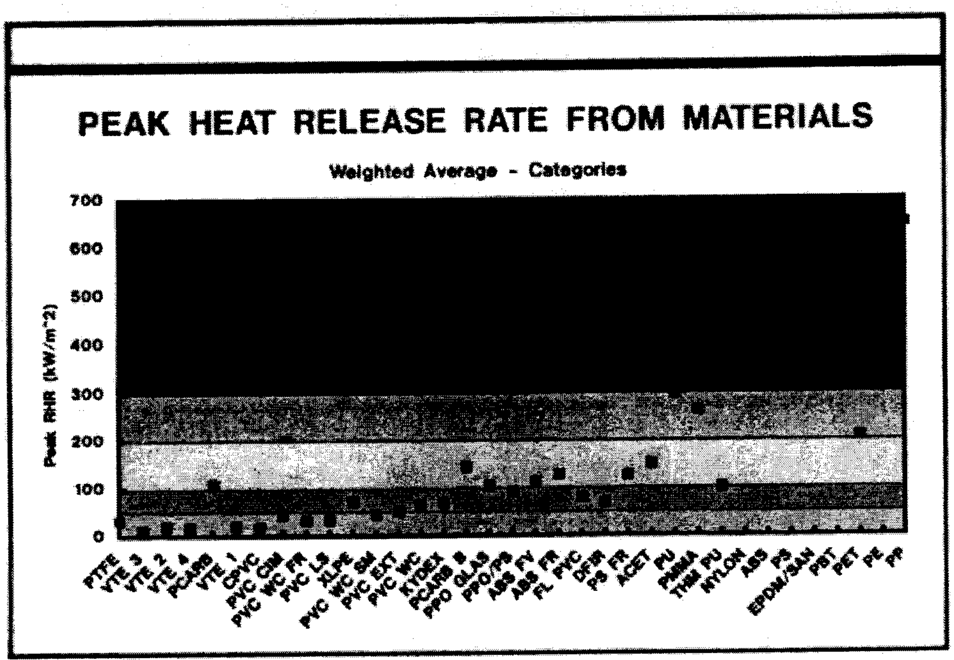
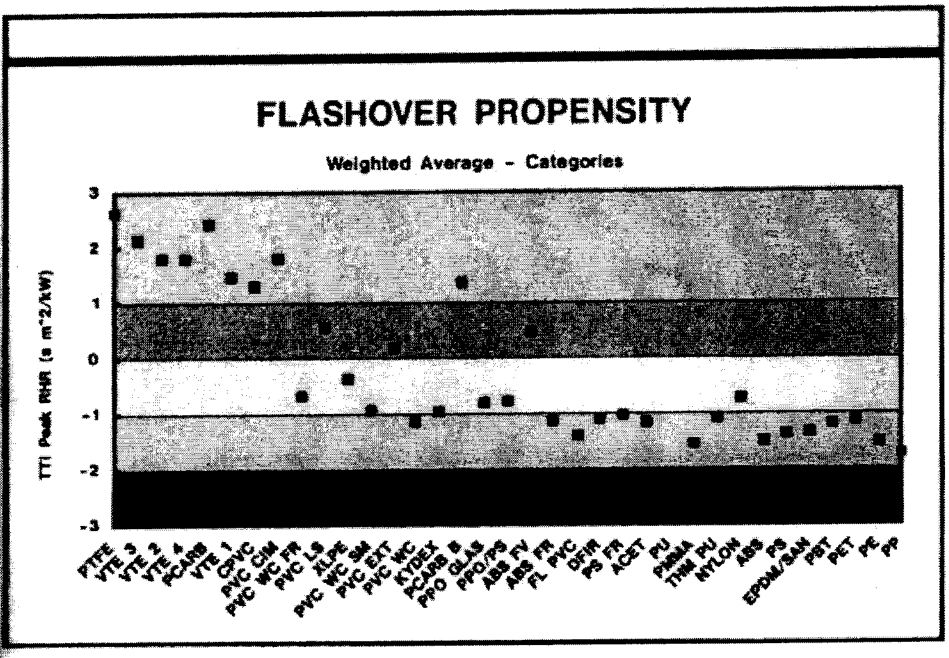


Figure 17. Predicted incident flux for obtaining a time to ignition of 100 s in the cone calorimeter.



ure 18. Categories of peak heat release rate for materials, from weighted aver
es in the cone calorimeter.



e 19. Categories of flashover propensity for materials, from weighted aver-
es in the cone calorimeter.

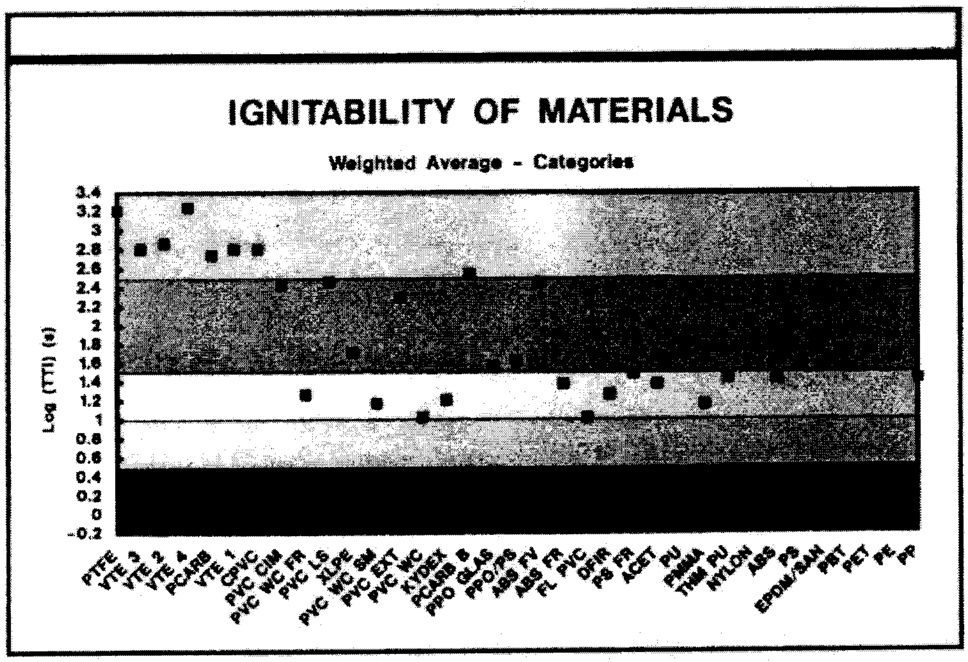


Figure 20. Categories of ignitability for materials, from weighted averages in the cone calorimeter.

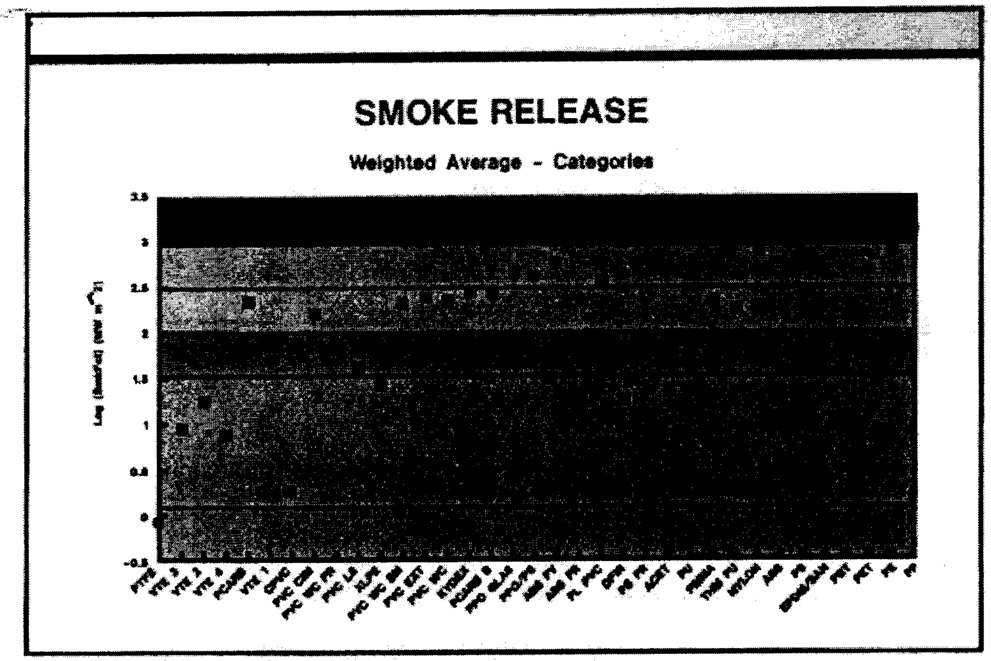


Figure 21. Categories of smoke release for materials, from weighted averages in the cone calorimeter.

GBH Attachment 7

AB59-COMM-7-7

Sara M. Debanne,[1] *Marcelo M. Hirschler,*[2] *and Gordon L. Nelson*[3]

The Importance of Carbon Monoxide in the Toxicity of Fire Atmospheres

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REFERENCE: Debanne, S. M., Hirschler, M. M., and Nelson, G. L., "**The Importance of Carbon Monoxide in the Toxicity of Fire Atmospheres,**" *Fire Hazard and Fire Risk Assessment, ASTM STP 1150*, Marcelo M. Hirschler, Ed., American Society for Testing and Materials, Philadelphia, 1992, pp. 9–23.

ABSTRACT: This paper addresses the issue of determining toxic fire hazard in a manner that is relevant to the large-scale fire scenarios that cause most lethalities, ventilation controlled flashover fires.

The work involves (a) a literature study of background information on the toxicity of carbon monoxide (CO) to humans, (b) two very extensive forensic studies (with 2 241 and 2 673 cases, respectively) on human lethality involving CO in fires and non-fires, (c) statistical analyses of the forensic data, to ensure full separation of variables, and (d) an analysis of the literature on the effects of different parameters in fire atmospheres and in small-scale tests.

This work addresses five issues essential to fire hazard assessment:

(1) Relative role of toxicants other than CO in causing fire fatalities and critical carboxyhemoglobin (COHb) values representing lethality.
(2) Differences in populations between fire victims and those dying in other CO-containing atmospheres.
(3) Comparison of modern fire atmospheres, containing smoke from man-made materials, with traditional fire atmospheres.
(4) CO yields in flashover fires and effects of fuel chemistry.
(5) CO yields in small-scale toxicity tests and fuel effects.

The work has shown that:

(1) The toxicity of fire atmospheres is determined almost exclusively by the amount of CO. The lethal CO threshold level depends on the physical condition of the victim, but COHb values > 20% can produce lethality with no other apparent cause.
(2) Fire and non–fire CO victim populations are very different: fire victims are much older or much younger and more infirm, and thus more sensitive to CO than those in non-fire exposures.
(3) Replacing large amounts of natural and traditionally used materials by man-made materials has made no difference to fire atmosphere toxicity.
(4) CO concentrations in large–scale flashover fire atmospheres are determined by oxygen availability and such variables, but are little affected by chemical composition of fuels.
(6) Small-scale tests give excessively low CO yields so that they cannot be used to predict toxic fire hazard for ventilation controlled flashover fires, although post computational CO concentration corrections can make these tests useful as part of fire hazard assessment calculations.

KEY WORDS: carbon monoxide, carboxyhemoglobin, fire fatalities, fire gases, fire hazard, fire scenario, flashover, smoke toxicity, toxicity test

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It has been discussed in the National Fire Protection Association (NFPA) Quarterly, in 1933, that the main direct cause of death in fires was combustion product toxicity [1]. For ASTM use, smoke is interpreted as the sum total of the gaseous, liquid, and solid airborne products of combustion (ASTM Terminology Relating to Fire Standards, E 176). Smoke is, thus, not a uniform material, so that its composition depends on the exact conditions under which it was generated. However, smoke always contains two principal types of toxic gases: asphyxiants and irritants.

All organic (that is, carbon-containing) materials give off carbon monoxide (CO), carbon dioxide, and water on combustion [2]. Many other combustion gases are released from burning materials, but most of them are characteristic of particular classes of fuels. Carbon monoxide is a highly toxic asphyxiant gas, which is odorless and tasteless. It is the individual toxic gas associated with the largest fire hazard. Many other components of smoke are much more toxic, but those are usually present in much smaller concentrations. On the other hand, some gases are present at higher concentrations (typically carbon dioxide and water) but they are of much lower toxicity. Two studies which sent fire fighters into actual buildings on fire, while equipped with combustion product monitors, [3,4] had the same conclusions; the overwhelming hazardous toxicant in fire is CO.

The other principal toxicants in fires are acrolein that has the second highest ratio, after CO, of peak level found to lethal level and is emitted by polyolefins and cellulosic materials), hydrogen cyanide (emitted by N-containing materials), and hydrogen chloride (emitted by Cl-containing materials) [5].

The mechanism by which CO acts on mammals is by competing with oxygen for the hemoglobin in blood and tying it up as COHb, rather than as the normal oxyhemoglobin. The hemoglobin (Hb) fraction tied up as COHb is normally expressed as percent COHb (which means the percentage of the total hemoglobin present as COHb rather than as oxyhemoglobin). Carbon monoxide reacts ~210 times faster with hemoglobin than does oxygen, so that it can lead to an oxyhemoglobin deficiency, even at low CO concentrations. This lack of oxyhemoglobin then leads to hypoxia, which can cause cerebral damage and eventual death by asphyxiation. However, the reaction of CO with hemoglobin to yield COHb is reversible, and COHb levels will decrease when the CO exposure ceases.

Traditional wisdom has set a value of 50% COHb as the threshold level for human lethality [5,6]. This has been taken to mean that blood COHb levels of ≥50% COHb inevitably leads to death, and that if a fatality is autopsied and its COHb level was <50%, CO poisoning could not be the sole cause of death. However, it is known that 25% COHb already causes myocardial damage [7].

Carbon monoxide is also present in non–fire atmospheres. Two typical examples are those resulting from malfunctioning unvented gas or charcoal heaters, or from automobile exhaust. In these two cases, CO is widely recognized as being virtually the only toxicant of any consequence present. This is an important difference from fire atmospheres, which contain several other toxicants, some of which may be present at high enough concentrations to cause serious concern.

Several fire hazard issues will be addressed in this paper, which includes a description of some of the major results from a series of studies sponsored by the Society of the Plastic Industry, Inc. [8].

(1) The presence of these other toxicants and their importance in the toxicity of fire atmospheres is an issue with important implications for fire hazard assessment because of the way in which smoke toxicity is normally determined. One of the issues that needs to be understood is the relative role of toxicants other than CO is causing fire fatalities and whether there is any critical value of COHb that represents lethality.

(2) Fire fatalities are most commonly unwitting victims of external events that overtake them, while many individuals who succumb to the intoxicating effects of automobile exhaust do so at their own initiative. Thus, it is worth investigating whether the populations that lose their lives in fire atmospheres and in other CO-containing atmospheres are identical. If it is found that the two populations are significantly different, the follow up query is whether the effects of CO can be separated from other effects, inherent in the characteristics of the population involved. Fire hazard or fire risk assessment models require this answer since they have to concentrate on the population most at risk in fires.

(3) The modern world in which we live contains a large proportion of products made from synthetic materials, for example, plastics. The combustion of these materials can generate toxicants which are different from those traditionally generated by natural materials. This has caused a great deal of speculation that the toxicity of modern fires may be significantly different from that of fires of another era. Therefore, another issue of importance to fire hazard is an understanding of the relative toxicity of fires involving new and traditional materials.

(4) The vast majority of the fire fatalities that occur in the United States are found away from the room of fire origin. That is a clear indication that those fires which lead to fatalities tend to be big fires. In other words, they are flaming fires, which have involved the entire room of origin and gone beyond it. These types of fires are often described as flashover or post-flashover fires [9]. Any smoke toxicity assessment that would attempt to address fire risk should, of course, address such high intensity flaming fires. Therefore, it is of interest to fire safety to understand what types of atmospheres are to be expected in these fires, particularly as regards their CO content.

(5) Small–scale toxicity tests are the most common means of assessing smoke toxicity of materials or products. The final question to be asked in this study regards the CO yields in such tests and how they compare to those in the real full-scale fires that cause the majority of fire fatalities.

Literature Search

Dr. Gordon L. Nelson, at the Department of Polymer Science at the University of Southern Mississippi, carried out a literature search on information available regarding human exposure to CO and fatalities. This study unearthed more than 100 references, and found several major forensic studies, both of fire victims and of victims of non-fire CO exposure. Full details of this study will be given elsewhere, together with those of other associated studies, all sponsored by the Society of the Plastics Industry [8]. However, the 12 most notable studies are described in Table 1. Only two of these studies have been very widely publicized, namely, those in Maryland and Glasgow. Interestingly, none of the referenced studies involved over 1 000 cases. This means that several of them would have had great difficulties making any statistically valid separate analyses of individual variables.

It is worth discussing some of the most interesting results of these studies. They have found that when various individuals are exposed to a particular atmosphere, their COHb levels can be very different. Furthermore, some people may even survive the exposures, and others, for no apparent reason, succumb. These studies have also found both survivors of CO exposure who have COHb levels of well over 50% and fatalities from pure CO exposure with COHb levels in the range of 20 to 40%. In fact, around the turn of the century, John Scott Haldane poisoned himself with CO and measured COHb levels of over 50%, without succumbing to the experience.

The age distribution of fire victims was found to have a bimodal distribution, both in the

TABLE 1—*Important carbon monoxide forensic studies.*

Site	Year(s)	Source	Cases	Authors	Ref No.
New York City	1942	non-fire	68	Gettler	[10]
United States	1960s	fire, aircraft	85	Dominguez	[11]
New York City	1966 to 1967	fire	311	Zikria et al.	[12,13]
Ontario	1965 to 1968	non-fire	304	Cimbura et al.	[14]
Japan	1960s	fire and non-fire	400	Kishitani	[15]
Oslo	1970s	fire and non-fire	141	Teige et al.	[16]
United States	1977	non-fire, gas heaters	22	Consumer Product Safety Commission	[17]
Poland	1975 to 1976	unknown	321	Pach et al.	[18]
Maryland	1972 to 1977	fire	530	Berl and Halpin	[19,20]
Glasgow	1977 to 1981	fire	298	Anderson and Harland	[21,22]
Las Vegas	1980	fire, hotel	84	Birky et al.	[23]
Copenhagen	1976 to 1981	fire	169	Gormsen et al.	[24]

Maryland and Glasgow studies [19–22] (Fig. 1). In contrast, the age distribution for non-fire suicide victims, from automobile exhaust in the Oslo study [15], is a simple distribution with a single peak (Fig. 2).

A histogram of victim frequency versus COHb levels for non-fires shows that there is a strong difference between accidental victims (CPSC study of gas heaters [17]) and those causing their own deaths (Oslo study of automobile exhaust [16]). Figure 3 shows that suicide victims end up with very high COHb levels, typically in the 65 to 85% levels. On the other hand, accidental victims of CO poisoning end up with much lower levels, between 26 and 81%, and with a median of 45%. This is a very important finding, because it indicates that accidental victims of CO poisoning can die at very low levels, without any additional factor being involved.

Figure 4 compares the frequency distribution of COHb levels for fire fatality studies with that of an accidental non-fire CO exposure forensic study. It is clear that the distributions are very similar and that both have significant proportions of fatalities at levels well under 50% COHb, the traditional lethal level.

This portion of the study shows that 50% COHb can not be a magical number such that it is the inevitable pass/fail lethality criterion for pure CO poisoning.

Forensic Investigation on CO Victims Across the United States

The Department of Polymer Science at the University of Southern Mississippi (USM) carried out an extensive investigation, on a countrywide basis, of fatalities associated with CO. The investigators were Gordon L. Nelson, Dennis V. Canfield, and James B. Larsen. This investigation prepared a data base of 2 241 cases, originating in 37 laboratories across the entire United States. The vast majority of the victims died over a relatively short time frame in the 1980s. Table 2 shows the variables investigated, and Table 3 presents some information on the data base itself. It is worth pointing out that the data base, which is

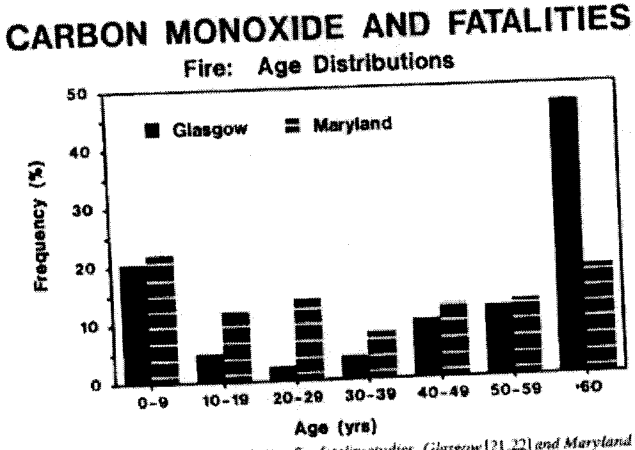


FIG. 1—*Age distributions for victims in two fire fatality studies, Glasgow* [21,22] *and Maryland* [19,20].

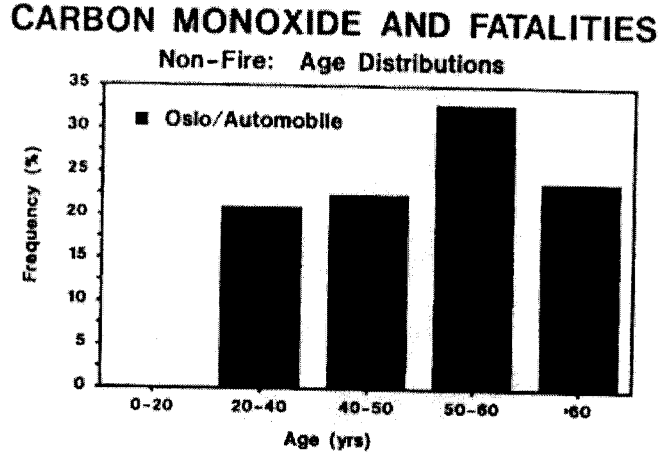


FIG. 2—*Age distribution for victims in a non-fire CO fatality study, associated mainly with automobile deaths,* [16].

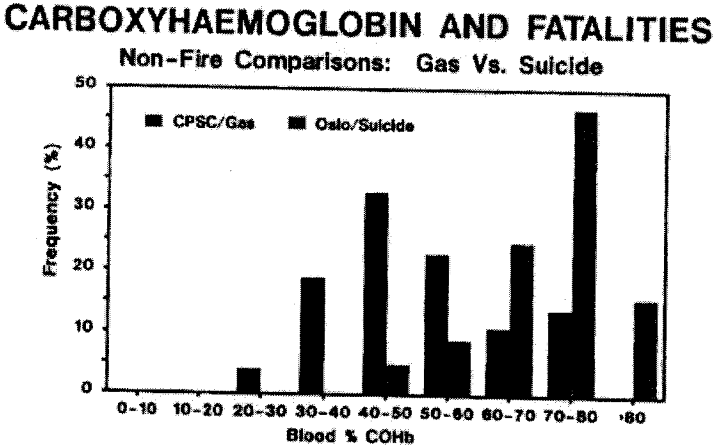


FIG. 3—*COHb distribution for victims in two non-fire CO fatality studies, one accidental (CPSC gas, space heater CO emissions,* [17]*) and one largely automobile suicides (Oslo,* [16]*).*

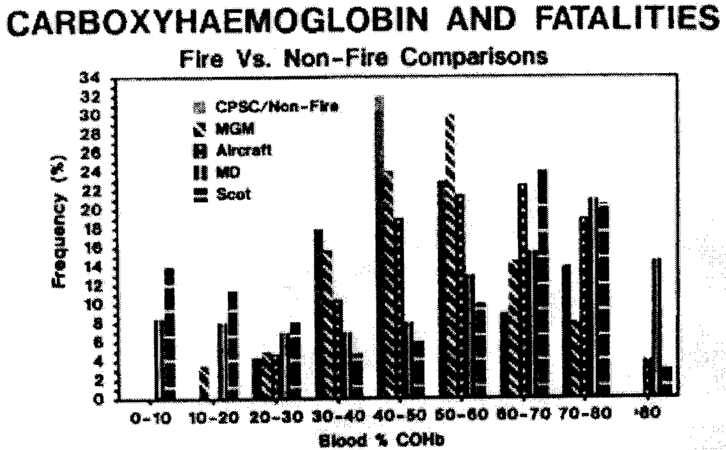


FIG. 4—*COHb distributions for victims in 5 studies, one of which is a non-fire fatality study (CPSC,* [17]*) while the others are fire fatality studies: MGM* [23], *Aircraft* [11], *MD* [19,20], *and Scot* [21,22].

much more extensive than any of the earlier ones, contains roughly twice as many victims of fires as of non-fire CO poisoning. More extensive details of this study will be given elsewhere [*8*].

The cases that were retained for further investigation where those where the COHb level was ≥ 20%, because it was decided that it was very unlikely that victims with lower levels of COHb would have died exclusively of CO poisoning. In this connection it is worth mentioning that smokers can exhibit COHb levels of up to 14% (for example, Ref 25).

Table 3 shows that only ~8% of all the cases in the data base had a known COHb blood level of under 20% saturation, evenly distributed among fire and non-fire cases.

Over 10% of the victims in either data base (fire or non-fire) had a blood COHb level

TABLE 2—*Victim variables included in the USM database.*

1. **Data about the Victim Itself:**
   - age
   - gender
2. **Data about the Incident:**
   - fire/non-fire
   - source of CO
   - data of incident
3. **Data from the Forensic Report**
   - COHb level
   - blood cyanide level
   - blood alcohol
   - presence of drugs
   - survival
   - cause of death
   - verdict

TABLE 3—*Details of USM database.*

	Fire	Non-fire	Unknown	Total
		ALL CASES		
No. of Cases	1203	660	378	2241
% Total	54	29	17	100
% Known source	65	35		100
		CASES WITH KNOWN % COHb LEVELS		
No. of Cases	1037	641	372	2050
% Total	51	31	18	100
% Known source	62	38		100
		CASES WITH COHb % ABOVE 20%		
No. of Cases	961	600	303	1864
% Cases in source	80	91	80	83
% Known source	93	94	81	91

between 20 and 50%. This proportion becomes even bigger when one excludes those victims with alcohol in their blood.

Figure 5 has the age distribution of the fire and non-fire victims in this study. It is clear that, just as was seen in Fig. 1, there is a bimodal distribution for fire fatalities, with most of the victims being either very young or elderly. On the other hand, non-fire victims have a unimodal age distribution, which peaks between 30 and 45, similar to the one shown in Fig. 2. The data discussed earlier have indicated that there is an effect of population characteristics on susceptibility to CO poisoning. Consequently, as expected, the COHb distributions for both sets of data are not identical, with the fire one being centered at a somewhat lower COHb level than the non-fire one (Fig. 6). The difference in age distributions, however, means that this disparity may well be due to a comparison of unequal populations. This will be analyzed in the next section.

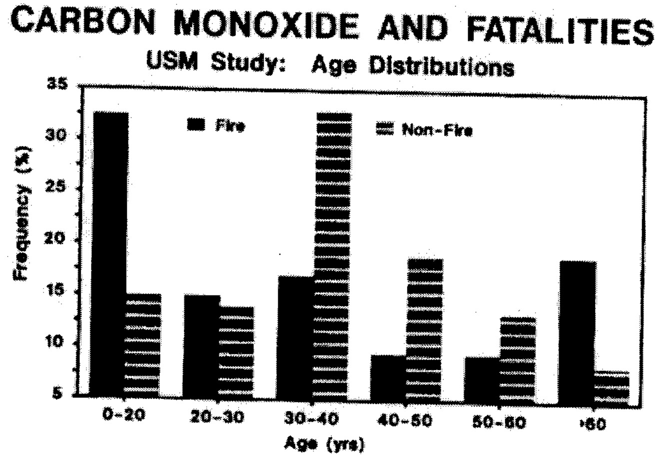


FIG. 5—*Age distributions for victims in the study carried out at the University of Southern Mississippi (USM) on fire and non-fire CO fatalities.*

This portion of the study reinforced the suggestion that CO can kill at COHb saturation levels of well under 50% without requiring an additional toxicant. This can now be considered a firm finding.

Statistical Analysis of Forensic Investigation

A team led by Sara M. Debanne and Douglas Y. Rowland, in the Department of Biostatistics and Epidemiology at Case Western Reserve University (CWRU) analyzed the University of Southern Mississippi data base, by means of a separation of variables. The main variables analyzed separately were: age, alcohol level, presence of drugs and preexisting physical condition, as well as the source of CO. Again, the full set of results will be published elsewhere [*8*], but a summary will be discussed here. The results were very interesting. They showed that the COHb frequency distributions are very similar, once these other factors have been accounted for. Figure 7 shows the distributions for two ethanol-free populations which are very comparable, all fire victims ages 6 to 20 and all non-fire victims above age 6. The similarity of the two curves indicates, or at least suggests very strongly, that CO is clearly, the principal, if not the overwhelming cause of death in fires.

This study suggests that there is generally no need to look for an additional source of lethality in fire atmospheres if the COHb level ranges between 20 and 50%. Since CO alone can account for all deaths, this indicates that the effect of other toxicants in fire atmospheres is invariably small, if not negligible, in the majority of cases. This gives a clear answer now to the first issue to be addressed.

This study also gives a fairly definitive answer to the second issue to be addressed; the populations of fire and non-fire victims are generally very different. Moreover, the fire victim population contains more individuals that are at higher risk of succumbing to carbon

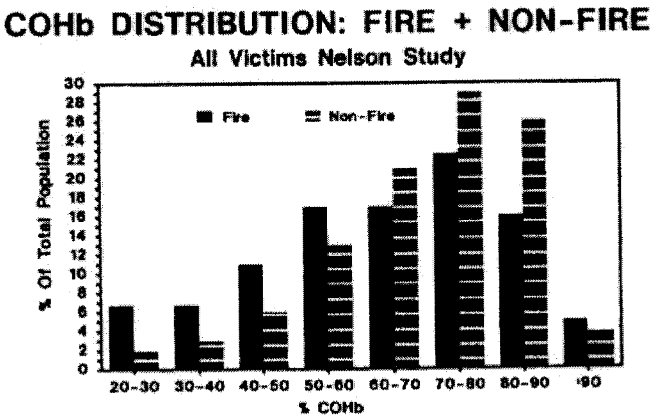
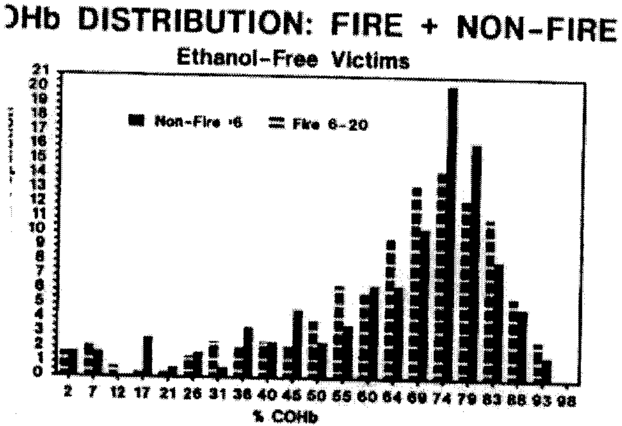


FIG. 6—*COHb distribution for all victims in the study carried out at the University of Southern Mississippi (USM) on fire and non-fire CO fatalities.*



OHb distribution for selected victims (comparable populations) in the study carried out at of Southern Mississippi (USM) on fire (ethanol-free 6 to 20 years old) and non-fire (ethanol- old) CO fatalities.

isoning than does the population as a whole or than does the population that) poisoning in non-fire cases.

stigation on CO victims across time in Cleveland, OH

eam at Case Western Reserve University also created a new data base of CO ; and non-fires. This data base contains all victims of CO poisoning investigated oga County Coroner's office between the years of 1938 and 1979. Cuyahoga iio, is the county surrounding the city of Cleveland. The reason for the choice that this coroner's department was headed by the same man (Dr. Samuel the entire period concerned. The Cuyahoga coroner's office investigated and topsies on the victims of every fire in the county as well as of every case of th and was respected for its high scientific integrity and accuracy. This data ig 2 637 cases, was somewhat different from the USM database. It contained ıs many non-fire victims as fire victims. This makes it the largest data base er on CO and fatalities. Table 4 shows some of the main features of the data e details to be shown elsewhere [8].

wo reasons to carry out this study. The first was to discover whether the which fire victims died have changed over the years and the second was to again, fire and non-fire data.

in the introduction, the modern world, particularly in the United States, pulation with a large number of products made with synthetic materials. were first developed in the 1930s and 1940s, and did not generate a large verall combustible products in use until the 1960s or 1970s. Their relative e in the United States is probably still rising.

nedian level of COHb found each year for the cases in the study is shown. sented as differences with the 1941 value and two curves are presented,

TABLE 4—*Details of CWRU database.*

	Fire	Non-Fire	Unknown	Total
		ALL CASES		
No. of Cases	944	1692	1	2637
% Total	36	64	0.04	100
		CASES WITH KNOWN % COHB LEVELS		
No. of Cases	944	1661	1	2607
% Total	36	64	0.04	100
		CASES WITH COHB % ABOVE 20%		
% Cases	93	94		
		SOURCE OF CO IN NON-FIRE CASES		
Automobile exhaust		1391 cases (82%)		
City gas		270 cases (16%)		
Other		31 cases (2%)		

one for fire and one for non-fire data. The results show a "U" shaped curve, for both sets of data. In other words, the COHb levels reached a minimum around 1960 and then started rising again. This pattern occurs in a parallel fashion for both fire and non-fire cases. Thus, it must be unrelated to the content of the fire atmospheres since the content of non-fire atmospheres is clearly unrelated to the composition of materials that burn. In other words, it appears that the fact that recent fire atmospheres have a much higher content of combustion products generated by the burning of synthetic materials this has caused no effect on the toxicity of the corresponding smoke.

Although it is not possible at this stage to answer unequivocally what causes the unusual change in population susceptibility to CO, this portion of the work has answered the third

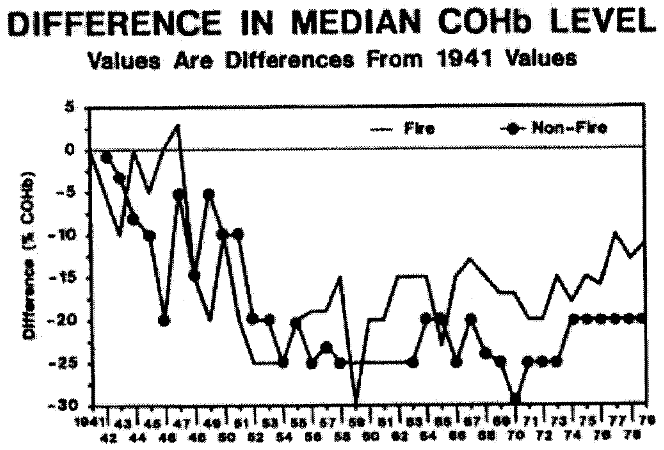


FIG. 8—*Differences in median yearly COHb values between 1941 and all subsequent years up to 1979, in the Case Western Reserve University study, for fire and non-fire CO fatalities.*

issue that was to be addressed: the effect of new materials on the toxicity of fire atmospheres appears to be negligible.

The separation of variables shows some remarkable similarities between this study and the previous one. That is, the populations of fire and non-fire victims are very different, and this difference can be seen to affect their sensitivity to CO poisoning.

Study of Fire Retarded and Non-Fire Retarded Products

Effect of Study on Usefulness of Small-Scale Tests

A study was carried out by the Center for Fire Research at the National Institute for Standards and Technology (NIST) for the Fire Retardant Chemicals Association [26]. This involved burning 5 sets of products in fire retarded and non-fire retarded versions: TV cabinets, business machines, upholstered chairs, circuit boards, and electrical cables.

The small-scale techniques used were the cone calorimeter and the NBS cup furnace smoke toxic potency test. In those apparatuses the individual materials were tested as mock-up combinations. The medium-scale technique used was the furniture calorimeter, where the entire products were tested individually. The full-scale test used involved combining all five products together in a single room.

The results indicated that the fire retarded products were safer than the non-fire retarded products, indicating that improved fire performance (by whatever means it is achieved) leads to lower fire hazard. The results showed that, in the full-scale tests:

- FR materials lost less than half the mass of non-fire retarded ones.
- FR materials released ¼ the heat of non-fire retarded ones.
- FR materials generated ⅓ of the toxic gases of non-fire retarded ones.
- FR and non-fire retarded materials generated similar smoke obscuration.

The results also indicated that the cone calorimeter could be used to predict full-scale ignitability, heat release, and flame spread. It could not be used, however, to predict release of CO. The authors found that the bench-scale tests were expected to give adequate yields of gases other than CO, but will almost inevitably give too low yields of CO. Thus, small-scale tests would be expected to be biased in favor of non-CO species, meaning that they exaggerate the relative importance of such non-CO species.

The production of combustion gases in small-scale tests is, thus, heavily influenced by the chemistry of the materials being burned. However, the production of CO in large-scale fire tests, and thus presumably in real fires, is only somewhat influenced by the chemical properties of the substance being burned.

Moreover, the CO production in large-scale fires appears to be much more influenced by the availability of oxygen in the fire. This, in turn, is affected by variables such as geometry, ventilation, configuration, turbulence, and mixing. Therefore, the authors conclude that the use of any less-than-room-sized tests for making CO predictions has to be deferred until these oxygen supply variables have been sorted out.

This indicates that the toxicity of the atmosphere in real fires is likely to be little affected by the type of materials causing the fire. The CO levels in large-scale fires are governed by the number and size of openings, the mass loading, and the burning characteristics (that is, ignitability, flame spread, and heat release) of the fuels.

Rough algorithms now exist for assessing the CO yields for various large-scale fire scenarios. These are probably not yet adequate for widespread use, but they indicate the way forward to assess the toxic hazard associated with any large-scale fire scenarios. Further studies are needed before these can be considered well documented [27].

Experience also shows that in full-scale tests where full flaming room involvement is achieved (those fires that cause the majority of fire fatalities) there is ventilation control and the oxygen levels get very close to zero. Small-scale tests are rarely carried out under conditions of low oxygen and high heat flux, because flaming combustion does not occur under such conditions.

Consequently, it is now possible to give answers to the last two issues to be investigated in this study. The atmospheres in those large-scale fires that cause most lethality have a toxicity determined mostly by the concentration of CO and by a low oxygen content. The yield of this CO is almost independent of the type of materials being burned.

Toxic potency of smoke is a quantitative expression which relates the concentration of smoke and the exposure time to the achievement of an adverse effect, usually lethality, on a test animal (E 176). It has to be stressed that the toxic potency of smoke is heavily dependent on the conditions under which the smoke is generated, which affect both the quality and the quantity of smoke.

During the 1970s and early 1980s, many small-scale tests for smoke toxic potency were developed [6]. These tests differ in many respects, including: fire model, being static or dynamic, use of animals or analytical tools, animal model for bioassay, and end point. Partly due to all these differences, the tests lead to tremendous ranking variations for the smoke of various materials. This was illustrated in a study of the toxic potency of 14 materials by 2 methods which ranked one material most toxic by one protocol and least toxic by the other protocol. Although neither of those protocols is in common use now, this work illustrates some of the inevitable problems of such tests.

The toxicity of smoke is a function of its composition, which depends, in turn, both on the fuel and the combustion mode. Thus, the composition of the smoke generated by any individual material varies broadly from test to test, and so will its toxic potency. In fact, the toxic potency of the smoke of most ordinary materials (whether natural or synthetic) is very similar [6]. Thus, relative smoke toxic potency rankings depend on the exact composition of the smoke being tested, that is, the small-scale test protocol, and are of little interest from the viewpoint of fire hazard assessment.

Moreover, small-scale smoke-toxicity tests give inadequately low yields of CO and adequate yields of other toxicants. Thus, such tests require post computational correction for CO before their results are directly relevant to fire hazard in the real fires that cause most fire deaths. This correction for CO yields has been addressed in recent toxicology work [28], where it has been applied to the results of full-scale and small-scale tests using rats as animal models, with an excellent outcome.

From the point of view of fire hazard assessment, the work described here puts into perspective the importance of one of the elements of fire hazard assessment, namely smoke toxicity. It shows that care must be taken when using toxicity data as input for fire hazard assessment.

Conclusions

This paper has addressed the five fire hazard issues presented in the introduction, which are:

(1) (a) The toxicity of fire atmospheres is determined to a very large extent by the amount of CO; the contribution of other toxicants is usually very small. (b) The lethal level of CO is heavily dependent on the individual concerned, and the 50% COHb threshold normally mentioned is not a realistic value. Both fire atmospheres and non-fire atmospheres containing mainly CO can cause lethality due exclusively to CO at COHb levels of 20%.

(2) The population of individuals who die in fires has a bimodal distribution, with an excess of very young and very old and infirm people, while that of people who die in automobile exhaust CO exposures has a unimodal distribution. Thus, it appears that fire victims are significantly more sensitive to CO poisoning than non-fire victims and may tend to die at lower COHb levels.

(3) The replacement of large amounts of natural and traditionally used materials by man-made materials among the normal products in everyday use has made no difference to the toxicity of fire atmospheres.

(4) The CO concentrations in the atmospheres of large-scale fires are determined by the oxygen availability, ventilation, mass loading, and other such variables, but are very minimally affected by the chemical composition of the fuels.

(5) Small-scale tests give excessively low CO yields while they can predict adequately the concentrations of other combustion products. Thus, such tests cannot be used to predict toxic fire hazard for the fire scenarios of greatest interest, ventilation controlled flashover fires, which cause most of the fire fatalities. The use of post computational correction for CO concentration, which is now becoming available, is required to make these tests relevant to the critical fire scenarios. They can only legitimately, however, be used as a part of a fire hazard assessment.

Acknowledgment

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GBH Attachment 8

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FIRE AND MATERIALS, VOL. 17, 79–90 (1993)

Comparison of the Smoke Toxicity of Four Vinyl Wire and Cable Compounds Using Different Test Methods

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Four vinyl wire and cable materials were tested using five smoke toxic potency test methods: the NBS cup furnace test (in its flaming and non-flaming modes), the NIST radiant test, the NIBS IT_{50} test (also using the radiant apparatus) and the UPITT test. One of the materials is a standard poly(vinyl chloride) (PVC) flexible wire and cable material, used commercially for wire insulation. The three other materials tested represent a new family of vinyl thermoplastic elastomer alloys, which are advanced materials with good fire performance, particularly in terms of heat release and smoke obscuration. It was found that the smokes from all four materials are similar in terms of their toxic potencies, and that they are all within the 'common' range of toxic potency found. In particular, the toxic potencies of the smoke from the new vinyl thermoplastic elastomer alloys are not significantly different from those of other traditional vinyl wire and cable compounds. The results of the tests were also interpreted in terms of the toxicities and concentrations of the individual gases emitted. The fractional effective dose of the toxicants analysed was sufficient to account for the toxicity of the smoke for the NBS cup furnace and the NIST radiant test. It was not able to account for the toxicity found in the UPITT test. The adequacy of the test protocols themselves was also investigated. It was found that the UPITT and the NIBS IT_{50} method are inadequate for measurement of smoke toxicity. It was also found that the NIST radiant test protocol is the one most likely to lead to the smallest amount of future testing.

INTRODUCTION

A number of smoke toxicity test methods have been used over the years to investigate the toxic potency of the smoke from materials.[1–6] A few years ago a comparative investigation was made[7] of four test methods: the UPITT test,[3] the NBS Cup furnace test (flaming and non-flaming mode)[1] and the radiant apparatus, in the protocol suggested by Dr Stephen Packham.[4] The five materials investigated were all wire and cable compounds: four poly(vinyl chloride) (PVC) materials and a nylon compound. The PVC materials were a conventional jacket compound, a conventional insulation compound, and two jacket compounds with progressively higher levels of acid-retention catalysts. It was found that the smokes from the materials were all of 'common' toxic potency. It was also found that, although there are some serious deficiencies associated with using any such tests for making fire-safety decisions, the UPITT test was particularly flawed. Since then, further information on the inappropriateness of the UPITT test method, particularly for predictions or use in fire hazard analyses, has been forthcoming.[8,9] However, unfortunately, the test is being used for regulatory purposes both in the state of New York and in the city of New York (although the latter is under revision).

The fire performance and the smoke toxicity of PVC materials have been the focus of numerous investigations and allegations. Some of the basic facts have been established years ago and published in textbooks.[10] More details on the overall fire performance and smoke toxicity of PVC and its compounds have been published in a recent review elsewhere.[11]

Recently, a new family of vinyl materials has been developed—vinyl thermoplastic elastomer alloys. These materials have excellent fire performance, in terms of both heat release and smoke release.[12–14] In order to investigate whether the smokes from these materials were in the 'common' range, just as those of the more traditional materials had been found to be, they were also subjected to several toxic potency tests. Three of the tests chosen and one of the materials chosen were a repeat of the earlier work, for control. The tests repeated were the NBS cup furnace (flaming and non-flaming) and the UPITT test, and the material retained was the standard insulation. The additional tests chosen were the latest variants of the radiant equipment: the NIST/SwRI toxicity test[15,16] and the NIBS IT_{50} test.[17–20] The three additional materials tested were all different vinyl thermoplastic elastomer alloys.

EXPERIMENTAL

Test methods

The test methods that were evaluated in this study are as follows: the National Bureau of Standards (NBS, today the National Institute for Standards and Technology) Cup Furnace Test Method (including both flaming and non-flaming modes),[1] the University of Pittsburgh (UPITT) Test Method[3] and the NIST/SwRI[15,16] and NIBS IT_{50}[17] variants of the Radiant Furnace Test Method. None of these test methods have become consensus standards.

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NBS Cup Furnace Test Method The apparatus of the NBS Cup Furnace Test Method consists of a cup furnace interfaced to the floor of a poly(methyl methacrylate) exposure chamber, with a volume of approximately 200 l (inside dimensions 1.22 × 0.37 × 0.45 m). The furnace is operated at a fixed temperature, at 25°C below or above the pre-determined auto-ignition temperature, to produce either non-flaming or flaming combustion, respectively. In each experiment, six male rats are exposed, in the head-only mode, for 30 min to the combustion atmosphere. A series of experiments with varying amounts of a material are conducted to establish a concentration–response lethality relationship and to derive an LC_{50} value by standard methods[21,22] for each of the two combustion modes. The LC_{50} value is an estimate of the quantity of material that should cause death of 50% of the animals during the 30-min exposure and a 14-day post-exposure period. This mass of material is divided by the chamber volume and the LC_{50} is expressed in units of mg l^{-1}.

University of Pittsburgh (UPITT) Test Method The apparatus of the UPITT method consists of a muffle furnace connected to a glass animal exposure chamber by means of a quartz tube. Weighed samples of material are thermally decomposed in the furnace, the temperature of which is increased at a constant rate of 20°C min^{-1}. The products are carried through the furnace by an air stream (at 11 l min^{-1}) and diluted and cooled with additional air (to 20 l min^{-1} total flow) before entering the exposure chamber. Gas analyses are made in the exposure chamber. In each experiment four male mice are exposed, in the head-only mode, to the combustion atmosphere for 30 min, starting from the time of a 1.0% weight loss of the material. The animals are maintained for a 10-min post-exposure period. At least four experiments are conducted in order to derive an LC_{50} value by the Weil method.[23] The LC_{50} is an estimate of the amount of material required to cause death of 50% of the animals during the 30-min exposure and 10-min recovery period, expressed in g.

Radiant Furnace Test Method The apparatus of the Radiant Furnace Test Method uses the same exposure chamber as the NBS Cup Furnace, but a radiant heater system is used to decompose the material thermally. The radiant heater system consists of four tubular quartz tungsten-filament lamps mounted in parabolic reflectors and directed into a quartz combustion cell. The combustion cell is a horizontal quartz tube with a 130 mm inside diameter and 324 mm long. It is sealed at one end and has a large standard taper outer joint at the other end. A sealed inner joint serves as a removable plug for the open end. The top of the cell has a rectangular opening parallel to the axis of the cylinder with a 'collar' which allows it to fit securely into a stainless steel chimney. The chimney is 30 × 300 mm in inside dimensions and 300 mm high, and is divided into three channels by stainless steel dividers. The effect of these channels is to create stable convective smoke flows back and forth between the combustion and exposure chambers. The system was used at a heat flux of 50 kW m^{-2} (±20%) to expose a coated wire sample. The use of a spark igniter promoted the flaming combustion of the material. The animals (rats) were exposed for 30 min and were continued to be observed for 14 days' post-exposure.

In the *NIST/SwRI protocol*[15,16] the sample, a coated wire, was exposed for 10 min before the smoke shutter between the combustion and exposure chambers was closed. In order to obtain the LC_{50} the length of wire exposed was changed, but the thickness of the wire coating was maintained the same throughout. The LC_{50} obtained was measured in terms of length of wire, using the same statistical protocol as for the NBS Cup Furnace Test Method.[21,22]

In the *NIBS* IT_{50} *protocol*, the coated wire was exposed for a short irradiation time, searching for the minimum irradiation time which would lead to the lethality of 50% of the test animals in 30 min + 14 days. The amount of coated wire exposed was a quantity sufficient to fill the 76 mm × 127 mm (3 in × 5 in) sample holder. The communication between the two chambers was closed at the end of the irradiation time. The sample loading was not changed.

Materials

All four test materials used were vinyl wire and cable coating compounds and they are BFGoodrich proprietary materials. One of them, Geon® 8884, FR natural 022, is a standard insulation (SI), a standard, commercially available 105°C rated compound used for the insulation of building wire; it contains moderate amounts of flame retardants. The other three are vinyl thermoplastic elastomer alloys (VTEs), two of which are commercial products: Flexel® 1000, Flexel® 1010 (VTE 740) and VTE 741, designed as jacketing materials. They all contain PVC, as well as a number of other ingredients, and they have excellent fire performance.[12–14] Flexel® 1000 and Flexel® 1010 have been designated VTE 1 and VTE 2, respectively, in an earlier study of fire performance.[14] VTE 741 is an example of another family of VTEs, but is not a commercial compound.

RESULTS AND DISCUSSION

Table 1 presents the overall toxic potency results for all materials: the LC_{50} for the sample mass loaded, with its corresponding confidence limits, the LC_{50} for smoke (i.e. for mass lost) and the LCt_{50} for the sample mass loaded (i.e. the product of the LC_{50} and exposure time). In the case of the radiant apparatus, the samples exposed were coated wires; therefore the LC_{50} values in terms of length were also converted to LC_{50} values on the basis of mass, knowing the length per unit mass of plastic. In the case of the NIBS IT_{50}, the results were expressed in terms of LC_{50} for smoke only, because sample LC_{50} values are not valid for this method (i.e. same initial loading for all experiments on the same product). Figure 1 shows graphically the results, of the LC_{50} values, based on mass charged, for all the materials in the static tests. Mass loss LC_{50} might also have been shown, but mass charged data are more useful, because materials are sold with additives.

For the UPITT method, a combustion time was estimated from the curves of mass loss and CO evolution as functions of temperature (converted to time). The combustion time began at the point of 1% mass loss and

Table 1. General toxic potency for all materials

		SI	Flexel 1000	Flexel 1010	VTE 741
NBS F					
LC_{50}	mg l^{-1}	28.2	28.2	34.3	32.1
Conf Limits	mg l^{-1}	23.8–31.0	23.8–33.9	30.8–38.3	[a]
Smoke LC_{50}	mg l^{-1}	26.7	26.2	28.0	26.1
Sample LCt_{50}	mg min l^{-1}	847	847	1030	964
NBS NF					
LC_{50}	mg l^{-1}	26.9	21.9	38.1	34.7
Conf Limits	mg l^{-1}	22.3–33.2	18.3–28.8	35.3–41.3	29.8–38.8
Smoke LC_{50}	mg l^{-1}	23.6	20.3	30.7	28.0
Sample LCt_{50}	mg min l^{-1}	808	658	1143	1042
NIST Radiant					
LC_{50}	cm	172.8	103.2	220.5	189.5
Conf Limits	cm	[a]	89.0–137.2	[a]	162.8–223.8
LC_{50}	mg l^{-1}	29.2	18.2	45.9	35.8
Conf Limits	mg l^{-1}	[a]	15.7–24.2	[a]	30.7–42.2
Smoke LC_{50}	mg l^{-1}	26.7	16.4	34.2	26.5
Sample LCt_{50}	mg min l^{-1}	875	546	1378	1073
NIBS IT_{50}					
IT_{50}	min	<2	<2	<2	<2
LC_{50} (loss)	mg l^{-1}	36.6	29.0	29.4	25.6
UPITT					
LC_{50}	g	3.0	8.5	12.5	10.0
Conf Limits	g	1.9–4.9	7.6–9.5	10.1–15.4	7.7–13.0
LC_{50}	mg l^{-1}	7.5	20.2	26.3	18.2
Smoke LC_{50}	mg l^{-1}	7.0	18.7	22.0	14.7
Sample LCt_{50}	mg min l^{-1}	152	423	625	500

[a] Not determined.

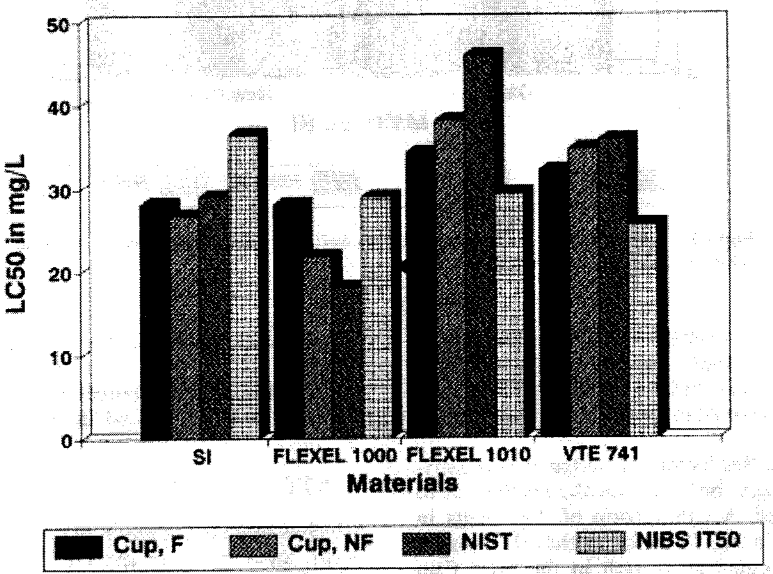

Figure 1. Toxic potencies of all materials using the four static test methods.

ended when the CO evolution fell to zero. The total volume was calculated as the product of the (constant) air flow (20 l min^{-1}) and the combustion time. The LC_{50} values in concentration units (mg l^{-1}) were calculated from the ratio of the LC_{50} in mass units (g) and the total volume.

The results indicate that the toxic potency of the smoke from these new materials is in the same order of magnitude as that of the standard vinyl materials (SI and SJ) tested in the earlier series of tests[7] (Table 2). David Purser has reported that the majority of common materials have toxic exposure dose (i.e. LCt_{50}) values of between 75 and

Table 2. Toxic potencies from previous data[7]

		SI	SJ	EX B	EX C	Nylon
NBS F						
LC_{50}	mg l^{-1}	35.0	29.6	60.8	159.0	49.0
Conf Limits	mg l^{-1}	31.3–39.2	22.7–37.4	53.0–70.0	127.0–199.0	42.0–57.0
NBS NF						
LC_{50}	mg l^{-1}	25.0	31.6	55.7	59.9	>100
Conf Limits	mg l^{-1}	20.0–32.4	27.8–36.1	44.5–66.0	52.5–64.9	
Radiant						
LC_{50}	mg l^{-1}	33.4	53.1	86.2	149.0	36.7
Conf Limits	mg l^{-1}	29.5–56.1	49.6–55.9	79.0–93.5	122.0–184.0	21.6–45.4
UPITT						
LC_{50}	g	5.6	5.5	10.0	21.6	5.3
Conf Limits	g	3.9–8.2	4.2–7.1	5.1–19.4	11.1–42.0	4.7–6.0
LC_{50}	mg l^{-1}	14.0	13.8	25.0	54.0	13.3

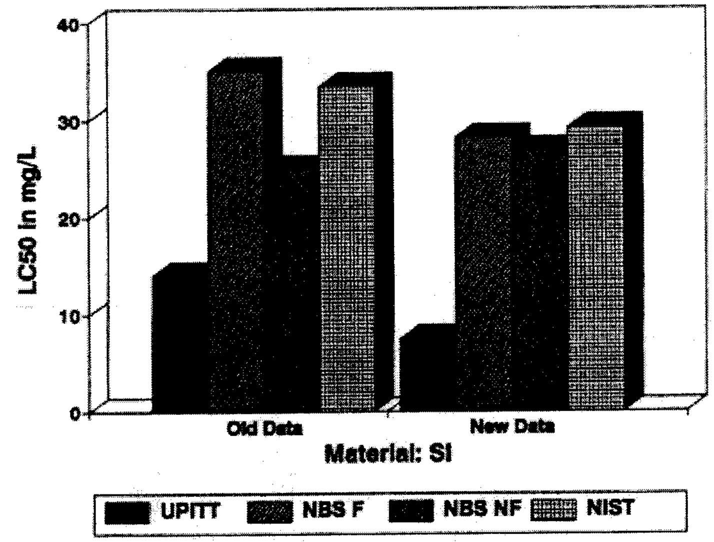

Figure 2. Comparison of the toxic potency values for the standard insulation material as measured in reference 7 and in this work.

3750 mg min l^{-1}.[24] This corresponds, at an exposure time of 30 min, to a smoke toxic potency range of 2.5 to 125 mg l^{-1}. Thus, the toxic potency of this smoke could therefore be considered to be in the 'common' range of all materials.

Having established this 'common' range, it is important to try to understand the effects on the results due to the test protocol used. A comparison of the results in Tables 1 and 2, and in Fig. 2, indicates that the control material, SI, has repeated fairly well in the NBS Cup Furnace Test (both flaming and non-flaming modes) and in the Radiant Test (even though the new test was performed slightly differently from the old one, and in a somewhat modified apparatus). The differences in LC_{50} between the current test series and the previous one are (Fig. 3):

NBS Cup Furnace (flaming)	+24%
NBS Cup Furnace (non-flaming)	−7%
Radiant	−14%

all of which could be considered within experimental error.

However, the differences in LC_{50} between the two series of tests performed in the UPITT test are much larger:

UPITT	−87%

which is outside the realm of an acceptable experimental error. Such errors in the UPITT test are not unusual. Broad variations in LC_{50} have also been found even for the reference material used in the UPITT test.[9] Moreover, in the case of various woods, it has been found that the UPITT test can yield different LC_{50} values for the same material, depending on the amount of sample initially used.[8] Therefore, the results obtained in the UPITT test are of questionable utility and will not be analysed further.

The NIBS IT_{50} test method gave very low irradiation times for lethality. This is an inevitable consequence of

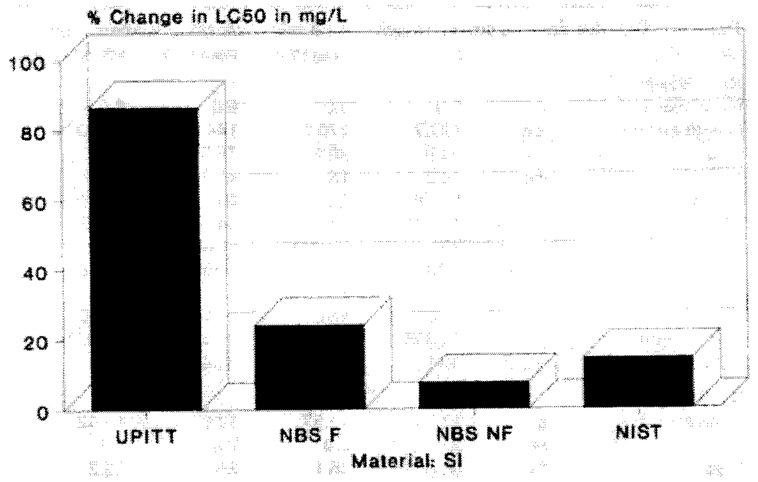

Figure 3. Fractional differences in toxic potency between values in reference 7 and this work.

Table 3. Detailed data on smoke toxicity of all materials in NBS Cup Furnace Test

(See note)		SI	Flexel 1000	Flexel 1010	VTE 741
NBS F					
Mass charge	g	6.0	6.0	6.0	6.0
Loss	%	94.7	92.8	83.3	83.7
LC_{50}	mg l^{-1}	28.2	28.2	34.3	32.1
Deaths		4 in 6	4 in 6	4 in 6	4 in 6
CO Ct	ppm min	108 723	106 275	74 020	97 479
HCl Ct	ppm min	39 000	73 300	47 724	41 000
Pk CO	ppm	3 923	3 957	2 778	3 577
Pk CO_2	%	0.1	0.2	0.1	0.1
Pk HCl	ppm	2 700	4 600	3 486	2 700
CO yield	g g^{-1}	0.15	0.15	0.11	0.15
NBS NF					
Mass charge	g	6.0	5.4	6.0	6.0
Loss	%	87.2	92.4	81.3	80.5
LC_{50}	mg l^{-1}	26.9	21.9	38.1	34.7
Deaths		3 in 6	4 in 6	0 in 6	1 in 6
CO Ct	ppm min	15 838	53 823	34 412	38 352
HCl Ct	ppm min	63 430	56 700	50 700	35 782
Pk CO	ppm	1 131	2 574	2 083	2 049
Pk CO_2	%	NA	NA	0.2	0.1
Pk HCl	ppm	3 700	3 500	2 940	2 200
CO yield	g g^{-1}	0.02	0.08	0.05	0.06

Note:
One run was chosen for these data, at roughly the same loading for all materials.

one of the inadequacies of this test, some of which have been discussed at length elsewhere:[18–20] the fact that it does not assess the whole smoke from the material being burnt but only the initial fraction (approximately 10%). This is incompatible with its intent of addressing post-flashover fires, where the whole contents of the room are burning. However, it is interesting that the results of this test, expressed in terms of the smoke from all four materials, are in the 'common' range of toxic potency, as discussed above.

Additional data are presented in Tables 3–5 on all materials using the various tests. The tables contain gas analysis, mass loss and animal lethality data at comparable mass charges. The mass charge chosen is as close as possible to that leading to an LC_{50} value of lethality, for at least one of the tests. The tables also contain the CO yield values, all of which are much lower than the value of 0.2 g g^{-1},[25] which would correspond to post-flashover fires (roughly 70% of US fire fatalities are characterized as being associated with a post-flashover fire[15–16] (see Fig. 4)). The CO yields are particularly low in the NIBS IT_{50} variant of the radiant apparatus, in the UPITT test and in the NBS Cup Furnace Test, non-flaming mode. They are highest in the NBS Cup Furnace, flaming mode (which is actually a flaming mode followed by non-flaming for many specimens). In Table 6 are the same

Table 4. Detailed data on smoke toxicity of all materials using Radiant Test

(See note)		SI	Flexel 1000	Flexel 1010	VTE 741
NIST Radiant					
Mass charge	g	6.0	6.0	6.0	6.0
Length charge	cm	177.7	170.0	144.0	159.0
Loss	%	84.0	88.8	76.8	75.0
LC_{50}	mg l^{-1}	29.2	18.2	45.9	35.8
Deaths		1 in 6	6 in 6	0 in 6	1 in 6
CO Ct	ppm min	70 334	43 664	34 182	39 694
HCl Ct	ppm min	30 330	90 700	45 400	29 000
Pk CO	ppm	2 701	1 764	1 398	1 618
Pk CO_2	%	0.5	1.1	1.3	0.5
Pk HCl	ppm	2 500	4 800	2 700	2 000
Mass/length	g cm^{-1}	0.0338	0.0353	0.0417	0.0377
CO yield	g g^{-1}	0.11	0.06	0.06	0.07
NIBS IT_{50}					
Mass charge	g	12.53	12.57	14.85	13.42
IT	min	2.0	2.0	2.0	2.0
Loss	%	60.8	46.1	39.5	38.2
IT_{50}	min	<2	<2	<2	2–4
LC_{50} (loss)	mg l^{-1}	36.6	29.0	29.4	25.6
Deaths		6 in 6	6 in 6	6 in 6	3 in 6
CO Ct	ppm min	108 000	1 268	20 300	9 800
HCl Ct	ppm min	84 300	147 500	82 000	60 900
Pk CO	ppm	3 980	56	759	376
Pk CO_2	%	2.9	1.0	1.4	1.1
Pk HCl	ppm	4 500	8 500	4 600	3 200
Mass/length	g cm^{-1}	0.0338	0.0353	0.0417	0.0377
CO yield	g g^{-1}	0.11	0.002	0.03	0.01

Table 5. Detailed data on smoke toxicity of all materials using UPITT Test

(See note)		SI	Flexel 1000	Flexel 1010	VTE 741
Mass charge	g	6.4	6.4	8.0	6.4
Loss	%	94.2	91.4	81.5	81.6
LC_{50}	g	3.0	8.5	12.5	10.0
Deaths		3 in 4	0 in 4	0 in 4	0 in 4
CO Ct	ppm min	38 558	23 774	20 657	25 367
HCl Ct	ppm min	33 600	39 100	26 100	18 800
Pk CO	ppm	4 310	3 833	4 773	3 979
Pk CO_2	%	0.7	2.4	3.4	2.7
Pk HCl	ppm	8 492	10 396	6 462	6 876
LC_{50}	mg l^{-1}	7.5	20.2	26.3	18.2
CO yield	g g^{-1}	0.10	0.06	0.05	0.07

Note.
One run was chosen for these data, at roughly the same loading for all materials.

results for the materials tested in the previous series on smoke toxicity testing of vinyl wire and cable compounds.[7] The trends do not differ from those in the current series.

Using the gas analysis and mass loss information and the lethal potencies for HCl and CO,[15] which are the common toxicants for PVC smoke,[11,26–27] it is possible to calculate a simple fractional effective dose (FED). It is also possible to calculate the fractional effective dose corresponding to CO alone (FED CO), which is of interest since CO is known[9,25,28–30] to be the principal toxicant in most real fires (post-flashover, with ventilation control). These data are presented in Tables 7 and 8, for the new set and the previous set of materials, respectively. Under the conditions of the NBS Cup Furnace Test, flaming mode, the major toxicant in all four of these compounds is clearly CO. However, under the conditions of the NBS Cup Furnace Test, non-flaming mode, and under those of the Radiant Test, the relative contribution of HCl is greater than that of CO for some materials and smaller for others.

In view of the fact that the yield of CO in flashover fires (with ventilation control) is estimated to be 0.2 g g^{-1},[15–16] it is possible to calculate a corrected LC_{50}, which takes into account the value to be obtained if the CO yield had been that corresponding to a flashover fire. The results in Tables 7 and 8 indicate that this correction will not affect the vinyl materials excessively, compared to the LC_{50} values given in Tables 1 and 2, respectively.

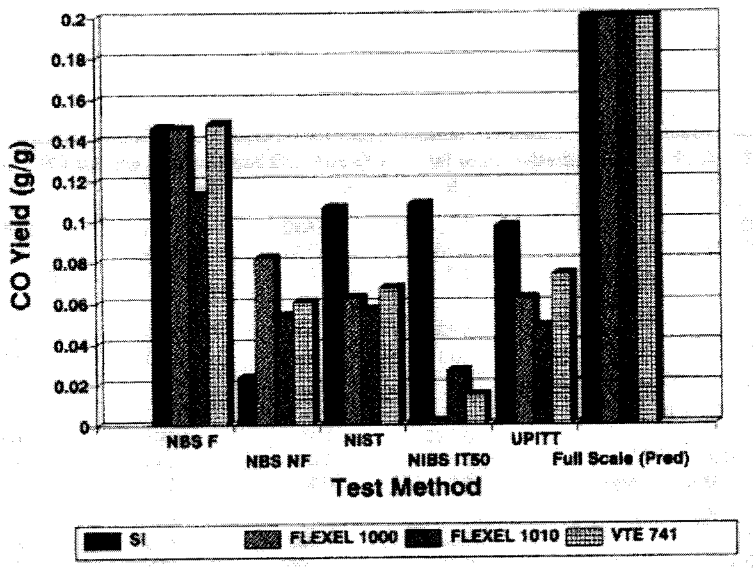

Figure 4. Carbon monoxide yields for all materials, in all tests, close to the LC_{50} loading.

Table 6. Detailed data on smoke toxicity of all old materials

(See note)		SI	SJ	EX B	EX C	Nylon
NBS F						
Mass charge	g	5.0	10.0	14.0	14.0	14.0
Loss	%	91.6	81.5	64.6	57.1	98.4
LC50	mg l^{-1}	35.0	29.6	60.8	159.0	49.0
Deaths		5 in 6	6 in 6	6 in 6	0 in 6	6 in 6
CO Ct	ppm min	75 540	97 500	102 090	65 850	45 180
HCl Ct	ppm min	51 270	67 050	16 500	420	1 086
CO yield	g g^{-1}	0.13	0.09	0.09	0.06	0.02
NBS NF						
Mass charge	g	7.0	7.0	14.0	14.0	20.0
Loss	%	89.1	79.7	53.8	45.9	32.9
LC50	mg l^{-1}	25.0	31.6	55.7	59.9	100.0
Deaths		6 in 6	5 in 6	5 in 6	6 in 6	0 in 6
CO Ct	ppm min	31 230	21 600	18 960	18 330	5 340
HCl Ct	ppm min	90 120	70 800	39 540	14 550	30
CO yield	g g^{-1}	0.04	0.03	0.02	0.02	0.01
Radiant						
Mass charge	g	7.0	14.0	14.0	20.0	7.0
Loss	%	93.4	82.8	65.6	55.5	99.9
LC50	mg l^{-1}	33.4	53.1	86.2	149.0	36.7
Deaths		4 in 6	6 in 6	0 in 6	1 in 6	2 in 6
CO Ct	ppm min	117 240	168 270	99 810	106 440	51 840
HCl Ct	ppm min	57 000	3 000	1 200	600	1 923
Co yield	g g^{-1}	0.14	0.11	0.08	0.07	0.06
UPITT						
Mass charge	g	6.3	7.1	8.3	12.0	8.0
Loss	%	94.0	85.0	64.0	47.0	99.0
LC50	g	5.6	5.5	10.0	21.6	5.3
Deaths		4 in 4	4 in 4	4 in 4	1 in 4	4 in 4
CO Ct	ppm min	22 001	31 014	18 811	19 354	26 600
HCl Ct	ppm min	20 280	45 030	2 880	420	5 853
LC50	mg l^{-1}	14.0	13.8	25.0	54.0	13.3
Co yield	g g^{-1}	0.06	0.08	0.05	0.05	0.04

Note:
One run was chosen for these data, at roughly the same loading for all materials.

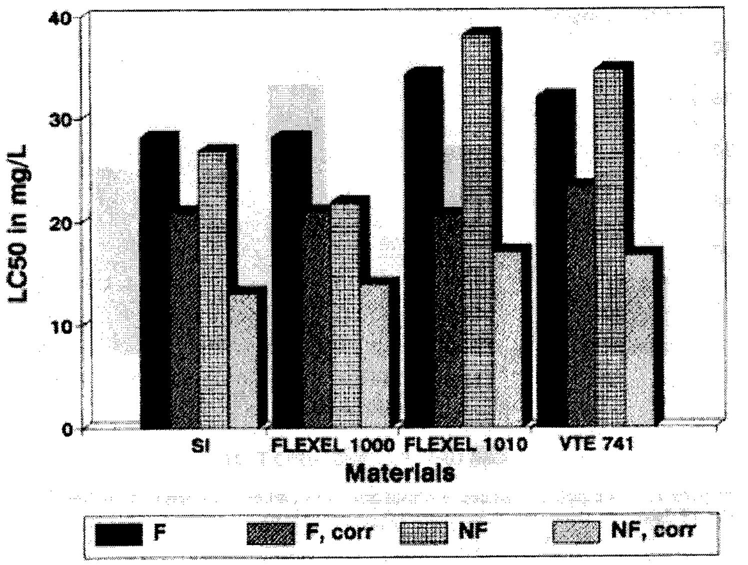

Figure 5. Toxic potency values, without and with carbon monoxide correction for the NBS Cup Furnace Tests.

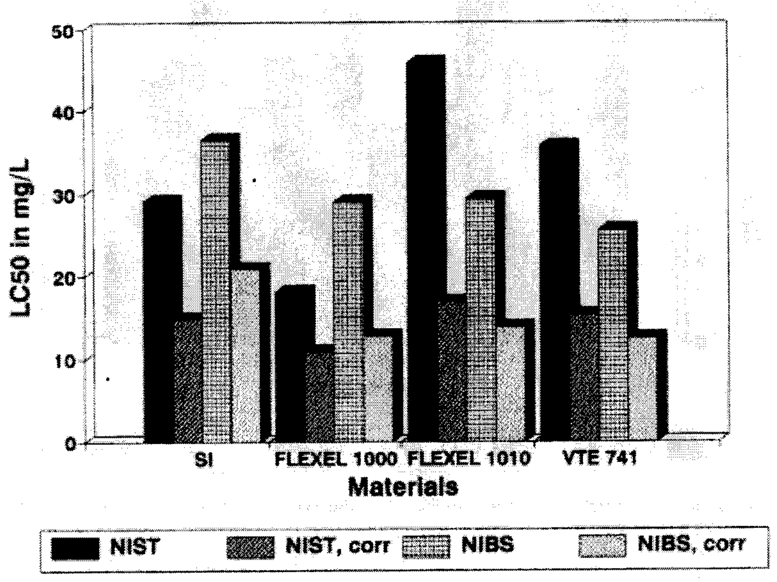

Figure 6. Toxic potency values, without and with carbon monoxide correction for the Radiant Furnace Tests.

Figures 5–7 plot the effect of the CO correction, as indicated in Table 7, on the LC_{50} values in each of the smoke toxicity tests used. In none of the cases is the correction as much as a factor of 2 from the original value. Figure 8 shows the effect of this CO correction on the results of all tests in a static apparatus, as presented in Fig. 1.

The FED can also be calculated using the formula developed by NIST,[15–16] with the added effects of oxygen depletion and of carbon dioxide on the toxic potency:

$$\mathrm{FED}=\frac{m(\mathrm{CO})}{(\mathrm{CO_2})-b}+\frac{(\mathrm{HCN})}{LC_{50}\mathrm{HCN}}+\frac{(\mathrm{HCl})}{LC_{50}\mathrm{HCl}}+\frac{21-(\mathrm{O_2})}{21-LC_{50}\mathrm{O_2}} \quad (1)$$

The constants to be used in Eqn (1) are:

m:	−18	Units: 1/ppm
b:	122000	Units: ppm
LC_{50}HCN:	200	Units: ppm

Table 7. Fractional effective doses for the CO and HCl combinations and for CO only

		SI	Flexel 1000	Flexel 1010	VTE 741
NBS F					
FED		1.139	1.430	0.966	1.076
FED CO		0.788	0.770	0.536	0.706
LC_{50} CO corr	mg l^{-1}	21.0	21.0	20.6	23.4
NBS NF					
FED		0.686	0.901	0.706	0.600
FED CO		0.115	0.390	0.249	0.278
LC_{50} CO corr	mg l^{-1}	13.1	14.0	17.1	16.8
NIST Radiant					
FED		0.783	1.134	0.657	0.549
FED CO		0.510	0.316	0.248	0.288
LC_{50} CO corr	mg l^{-1}	14.9	10.9	16.9	15.4
NIBS IT_{50}					
FED		1.542	1.338	0.886	0.620
FED CO		0.783	0.009	0.147	0.071
LC_{50} CO corr	mg l^{-1}	21.0	12.8	13.8	12.5
UPITT					
FED		0.582	0.625	0.385	0.353
FED CO		0.279	0.172	0.150	0.184
LC_{50} CO corr	mg l^{-1}	6.0	11.5	13.0	11.0

Note:
Gas LC_{50} data used for FED: CO: 4600 ppm/(30 min); HCl: 3700 ppm/(30 min).

Table 8. Fractional effective doses for the CO and HCl combinations and for CO only (Previous data only)[7]

		SI	SJ	EX B	EX C	Nylon
NBS F						
FED		1.009	1.311	0.888	0.481	0.508
FED CO		0.547	0.707	0.740	0.477	0.327
LC_{50} CO corr	mg l^{-1}	22.2	17.3	24.0	27.4	17.0
NBS NF						
FED		1.038	0.784	0.494	0.264	0.044
FED CO		0.226	0.157	0.137	0.133	0.039
LC_{50} CO corr	mg l^{-1}	13.2	14.5	17.3	17.9	19.0
UPITT						
FED CO		0.159	0.225	0.136	0.140	0.193
FED		0.342	0.630	0.162	0.144	1.168
LC_{50} CO corr	mg l^{-1}	8.2	9.2	12.8	17.6	8.8
Radiant						
FED		1.363	1.246	0.734	0.777	0.696
FED CO		0.850	1.219	0.723	0.771	0.376
LC_{50} CO corr	mg l^{-1}	22.7	25.9	26.7	28.8	17.0

Notes:
(1) Gas LC_{50} data used for FED: CO: 4600 ppm/(30 min); HCl: 3700 ppm/(30 min).
(2) For Nylon FED CO and HCN data were used, with HCN LC_{50}: 200 ppm/(30 min).

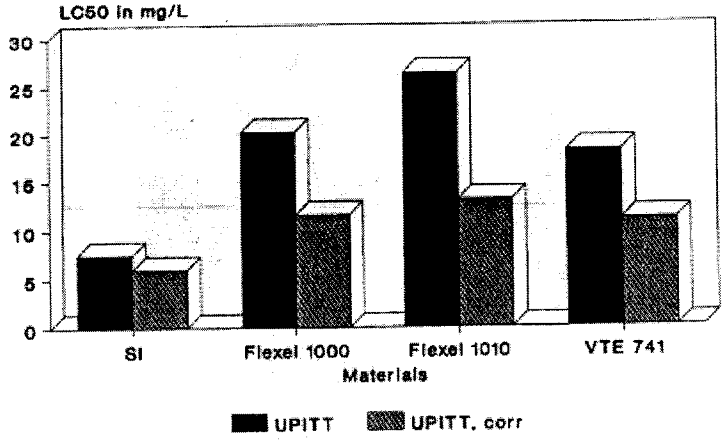

Figure 7. Toxic potency values, without and with carbon monoxide correction for the UPITT Test.

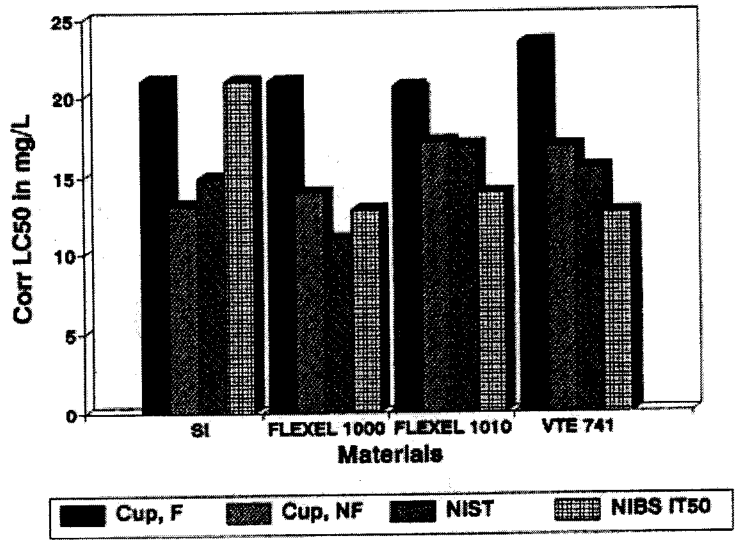

Figure 8. Toxic potencies of all materials using the four static test methods, corrected for carbon monoxide.

LC_{50}HCl: 3700 Units: ppm
$LC_{50}O_2$: 4.5 Units: %

This was also calculated in the present work and is shown as FED NIST, in Table 9. There is relatively little difference between the results of simply using the CO and HCl lethalities and adding the oxygen depletion and carbon dioxide potentiation effects. This is probably due to the low levels of both found in the tests considered. The combination of the fractional effective doses of HCl and CO are well over 0.5, and in fact quite close to 1, for the NBS Cup Furnace Test (both modes) and for the Radiant Test in the NIST mode. This indicates that any other toxicants may be of minor interest only. The table also presents an analysis of both calculations of FED when the mass charged is corrected to obtain the value at the exact LC_{50} level (indicated as FED at LC_{50}). This calculation is also presented for the fractional effective dose data based on the NIST formula. It is notable that some of the FED results are only approximately 0.7, which is lower than would normally have been expected. It is of interest to note that, once the results are related to the LC_{50} values, the NIBS IT_{50} data do not fall in line with the others.

Table 9. Fractional effective doses, corrected to the LC_{50} level (this study)

	SI	Flexel 1000	Flexel 1010	VTE 741
NBS F				
Mass charge g	6.0	6.0	6.0	6.0
% of LC_{50}	106	106	87	93
FED NIST[a]	0.973	1.269	0.874	0.933
FED NIST at LC_{50}	0.915	1.193	0.999	0.999
FED CO, HCl	1.139	1.430	0.966	1.076
FED CO, HCl at LC_{50}	1.071	1.345	1.105	1.151
NBS NF				
Mass charge g	6.0	5.4	6.0	6.0
% of LC_{50}	112	123	79	86
FED NIST[a]	0.717	0.851	0.697	0.583
FED NIST at LC_{50}	0.643	0.690	0.886	0.674
FED CO, HCl	0.686	0.901	0.706	0.600
FED CO, HCl at LC_{50}	0.615	0.731	0.897	0.694
NIST Radiant				
Mass charge g	6.0	6.0	6.0	6.0
% of LC50	103	165	65	84
FED NIST[a]	0.698	1.105	0.648	0.529
FED NIST at LC_{50}	0.679	0.671	0.993	0.632
FED CO, HCl	0.783	1.134	0.657	0.549
FED CO, HCl at LC_{50}	0.762	0.688	1.005	0.655
NIBS IT_{50}				
Mass charge g	12.53	12.57	14.85	13.42
% of LC_{50}	171	217	253	262
FED NIST[a]	1.377	1.399	0.907	0.663
FED NIST at LC_{50}	0.805	0.646	0.359	0.253
FED CO, HCl	1.542	1.338	0.886	0.620
FED CO, HCl at $_{50}$	0.901	0.617	0.351	0.236
IT min	2.0	2.0	2.0	2.0
UPITT				
Mass charge g	6.4	6.4	8.0	6.4
% of LC_{50}	213	75	64	64
FED NIST[a]	0.565	0.538	0.405	0.364
FED NIST at LC_{50}	0.265	0.715	0.633	0.568
FED CO, HCl	0.582	0.525	0.385	0.353
FED CO, HCl at LC_{50}	0.273	0.697	0.601	0.552

[a] Using Eqn (1).

Under the conditions of the UPITT test, the FED values (Tables 7–9) are insufficient for these toxicants to account for the toxicity of the smoke. This is not consistent with the fact that animals are, of course, killed in the test. This inconsistency is probably another indication of the problems associated with the UPITT smoke toxicity test. It is of interest, in contrast to the effect of the vinyl smokes, that the partial contribution of HCN in the case of nylon is sufficiently high to obtain a reasonable FED for that smoke in the UPITT test.

CONCLUSIONS

This work has shown that the smoke of vinyl thermoplastic elastomer alloys (VTEs) has a toxic potency within the range of 'common' materials. Moreover, the toxic potency of three different vinyl thermoplastic elastomers is very similar and it is also similar to that of other vinyl wire and cable coating materials.

An analysis was also made of the various toxic potency methods in use today. The results on toxic potency of the NBS Cup Furnace and the NIST Radiant Tests can be explained reasonably well in terms of the toxicity of carbon monoxide and hydrogen chloride. Neither the UPITT nor the NIBS IT_{50} tests are adequate measures of toxic potency.

It is also worth mentioning that if the concepts accompanying the NIST Radiant Test are accepted in the fire science community, this would lead to a minimization of testing, thus decreasing the need for experimentation using animals.

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GBH Attachment 9

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BCC Flame Retardancy Conference - May 23-25, 1995 - Stamford, CT

SMOKE TOXICITY
HOW IMPORTANT IS IT FOR FIRE SAFETY?

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ABSTRACT

The majority of fire fatalities are a result of inhalation of smoke and combustion products, rather than the simple effect of burns. International standards organizations as well as American ones are trying to develop standard test methods and guide documents on smoke toxicity. Emotional responses arise from discussions on interpretation of results or requirements for the use of animals as test surrogates. This paper offers an analysis of the issues involved and the approaches taken (and suggested) for assessment of smoke toxicity within the context of overall fire safety.

INTRODUCTION

Fire fatalities are usually reported as resulting from smoke inhalation. However, the real cause of most fire fatalities is the fire, which generated enough combustion products to create a lethal atmosphere. In order to understand, and put into perspective, the smoke toxicity of materials and products in actual fires, it is essential to follow a pattern of research that has led to the level of knowledge of fire, smoke and toxicity in the 1990's.

Many smoke toxicity test methods have been proposed over the years to investigate the toxic potency of the smoke from materials [e.g. 1-6]. As well as the tests mentioned, most of which involve some type of animal bioassay, a fairly popular test, particularly used in specifications of halogen-free materials, has been the analytical test developed by the British Royal Navy [7].

Abundant published data exists on the smoke toxic potency resulting from many materials, using one or more of these methods. Unfortunately, much published information is not specific (mainly due to commercial confidentiality needs) as to formulation details of the material tested. Thus, as new materials are developed by a manufacturer, more testing must be done, at high added expense. This is very often unproductive, for one of three reasons:

- It may lead to data statistically indistinguishable from existing information: new testing was then a waste of money.
- It may lead to data statistically distinguishable but toxicologically indistinguishable: new testing then leads to supporting marketing ploys which add nothing to fire safety.
- It may lead to new data showing improvements in one fire property (smoke toxicity) at the expense of (often hidden) deterioration in another fire property (e.g. heat release or flame spread): new testing then resulted in lower fire safety.

The fire performance and the smoke toxicity of materials have been the focus of many investigations; recent work can now focus on those fire properties most applicable to fire hazard assessment. There has been considerable speculation with regard to the relative importance, or lack of it, of smoke toxicity test data. In particular, the effect on fire performance of adding fire retardants has been very controversial. People interested in fire hazard assessment have, recently, wanted to combine what is known from the abundant tests carried out on the smoke toxicity of materials with the practical experience from full scale fires and the fire modelling capabilities available today. The most important results of this type of work were obtained at the National Institute for Standards and Technology. This process had various stages: comparison of products made with fire retarded and non-fire retarded materials [8], analysis of the carbon monoxide (CO) yields in large full scale fires [9], study of full scale testing of materials (including a rigid PVC compound) and a comparison with small scale test results [10] and finally development of a small scale radiant test for toxic potency measurement [11]. The work must be understood combined with an analysis of effects of carbon monoxide, the most hazardous toxicant affecting fire victims in real fire atmospheres, as shown in a comprehensive study of fire and non fire fatalities [12-13].

TEST METHODS FOR SMOKE TOXICITY DATA

Most smoke toxicity tests, at least in the United States, are based on the use of animal bioassays to determine the end-point. The most common animal model is the rat, used in the NBS cup furnace test [1], and in the various radiant tests developed from it [4, 11-14]. One of the more prominent tests used for regulation, however, uses as an animal model the mouse: the UPITT test [3], used in New York (USA). This is unfortunate, since it is known that the mouse is excessively sensitive [13-15]. In particular, the mouse is 4-10 times more sensitive than the rat towards irritant gases, like hydrogen chloride, but has similar sensitivity towards common asphyxiants, like carbon monoxide [15, 17-18], which are the most important smoke toxicants.

A few years ago a comparative investigation was made [17] of four test methods: the UPITT test [3], the NBS Cup furnace test (flaming and non flaming mode) [1] and the radiant apparatus, in the protocol suggested by Dr. Stephen Packham [4]. The 5 materials tested were all wire and cable compounds: four poly(vinyl chloride) (PVC) materials and a nylon compound. The PVC materials were a conventional jacket compound, a conventional insulation compound, and two jacket compounds with progressively higher levels of acid retention catalysts. It was found that, although there are some serious deficiencies with using any such tests for making fire safety decisions, the UPITT test was particularly flawed. Since then, further information on the inappropriateness of the UPITT test method, particularly for predictions or use in fire hazard analyses, has been forthcoming [18-20]. However, unfortunately, the test is being used for regulatory purposes in the USA, both in the state of New York and in the city of New York. More recently, a new investigation was conducted to compare the results of various smoke toxicity tests, using the same materials for all tests [21]. The materials chosen were a flexible PVC wire and cable compound used in the earlier work [17] and three components of a new family of vinyl thermoplastic elastomer alloys. These vinyl alloys have excellent fire performance, both in terms of heat release and of smoke release [22]. In order to investigate whether the smokes from these materials were in the "common" range, just as those of the more traditional vinyl materials had been found to be, they were also subjected to several toxic potency tests. The tests chosen were the NBS cup furnace (flaming and non flaming), the UPITT test (as before) and the latest variants of the radiant equipment apparatus: the NIST radiant toxicity test [10-11] and the NIBS test [14, 23-25]. The results showed: (a) that the NIBS and the UPITT tests were the least satisfactory procedures, (b) that there was no significant difference between the toxic potency of all the vinyl materials used and (c) that the smoke toxicity could be reasonably well predicted from the results of analytical studies of gas emissions.

There is, in modern times, a logical reluctance to use animals for research, unless they are essential. In view of the fact that, for many combustible materials, the smoke toxicity can be ascribed mainly to a few individual gases, there has been a tendency to use tests which do not include animal bioassays. In order to be able to properly characterize smoke toxicity by chemical analysis two issues must be taken into account: use of a fire model that properly represents a certain stage in a fire and use of toxicity indices for individual toxicants which have been validated against actual animal experiments (of which there have been an abundance). One potential problem with chemical analysis tests is that they do not offer an adequate degree of assurance that a "supertoxicant" cannot "filter through". Virtually no supertoxic smokes have been discovered in years of testing. However, a few materials have been found which generate smoke much more toxic than would be calculated from the sum of the concentrations of the common toxic gases. A potential compromise is the use of analytical methods, which are validated, occasionally and for untested materials, with animal experiments.

There are two additional problems with some of the existing toxic potency tests which do not use an animal model: the fire model and the "toxicity indexes" used. The most prominent smoke toxicity test using chemical analysis is NES 713 [7]: it does not generate adequate results, because both the fire model and the toxicity indices are flawed. In particular, the toxicity indices are geared towards producing "unacceptably" high values for materials containing halogens. Other tests using chemical analysis of smoke gases are recent versions of tube furnace tests (such as the DIN 53436 test). In those cases, it is purely the fire model that is flawed, while adequate toxicity indices are being used today.

EFFECTS OF HEAT RELEASE AND TOXIC POTENCY ON FIRE HAZARD

It has been shown, in recent times, that the most important fire property is the rate of heat release [e.g. 26], since it is the one that both governs the intensity of a fire, and the survivability in a fire scenario. Table 1 illustrates this fact, by determining survival time (through computer modelling via HAZARD I) in a standard room, with a normal chair. When the chair is constructed with a material with half the time to ignition, the survival time does not change. Similarly doubling the toxic potency of the chair materials has very little effect on survival time, while doubling the rate of heat release immediately decreases, by a factor of over 3, the survival time. This is a very important concept, because it puts into perspective the importance (or lack of it) of smoke toxic potency data in terms of fire hazard assessment, or simply of fire safety.

Another example worth mentioning is the study, conducted by the National Fire Protection Research Foundation, where they investigated the effect of assuming that materials were more toxic on fire fatalities. This was done in a case study that analyzed fire risk for one of the most severe cases known: upholstered furniture in residences, which represents hundreds of fire fatalities per year. After the analysis was done, the risk assessment was repeated but the toxic potency of burning chairs was increased ten-fold. However, a 1,000% increase in toxic potency resulted in only a 46% increase in fatalities [27]. Another sensitivity study conducted within the same overall investigation addressed electric cables contained in concealed spaces above function rooms of hotels [28]. With existing cable materials, no fire fatalities, on average, are found if the fire starts in the concealed space, and the fire risk assessment did not find fatalities either. They then increased the rate of rise of heat release rate by a factor of 2 (100%, corresponding to a 50% increase in peak rate of heat release) for the electric cables used, and found that the same scenario led to a predicted 100 deaths. This indicates that smoke toxic potency is of less importance than other factors in addressing fire hazard.

One of the most important studies that has illustrated the concept of the decrease in fire hazard due to improved fire performance is the NIST work on the comparison between fire retarded and non fire retarded versions of the same product [8]. In this work, done by NIST for the Fire Retardant Chemicals Association (FRCA), five different categories of products were assembled and tested in full-scale room fires. In one series, all five products were fire-retardant, whereas in the other series the same base polymers were used, but without fire retardant agents. The products tested were: upholstered furniture mock-ups, business machine housings, television housings, electric cables, and electronic circuit board laminates. The most interesting results were those from the full scale fire tests, which also helped to identify the importance of heat release rate as the most important physical variable in these tests which is a predictor of the fire hazard. Table 2 shows the most important results of the burns. During the first burn carried out with the fire retarded products under the same conditions as the non fire retardant products (a single 50 kW burner) very little combustion took place. Thus, all successive tests with the fire retarded included an additional 120 kW burner, which allowed all the products to burn.

In the study, the use of the fire retarded products, which was associated with an average 4-fold decrease in rate of heat release led to a three-fold decrease in smoke toxicity in the room, and to a ten-fold increase in tenability time (even though the ignition source used was over three times as intense). This is a clear indication that considerable improvements in toxicity will be obtained by decreasing the heat release rate of the materials/products considered, almost irrespective of the actual toxic potency of the materials/products involved. Thus, toxic hazard is a direct function of heat release rate, provided there has been proper flame retardancy. In contrast, in at least one other study no improvement in toxic hazard was found following the use of materials (upholstered furniture) containing fire retardants [29]. An analysis of the materials involved indicates that the so-called fire-retarded materials simply contained very low levels of flame retardants, insufficient to make a substantial difference to the heat release rate of the final product. Thus, no real improvement in fire performance occurred, resulting to no improvement in toxic hazard.

Table 3 is a compilation of a few of the data available wherein the same basic material was tested, using the same technique before and after the addition of flame retardants. The data indicates that, in fact, considerable improvements in rate of heat release are commonplace, including increases of over 10-fold. The range of materials presented in the table is also very broad, including thermoplastics, cross-linked materials, thermosets and cellulosics. This is crucial data, because it indicates that the effect of fire retardants can, indeed, lead to great improvements in smoke toxicity. In order to understand its further implications with respect to smoke toxicity, it is essential to investigate toxic potency ranges for different materials.

The following issues are now accepted by many fire scientists [8-13]:

- Most fire fatalities occur in fires that become very large. In fact, US statistics indicate that such fires account for over six times more fatalities than all other fires. Table 4 shows statistics of US fires in the 1986-1990 time period, illustrating this issue [30].
- Carbon monoxide concentrations in the atmospheres of flashover fires (the fires most likely to produce fatalities), are determined by geometric variables and oxygen availability, but are virtually unaffected by chemical composition of fuels.
- All small scale fire tests underpredict CO yields. They cannot be used, thus, to predict toxic fire hazard for ventilation controlled flashover fires, unless CO yields are calculated by analogy with full scale fire test results. Such tests do not underpredict yields of other toxicants, such as hydrogen chloride or hydrogen cyanide.
- CO yields in full scale flashover fires are approximately 0.2 g/g, which translates to a toxicity of 25 mg/L. A set of 24 studies where such results are shown is in Table 5.
- Toxic potency values from the new NIST radiant small scale test (with rats as the animal model, but used only for confirmatory purposes) is well validated with regard to toxicity in full scale fires. However, such validation cannot be done to a better approximation than a factor of 3.
- The consequence of this is that any toxic potency (LC_{50}) higher than 8 mg/L (i.e. any toxicity

lower than 8 mg/L) will be subsumed within the toxicity of the atmosphere, and is of no consequence. Thus, values 8 or greater should be converted to 8 mg/L for reporting purposes.

- In order to correct small scale test data, the CO yield that should have been obtained can be calculated by making a CO correction.
- The background for the corrections of CO yields are based on the comprehensive study of fire (and non fire) fatalities associated with CO [12-13]. This study, of almost 5,000 fatalities, found that:
  - The toxicity of fire atmospheres is determined almost solely by the amount of CO, since victims of poisoning by pure CO die at virtually identical levels, once other factors have been considered. There is no universal lethal CO threshold level (which was previously thought to be 50% carboxyhemoglobin, COHb). This depends on the age and physical condition of the victim. Any blood COHb value > 20 % can produce lethality on its own.
  - The populations of victims of fire and of non fire CO exposures are inherently very different: fire victims are both much older and much younger, and suffer from more preexisting disease. Thus fire victims are more sensitive to CO than those in non fire exposures.
  - A comparison of fire fatalities before and after the plastics era indicates that the use of man-made materials to make household goods has made no difference to fire atmosphere toxicity.

It must be explained that there is considerable controversy in the area of smoke toxicity with regard to three of the previous statements: (a) that the yield of CO is 0.2 g/g in post-flashover studies, (b) that validation of full scale toxicity values cannot be made to better than a factor of 3 and (c) that most fire fatalities occur in post-flashover fires. These issues need some additional explanation.

Table 4 shows that, in the United States, indeed fire fatalities overwhelmingly occur in post-flashover fires; however, European statistics tend to suggest that this may not be the case in some other countries. Thus, it may be possible that the approach to smoke toxicity measurements applicable to the United States needs to be modified for use in Europe (this is reinforced further by the fact that the use of test animals is politically unacceptable in many European countries).

There have been extensive studies indicating that carbon monoxide yields of 0.2 g/g for post-flashover fires are widespread (Table 5). Moreover, it has been shown that CO yields in small scale tests are very low [10, 11, 23]. Evidence exists that CO yields can be higher than 0.2 g/g if significant amounts of oxygen-containing material (typically when cellulosic materials, such as wood) pyrolyzes in the upper layer [36]. Such an increased yield does not affect the conservative nature of the approach outlined here, since the importance of the CO produced by the room is higher. There is no evidence to date of cases with CO yields substantially lower than 0.2 g/g in the original fire compartment. This does not invalidate the procedure, since the assumption that the CO present is equivalent to a yield of 0.2 g/g is more conservative than if the yield is actually higher (and post-flashover fires are even more toxic). No information exists to suggest that post-flashover yields are lower, on average, than 0.2 g/g.

The factor of three is a result of the experimental observations, by NIST [10, 11] that such an uncertainty is needed to account for differences in formations of individual combustion products and general geometric factors or other variables. It is likely that further research will improve the level of agreement between real-scale and bench scale smoke toxicity results. If this occurs, it will be necessary to revise the "cut-off" value of LC_{50} for post-flashover fires from the present recommendation of 8 mg/L. Unfortunately no experimental work of this kind is underway or is being planned.

Thus, instead of exposing animals, Equation 1 is a predictor of smoke toxicity, where smoke is lethal if FED (fractional effective dose) is near unity:

$$FED = \frac{m[CO]}{[CO_2]-b} + \frac{[HCN]}{LC_{50}HCN} + \frac{[HCl]}{LC_{50}HCl} + \frac{[HBr]}{LC_{50}HBr} + \frac{21-[O_2]}{21-LC_{50}O_2} \qquad (Eq.\ 1)$$

The constants for use in Equation 1 (which refers to 30 min exposure) are:

m:	-18	Units: 1/ppm
b:	122,000	Units: ppm
LC_{50} HCN:	200	Units: ppm
LC_{50} HCl:	3,700	Units: ppm
LC_{50} HBr:	3,000	Units: ppm
LC_{50} O_2:	5.4	Units: %

if concentrations of carbon dioxide are 5% or less. If there is over 5% carbon dioxide, m = 23 and b = -38,600. If there is 3-5% carbon dioxide (normal range to be expected in a large fire), the LC_{50} of CO will range between 5,100 and 4,000 ppm. The other terms in the equation are concentrations of CO, hydrogen cyanide, hydrogen chloride, hydrogen bromide (all in ppm) and oxygen (in %). This is now a standard ASTM test method (ASTM E1678, [36]). It must be pointed out that, if the data is to be used for flashover fires, [CO] must be corrected (as discussed above), using Equation 2, giving the added [CO] (as suggested in a draft ASTM standard [37]):

$$\Delta[CO] = 0.2 - \frac{[CO]\ x\ 0.200}{m_{100}}\ x\ \frac{28}{24.5x10^{6}} \qquad (Eq.\ 2)$$

The toxic potency (LC_{50} (corr)) to be used for flashover fires is calculated by using the corrected CO concentration, or directly with Equation 3:

$$LC_{50}(corr) = \frac{1}{\frac{1}{LC_{50}} + 44x10^{-3} - 5.0x10^{-5}\frac{[CO]}{m_{100}}} \qquad (Eq.\ 3)$$

where LC_{50} values are in mg/L and m_{100} is the mass of specimen burned (in g).

With these considerations, there is now an appropriate procedure for smoke toxicity testing, useful for input into hazard analyses. It involves conducting analytical experiments, using the NIST radiant toxicity test. Moreover, if the material chemical composition is similar to that of materials that have already been tested, further testing is unnecessary. Animal testing is purely a confirmatory check or for those cases where no experience with similar materials.

Table 6 shows test results with the radiant apparatus [10-11] for a large number of materials, with very different chemical composition, both before and after CO correction. The results are extremely satisfactory in two ways: first, because they show that the method is applicable to many different materials and second, because all materials tested have a smoke toxic potency lower than that of pure CO, indicating that they are of "normal smoke toxicity". Therefore, the technique of the CO correction "works", in that it predicts that most common materials and products in use today are not associated with toxic potencies that require special investigation for post-flashover fires. In fact, once these concepts are applied, smoke toxicity testing will only be required for novel products, for post-flashover fire situations.

The chemical analysis technique cannot, to date, identify the major toxicants associated with the smoke of fluoropolymers, which are none of the simple gases mentioned above. This is, usually, of little consequence for real fires because fluoropolymers, which generally have very good fire performance, will rarely burn on their own, so that the toxicity of the fire atmosphere is probably dominated by that of the other fuels present.

European activities in the area of smoke toxic potency measurements are tending in the direction of the use of tube furnace test methods, with analytical determinations. The best known tube furnace test method is the DIN 53436 fire model, originally proposed by Kimmerle [2]. Similar furnaces are also used for determinations of acid gas emission, pH and conductivity (proposed surrogates for smoke corrosivity). For these reasons, there are many such test furnaces in existence, and it seems prudent to attempt to rationalize smoke toxic potency testing by employing them. It is likely that standard test methods will be developed from this effort.

Smoke toxic potency in pre-flashover fires is of potential concern worldwide, and should not be ignored, as improvements due to new product development can still be valuable for fire safety. A number of scenarios exist (for example in transport applications or in institutions where occupants may be impaired or otherwise inhibited from escape) where prevention of flashover is insufficient protection, and severe fire hazard can occur before flashover.

CONCLUSIONS

- Fire hazard is a function of several fire properties, but rate of heat release of the materials or products involved is probably the most important one of them. The importance of heat release rate vastly exceeds that of smoke toxic potency.
- Improving smoke toxic potency for pre-flashover fires is valuable, for some scenarios.
- However, adequate smoke toxicity testing shows that most materials have similar smoke toxic potency: lower than the CO inevitably present in post-flashover fires.
- Therefore, adequate flame retardance considerably decreases fire hazard, by decreasing heat release rates and improving time to escape.
- Smoke toxicity activity should focus on improvements in fire performance.

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Table 1. Effects of Different Properties on Time to Lethality

Product	Time Incapacitation	Time to Lethality
Primary chair	180 s	> 600 s
Double ignitability	140 s	> 600 s
Double toxic potency	180 s	> 600 s
Double heat release rate	160 s	180 s

Table 2. Effects of Flame Retardant Additives on Overall Smoke Toxicity

Products	Peak Temp (°C)	Smoke Toxicity (kg CO)	Tenability time in room: Burn (s)	Target (s)	CO yield (g/g)	Pk RHR (kW)
non-FR	> 600	21	110	200	0.22	1590
non-FR	> 600	17	112	215	0.18	1540
non-FR	> 600	16	116	226	0.14	1790
FR 1B	185	2.6	NA	NA	0.22	220
FR	273	5.5	1939	NA	0.23	370
FR	285	6.1	2288	NA	0.23	350
FR	334	5.6	1140	1013	0.23	450

Notes: Peak Temp: maximum temperature in burn room; Smoke Toxicity: level of toxicity, calculated in equivalent mass of carbon monoxide; Tenability Time in room: time to reach untenable conditions in burn room or target room (via smoke toxicity or by having reached flashover, i.e. temperatures over 600°C); CO yield: mass of carbon monoxide formed per mass of fuel burnt; Pk RHR: maximum heat release rate in room; non-FR: non fire-retarded products; FR: fire-retarded products; FR 1B: fire retarded products without an auxiliary burner.

Table 3. Comparison of Heat Release Rate Data for FR and Non FR Materials

Material	Heat Flux kW/m^2	NFR Pk RHR kW/m^2	FR Pk RHR kW/m^2	NFR/FR Ratio -	
ABS (+ FR1)	20	614	224	2.7	
ABS (+ FR1)	40	944	402	2.3	
ABS (+ FR1)	70	1311	409	3.2	
ABS (+ FR2)	20	614	224	2.7	
ABS (+ FR2)	40	944	291	3.2	
ABS (+ FR2)	70	1311	419	3.1	
EVA (Cross-linked)	30	463	110	4.2	
EVA (Thermoplastic)	30	574	83	6.9	
HDPE	30	1803	114	15.8	
HDPE # 2	50	1167	476	2.5	
LDPE	20	913	88	10.3	
LDPE	40	1408	192	7.3	
LDPE	70	2735	268	10.2	
Polypropylene	30	1555	174	8.9	
PVC Rigid	20	102	25	4.0	
PVC Rigid	40	183	84	2.2	
PVC Rigid	70	190	93	2.1	
PVC Rigid # 2	30	98	42	2.3	
PVC Rigid # 3	30	118	56	2.1	
PVC Wire & Cable	20	116	9	12.8	
PVC Wire & Cable	40	167	64	2.6	
PVC Wire & Cable	70	232	100	2.3	
PVC Wire & Cable # 2	20	116	72	1.6	
PVC Wire & Cable # 2	40	167	92	1.8	
PVC Wire & Cable # 2	70	232	134	1.7	
Particle Board	25	151	66	2.3	*
Particle Board B (+FR 1)	25	160	70	2.3	
Particle Board B (+FR 1)	50	227	141	1.6	
Particle Board B (+FR 2)	50	227	52	4.4	
Plywood	25	114	43	2.7	
Plywood	50	150	75	2.0	
Polyester	30	186	95	2.0	
Polystyrene	20	723	277	2.6	
Polystyrene	40	1101	334	3.3	
Polystyrene	70	1555	445	3.5	

Note: * All data presented was obtained using the cone calorimeter (ASTM E1354), except for this data, obtained using ASTM E906 (Ohio State University rate of heat release calorimeter)

Table 6. Radiant Toxicity Test Results (ASTM E1678, NFPA 269)

SPECIMEN	LC_{50} mg/L	Corr LC_{50} mg/L
ABS	17.8	11.8
Acrylic F + MELFM	9.6	6.9-8.2
Ceiling tile	30.5	21.9
Composite	20.0	not given
Cork	ca. 40	not given
Dg FIR	100-200	21-23
Dg FIR	56.0	21.0
Dg FIR (full scale)	> 70	> 70
FLX PU FM	52.0	18.0
MELFM	12.5	8.0
Nylon	36.7	17.0
Nylon Rug (Tr)	28.5	14.2 FED 1.2
Nylon Rug (Tr)	42.9	18.1 FED 2.0
Nylon Rug (Un)	> 41	> 16
PVC CB	36.0	not given
PVC INS	33.4	22.7
PVC INS	29.2	14.9
PVC JK	53.1	25.9
PVC Lw HCl	146.9	28.8
PVC Md HCl	86.2	26.7
PVC PRF	26.0	16.0
PVC PRF	20-30	13-17
PVC PRF (full scale)	35-45	35-45
Particle board	120-138	not given
Rg PU FM	22.0	14.0
Rg PU FM	20-30	14-19
Rg PU FM (full scale)	30-40	30-40
Vinyl F	32.0	19.0
Vinyl F + MELFM	26.0	15.0
Vinyl FLR	82.0	not given
VTE 1 - 6	18.2	10.9
VTE 2 - 3	45.9	16.9
VTE 3 - 2	35.8	15.4
Pr Full		8.0

Legends: Acrylic F: Acrylic fabric; Composite: Naval composite board; Dg FIR: Fire retarded Douglas fir board; FLX PU FM: Flexible polyurethane foam; MELFM: Melamine polyurethane foam; Nylon: Nylon Wire coating compound; Nylon Rug (Tr): Rug treated with PTFE coating; Nylon Rug (Un): Untreated rug; Pr Full: Predicted Carbon Monoxide Post Flashover Toxicity; PVC CB: PVC cable insulation; PVC INS: traditional PVC wire insulation compound; PVC JK: traditional PVC wire jacketing compound; PVC Lw HCl: PVC jacket compound & abundant amounts of acid retention filler; PVC Md HCl: PVC jacket compound & moderate amounts of acid retention filler; PVC PRF: Rigid PVC profile; Rg PU FM: Rigid polyurethane foam; Vinyl F: Vinyl fabric; Vinyl FLR: Vinyl flooring over plywood.

Table 4. Yields of Carbon Monoxide in Literature

Material	Yield	Reference	Organizatio
Plywood walls, wood fiberboard ceiling	0.35	Budnick 1978 [31]	HUD
FR plywood walls, wood fiberboard ceiling	0.42	Budnick 1978 [31]	HUD
Plywood walls, no ceiling	0.10	Budnick 1978 [31]	HUD
Upholstered chair, bed FR plywwod walls	0.36	Budnick et al 1978 [32]	HUD
Plywood walls, bed	0.31	Budnick et al 1978 [32]	HUD
Plywood walls, wood cribs, cellulosic ceiling tile	0.29	Levine and Nelson 1990 [33]	NIST
Non FR chair, TV cabinets, cables, etc	0.22	Babrauskas et al. 1988 [19]	FRCA
FR chair, TV cabinets, cables, etc	0.23	Babrauskas et al. 1988 [19]	FRCA
PMMA walls	0.28	NIST unpublished	NIST
Wood cribs	0.15	Gottuk et al. 1992 [34]	VPI
Flexible PU foam	0.25	Gottuk et al. 1992 [34]	VPI
PMMA	0.30	Gottuk et al. 1992 [34]	VPI
Hexane	0.23	Gottuk et al. 1992 [34]	VPI
Propane	0.23	Beyler 1986 [35]	Harvard
Propene	0.20	Beyler 1986 [35]	Harvard
Hexanes	0.20	Beyler 1986 [35]	Harvard
Toluene	0.11	Beyler 1986 [35]	Harvard
Methanol	0.24	Beyler 1986 [35]	Harvard
Ethanol	0.22	Beyler 1986 [35]	Harvard
Isopropanol	0.17	Beyler 1986 [35]	Harvard
Acetone	0.30	Beyler 1986 [35]	Harvard
Polyethylene	0.18	Beyler 1986 [35]	Harvard
PMMA	0.19	Beyler 1986 [35]	Harvard
Pine	0.14	Beyler 1986 [35]	Harvard
Average	**0.236**	Cases: Total #: 24	Total #: 5

Table 5. Statistics of United States Fire Fatalities in Post-Flashover Structure Fires 1986-90 [30]

Explanation	Numbers	Percentages of Total
Post-Flashover Fires		
Civilians Killed by Smoke Inhalation Only	621	78.3
Civilians Killed by Burns Only	125	58.1
Civilians Killed by Combination of Smoke Inhalation and Burns	2,406	83.3
Combination of All of the Above	3,152	80.9
Other Data, for Comparison		
Total Civilian Fire Fatalities in Structure Fires	3,896	100.0
Total Civilian Fire Fatalities in Structure Fires Intimate With Ignition	670	17.2

GBH Attachment 10

AB59-COMM-7-10

FIRE HAZARD AND SMOKE TOXICITY: POST-FLASHOVER FIRE ISSUES OR INCAPACITATION VIA IRRITANCY?

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ABSTRACT

In recent years strategies have been underway to address toxic incapacitation, via irritant smoke, as a critical element in fire hazard. This effort has even led to draft standard documents. In actual fact, fire hazard is most critically affected by the need to prevent fires from getting big, and the smoke toxicity of most common materials is very similar. Thus, this work initially discusses what is known about smoke toxicity and fire hazard, and points out some potential disadvantages of focussing too strongly on toxic potency of smoke. An investigation of the yields of common combustion products in fires and fire tests forms the basis for an analysis of the implications of those yields to consider lethality and incapacitation. Proposed incapacitation limit levels, based on flawed incapacitation concentration (rather than dose) concepts, are shown to lead to unrealistic limitations in building contents, while not addressing the real toxic hazard. This work suggests that more realistic criteria are needed. Finally, a procedure is presented for assessing hazard (with emphasis on toxic hazard) for post-flashover fires (the most severe ones), without using the concept of incapacitation. This combines the information on toxicant yields with a toxic fire hazard assessment for those fires that cause the vast majority of fatalities: the ones reaching beyond the room of fire origin and associated with flashover. It presents a procedure for assessing fire hazard in post-flashover fires, based on proven fire safety engineering concepts. The toxic potency of common materials in post-flashover fires is 8 mg/L and the yield of carbon monoxide is 20% of the mass burnt. Therefore, toxic fire hazard can be calculated as just one element in overall fire hazard. In other words, life threat in fires is best addressed by assessing the fire hazard of a product in a certain fire scenario and comparing the time to safe escape (or evacuation) with the time required to reach lethality (based on proven tenability levels).

INTRODUCTION

It is common to see fire fatalities reported as resulting from smoke inhalation. The real cause of the overwhelming majority of fire fatalities is, however, that the fire, has generated enough combustion products to bring about a lethal atmosphere. It is important, thus, to follow the research that has led to the level of knowledge of fire, smoke and toxicity in the 1990's.

Multiple test methods have been developed to investigate the toxic potency of material smoke[1-7] some of which involve bioassay. Abundant published data exists on the smoke toxic potency resulting from many materials, using one or more of these methods. Unfortunately, not all the published information is specific (mainly because of trade secret needs) on formulation details of the material tested. Therefore, specifications, and competitive marketing, often result in more toxicity testing by manufacturers, as new materials are developed, at high added expense. This is very often unproductive, for one of three reasons:

- It may result in data that is statistically indistinguishable from existing information: new testing is then a waste of money.
- It may result in data that is statistically distinguishable but toxicologically indistinguishable: new testing then does nothing but support marketing ploys which do not add to fire safety.
- It may result in new data showing improvements in one fire property (smoke toxicity) at the expense of (often hidden) deterioration in another fire property (e.g. heat release or flame spread): new testing then lowers fire safety.

Fire performance and smoke toxicity of materials have been the focus of so many investigations that work can, and should, now focus on the fire properties most applicable to fire hazard assessment. Some critical work was conducted in this area at the US National Institute for Standards and Technology, in various stages: comparison of products made with fire retarded and non-fire retarded materials[8], analysis of the carbon monoxide (CO) yields in large full scale fires[9], study of full scale testing of materials (including a rigid PVC compound) and a comparison with small scale test results[10] and finally development of a small scale radiant test for toxic potency measurement[11]. The work must be understood combined with an analysis of the effects of carbon monoxide, the most hazardous toxicant affecting fire victims in real fire atmospheres, as shown in a comprehensive study of fire and non fire fatalities[12-13]. In consequence, many fire scientists now accept that:

- Most fire fatalities occur in fires that become very large. In fact, US statistics indicate that such fires account for over six times more fatalities than all other fires combined.
- Carbon monoxide concentrations in the atmospheres of flashover fires (the fires most likely to produce fatalities), are determined by geometric variables and oxygen availability, but are virtually unaffected by chemical composition of fuels.
- All small scale fire tests underpredict CO yields. They cannot be used, thus, to predict toxic fire hazard for ventilation controlled post-flashover fires, unless CO yields are calculated by analogy with full scale fire test results. Such tests do not underpredict yields of other toxicants, such as hydrogen chloride or hydrogen cyanide.
- CO yields in full scale post-flashover fires are approximately 0.2 g/g, which translates to a toxicity of 25 mg/L. If this is combined with a margin of error of a factor of 3, the consequence is that any toxic potency (LC_{50}) higher than 8 mg/L (i.e. any toxicity lower than 8 mg/L) will be subsumed within the toxicity of the atmosphere, and is of no consequence. Thus, values ≥ 8 should be converted to 8 mg/L for reporting purposes.
- In order to correct small scale test data, the CO yield that should have been obtained can be calculated by making a CO correction.
- Toxic potency analyses show relatively small differences between materials, even in fires that have not reached flashover.
- The background for CO yield corrections are comprehensive studies of fire (and non fire) fatalities associated with CO[12-13]. By investigating almost 5,000 fatalities, they found:
    - Fire atmosphere toxicity is governed almost solely by CO levels, as victims of CO poisoning (non fire) die at virtually identical levels, after considering other factors. No universal lethal CO threshold level exists (previously it was thought to be 50% carboxyhemoglobin, COHb). Lethal levels depend on the victim age and physical condition; any blood COHb value > 20 % can produce lethality on its own.
    - Populations of fire and non fire victims of CO exposures are inherently very different: fire victims have a bimodal distribution, with maxima in much older and much younger victims, and suffer from more preexisting disease; non fire CO victims have a simple age distribution with a maximum at a middle age. Thus fire victims are more sensitive to CO than those in non fire exposures.
    - Fire fatality patterns before and after the plastics era are identical: using man-made materials for household goods has made no difference to fire atmosphere toxicity.

YIELDS OF COMBUSTION PRODUCTS AND THEIR IMPLICATIONS

As stated above, the single critical yield of combustion products needed to assess the toxic hazard in post-flashover fires is that of CO, which is 0.2 g/g. Other combustion product yields depend on the material burning and on the fire scenario; examples are shown in Table 1. The table illustrates the fact that quite a lot is known about the yields of carbon monoxide, from many materials and often under more than one circumstance. However, little if anything is known about yields of most other toxicants; particularly those of irritants. This is due, in part, to experimental difficulties involved in measuring minor combustion products (which require the use of new, complex and expensive, Fourier Transform InfraRed spectral techniques), and, in part, to the fact that not all combustion products have been, as yet, fully identified. Also of interest is the fact that an analysis of irritancy showed that the common irritants contained in fire atmospheres are not the most potent irritants found in fire atmospheres[14]. Thus, for example, halogen-free polyolefins, which do not release significant amounts of any of the materials considered typical irritant combustion products, were found to be 3-5 times more irritating than poly(vinyl chloride) materials intended for the same use (in this case wire and cable). In the work, a variety of combustion products were analyzed, with their known irritant effect, and yet the irritancy of the polyolefins could not be attributed to that of the compounds found. Thus, an analysis based on the well-known irritants, or even many of the measurable irritants, would lead users to ignore the actual major irritants present.

Table 1. Yields of Toxicants From Common Materials[8, 10, 14]

Material/Yield	CO (g/g)	HCl (g/g)	HCN	Irritants
General Flashover	0.2	Decay	Decay	?
PVC	0.06-0.07	0.25-0.40	-	HCl + I
PVC (flashover)	0.2	0.4	-	0.4
Polyolefins	0.08-0.10	-	-	(HCl + I) * 3
Douglas Fir	0.011-0.02	-	-	?
DFir (flashover)	0.2	-	-	?
FR Rigid Polyurethane	0.06-0.08	-	0.002-0.005	?
FR Rig PU (flashover)	0.2	-	0.005-0.011	?
Polystyrene	0.1-0.5	-	-	?
Polyphen. Oxide	0.1-0.3	-	-	?
Flex. Polyurethane	0.01	-	0.001	?
Ethyl. Vinyl Acetate	0.1-0.3	-	-	?
GR Polyester	0.1	-	-	?

Carbon monoxide is an asphyxiant toxicant, and the most common other asphyxiant toxicant is hydrogen cyanide. They act by inhibiting the normal distribution of oxygen to body tissues (especially the cardiovascular system and the brain), thereby causing hypoxia, and, if severe, eventual death by asphyxiation. The fatality occurs immediately following the exposure, if a sufficiently high dose is involved. On the other hand, irritant combustion products can have two principal effects. First, they can cause the more immediately noticeable sensory irritation, which results in an immediate painful sensory stimulation of the eyes, nose, throat and lungs, accompanied by upper respiratory tract damage, breathing difficulties and hypoxia. Second, they can cause deep lung inflammation and oedema, and perhaps eventual death due to impairment of respiration, usually several hours after exposure[15]. Inhalation toxicological exposure is always related to exposure dose, i.e. a certain exposure maintained over a sufficiently long period to cause an undesirable effect. Thus, thresholds must be based on the concept of dose, in other words the product of the concentration of a toxicant times the exposure time. Equation (1) is the traditional N-gas model prediction of smoke toxicity[10], where smoke is lethal if FED (fractional effective dose) is near unity:

$$FED = \frac{m[CO]}{[CO_2]-b} + \frac{[HCN]}{LC_{50}HCN} + \frac{[HCl]}{LC_{50}HCl} + \frac{[HBr]}{LC_{50}HBr} + \frac{\,}{21} \qquad (1)$$

The constants for use in Equation (1) (which refers to 30 min exposure) are:

m:	-18	Units: 1/ppm
b:	122,000	Units: ppm
LC_{50} HCN:	200	Units: ppm
LC_{50} HCl:	3,700	Units: ppm
LC_{50} HBr:	3,000	Units: ppm
LC_{50} O_2:	5.4	Units: %

Work in different organizations has shown that the individual effects of asphyxiants and of toxicants can be added in the N-gas model as shown in Equation (1)[10, 16, 17].

With regard to one specific irritant (the work addressed hydrogen chloride, but the finding is probably more general), "the data generated ... suggest that 820 ppm of HCl is lower than the threshold lethal concentration and concentrations of this level or less do not provide any additive toxicity in combination with other gases"[10]. This concentration value may not be exact, as combined effects of CO and HCl were found in another study[17], but is indicative of the existence of a minimum threshold before irritant gases start causing severe health effects. These low level effects of irritants, particularly on humans (generally the researchers themselves), were studied exhaustively around the end of the 19th century at European universities[18-22].

INCAPACITATION

Recent work, within the international standards community (namely a group of ISO TC92, Subcommittee 3 on Toxicity) has focussed on a different concept than lethality: incapacitation due to smoke. Unfortunately, this would create serious problems, that will be analyzed here. Normally, codes addressing fire safety, intend to protect building occupants so they do not die in fires (except people either responsible for the fire or in close vicinity to its initiation). For example, NFPA 101, Life Safety Code, states: “As related to fire safety, the objective of this Code is to protect the occupants not intimate with the initial fire development from loss of life and to improve the survivability of those who are intimate with the fire development.” This is a very logical, and achievable, objective. On the other hand, the draft document[23] (ISO DIS 13571) prepared by ISO TC92SC3WG5, states: “The ... protection, if occupant exposure should occur, is to ensure that the consequences of such exposure are not serious and that safe escape or refuge can be accomplished” and recommends “ ... establishing levels of exposure that would not be expected to seriously impede escape nor impair health”. Thus ISO DIS 13571 suggests a much higher level of fire protection to occupants than has ever been considered reasonable. The problem with such unreasonable protection, as will be shown here, is that it leads to imposing excessive (and unwarranted) limitations in the amount of material that can be used in an interior application for the type of life style that is now prevalent in developed countries. When incapacitation concepts are being used by the ISO working group, the draft document states: “The basic principle for assessing the irritant gas component of toxic hazard analysis involves only the *concentration* of each irritant. Fractional Effective Concentrations (FECs) are determined for each irritant at each discrete increment of time. Their sum at each time increment is then compared with a predetermined total FEC threshold value. If the total FEC value is greater than the threshold FEC, the incidence and severity of irritation effects for those exposed are considered to represent a significant potential for adversely affecting occupants’ safe escape.” See Equation (2) for the use of the FEC concept (exclusively looking at irritancy).

$$FEC = \frac{[HCl]}{IC_{HCl}} + \frac{[HBr]}{IC_{HBr}} + \frac{[HF]}{IC_{HF}} + \frac{[SO_2]}{IC_{SO_2}} + \frac{[NO_2]}{IC_{NO_2}} + \frac{[acrolein]}{IC_{acrolein}} + \frac{[f}{} \qquad (2)$$

The constants proposed by ISO DIS 13571 for Equation (2) (which has no time component) can be compared with literature data for lethal toxic potency (over a 30 min exposure).

IC HCl	100 ppm	LC_{50} (30 min)	3700 ppm[10]
IC HBr	100 ppm	LC_{50} (30 min)	3700 ppm[10]
IC HF	50 ppm	LC_{50} (30 min)	900-3600 ppm[24]
IC SO_2	15 ppm	LC_{50} (30 min)	300-500 ppm[24]
IC NO_2	25 ppm	LC_{50} (30 min)	60-250 ppm[24]
IC acrolein	3 ppm	LC_{50} (30 min)	140-170 ppm[24]
IC formaldehyde	25 ppm	LC_{50} (30 min)	700-800 ppm[24]

There is, however, no toxicological evidence that incapacitation of exposed victims ever occurs as a function of a certain concentration of any toxicant. In consequence, the concept of “FEC” has no technical validity and has not been proven with experimental studies. Moreover, this concept of incapacitation levels being lower than lethality levels, although logical on paper, is flawed in reality, when applied to irritants. It has been shown that irritants (such as hydrogen chloride or acrolein) do not cause incapacitation at dose levels so high that the victim eventually dies of inhalation toxicity after the exposure. This is a complex concept, but is critical: when primates have been exposed to doses of irritants at levels where they died a few days after exposure, they were still capable of performing the necessary avoidance responses to escape the exposure, thus not being incapacitated[25]. Interestingly, the concept of incapacitation is only applied to irritants; see Equation (2). Interestingly, it has also been found that incapacitation from asphyxiants occurs at levels very similar to those leading to lethality, and not at levels an order of magnitude lower[26].

The issue of decay of concentration of reactive combustion products (particularly hydrogen halides and other acids, most of which are included among typical irritants) has been studied in depth[27-34]. This has shown that the concentration, of hydrogen chloride, for example, can be much lower than the initial emitted levels after it has travelled some distance from the fire source (in some cases becoming undetectable). This issue must be considered when dealing with toxicity of combustion products, especially regarding incapacitation by irritants.

The ISO DIS 13571 draft raises a different, very interesting, and valuable, issue: people in a fire environment are affected by convected heat and by being unable to see due to smoke obscuration, as well as being affected by the toxicity of the atmosphere.

PRACTICAL IMPLICATIONS OF INCAPACITATION THRESHOLDS

Under the assumption that a typical 50 kW fire requires 0.19 m^2 (2 ft^2) of burning surface[35], it is possible to calculate the amount of the critical toxicant that would be emitted from such a surface burning for four different materials. The estimates were made based on the yields of combustion products found in the literature[10, 14] and on fire test data.[10, 36] The results indicate the following:

1. A small amount of PVC (corresponding, for example, to a floor cove trim 6 ft long and 4 inches wide) weighing 0.6 kg could not be used in a room, because it would drastically exceed the recommended level for IC HCl (100 ppm). However, when the material burns, its heat release rate is only ca. 20 kW, a level smaller than a burning waste basket. Such small fires are usually not reported to the fire departments, but controlled in house.
2. A similar amount of a halogen-free cross-linked polyolefin material (perhaps intended for a similar application) releases ca. 2.5 times the level of irritants. However, in spite of generating a much higher incapacitating level, the irritants it generates are of unknown composition, and thus not usually assessed by Equation (2), although they should actually be included in the term that has the summation of irritant concentrations (if the IC levels were known). From the point of view of a realistic fire hazard (namely heat release) such a material releases only 30 kW, still less than a burning waste basket.
3. A similar surface and thickness of fire retarded wood (with smaller mass, because of its lower density, which could also be used as interior trim) releases CO and virtually no irritants, and is thus unaffected by the assessment in Equation (2). From the point of view of a realistic fire hazard (namely heat release) this material releases 60 kW, making it a slightly more severe problem than the two earlier materials (and one that is likely to be reported), but still a small fire.
4. A similar surface (but at 10 times the thickness, to account for logical use as foam) also releases only asphyxiants as measurable combustion products, and thus is unaffected by Equation (2) (unless measurements of other gases are made). If a quarter of the HCN released had been converted to NO_2, this material would have exceeded the corresponding Equation (1). However, this material has very large heat release rate, so that now it is likely that a large fire has occurred, and not only has the fire department been notified, but severe destruction may have followed, via burning of adjacent materials/products.

This analysis indicates that a small amount of any material releasing notorious irritants (such as halogen acids, sulphur dioxide, nitrogen oxides, formaldehyde or acrolein) even if it causes a fire that is probably not even reported, would trigger the threshold for incapacitation of Equation (2). This would then indicate to a designer, architect, or specifier, that 1 kg of that material cannot be used in any compartment! The preceding analysis has ignored the fact that draft ISO DIS 13571, at the same time it contains illogically small threshold values for irritants, also contains equally illogical threshold values for asphyxiants. Thus, the problems discussed here can be extended to other materials.

Dr. Fredric Clarke has been the intellectual author of the analysis in the following paragraph, consequent to the fact that fires with small amounts of PVC cause incapacitation.

> NFPA data shows 54,000 residential fires, as reported to US fire departments between 1989-1993, where the material first ignited is wire and cable insulation or a wall covering, many (if not most) of which are made of PVC. Some 14,000 of the fires were big enough to spread beyond the room of fire origin (and thus reach flashover). Flashover fires where upholstered furniture was the item first ignited kill at least 10 people for each 100 fires, and it is logical to suppose that other residential flashover fires cause similar fatalities, and expose at least 10 times as many people. As < 1 kg of burning PVC is sufficient to cause incapacitation, it is logical to

assume that virtually all exposed people in a flashover fire became incapacitated, and most died. However, the actual number of fatalities in these fires was not 14,000, as results from this analysis, but a *miraculously low* 343 fatalities, more than 40 times less.

Table 2. What Happens When 0.19 m^2 (2 ft^2) of Four Different Materials Burn

Estimates	PVC	Non FR Polyurethane Foam	FR Douglas Fir	XL Polyolefin
RHR (kW)	20	350	60	30
Density (kg/m^3)	1490	100	550	1500
Thickness (mm)	2	20	2	2
Material Mass (kg)	0.6	0.4	0.2	0.6
Ht Combustion (MJ/kg)	12	25	15	20
Toxicant yield (g/g)	0.4 (HCl)	0.005 (HCN)	0.1 (CO)	> 1 * (irritant)
Burning rate (g/s)	1.5	14.9	3.7	1.4
Toxicant Emission (g/s)	0.6	0.07	0.4	1.7 *
Air Entrainment (L/s)	490	490	490	490
Toxicant Level (ppm)	900	100	500	2400 *
FED (Lethality) Toxicant	0.24	0.50	ca. 0.12	?
Exceeds ISO 13571 FEC?	Yes	No	No	No
Ht Hazard (Low is Best)	1	4	3	2

*: Based on the finding that the irritancy of the combustion products of such materials exceeds that of PVC combustion products by a factor of 3-5[14].

The thresholds in draft ISO DIS 13571 will not result in credit to a material that has been adequately fire retarded since they do not address fire performance properties of a material or product, including ignition resistance, lower heat release rate, lower burning rate or lower flame spread. In consequence, it appears clear that the implications of using those threshold levels would be that products made with combustible materials should be removed from inhabited areas, and replaced by ones made with non combustible ones (steel, concrete, ceramics). This would, of course, be very welcome by hermits desirous of an ascetic life in a cave, but not by those wishing the comforts of modern life.

ASSESSMENT OF FIRE HAZARD IN POST-FLASHOVER FIRES

The procedure of conducting a fire hazard assessment of the toxic fraction of smoke in a post-flashover scenario requires developing fire safety objectives, choosing detailed fire scenarios, applying relevant additional assumptions, making calculations and then incorporating all calculations into an overall hazard assessment. The primary fire safety objective when assessing toxic fire hazard in post-flashover fires is to ensure the safe evacuation of all occupants in a post-flashover fire scenario. Then, a second fire safety objective, is to maintain a safe working environment for safety personnel, including fire fighters. The primary fire safety objective is achieved if the time required, in the event of a fire, to evacuate the people in compartments remote from the fire, is less than the time for the fire to create untenable conditions (ideally for the fire not to create conditions causing harm to people, whenever possible). Evacuation time includes the time required for people to reach, or be transported to, a safe location. Time to untenability is calculated based on the shortest time until untenable conditions are created for an occupant along the evacuation path. Tenability is assessed on the basis of fire effects on humans, including both direct effects, such as heat, toxic gases or lack of oxygen, and indirect effects, such as reduced visibility due to smoke obscuration. A tenable environment will therefore prevent loss of life and reduce the likelihood of harm, including non-fatal injury to people. Levels of tenability must be set based on literature data that show: the maximum temperatures which human beings can withstand, the maximum convected heat humans can tolerate, the heat flux required to blister or burn skin, the restrictions to escape imposed by smoke obscuration, the effects of the primary toxic gases, the overall effects of smoke toxicity or various ways to combine one or more of these effects. The documentation for HAZARD I[37-38] contains data that can be used safely, if no specific information is available to suggest that some of the information needs to be changed.

This fire hazard assessment procedure does not assess incapacitation. Incapacitation must be inferred from lethal toxic potency values. Moreover, the effects of sensory irritation are not addressed by this procedure, as the above discussion indicated that such an assessment is flawed.

The two critical fire scenarios to be investigated are: a fire that originates in the room immediately next to the room of interest and a fire that originates in another room, further away from the room of interest, and endangers the evacuation route from the room of interest through the spread of flames or smoke into the evacuation route. This assumes that other fire scenarios either are less severe and therefore will lead to achievement of the fire safety objectives if the design achieves the objectives for the specified fire scenarios, or are sufficiently unlikely that they need not be considered as part of the overall fire hazard assessment, although they may be considered individually. Additional assumptions must also be made. These must include the occupancy of the room of interest and any other relevant occupiable spaces to which occupants may move during evacuation. It is critical to set them, for analysis purposes, to levels that pose the greatest challenge to the fire safety objectives. Thus, a logical assumption would be occupancy to capacity and a mix of occupants of different abilities (where some will have various physical or mental disabilities) and capabilities (for example, some will be assumed to be impaired by alcohol or drugs or by age-related limitations). The assumptions regarding age distributions of the occupants must reflect data on age patterns relevant to the occupancy class based on patterns in the general population, or known applications, if they differ. Assumptions regarding alcohol or drug impairment among occupants should also be based on patterns in the general population, weighted to reflect the age and economic distribution of known occupants. If such data are not available, conservatively assume 10 % of adult occupants are impaired by alcohol.

The calculations for the toxic hazard fraction of post-flashover fires should be done as follows. For post-flashover fires, the toxic potency of materials of "normal toxicity" can be, as indicated above, assigned a value of 8 g/m^3 (for a 30 min exposure period) (see ASTM E1678)[39] or NFPA 269[40]. The smoke layer in a post-flashover fire can be assumed to have endured a CO generation corresponding to 20% of the overall mass loss during the fire. The actual concentration of CO, and that of overall smoke, should be calculated, minute by minute, based on the fuel mass loss during the fire. The toxic potency of CO can also be assigned a value of 8 g/m^3 (for a 30 min exposure period). It can also be assumed that the concentration-time curve for smoke of "normal toxicity" is linear, so that lethality is associated with a toxic load of 240 g min/m^3, so that lethality would be expected once the exposure concentration exceeds 240 g/m^3. Using information on the fire itself (in particular the mass loss as a function of time) and of the fire scenario, the toxic load should be calculated in the room of fire origin and in the room of interest, in the absence and presence of the product being investigated.

The complete fire hazard assessment (which should preferably follow the guidelines shown in ASTM E1546[41]) then involves using one or more additional calculation procedures to determine whether the fire safety objectives will be met. Such calculations assess the overall fire hazard, specifically those aspects of the tenability dealing with thermal exposure (both radiant and convected heat) and smoke obscuration. As explained before, choices can be made on tenability levels and calculation procedures for their assessment, as input to generate a valid fire hazard assessment. This must be followed by:

(a) Translation of the fire scenario specifications into a description of the fire in its initial stages, as a function of time in the initially involved space. The fire-test-response characteristics of the materials or products initially involved that should be considered for such a description are rate of heat release, rate of mass loss, total heat release (if burned to completion, or cumulative heat release to end of burning otherwise), flame spread, cumulative full-scale smoke obscuration and toxic potency of the products of combustion released. A thorough analysis of the actual fire scenario should result in a final decision on the properties required for the fire hazard assessment. The data to be used for this fraction of the calculation must come from test methods that both can represent the fire scenario being investigated and generate data in fire safety engineering units. Typically, such data is measured in heat release rate calorimeters. See, for example[42-56], guidance in ASTM E603, upholstered furniture testing in ASTM E1537, mattress testing in ASTM E1590, cable testing in cable trays in ASTM D5424 and ASTM D5537, interior finish testing in a room corner configuration in NFPA 265, NFPA 286 or ISO 9705, stacked chair testing in ASTM E1822, foam display testing in UL 1975, or small scale testing in ASTM E1354 (generic cone calorimeter) or its applications: ASTM E1474 (upholstered furniture or mattress composites), ASTM E1740 (wall covering composites), ASTM F1550 (vandalized mattresses in prisons), ASTM D6113 (electric materials).

(b) Translation of the design specifications into characteristics of the fuel load environment near the initial fire. These and the time-based description of the initial fire as a function of time should be used to calculate the spread of fire to secondary items and the ignition of those secondary items.

(c) For each space, the time at which the major fire events occur must be assessed. This should include the onset of flashover; and fire spread from one space to an adjacent space, whether through barriers or not, particularly from outside the room of interest. The calculation of fire spread from one space to another will require measurement of barrier fire resistance characteristics.

(d) For each potentially exposed occupant, calculations must be made of the time to reach safe refuge and this must be compared to the calculated time until exposure to an unacceptable potential for harm (hazard). The former requires calculation of occupant alerting, response, travel speed, and other behavior. For occupants requiring rescue, calculations will need to estimate the size, capabilities, and arrival time of fire department or other rescue personnel. The latter can be calculated as time to exposure to untenable cumulative doses of fire effects or conservatively calculated as time to first exposure to unacceptably hazardous fire conditions. Calculations will be required for the area of fire origin, any occupied spaces, and any spaces that are part of escape or rescue routes.

(e) It is critical to incorporate the activation and effects of fire protection systems, including automatic or manual fire suppression, detection, and smoke control systems.

(f) It is also critical to develop "safety factors" needed to offset the uncertainties and biases associated with the method or with the data used by the method. Any calculation method is valid only for certain applications and within the limits of its own uncertainties and biases and the uncertainties of its source data. Therefore, evidence of validity from the calculation method documentation will provide the basis for specifying safety factors.

In summary, the overall effect of the product being investigated on fire hazard is a combination of its effects on the toxic tenability and on other types of tenability investigated.

CONCLUSIONS

- Fire hazard (which is "the potential for harm associated with a fire") is associated with the critical fire properties of the materials and products contained in the fire scenario and that can prevent or inhibit the escape of exposed people. These are, primarily, heat release, burning rate, flame spread and smoke production tendency (of all materials or products) and ignitability (of materials or products adjacent to the material first ignited).
- The use of Fractional Effective Doses for assessment of lethal toxicity is very reasonable, while the use of Fractional Effective Concentrations (with threshold levels causing "severe effects" for incapacitation, and no time component) is not based on scientific data but on speculative assumptions, which this work has proven to be inadequate.
- The levels of combustion products causing incapacitating levels are known in a significant number of cases: they are marginally smaller than those levels causing lethality (for common asphyxiants) and higher than those levels that will eventually cause post-exposure lethality (for many irritants). Assumptions that make them orders of magnitude smaller than lethal levels have no basis in scientific fact, and result in unrealistic material usage thresholds.
- The analysis of combustion product yields in this work shows that the concept of critical irritant concentrations, and the associated recommended threshold values, would lead to severe restrictions (and almost bans) in the use of the combustible materials and products which are generating the comforts with which modern life has been associated in recent years.
- A toxic fire hazard assessment in pre-flashover fires must consider lethal levels of toxic products, as they have been assessed adequately, and can be combined by the N-gas model, irrespective of whether they are asphyxiants or irritants.
- A toxic fire hazard assessment must consider first scenarios causing most fire fatalities, i.e. post-flashover fires. In such cases, material selection should ensure that mass loss, heat and smoke release are minimized, as toxicity is a direct result of mass loss: CO dominates post-flashover toxicity, and its yields are 20% of the mass of the combustible materials burning.
- The detailed procedure presented shows how to assess fire hazard for post-flashover fire scenarios, emphasizing smoke toxicity, but within the context of fire safety engineering concepts. This subsumes smoke toxicity as one element, together with heat release and other fire

properties, to assess a realistic time to escape. ***Thus, the answer to the question in the title is: post-flashover fire hazard is the critical issue, and not incapacitation via irritancy.***

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GBH Attachment 11

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Fire Retardance, Smoke Toxicity and Fire Hazard

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ABSTRACT

Fire fatalities are usually reported as resulting from smoke inhalation. However, the real cause of most fire fatalities is the fire, which generated enough combustion products to create a lethal atmosphere. It is known that mass loss rate and amounts of smoke and combustion products produced are directly correlated with heat release rate. Moreover, improved flame retardance decreases the heat released by the resulting products. Thus, if products are adequately flame retarded they will result in lower levels of toxic gas emissions. However, increased smoke toxicity can result if the fire performance is inadequate for the expected insult.

A recent statistical study, involving almost 5,000 fatalities, showed that the vast majority of fire deaths are attributable to carbon monoxide poisoning, which results in lethality at concentrations much lower than previously believed. Moreover, the same study showed that blood carbon monoxide loadings in fire victims have not changed significantly from the days in which synthetic materials did not exist. Other studies showed that carbon monoxide yields (but not concentrations) in big fires are almost independent of the chemical composition of the material burning.

Consequently, both the toxicity of the overall smoke in real fires and the resulting fire hazard will decrease if products are designed with the proper fire performance for the intended application.

INTRODUCTION

In order to understand, and put into perspective, the smoke toxicity of plastic compounds it is essential to follow a pattern of research that has led to the level of knowledge of fire, smoke and toxicity in the 1990's.

A large number of smoke toxicity test methods have been proposed over the years to investigate the toxic potency of the smoke from materials [e.g. 1-6]. As well as the tests mentioned, most of which involve some type of animal bioassay, a fairly popular test, particularly used in specifications of halogen-free materials, has been the analytical test developed by the Royal Navy [7].

Extensive amount of published data exists on the toxic potency of the smoke resulting from many materials using one or more of these methods. Unfortunately, it is often the case that the published information is not specific (to a large extent due to the needs of commercial confidentiality) as to formulation details of the material which was tested. Consequently, as a manufacturer develops a new material, testing must be repeated, at a considerable added expense. This is very often unproductive, for one of three reasons:

- It may lead to data which is statistically indistinguishable from the published information: new testing was then simply a waste of money.
- It may lead to data which is statistically distinguishable but toxicologically indistinguishable: new testing then results in the promulgation of marketing ploys which add nothing to fire safety.
- It may lead to the new data appearing to show an improvement in one fire property (smoke toxicity), but obtained at the expense of a (often hidden) deterioration in another fire property (such as heat release or flame spread): new testing then resulted in lower fire safety.

Separately, the fire performance and the smoke toxicity of materials have also been the focus of numerous investigations, with recent work being able to focus on those fire properties most applicable to fire hazard assessment. There has been considerable speculation with regard to the relative importance, or lack of it, of smoke toxicity test data. In particular, the effect on fire performance of adding fire retardants has been very controversial.

There has been a desire, on the part of those interested in fire hazard, in combining what is known from the abundant tests carried out on the smoke toxicity of materials, the practical experience from full scale fires and the fire modelling capabilities available today. The most important results of this type of work were obtained at the National Institute for Standards and Technology. This involved several stages: comparison of products made with fire retarded and non-fire retarded materials [8], the analysis of the carbon monoxide (CO) yields in large full scale fires [9], then the study of full scale testing of materials (including a rigid PVC compound) and a comparison with small scale test results [10] and finally the development of a small scale radiant test for toxic potency measurement [11]. This work needs to be understood in the perspective of an analysis of the effects of carbon monoxide, the most hazardous component of real fire atmospheres, on fire victims, as carried out by a comprehensive study of fire and non fire fatalities [12-13].

This paper will make an analysis of the proper way to carry out an analysis of material smoke toxicity, and look at the effects of fire retardants on both smoke toxicity and fire hazard.

SMOKE TOXICITY TEST METHODS

The majority of smoke toxicity tests, at least in the United States, are based on the use of animal bioassays to determine the end-point. The most common animal model used is the rat, used in the NBS cup furnace test [1], and in the various radiant tests developed from it [4, 11-14]. Two of the more prominent tests used for regulation, however, use as an animal model the mouse: the DIN 53436 test [2], used in Germany, and the UPITT test [3], used in New York (USA). This is rather unfortunate, since it has been shown that the mouse is an excessively sensitive animal [13-15]. In particular, the mouse is 4-10 times more sensitive than the rat towards irritant gases, like hydrogen chloride, but has similar sensitivity towards common asphyxiants, like carbon monoxide [15, 17-18], which are the most important smoke toxicants.

A few years ago a comparative investigation was made [17] of four test methods: the UPITT test [3], the NBS Cup furnace test (flaming and non flaming mode) [1] and the radiant apparatus, in the protocol suggested by Dr. Stephen Packham [4]. The five materials investigated were all wire and cable compounds: four poly(vinyl chloride) (PVC) materials and a nylon compound. The PVC materials were a conventional jacket compound, a conventional insulation compound, and two jacket compounds with progressively higher levels of acid retention catalysts. It was found that, although there are some serious deficiencies with using any such tests for making fire safety decisions, the UPITT test was particularly flawed. Since then, further information on the inappropriateness of the UPITT test method, particularly for predictions or use in fire hazard analyses, has been forthcoming [18-20]. However, unfortunately, the test is being used for regulatory purposes in the USA, both in the state of New York and in the city of New York.

More recently, a new investigation was carried out to compare the results of various smoke toxicity tests, using the same materials for all tests [21]. The materials chosen were a flexible PVC wire and cable compound used in the earlier work [17] and three components of a new family of vinyl thermoplastic elastomer alloys. These vinyl alloys have excellent fire performance, both in terms of heat release and of smoke release [22]. In order to investigate whether the smokes from these materials were in the "common" range, just as those of the more traditional vinyl materials had been found to be, they were also subjected to several toxic potency tests. The tests chosen were the NBS cup furnace (flaming and non flaming), the UPITT test (as before) and the latest variants of the radiant equipment apparatus: the NIST radiant toxicity test [10-11] and the NIBS test [14, 23-25]. The results showed: (a) that the NIBS and the UPITT tests were the least satisfactory procedures, (b) that there was no significant difference between the toxic potency of all the vinyl materials used and (c) that the smoke toxicity could be reasonably well predicted from the results of analytical studies of gas emissions.

There is, in modern times, a logical reluctance to use animals for research, unless they are essential. In view of the fact that, for many combustible materials, the smoke toxicity can be ascribed mainly to a few individual gases, there has been a tendency to use tests which do not include animal bioassays. In order to be able to properly characterize smoke toxicity by chemical analysis two issues must be taken into account: use of a fire model that properly represents a certain stage in a fire and use of toxicity indices for individual toxicants which have been validated against actual animal experiments (of which there have been an abundance). One potential problem with chemical analysis tests is that they do not offer an adequate degree of assurance that a "supertoxicant" cannot "filter through". Virtually no supertoxic smokes have been discovered in years of testing. However, a few materials have been found which generate smoke much more toxic than would be calculated from the sum of the concentrations of the common toxic gases. A potential compromise is the use of analytical methods, which are validated, occasionally and for untested materials, with animal experiments.

There are two additional problems with some of the existing toxic potency tests which do not use an animal model: the fire model and the "toxicity indexes" used. The most prominent smoke toxicity test using chemical analysis is NES 713 [7]: it does not generate adequate results, because both the fire model and the toxicity indices are flawed. In particular, the toxicity indices are geared towards producing "unacceptably" high values for materials containing halogens. Other tests using chemical analysis of smoke gases are recent versions of tube furnace tests (such as the DIN 53436 test). In those cases, it is purely the fire model that is flawed, while adequate toxicity indices are being used today.

FIRE HAZARD AND HEAT RELEASE

It has been shown, in recent times, that the most important fire property is the rate of heat release [e.g. 26], since it is the one that both governs the intensity of a fire, and the survivability in a fire scenario. Table 1 illustrates this fact, by determining survival time (through computer modelling) in a standard room, with a common chair. When the chair is made of a material with half the time to ignition, the survival time does not change. Similarly doubling the toxic potency of the chair materials has very little effect on survival time, while doubling the rate of heat release immediately decreases, by a factor of over 3, the survival time. This is a very important concept, because it starts putting into perspective the importance (or lack of it) of smoke toxic potency data in terms of fire hazard assessment, or simple of fire safety.

One of the most important studies that has illustrated this concept is the NIST work on the comparison between fire retarded and non fire retarded versions of the same product [8]. In this work, done by NIST for the Fire Retardant Chemicals Association (FRCA), five different categories of products were assembled and tested in full-scale room fires. In one series, all five products were fire-retardant, whereas in the other series the same base polymers were used, but without fire retardant agents. The products tested were: upholstered furniture mock-ups, business machine housings, television housings, electric cables, and electronic circuit board laminates. The most interesting results were those from the full scale fire tests, which also helped to identify the importance of heat release rate as the most important physical variable in these tests which is a predictor of the fire hazard. Table 2 shows the most important results of the burns. During the first burn carried out with the fire retarded products under the same conditions as the non fire retardant products (a single 50 kW burner) very little combustion took place. Thus, all successive tests with the fire retarded included an additional 120 kW burner, which allowed all the products to burn.

In the study, the use of the fire retarded products, which was associated with an average 4-fold decrease in rate of heat release led to a three-fold decrease in smoke toxicity in the room, and to a ten-fold increase in tenability time (even though the ignition source used was over three times as intense). This is a clear indication that considerable improvements in toxicity will be obtained by decreasing the heat release rate of the materials/products considered, almost irrespective of the actual toxic potency of the materials/products involved. Thus, toxic hazard is a direct function of heat release rate, provided there has been proper flame retardancy. In contrast, in at least one other study no improvement in toxic hazard was found following the use of materials (upholstered furniture) containing fire retardants [27]. An analysis of the materials involved indicates that the so-called fire-retarded materials simply contained very low levels of flame retardants, insufficient to make a substantial difference to the heat release rate of the final product. Thus, no real improvement in fire performance occurred, resulting to no improvement in toxic hazard.

HEAT RELEASE EFFECTS FEASIBLE ON ADDITION OF FIRE RETARDANTS

Table 3 is a compilation of a few of the data available wherein the same basic material was tested, using the same technique before and after the addition of flame retardants. The data indicates that, in fact, considerable improvements in rate of heat release are commonplace, including increases of over 10-fold. The range of materials presented in the table is also very broad, including thermoplastics, cross-linked materials, thermosets and cellulosics. This is crucial data, because it indicates that the effect of fire retardants can, indeed, lead to great improvements in smoke toxicity. In order to understand its further implications with respect to smoke toxicity, it is essential to investigate toxic potency ranges for different materials.

TOXIC POTENCY OF SMOKE AND FIRE HAZARD

The following is now widely accepted [8-13]:

- Most fire fatalities occur in fires that become very large. In fact, US statistics indicate that such fires account for over six times more fatalities than all other fires.
- Carbon monoxide concentrations in the atmospheres of flashover fires (the fires most likely to produce fatalities), are determined by geometric variables and oxygen availability, but are virtually unaffected by chemical composition of fuels.
- All small scale fire tests underpredict CO yields. They cannot be used, thus, to predict toxic fire hazard for ventilation controlled flashover fires, unless CO yields are calculated by analogy with full scale fire test results. Such tests do not underpredict yields of other toxicants, such as hydrogen chloride or hydrogen cyanide.
- CO yields in full scale flashover fires are approximately 0.2 g/g, which translates to a toxicity of 25 mg/L.
- Toxic potency values from the new NIST radiant small scale test (with rats as the animal model, but used only for confirmatory purposes) is well validated with regard to toxicity in full scale fires. However, such validation cannot be done to a better approximation than a factor of 3.
- The consequence of this is that any toxic potency (LC_{50}) higher than 8 mg/L (i.e. any toxicity lower than 8 mg/L) will be subsumed within the toxicity of the atmosphere, and is of no consequence. Thus, values 8 or greater should be converted to 8 mg/L for reporting purposes.
- In order to correct small scale test data, the CO yield that should have been obtained can be calculated by making a CO correction.
- The background for the corrections of CO yields are based on the comprehensive study of fire (and non fire) fatalities associated with CO [12-13]. This study, of almost 5,000 fatalities, found that:
  - The toxicity of fire atmospheres is determined almost solely by the amount of CO, since victims of poisoning by pure CO die at virtually identical levels, once other factors have been considered. There is no universal lethal CO threshold level (which was previously thought to be 50% carboxyhemoglobin, COHb). This

depends on the age and physical condition of the victim. Any blood COHb value > 20 % can produce lethality on its own.

- The populations of victims of fire and of non fire CO exposures are inherently very different: fire victims are both much older and much younger, and suffer from more preexisting disease. Thus fire victims are more sensitive to CO than those in non fire exposures.
- A comparison of fire fatalities before and after the plastics era indicates that the use of man-made materials to make household goods has made no difference to fire atmosphere toxicity.

Thus, instead of exposing animals, Equation 1 is a predictor of smoke toxicity, where smoke is lethal if FED (fractional effective dose) is near unity:

$$FED = \frac{m[CO]}{[CO_2]-b} + \frac{[HCN]}{LC_{50}HCN} + \frac{[HCl]}{LC_{50}HCl} + \frac{[HBr]}{LC_{50}HBr} + \frac{21-[O_2]}{21-LC_{50}O_2} \qquad (Eq.\ 1)$$

The constants for use in Equation 1 (which refers to 30 min exposure) are:

m:	-18	Units: 1/ppm
b:	122,000	Units: ppm
LC_{50} HCN:	200	Units: ppm
LC_{50} HCl:	3,700	Units: ppm
LC_{50} HBr:	3,000	Units: ppm
LC_{50} O_2:	5.4	Units: %

if concentrations of carbon dioxide are 5% or less. If there is over 5% carbon dioxide, m = 23 and b = -38,600. If there is 3-5% carbon dioxide (normal range to be expected in a large fire), the LC_{50} of carbon monoxide will range between 5,100 and 4,000 ppm. The other terms in the equation are the concentrations of carbon monoxide, hydrogen cyanide, hydrogen chloride, hydrogen bromide (all in ppm) and oxygen (in %). It must be pointed out that, if the data is to be used for flashover fires, [CO] must be corrected (as discussed above), using Equation 2, giving the added [CO]:

$$\Delta[CO] = 0.2 - \frac{[CO] \times 0.200}{m_{100}} \times \frac{28}{24.5 \times 10^6} \qquad (Eq.\ 2)$$

The toxic potency (LC_{50} (corr)) to be used for flashover fires is calculated by using the corrected CO concentration, or directly with Equation 3:

$$LC_{50}(corr) = \frac{1}{\frac{1}{LC_{50}} + 44x10^{-3} - 5.0x10^{-5}\ \frac{[CO]}{m_{100}}} \qquad (Eq.\ 3)$$

where LC_{50} values are in mg/L and m_{100} is the mass of specimen burned (in g).

With all these considerations, it is clear that there is now an appropriate procedure for smoke toxicity testing, which can then be used for input into hazard analyses. It consists of carrying out analytical experiments, using the NIST radiant toxicity test. Moreover, if the material has a chemical composition very similar to that of a material that has already been tested, further testing is unnecessary. Animal testing is purely a confirmatory check or for those cases where no experience with similar materials.

Table 4 shows test results with the radiant apparatus [10-11] for a large number of materials, with very different chemical composition, both before and after CO correction. The results are extremely satisfactory in two ways: first, because they show that the method is applicable to many different materials and second, because all materials tested have a smoke toxic potency lower than that of pure CO, indicating that they are of "normal smoke toxicity".

The chemical analysis technique cannot, to date, identify the major toxicants associated with the smoke of fluoropolymers, which are none of the simple gases mentioned above. This is, usually, of little consequence for real fires because fluoropolymers, which generally have very good fire performance, will rarely burn on their own, so that the toxicity of the fire atmosphere is probably dominated by that of the other fuels present.

CONCLUSIONS

- Fire hazard is primarily a function of the rate of heat release of the materials or products involved. The importance of heat release rate vastly exceeds that of smoke toxic potency.
- Heat release rate can be decreased by factors of 10 or more by using flame retardants.
- Adequate smoke toxicity testing techniques show that most materials are of very similar smoke toxic potency (at least lower than the carbon monoxide inevitably present in large fires).
- Therefore, adequate flame retardance considerably decreases fire hazard, by decreasing heat release rates and improving time to escape.

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Table 1. Effects of Different Properties on Survival Time

Product	Survival Time
Primary chair	Over 10 min
Double ignitability	Over 10 min
Double toxic potency	Over 10 min
Double heat release rate	3 min

Table 2. Effects of Flame Retardant Additives on Smoke Toxicity

Products	Peak Temp (°C)	Smoke Toxicity (kg CO)	Tenability time in room: Burn (s)	Target (s)	CO yield (kg/kg)	Pk RHR (MW)
non-FR	> 600	21	110	200	0.22	1.59
non-FR	> 600	17	112	215	0.18	1.54
non-FR	> 600	16	116	226	0.14	1.79
FR 1B	185	2.6	NA	NA	0.22	0.22
FR	273	5.5	1939	NA	0.23	0.37
FR	285	6.1	2288	NA	0.23	0.35
FR	334	5.6	1140	1013	0.23	0.45

Notes: Peak Temp: maximum temperature in burn room; Smoke Toxicity: level of toxicity, calculated in equivalent mass of carbon monoxide; Tenability Time in room: time to reach untenable conditions in burn room or target room (via smoke toxicity or by having reached flashover, i.e. temperatures over 600°C); CO yield: mass of carbon monoxide formed per mass of fuel burnt; Pk RHR: maximum heat release rate in room; non-FR: non fire-retarded products; FR: fire-retarded products; FR 1B: fire retarded products without an auxiliary burner.

Table 3. Comparison of Heat Release Rate Data for FR and Non FR Materials

Material	Heat Flux kW/m^2	NFR Pk RHR kW/m^2	FR Pk RHR kW/m^2	NFR/FR Ratio -	Test
ABS (+ FR1)	20	614	224	2.7	Cone
ABS (+ FR1)	40	944	402	2.3	Cone
ABS (+ FR1)	70	1311	409	3.2	Cone
ABS (+ FR2)	20	614	224	2.7	Cone
ABS (+ FR2)	40	944	291	3.2	Cone
ABS (+ FR2)	70	1311	419	3.1	Cone
EVA (Cross-linked)	30	463	110	4.2	Cone
EVA (Thermoplastic)	30	574	83	6.9	Cone
HDPE	30	1803	114	15.8	Cone
HDPE # 2	50	1167	476	2.5	Cone
LDPE	20	913	88	10.3	Cone
LDPE	40	1408	192	7.3	Cone
LDPE	70	2735	268	10.2	Cone
Polypropylene	30	1555	174	8.9	Cone
PVC Rigid	20	102	25	4.0	Cone
PVC Rigid	40	183	84	2.2	Cone
PVC Rigid	70	190	93	2.1	Cone
PVC Rigid # 2	30	98	42	2.3	Cone
PVC Rigid # 3	30	118	56	2.1	Cone
PVC Wire & Cable	20	116	9	12.8	Cone
PVC Wire & Cable	40	167	64	2.6	Cone
PVC Wire & Cable	70	232	100	2.3	Cone
PVC Wire & Cable # 2	20	116	72	1.6	Cone
PVC Wire & Cable # 2	40	167	92	1.8	Cone
PVC Wire & Cable # 2	70	232	134	1.7	Cone
Particle Board	25	151	66	2.3	OSU
Particle Board B (+FR 1)	25	160	70	2.3	Cone
Particle Board B (+FR 1)	50	227	141	1.6	Cone
Particle Board B (+FR 2)	50	227	52	4.4	Cone
Plywood	25	114	43	2.7	Cone
Plywood	50	150	75	2.0	Cone
Polyester	30	186	95	2.0	Cone
Polystyrene	20	723	277	2.6	Cone
Polystyrene	40	1101	334	3.3	Cone
Polystyrene	70	1555	445	3.5	Cone

Note: Cone: ASTM E1354 (Cone calorimeter); OSU: ASTM E906 (Ohio State University rate of heat release calorimeter)

Table 4. NIST Radiant Toxicity Test Results

SPECIMEN	LC_{50} mg/L	Corr LC_{50} mg/L	
ABS	17.8	11.8	
Acrylic F + MELFM	9.6	6.9-8.2	
Ceiling tile	30.5	21.9	
Composite	20.0	not provided	
Cork	ca. 40	not provided	
Dg FIR	100-200	21-23	
Dg FIR	56.0	21.0	
Dg FIR (full scale)	> 70	> 70	
FLX PU FM	52.0	18.0	
MELFM	12.5	8.0	
Nylon	36.7	17.0	
Nylon Rug (Tr)	28.5	14.2	FED 1.2
Nylon Rug (Tr)	42.9	18.1	FED 2.0
Nylon Rug (Un)	> 41	> 16	
PVC CB	36.0	not provided	
PVC INS	33.4	22.7	
PVC INS	29.2	14.9	
PVC JK	53.1	25.9	
PVC Lw HCl	146.9	28.8	
PVC Md HCl	86.2	26.7	
PVC PRF	26.0	16.0	
PVC PRF	20-30	13-17	
PVC PRF (full scale)	35-45	35-45	
Particle board	120-138	not provided	
Rg PU FM	22.0	14.0	
Rg PU FM	20-30	14-19	
Rg PU FM (full scale)	30-40	30-40	
Vinyl F	32.0	19.0	
Vinyl F + MELFM	26.0	15.0	
Vinyl FLR	82.0	not provided	
VTE 1 - 6	18.2	10.9	
VTE 2 - 3	45.9	16.9	
VTE 3 - 2	35.8	15.4	
Pr Full		8.0	

Legends: Acrylic F: Acrylic fabric; Composite: Naval composite board; Dg FIR: Fire retarded Douglas fir board; FLX PU FM: Flexible polyurethane foam; MELFM: Melamine polyurethane foam; Nylon: Nylon Wire coating compound; Nylon Rug (Tr): Rug treated with PTFE coating; Nylon Rug (Un): Untreated rug; Pr Full: Predicted Carbon Monoxide Post Flashover Toxicity; PVC CB: PVC cable insulation; PVC INS: traditional PVC wire insulation compound; PVC JK: traditional PVC wire jacketing compound; PVC Lw HCl: PVC jacket compound & abundant amounts of acid retention filler; PVC Md HCl: PVC jacket compound & moderate amounts of acid retention filler; PVC PRF: Rigid PVC profile; Rg PU FM: Rigid polyurethane foam; Vinyl F: Vinyl fabric; Vinyl FLR: Vinyl flooring over plywood.

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GBH Attachment 12

AB59-COMM-7-12

Comparison of Smoke Release Data from Full Scale Room Tests with Results in the Cone Calorimeter and the NBS Smoke Chamber

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ABSTRACT

Some modern small scale tests are now known to be very adequate predictors of real scale product fire performance, particularly in terms of heat release and flame spread. The best studied example are wall lining materials. It is, as yet, unclear whether prediction of large scale smoke obscuration results from small scale test data is equally possible.

Seven materials were tested in a full scale room corner configuration. The room used was 2.4 by 4.0 m, at a height of 2.4 m, with a standard 0.9 by 2.1 m high door. The panels tested were 1 m each side of the corner and 2.3 m high, with a 6.3 kg wood crib as heat source. The materials used had diverse chemical compositions. The thickness of the samples used were those of their potential use, and ranged from 1.2 to 3.2 mm. Heat release, smoke obscuration, temperatures at the doorway, mass loss of sample, mass of smoke and concentrations and yields of carbon oxides were among the measurements made.

All the materials were also tested in the NBS smoke chamber (ASTM E662, flaming mode, at the standard incident flux level of 25 kW/m^2) and in the cone calorimeter (ASTM E1354), horizontally at incident fluxes of 20, 25, 40 and 70 kW/m^2.

In three of the large scale tests, the mass lost by the sample was lower than the mass of the wood crib used for ignition. Those three tests were the ones that gave least smoke.

For comparison purposes, some results from a different laboratory were compared with those reported here. Some proposed predictive measures were cursorily investigated. Overall, it appears that trends for total smoke release are similar, at least to a very rough first approximation, to those obtained simply from the peak rate of heat release of the cone calorimeter at an incident flux of 25 kW/m^2. Other predictive measures tested are poorer.

INTRODUCTION

An important issue, which has never been addressed properly, is the prediction of full scale smoke obscuration results from small scale test data. The traditional way of doing this has been by means of the NBS smoke density chamber (known by various names, e.g. ASTM E662, ASTM F814, NFPA 258, BS 6401, NES 711). It has been shown, extensively, that the results from this test are not adequate predictors of full scale smoke release [1-6].

However, it can be predicted that standard smoke obscuration results from other small scale tests, even if they have an excellent fire model, like the cone calorimeter (ASTM E1354, ISO 5660) [7-8], can probably also not be used in isolation to predict full scale smoke obscuration. This work has been carried out to investigate how well standard data from the cone calorimeter and from the NBS smoke chamber test can be used as a direct predictor of full scale smoke obscuration.

EXPERIMENTAL

A series of seven materials, which have potential uses as wall linings, have been tested in three configurations:

- Full scale room corner test (with a 6.3 kg wood crib, non standard)
- NBS smoke density chamber (flaming mode), at a flux of 25 kW/m^2.
- Cone calorimeter, at 20, 25, 40 and 70 kW/m^2, horizontally.

The materials used will not be identified, because the objective of this work is to study test methods and not to compare the fire performance of materials. It is important to not, however, that all the materials used were chosen to have sufficiently adequate fire performance so that it is expected that they will not spread flame easily, in the absence of an external heat source. Thus, all the materials have either intrinsically good fire performance or have been treated so that they have become adequately fire retarded. Their overall chemical composition varied widely, and including some containing chlorine, nitrogen, bromine and no heteroatom. They were all used at a potential use thickness.

Full scale test:

A concrete block test room was used, which measured 3.95 m x 2.42 m by 2.35 m height, with a single door opening, measuring 0.90 m wide by 2.13 m high. The panels of materials attached to the walls of the room were 2.3 m x 2.0 m, half of which was attached at either side of the corner. The width of the exposed panel was relatively small because of the expected adequate performance. All the materials were exposed to the heat from burning wood cribs, weighing 6.3 kg, with ca. 400 g of excelsior and 100 mL of ethanol being used as kindling. The cribs were constructed with 38 x 38 mm pine sticks. Two calibration tests were carried out, wherein a crib was ignited, but no wall lining material was used. Temperatures and gas concentrations (carbon monoxide, carbon dioxide, oxygen and hydrogen chloride) were all measured with traditional equipment, and this will not be dealt with in any detail. The smoke obscuration was measured by means of an optical density photoelectric detector system used vertically in the exhaust stream (with a path length of 0.3 m) and reported on the basis of optical density per unit path length (OD/m). Following the recommendations of King [9], that there is a constant, for most plastic materials, conversion factor between the optical density per unit length and the weight of smoke per unit volume, the smoke obscuration was also reported, on the basis of the total volume of second produced, as mass of smoke (in g). The properties of the wood used were: an average heat release rate of 5.67 W/g (crib had ca. 35 kW) and a smoke yield of 0.009 g/g.

The cone calorimeter test was run in the horizontal orientation and the NBS smoke chamber in the vertical orientation (in the flaming mode). Materials were tested, in both apparatuses, at the same thickness as they were run in the full scale test. The main parameters reported have all been described before, e.g. in reference [8]. There is one magnitude that deserves special mention: smoke factor. It is an empirical smoke/fire hazard variable used to estimate the potential realistic amount of smoke that a product would generate under full scale fire conditions. It takes into account both the potential for smoke obscuration after full sample destruction and the potential to cause other products to burn and release smoke in real fires. It does so by incorporating the burning rate (as peak RHR). Smoke factor is a continuous function calculated as the product of total smoke released and peak RHR. The single value presented here is that at 5 min.

Table abbreviations: Table 1: T: doorway temperature; Smoke: mass or optical yield of smoke; CO, CO2 and HCl: peak volumetric measurements of gas concentrations; O2 dif.: minimum value of oxygen measured; Yields of Gases, Heat, Smoke, CO, CO2 and HCl: total cumulative amounts determined after 13 min of test; Crib Wt: initial weight of wood crib; Init. Wt: initial weight of wall lining sample; Wt. Loss: measured weight loss of wall lining sample; Ave RHR: average rate of heat release over the 13 min test period; WllAvRHR: amount of the heat release rate due to the wall lining material (negative values are indications of error bars); Co Yld and Smoke Yld: yields based on mass of wall lining material; CO/CO2: molar ratio of carbon oxides generated; Wll Sm Yld: amount of smoke yield due to wall lining material, per unit mass (negative values are indications of error bars); Thickness: material thickness; RH: relative ambient humidity; Air Temp.: external air temperature. Table 2: TTI: time to sustained flaming; Avg RHR: average heat release rate between ignition and 3 min after ignition; Pk RHR: peak rate of heat release; THR: total heat release during the test; MLRP: mass loss rate parameter [3]; TSR: total smoke released; Pk RSR: peak rate of smoke release; SmkFct: smoke factor; AvExtAr13, THR13, TSR13 and AvgRHR13: average extinction area, total heat release, total smoke release and average heat release rate up to 13 min; Ht Comb: average effective heat of combustion and TTI/Pk RH: fire performance index [11] and Table 3: NBS (F) D_m: peak optical density of smoke, in the flaming mode.

RESULTS and DISCUSSION

Tables 1-3 contain all the data obtained for this series of experiments. It is immediately clear that there is no easy direct correlation between any magnitude measured and full scale smoke obscuration. In Figure 1 the results of the NBS smoke chamber test are compared with those of the full scale tests, showing the obvious disparities, particularly for materials 1, 2 and 5. Figure 2 shows that the smoke factor, at 40 kW/m^2, does a better job of predicting full scale smoke results, showing the trends for all materials, although inadequately for material number 2. Figure 3 shows that a comparison of the full scale smoke with the peak rate of heat release in the cone at 25 kW/m^2 seems to do the best prediction of these data. There is one outlier, material number 6, which gives much more smoke than would be predicted from the heat release results. This material, however, is the one with the poorest overall fire performance of those tested, and it has a very high specific smoke production tendency, as measured in almost any test (small or large scale).

Figure 4 contains all the data from Figure 3, plus a series of materials, labelled with a C prefix, originating in work carried out by Kim, at the National Research Council of Canada [10]. In this latter work the full scale test conditions were somewhat different than those in the work reported here (propane gas heat sources of 40 and 160 kW), but the general trends are clearly the same. This suggests that a simple analysis based on peak rate of heat release in the cone calorimeter is an excellent first indicator of smoke obscuration in full scale tests. In fact a least squares approximation gives a regression correlation coefficient of ca 70%. It is of further interest that most of the materials that have a poor approximation to the trend tend to be those where the smoke is higher than would be predicted simply by means of the peak heat release rate. In those cases, the use of a smoke factor gives the opposite end of the prediction, since it tends to exaggerate the full scale smoke release (compare, for example, the results for material 7, in Tables 1 and 2).

A number of proposals have been made, to suggest ways of predicting full scale smoke based on small scale cone calorimeter data. One of the most worthwhile of them is the set of efforts by Ostman [e.g. 12], who measures a kind of rate of smoke release (on a volumetric base, rather than an area base), in the cone calorimeter. She then uses it to calculate a "smoke potential", which is the ratio of that RSR to mass loss rate. This does not seem to be a useful parameter for the present data (see Figure 5, correlation of 1%). However, both ratio of total smoke released (in the cone, at the end of the full scale test duration) to average mass loss rate (65% correlation) and smoke factor (40% correlation) (each at a flux of 40 kW/m^2) are capable of giving predictions of full scale smoke release, but neither appear to improve on peak heat release rate (see also Figure 5).

CONCLUSIONS

The prediction of smoke release in full scale tests still remains an unsolved issue. It appears that, for a full scale heat source of ca. 40 kW, a straight correlation between total smoke released in the full scale test and peak rate of heat released in the cone calorimeter at an incident flux of 25 kW/m^2 is a reasonable first approximation. This can be improved by incorporating some added specific parameters based on smoke production tendency, since peak rate of heat release underestimates the smoke release from materials with very high smoke extinction area and mediocre-to-poor heat release characteristics.

Table 3: NBS Smoke Chamber Results

Material	Thickness (mm)	NBS (F) D_m
1	2.3	780
2	6.4	106
3	2.0	94
4	1.1	53
5	2.4	247
6	2.4	900
7	2.6	435

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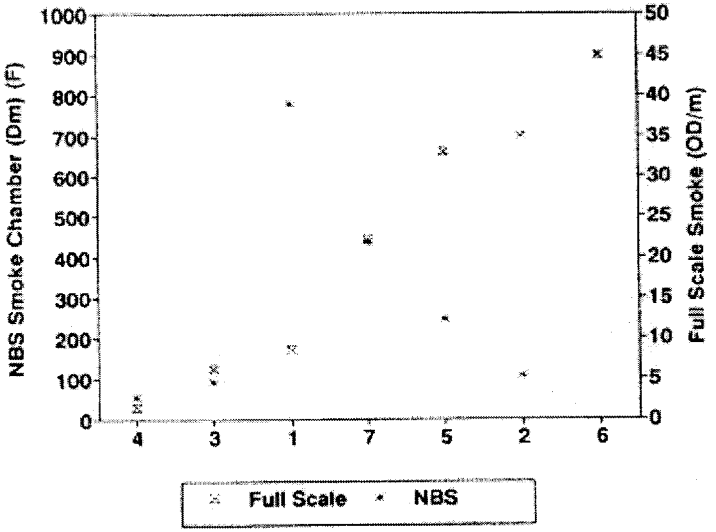
Table 1: Full Scale Room Test Results

	Peak values for 13 min test			Peak values for 13 min test			Yields for 13 min test			Yields for 13 min test		
	T	Smoke	CO	CO2	HCl	O2 dif	Gases	Heat	Smoke	CO	CO2	HCl
	deg C	OD/m	Vol %	Vol %	Vol %	Vol %	m^3	MJ	g	g	g	g
1	180	8.52	0.18	1.47	1.60	3.7	364	29.9	368.0	238.0	4611.0	2044.0
2	558	35.00	1.47	8.48	0.02	5.8	668	85.2	868.1	1235.0	22433.0	0.4
3	178	6.18	0.12	1.08	0.56	2.6	350	25.6	202.0	180.0	3107.0	1149.0
4	169	1.40	0.05	1.13	0.54	2.3	424	30.2	26.0	99.2	3776.0	848.0
5	418	33.00	1.01	5.99	0.00	3.5	994	133.9	4218.0	1450.0	24824.0	0.0
6	748	44.90	2.86	4.11	0.70	8.7	538	70.2	3432.0	2338.0	9652.0	318.0
7	322	22.10	0.52	1.91	4.79	4.2	430	36.6	483.0	275.0	3431.0	2633.0
Crib	162	1.96	0.03	1.24	0.00	1.2	382	27.0	47.9	48.7	4015.0	0.0
Crib	171	1.66	0.04	1.05	0.02	3.5	425	30.6	74.1	55.9	3166.0	17.2
	Crib Wt	Init. Wt.	Wt. Loss	Ave RHR	Wll AvRHR	CO Yld	CO/CO2	Smoke yld	Wll Sm Yld	Thickness	RH	Air Temp.
	kg	kg	kg	kW	kW	g/g	mol/mol	g/g	g/g	mm	%	deg C
1	6.3	15.0	2.0	38.3	2.6	0.029	0.081	0.0441	0.153	2.3	64	7.2
2	6.4	32.5	32.5	109.2	73.2	0.032	0.087	0.0223	0.025	6.4	51	23.9
3	6.4	15.7	1.2	32.8	-3.2	0.024	0.091	0.0268	0.124	2.0	78	6.7
4	6.3	9.9	0.6	38.7	3.0	0.014	0.041	0.0038	-0.050	1.1	63	21.1
5	6.4	14.7	14.7	171.7	135.6	0.069	0.092	0.2000	0.282	2.4	62	18.9
6	6.4	11.8	11.8	90.0	54.0	0.129	0.381	0.1887	0.285	2.4	51	17.8
7	6.4	18.3	18.3	46.9	10.9	0.011	0.126	0.0196	0.023	2.6	51	16.7
Crib	6.4	0.0	0.0	34.6	-1.4	0.008	0.019	0.0075		0	67	17.8
Crib	6.3	0.0	0.0	39.2	3.5	0.009	0.028	0.0118		0	76	11.1

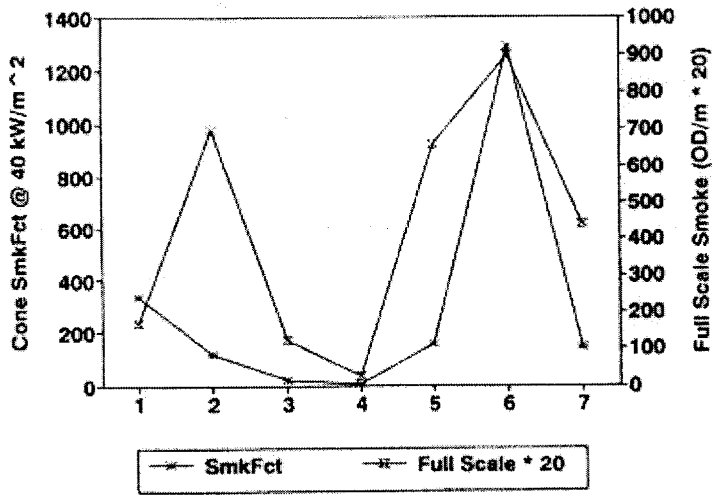
Table 2. Cone calorimeter results

	TTI	Avg RHR	Pk RHR	THR	MLRP	TSR	Pk RSR	SmkFct	AvExtAr13	Ht Comb	THR @ 13	TSR @ 13	TTI/Pk RH	AvRHR13
	s	kW/m²	kW/m²	MJ/m²	g/(m² s²)	-	1/s	MW/m²	m²/kg	MJ/kg	MJ/m²	-	s m²/kW	kW/m²
							20 kW/m²							
1	451	11.8	109	12	0.40	691	9.93	11	279.17	4.7	11.29	523	4.15	8.8
2	276	96.5	385	85	1.47	871	6.53	45	122.80	13.1	73.03	737	0.72	57.0
3	4280	4.2	62	21	0.05	159	0.92	2	34.95	5.3	1.75	77	68.98	1.4
4	10000	0.3	17	23	0.00	115	0.36	0.4	27.66	6.8	1.67	58	600.00	1.3
5	2167	5.8	363	38	0.21	1938	16.40	16	129.69	12.1	0.04	100	5.97	0.0
6	690	9.2	158	10	0.37	2123	22.46	124	831.23	4.2	6.56	1449	4.36	5.1
7	986	6.3	62	20	0.36	225	2.51	4	53.22	4.9	2.93	112	15.92	2.3
							25 kW/m²							
1	152	31.9	105	21	1.10	1241	9.62	85	420.45	7.0	19.25	1195	1.44	15.0
2	135	130.5	367	78	2.73	638	2.35	73	101.23	12.1	70.92	619	0.37	55.3
3	1019	6.3	54	34	0.12	148	0.50	3	27.33	7.8	4.94	73	18.94	3.9
4	344	9.1	42	15	0.46	59	0.89	2	17.15	5.0	11.28	48	8.18	8.8
5	993	24.5	351	52	0.14	1569	14.01	1	32.50	14.4	2.92	29	2.83	2.3
6	77	44.5	165	18	2.61	4234	33.51	559	1221.50	5.0	16.52	4045	0.46	12.9
7	83	16.0	124	13	2.23	682	10.61	49	205.55	4.1	10.20	578	0.67	8.0
							40 kW/m²							
1	47	50.0	224	26	3.91	1613	26.15	336	457.50	7.5	23.99	1582	0.21	18.7
2	39	214.3	435	140	4.42	359	6.95	121	54.91	18.8	95.86	348	0.09	74.8
3	49	26.3	91	27	4.33	326	6.56	24	81.22	6.4	21.10	81	0.54	16.5
4	170	18.5	54	20	1.08	124	2.82	6	36.36	5.7	17.32	123	3.12	13.5
5	80	60.1	233	59	2.82	1612	8.21	159	455.85	15.9	56.48	1610	0.34	44.1
6	38	99.6	264	36	6.92	4941	50.41	1290	1039.50	7.5	35.16	4931	0.14	27.4
7	23	65.2	109	45	10.25	1617	13.99	145	349.60	9.2	37.97	1563	0.21	29.6
							70 kW/m²							
1	20	77.2	270	31	10.41	2171	42.66	577	560.10	8.0	30.76	561	0.07	24.0
2	17	291.6	661	139	10.48	645	4.11	369	89.64	18.1	99.44	619	0.02	77.6
3	12	76.5	95	49	18.14	1074	11.65	90	241.45	10.4	41.54	1067	0.13	32.4
4	60	37.9	94	29	3.09	409	4.11	30	112.70	8.2	26.12	408	0.64	20.4
5	26	145.5	297	74	8.73	2072	14.40	499	493.30	17.0	69.94	2051	0.09	54.6
6	12	146.7	341	46	22.38	5878	73.07	1945	1174.00	9.2	44.41	5835	0.04	34.6
7	10	132.7	183	56	24.53	2232	38.21	385	432.23	10.2	48.48	2220	0.05	37.8

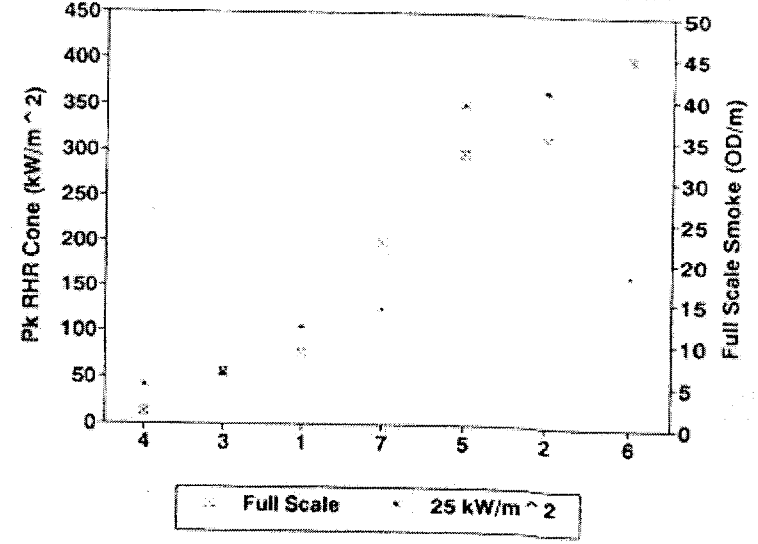
Full Scale Smoke vs. NBS Smoke Chamber



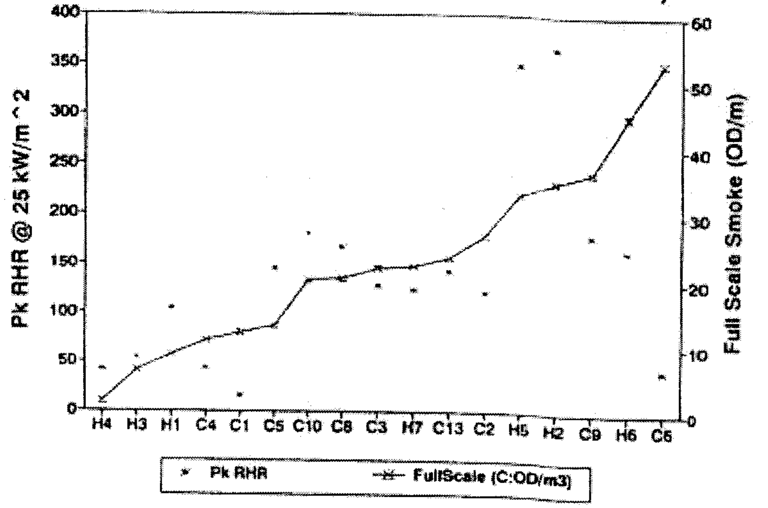
Cone Calorimeter Tests
Smoke Results - 40 kW/m ^ 2



Full Scale Smoke vs. Cone Pk RHR

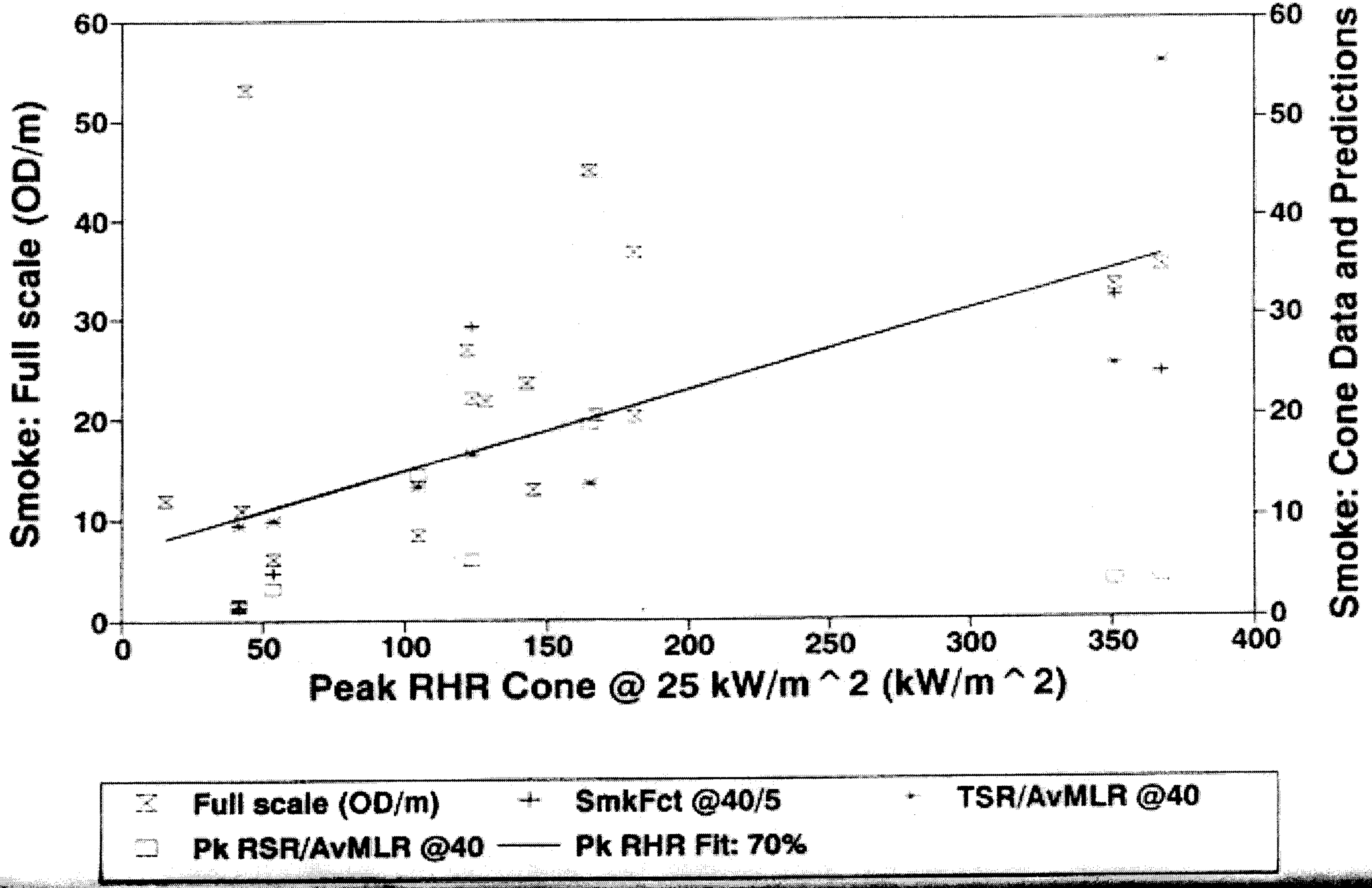


Full Scale Smoke vs. Cone Pk RHR
Cone Results - 25 kW/m ^ 2 (+ NRC Canada)



Full Scale Smoke vs. Cone Pk RHR

Cone Results - 25 kW/m ^ 2 (+ NRC Canada)



SIXTH INTERNATIONAL FIRE CONFERENCE

INTERFLAM '93

PROCEEDINGS

BUILDING AND FIRE RESEARCH LABORATORY

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GBH Attachment 13

AB59-COMM-7-13

Fire Testing of Interior Finish

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ABSTRACT

This paper discusses the following issues: (1) what is interior finish (and distinguishes between interior wall and ceiling finish and interior floor finish), (2) traditional testing for flame spread and smoke release of interior wall and ceiling finish, (3) testing for interior floor finish, (4) modern testing for interior wall and ceiling finish (for heat and smoke release) and (5) comparisons between code use and fire safety engineering considerations.

Interior finish is defined by the National Fire Protection Association (NFPA, in NFPA 5000-2003) as "The exposed surfaces of walls, ceilings, and floors within buildings.", with the explanation that "Interior finish is not intended to apply to surfaces within spaces, such as those that are concealed or inaccessible. Furnishings that, in some cases, might be secured in place for functional reasons should not be considered as interior finish." NFPA also defines separately: Interior Ceiling Finish as "The interior finish of ceilings.", Interior Wall Finish as "The interior finish of columns, fixed or movable walls, and fixed or movable partitions." and Interior Floor Finish as "The interior finish of floors, ramps, stair treads and risers, and other walking surfaces." The International Code Council (ICC, in its building code IBC-2003) states that "Interior finish includes interior wall and ceiling finish and interior floor finish.", that Interior Wall and Ceiling Finish is "The exposed interior surfaces of buildings including, but not limited to: fixed or movable walls and partitions; columns; ceilings; and interior wainscotting, paneling or other finish applied structurally or for decoration, acoustical correction, surface insulation, structural fire resistance or similar purposes, but not including trim." and that Interior Floor Finish is "The exposed floor surfaces of buildings including coverings applied over a finished floor or stair, including risers." Thus, when dealing with testing of interior finish, a distinction needs to be drawn between walls (and ceilings) and floors.

The fire performance of interior wall and ceiling finish is critical to the development of a fire: interior finish offers fuel contribution and a surface through which a fire can spread and transport heat and smoke to other parts of the compartment, or even to other compartments. Therefore, the fire performance of such materials needs to be controlled. The traditional test used

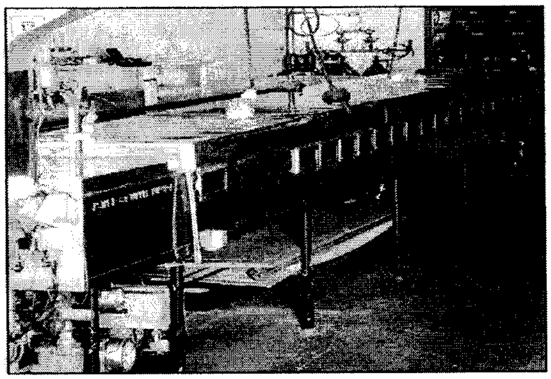


Figure 1: Photograph of Steiner Tunnel

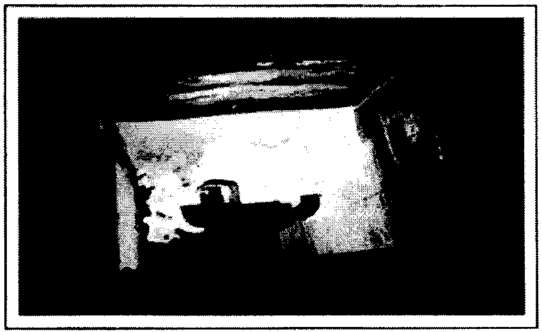


Figure 2: Flame in Steiner Tunnel Test

for assessing the fire performance of interior wall and ceiling finish is the Steiner tunnel fire test method for surface flame spread and smoke development was developed by Al Steiner for testing building materials, such as wood or gypsum board, at Underwriters Laboratories in 1944 (Figure 1). Since then, the test has been standardized by the major North American standards writing organizations (ASTM E84, NFPA 255, UL 723, ULC S102) and widely adopted by every North American building and fire code for assessing the potential fire problem posed by wall and ceiling interior finish. In the test, a specimen (7.3 m x 0.56 m, normally up to 0.15 m thick), either in one unbroken length or in separate sections joined end to end, is mounted face downwards so as to form the roof of a horizontal tunnel 305 mm high. The fire source, two gas burners, ignites the sample from below with an 89 kW intensity (Figure 2) and the combustion products are carried away by a controlled air flow of 73 m/min. The normal output is a flame spread index (FSI), and a smoke developed index (SDI). Flame spread is assessed visually by the progression of the flame front while smoke obscuration is assessed based on measurements of optical density of smoke at the tunnel outlet. This information is used to plot time-based graphs of flame spread distance and of optical density. FSI and SDI are then calculated based on the ratio between the areas under the curves for the material being tested and those for a cementitious board (assigned FSI and SDI values of 0) and for red oak flooring (assigned FSI and SDI values of 100). The building, fire and life safety codes (IBC, IFC, NFPA 5000, NFPA 101 and NFPA 1/UFC) all contain requirements for interior wall and ceiling finish of Class A ($FSI \leq 25$; $SDI \leq 450$), Class B ($25 < FSI \leq 75$; $SDI \leq 450$) or Class C ($75 < FSI \leq 200$; $SDI \leq 450$). This fire test is, clearly, not able to provide results in engineering units, and the test results cannot, thus, be used for a fire hazard analysis or a fire risk analysis. When plastics started being used in construction, this test continued to be applied to them, in spite of the fact that it is not always appropriate. For example, samples that cannot be retained in place above the tunnel floor, or which melt and continue burning on the tunnel floor (typical behavior for most thermoplastics) are still being tested with this equipment in spite of giving results that are not representative of the use of the material in realistic situations. The same can also be stated about very thin materials, which often give low FSI values mainly due to there being insufficient material in the test method to permit flame spread to be assessed properly. An understanding of some of these limitations has caused the codes to consider alternatives, either as replacements for the Steiner tunnel or as additional options (see heat release).

Issues are different for interior floor finish than for other interior finish, because heat and smoke rise in a fire. Thus, floor finish is involved either as the initial material ignited in a fire or as an additional fuel once a fire has become uncontrolled. Typically, thus, it is necessary to ensure

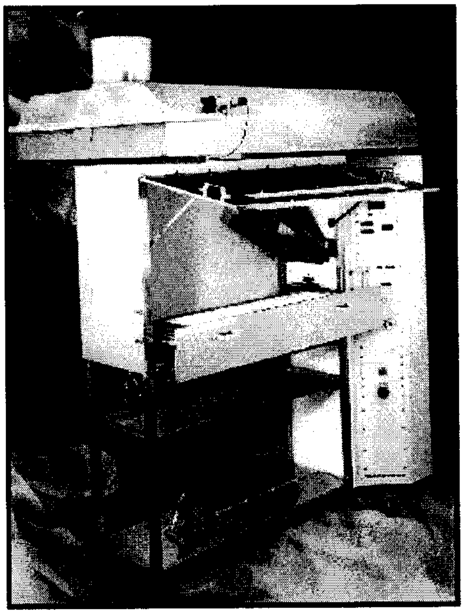


Figure 3: Flooring Radiant Panel Test Apparatus (ASTM E 648)

that interior floor finish is relatively difficult to ignite and is not capable to slowly spread flame from the compartment of fire origin to a different one. The Steiner tunnel cannot assess ignitability and its fuel source is not appropriate to assess slow flame spread. Experience has shown that many flooring materials (traditional floor finishes such as wood flooring or resilient materials) will not ignite unless exposed to an ignition source of > 1 kW/m^2, but that carpet-like materials may ignite at such low heat fluxes. Therefore, all carpets sold in the United States must meet the "methenamine pill" test (ASTM D 2859) which ensures that flame spread will be minimal. Most codes also regulate interior floor finish (in those occupancies where fire risks need to be especially minimized) to be tested with the flooring radiant panel (ASTM E 648, NFPA 253, Figure 3) and require a "critical radiant flux" for ignition in excess of 4.5 kW/m^2 (Class I) or 2.2 kW/m^2 (Class II). In the flooring radiant panel, the floor finish (such as a carpet) is exposed to an incident heat flux from an angled gas-fired radiant panel, with a minimum heat flux of 11 kW/m^2 at the farthest end. The test method assesses the critical incident flux (as a distance from the igniter) required for continued flame propagation. This approach (even if it is based on old-fashioned tests) is quite suitable for interior floor finish. Some applications, typically in the transportation vehicle arena, also require flooring materials to meet one of a variety of smoke obscuration requirements, typically based on a static smoke chamber box, either with a traditional radiant heater (ASTM E 662) or with a conical heater (ISO 5659-2, IMO Fire Test Procedures Code part 2, also known as ASTM E 1995 and NFPA 270).

Of course, the key question to ask in any fire is: "How big is the fire?", and that is covered by the rate of heat release. A burning product will spread a fire to nearby products only if it gives off enough heat to ignite them. Moreover, the heat has to be released fast enough not to be dissipated or lost while traveling through the cold air surrounding any product that is not on fire. Therefore, heat release rate dominates fire hazard, and it has been shown to be much more important than either ease of ignition, smoke toxicity or flame spread in controlling the time available for potential victims of a fire to escape. These concepts have now been applied to fire testing of interior (wall and ceiling) finish and all US codes use a room-corner test for the purpose. The use of the room-corner test can be an option to the Steiner tunnel test (for most interior finish materials), or the actual requirement (for foam plastic insulation and textile wall coverings). Thus, the building, fire and life

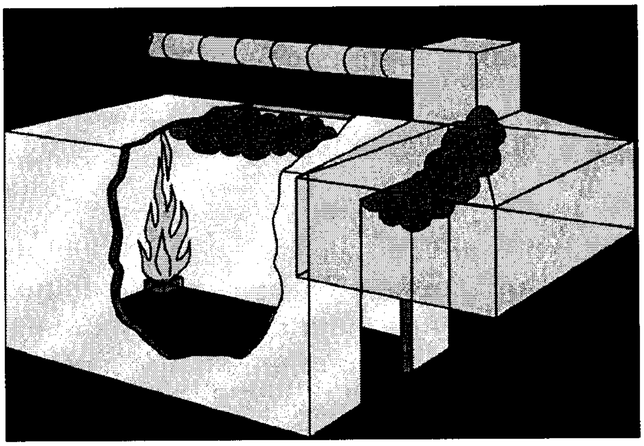


Figure 4: Room-Corner Fire Test

safety codes all state that most interior wall and ceiling finish can be tested using the NFPA 286 room-corner test (Figure 4), and cannot cause flashover in the test or emit a total amount of smoke exceeding 1,000 m^2. Special rules apply to some materials or products, as follows:

- Textile wall and ceiling covering materials are required to meet a Class A flame spread index and smoke developed index (using the Steiner tunnel fire test) and be used in a sprinklered environment or have passed a specific room-corner test for textile wall coverings (NFPA 265, a less severe test, and one where there are no smoke obscuration requirements), which requires that flashover not occur.
- Expanded vinyl wall coverings can be treated like textile wall coverings (see above: use Steiner tunnel or NFPA 265) or like most other interior finish (use Steiner tunnel or NFPA 286).
- Cellular or foamed plastic materials must always meet a Class B flame spread index (using the Steiner tunnel test). They can be used as interior trim if the density of the material is high enough (> 320 kg/m^3), and then the amount is limited to 10% of the wall or ceiling. Alternatively, cellular or foamed plastic materials must meet the standard smoke obscuration requirement (smoke developed index of ≤ 450, using the Steiner tunnel test) and must either be covered by a thermal barrier or meet a large scale fire test that fully represents the fire hazard in the scenario in question. One of such tests is the NFPA 286 room-corner test.

In the NFPA 286 room-corner test three walls and ceiling (or ceiling only, for interior ceiling finish) of a 2.4 m x 3.7 m (x 2.4 m high) room, with a standard doorway, are lined with the material to be tested. The ignition source is a gas burner, placed in one corner (on the wall furthest from the doorway) flush against both walls, and which generates 40 kW for a 5 min period, followed by 160 kW, for a further 10 min period. Heat release (via the principle of oxygen consumption calorimetry) and smoke release are measured in the exhaust duct, and temperatures and heat fluxes are measured in the room. The severity of the ignition source was designed to ensure that the gas burner flame alone reaches the ceiling, without contribution from the test material (Figure 5). Even though the test measures heat release, the codes simply require assessment of whether flashover occurs during the test. Two additional important criteria required by the codes are that the flame spread does not reach any of the

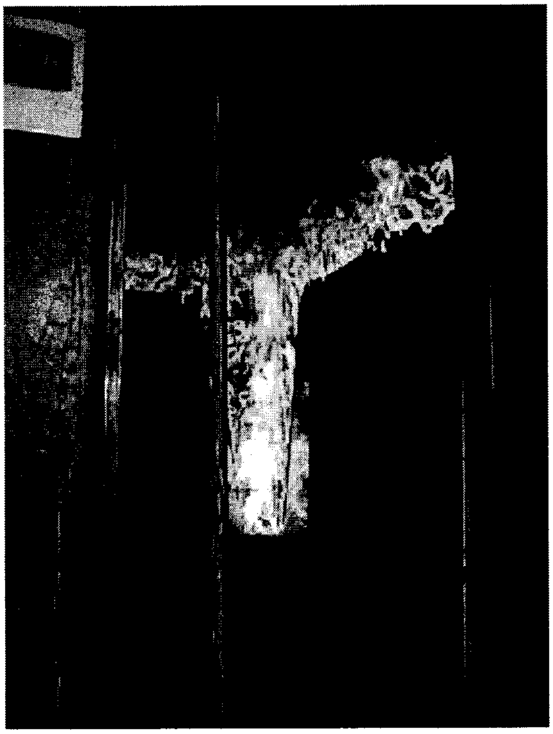


Figure 5: Flame in Room-Corner Test

extremities of the test sample and that the total smoke release (namely the time integral of the rate of smoke release), which cannot exceed 1,000 m^2, over the entire 15 min test period. If all criteria are met, the codes consider that the material is suitable for use in all applications where the codes require a material to be tested by the Steiner tunnel, and where Class A, B, or C requirements exist. In practice, it is very rare that a material spreads flame to its extremities and does not cause flashover, since that would mean that the flame would reach the edge of the door and stop there without exiting the doorway (one of the criteria for flashover). This means that any material that does not cause flashover and releases < 1,000 m^2 of smoke is considered equivalent to a Class A material.

NFPA 265 is a somewhat less severe variation of NFPA 286, which applied exclusively to textile wall coverings (and expanded vinyl wall coverings). In it, the same room and the same burner are used, but the burner is placed 51 mm away from each of the walls (in the same corner as in NFPA 286). Moreover, after the first 5 min at 40 kW, the burner intensity is raised to 150 kW only. Finally, smoke release measurements using NFPA 265 are not required in the codes. It is likely that, eventually, textile wall coverings will be required to be treated similarly to other interior finish.

Now that the actual tests used have been presented, it is important to discuss the validity of the test methods and whether improvements should be put in place. Starting with interior floor finish, clearly a test method based on heat release (such as the cone calorimeter for example, ASTM E 1354, NFPA 271, ISO 5660, as a bench-scale test) would permit a much more logical approach to using fire safety engineering methods. In fact, two ASTM guides and one NFPA guide addressing fire hazard assessment, ASTM E 2280 (for health care occupancies), ASTM E 2067 (for rail cars) and NFPA 555 (on potential for flashover), all recommend the use of the cone calorimeter to assess heat and smoke release of interior floor finish, at incident heat fluxes of 25-30 kW/m^2. However, it must also be recognized that the combination of the methenamine pill test and the flooring radiant panel test are sufficient to eliminate the vast majority of "bad actors". Thus, the methods being used are fairly adequate for a prescriptive fire safety approach that does not discriminate against materials. The additional smoke release testing (used mostly in transportation environments) is not of very high real value, but it may serve to eliminate some poor performing materials.

Smoke release by interior wall and ceiling finish has traditionally been based on the smoke obtained from the Steiner tunnel fire test, even though its inadequacies are well known, for some materials. Thus, the question was posed: is it necessary to test for smoke release if a much better test is used, in the room corner test, or is it enough to just develop low heat release products? Figure 6 shows that of five series of tests conducted in room-corner tests (2 of them in Europe), with a total of 84 materials tested, systematically some 10% of the materials (in fact 10 of the 84) give low heat release but unacceptably high smoke release. Thus, it is clear that it is important to assess smoke release of interior wall and ceiling finish, in a large scale test. This means that it is inappropriate to assess the fire performance of interior wall and ceiling finish materials with the Steiner tunnel test (using both flame spread and smoke) but to assess only heat release in the room-corner test. The data in Figure 7 shows that this can be resolved by using equivalent criteria in both tests, since materials with very high smoke developed index (SDI) are also likely to have a very high total smoke release (TSR) in the room corner test, which is how the 1,000 m^2 pass fail criterion was developed.

Fig. 6 Room Corner Testing, Heat & Smoke Release

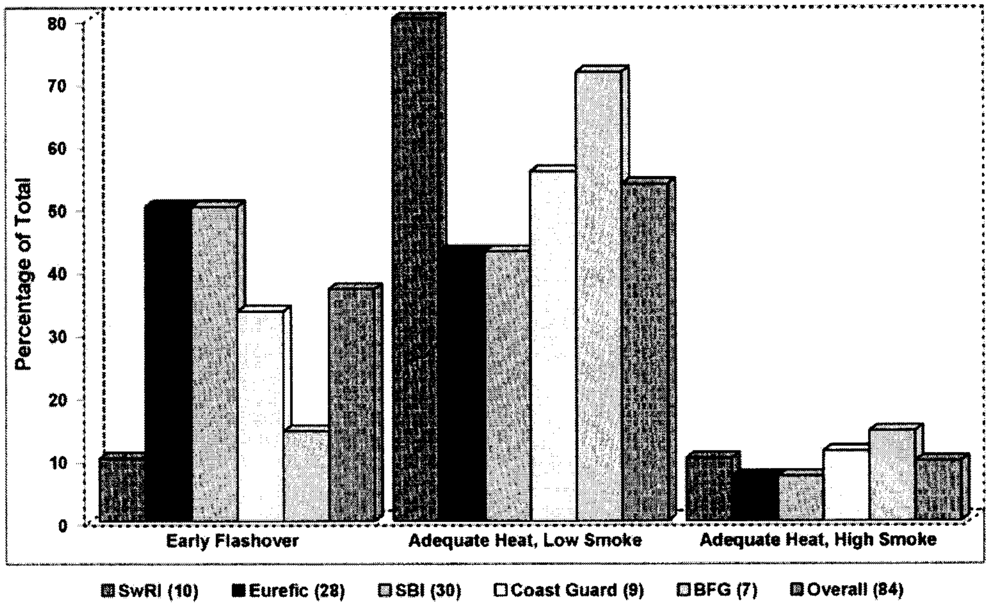
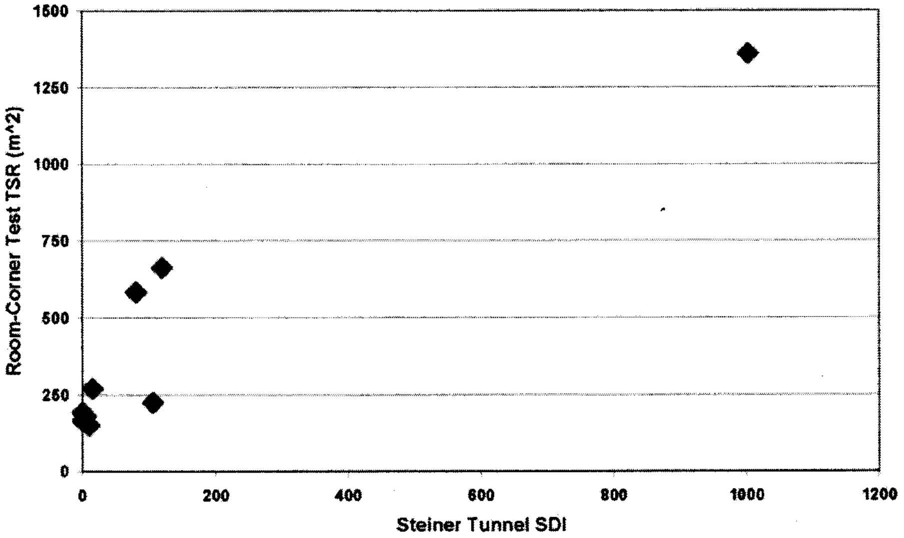


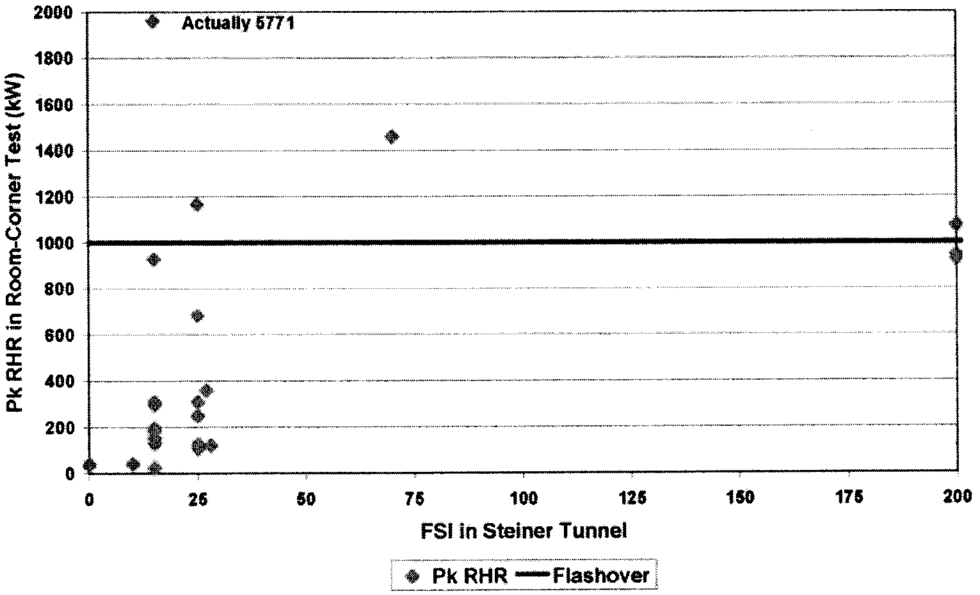
Fig. 7 Smoke Release of Interior Finish



Finally, the approach of the codes to testing interior wall and ceiling finish is an interesting (and reasonable), but slightly flawed, concept. Clearly the room-corner test is a much more suitable way of assessing fire performance than the Steiner tunnel test. However, the codes admit the NFPA 286 room-corner test results based on the premise that materials that don't cause flashover (or high smoke release) in the room-corner test are known to also have flame spread indices of < 200 and smoke developed indices of less than 450 in the Steiner tunnel test. This is excellent as far as it goes, but needs refinement. The Steiner tunnel test is very likely to give falsely favorable results (in fact that happens often with materials that melt and drip and with materials that are thin films) but it rarely gives falsely unfavorable results (meaning that a high flame spread index, or FSI, is almost always indicative of a material with mediocre or poor fire performance). The room-corner test results are potentially much more suitable to classification of materials, because the heat release rate history is obtained in the test. However, the fact that the heat release rate history is not used for code classification purposes results in some inconsistencies occurring when comparing results from both tests. Therefore, it would be important to use the heat release rate history in the room-corner test and not just whether flashover does or does not occur. Figure 8 shows the comparative fire performance of 25 materials tested in the Steiner tunnel and in the room-corner and illustrates the problem:

- 5 materials had an FSI of 200 or less (i.e. Class A, B, or C) in the Steiner tunnel but caused flashover in the room corner test. The Steiner tunnel test classifies them as acceptable and the room-corner test as unacceptable.
- 14 materials had an FSI of 25 or less (i.e. Class A) in the Steiner tunnel and released less than 400 kW in the room corner test. Both tests classify them as Class A.
- 2 materials had an FSI of > 25 and 75 (i.e. Class B) in the Steiner tunnel and released less than 400 kW in the room corner test. The Steiner tunnel test classifies them as Class B and the room-corner test as Class A.
- 2 materials had an FSI of 25 or less (i.e. Class A) in the Steiner tunnel and released more than 400 kW but less than flashover in the room corner test. Both tests classify them as Class A.
- 2 materials had an FSI of 200 or less (i.e. Class C) in the Steiner tunnel and released a heat release very close to flashover (but less than flashover) in the room corner test. The Steiner tunnel test classifies them as Class C and the room-corner test as Class A.

Fig. 8 Rate of Heat Release vs Flame Spread



In conclusion, fire testing of interior finish is probably adequate to eliminate the poorest performers (both in terms of heat release, or flame spread, and smoke release). However, the emphasis on the supremacy of the Steiner tunnel test for all interior wall and ceiling finish materials means that the full capabilities of the room-corner test, including the actual heat release rates measured, are not being used, and improvements in that area would be welcome.

GBH Attachment 14

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FIRE HAZARD ASSESSMENT IN POST-FLASHOVER FIRES: ANALYSIS OF THE TOXIC FRACTION OF FIRE HAZARD

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"Fire Hazard Assessment in Post-Flashover Fires: Analysis of the Toxic Fraction of Fire Hazard" M.M. Hirschler, in Proc. Fire Risk and Hazard Research Application Symposium, NFPRF, San Diego, CA, June 23-25, 1999, pp. 86-100.

ABSTRACT

This work is in four parts: (a) background on smoke toxicity and research information available; (b) analysis of toxicant yields and the implications for toxicity; (c) the flawed analyses of incapacitation via irritants and (d) a procedure for assessing hazard (with emphasis on toxic hazard) for post-flashover fires, without requiring the use of the concept of incapacitation.

The first part of this work discusses what is known about smoke toxicity, and points out some potential disadvantages of focussing too strongly on toxic potency of smoke.

The second part presents some data on yields of common toxicants (combustion products) in fires and fire tests and analyzes the implications of those yields to consider lethality.

The third part looks at incapacitation limit levels. Recent limits, suggested in draft ISO DIS 13571, based on predicted incapacitation concentration concepts, have been suggested and analysis of actual fire data indicates that it is essential to replace them by realistic criteria that do not require severe and unreasonable building contents limitations.

The final part combines the information on toxicant yields with a toxic fire hazard assessment for those fires that cause the vast majority of fatalities: the ones reaching beyond the room of fire origin and associated with flashover. It presents a procedure for assessing fire hazard in post-flashover fires, based on proven fire safety engineering concepts. The toxic potency of common materials in post-flashover fires is 8 mg/L and the yield of carbon monoxide is 20% of the mass burnt. Therefore, toxic fire hazard can be calculated as just one element in overall fire hazard. In other words, the fire hazard assessment of a product in a certain fire scenario compares the time to safe escape (or evacuation) with the time required to reach lethality (based on proven tenability levels).

INTRODUCTION

It is common to see fire fatalities reported as resulting from smoke inhalation. The real cause of the overwhelming majority of fire fatalities is, however, that the fire, has generated enough combustion products to bring about a lethal atmosphere. It is important, thus, to follow the research that has led to the level of knowledge of fire, smoke and toxicity in the 1990's.

Multiple test methods have been developed to investigate the toxic potency of material smoke [e.g. 1-7], some of which involve bioassay. Abundant published data exists on the smoke toxic potency resulting from many materials, using one or more of these methods. Unfortunately, not all the published information is specific (mainly because of trade secret needs) on formulation details of the material tested. Therefore, specifications, and competitive marketing, often result in more toxicity testing by manufacturers, as new materials are developed, at high added expense. This is very often unproductive, for one of three reasons:

- It may result in data that is statistically indistinguishable from existing information: new testing is then a waste of money.
- It may result in data that is statistically distinguishable but toxicologically indistinguishable: new testing then does nothing but support marketing ploys which do not add to fire safety.
- It may result in new data showing improvements in one fire property (smoke toxicity) at the expense of (often hidden) deterioration in another fire property (e.g. heat release or flame spread): new testing then lowers fire safety.

The fire performance and the smoke toxicity of materials have been the focus of so many investigations that work can, and should, now focus on the fire properties most applicable to fire hazard assessment. Some of the critical work conducted in this area was conducted at the US National Institute for Standards and Technology, in various stages: comparison of products made with fire retarded and non-fire retarded materials [8], analysis of the carbon monoxide (CO) yields in large full scale fires [9], study of full scale testing of materials (including a rigid PVC compound) and a comparison with small scale test results [10] and finally development of a small scale radiant test for toxic potency measurement [11]. The work must be understood combined with an analysis of the effects of carbon monoxide, the most hazardous toxicant affecting fire victims in real fire atmospheres, as shown in a comprehensive study of fire and non fire fatalities [12-13]. In consequence, many fire scientists now accept that:

- Most fire fatalities occur in fires that become very large. In fact, US statistics indicate that such fires account for over six times more fatalities than all other fires combined.
- Carbon monoxide concentrations in the atmospheres of flashover fires (the fires most likely to produce fatalities), are determined by geometric variables and oxygen availability, but are virtually unaffected by chemical composition of fuels.
- All small scale fire tests underpredict CO yields. They cannot be used, thus, to predict toxic fire hazard for ventilation controlled post-flashover fires, unless CO yields are calculated by analogy with full scale fire test results. Such tests do not underpredict yields of other toxicants, such as hydrogen chloride or hydrogen cyanide.
- CO yields in full scale post-flashover fires are approximately 0.2 g/g, which translates to a toxicity of 25 mg/L. If this is combined with a margin of error of a factor of 3, the consequence is that any toxic potency (LC_{50}) higher than 8 mg/L (i.e. any toxicity lower than 8 mg/L) will be subsumed within the toxicity of the atmosphere, and is of no consequence. Thus, values ≥ 8 should be converted to 8 mg/L for reporting purposes.
- In order to correct small scale test data, the CO yield that should have been obtained can be calculated by making a CO correction.
- Toxic potency analyses show relatively small differences between materials, even in fires that have not reached flashover.

- The background for CO yield corrections are comprehensive studies of fire (and non fire) fatalities associated with CO [12-13]. By investigating almost 5,000 fatalities, they found:
    - Fire atmosphere toxicity is governed almost solely by CO levels, as victims of CO poisoning (non fire) die at virtually identical levels, after considering other factors. No universal lethal CO threshold level exists (previously it was thought to be 50% carboxyhemoglobin, COHb). Lethal levels depend on the victim age and physical condition; any blood COHb value > 20 % can produce lethality on its own.
    - Populations of fire and non fire victims of CO exposures are inherently very different: fire victims have a bimodal distribution, with maxima in much older and much younger victims, and suffer from more preexisting disease; non fire CO victims have a simple age distribution with a maximum at a middle age. Thus fire victims are more sensitive to CO than those in non fire exposures.
    - Fire fatality patterns before and after the plastics era are identical: using man-made materials for household goods has made no difference to fire atmosphere toxicity.

YIELDS OF COMBUSTION PRODUCTS AND THEIR IMPLICATIONS

As stated above, the single critical yield of combustion products needed to assess the toxic hazard in post-flashover fires is that of CO, which is 0.2 g/g. Other combustion product yields depend on the material burning and on the fire scenario; examples are shown in Table 1.

The table illustrates the fact that quite a lot is known about the yields of carbon monoxide, from many materials and often under more than one circumstance. However, little if anything is known about yields of most other toxicants; particularly those of irritants. This is due, in part, to experimental difficulties involved in measuring minor combustion products (which require the use of new, complex and expensive, Fourier Transform InfraRed spectral techniques), and, in part, to the fact that not all combustion products have been, as yet, fully identified.

Also of interest is the fact that an analysis of irritancy showed that the common irritants contained in fire atmospheres are not the most potent irritants found in fire atmospheres [14]. Thus, for example, halogen-free polyolefins, which do not release significant amounts of any of the materials considered typical irritant combustion products, were found to be 3-5 times more irritating than poly(vinyl chloride) materials intended for the same use (in this case wire and cable). In the work, a variety of combustion products were analyzed, with their known irritant effect, and yet the irritancy of the polyolefins could not be attributed to that of the compounds found. Thus, an analysis based on the well-known irritants, or even many of the measurable irritants, would lead users to ignore the actual major irritants present.

Table 1. Yields of Toxicants From Common Materials [8, 10, 14]

Material/Yield	CO (g/g)	HCl (g/g)	HCN	Irritants
General Flashover	0.2	Decay	Decay	?
PVC	0.06-0.07	0.25-0.40	-	HCl + I
PVC (flashover)	0.2	0.4	-	0.4
Polyolefins	0.08-0.10	-	-	(HCl + I) * 3
Douglas Fir	0.011-0.02	-	-	?
DFir (flashover)	0.2	-	-	?
FR Rigid Polyurethane	0.06-0.08	-	0.002-0.005	?
FR Rig PU (flashover)	0.2	-	0.005-0.011	?
Polystyrene	0.1-0.5	-	-	?
Polyphen. Oxide	0.1-0.3	-	-	?
Flex. Polyurethane	0.01	-	0.001	?
Ethyl. Vinyl Acetate	0.1-0.3	-	-	?
GR Polyester	0.1	-	-	?

Carbon monoxide is an asphyxiant toxicant, and the most common other asphyxiant toxicant is hydrogen cyanide. They act by inhibiting the normal distribution of oxygen to body tissues (especially the cardiovascular system and the brain), thereby causing hypoxia, and, if severe, eventual death by asphyxiation. The fatality occurs immediately following the exposure, if a sufficiently high dose is involved. On the other hand, irritant combustion products can have two principal effects. First, they can cause the more immediately noticeable sensory irritation, which results in an immediate painful sensory stimulation of the eyes, nose, throat and lungs, accompanied by upper respiratory tract damage, breathing difficulties and hypoxia. Second, they can cause deep lung inflammation and oedema, and perhaps eventual death due to impairment of respiration, usually several hours after exposure [15].

Inhalation toxicological exposure is always related to exposure dose, i.e. a certain exposure maintained over a sufficiently long period to cause an undesirable effect. Thus, thresholds must be based on the concept of dose, in other words the product of the concentration of a toxicant times the exposure time. Equation (1) is the traditional N-gas model prediction of smoke toxicity [10], where smoke is lethal if FED (fractional effective dose) is near unity:

$$FED = \frac{m[CO]}{[CO_2]-b} + \frac{[HCN]}{LC_{50}HCN} + \frac{[HCl]}{LC_{50}HCl} + \frac{[HBr]}{LC_{50}HBr} + \frac{21-}{21-l} \qquad (1)$$

The constants for use in Equation (1) (which refers to 30 min exposure) are:

m:	-18	Units: 1/ppm
b:	122,000	Units: ppm
LC_{50} HCN:	200	Units: ppm
LC_{50} HCl:	3,700	Units: ppm
LC_{50} HBr:	3,000	Units: ppm
LC_{50} O_2:	5.4	Units: %

Work in different organizations has shown that the individual effects of asphyxiants and of toxicants can be added in the N-gas model as shown in Equation (1) [10, 16, 17].

With regard to one specific irritant (the work addressed hydrogen chloride, but the finding is probably more general), "the data generated ... suggest that 820 ppm of HCl is lower than the threshold lethal concentration and concentrations of this level or less do not provide any additive toxicity in combination with other gases" [10]. This concentration value may not be exact, as combined effects of CO and HCl were found in another study [17], but is indicative of the existence of a minimum threshold before irritant gases start causing severe health effects. These low level effects of irritants, particularly on humans (generally the researchers themselves), were studied exhaustively around the end of the 19th century at European universities [18-22].

INCAPACITATION

Recent work, within the international standards community (namely a group of ISO TC92, Subcommittee 3 on Toxicity) has focussed on a different concept than lethality: incapacitation due to smoke. Unfortunately, this would create serious problems, that will be analyzed here.

Normally, codes addressing fire safety, intend to protect building occupants so they do not die in fires (except people either responsible for the fire or in close vicinity to its initiation). For example, NFPA 101, Life Safety Code, states: "As related to fire safety, the objective of this Code is to protect the occupants not intimate with the initial fire development from loss of life and to improve the survivability of those who are intimate with the fire development." This is a very logical, and achievable, objective. On the other hand, the draft document ([23], ISO DIS 13571) prepared by ISO TC92SC3WG5, states: "The ... protection, if occupant exposure should occur, is to ensure that the consequences of such exposure are not serious and that safe escape or refuge can be accomplished" and recommends " ... establishing levels of exposure that would not be expected to seriously impede escape nor impair health". Thus ISO DIS 13571 suggests a much higher level of fire protection to occupants than has ever been considered reasonable.

The problem with such unreasonable protection, as will be shown here, is that it leads to imposing excessive (and unwarranted) limitations in the amount of material that can be used in an interior application for the type of life style that is now prevalent in developed countries.

When incapacitation concepts are being used by the ISO working group, the draft document states: "The basic principle for assessing the irritant gas component of toxic hazard analysis involves only the *concentration* of each irritant. Fractional Effective Concentrations (FECs) are determined for each irritant at each discrete increment of time. Their sum at each time increment is then compared with a predetermined total FEC threshold value. If the total FEC value is greater than the threshold FEC, the incidence and severity of irritation effects for those exposed are considered to represent a significant potential for adversely affecting occupants' safe escape." See Equation (2) for the use of the FEC concept (exclusively looking at irritancy).

$$FEC = \frac{[HCl]}{IC_{HCl}} + \frac{[HBr]}{IC_{HBr}} + \frac{[HF]}{IC_{HF}} + \frac{[SO_2]}{IC_{SO_2}} + \frac{[NO_2]}{IC_{NO_2}} + \frac{[acrolein]}{IC_{acrolein}} + \frac{[}{} \qquad (2)$$

The constants proposed by ISO DIS 13571 for Equation (2) (which has no time component) are can be compared with literature data for lethal toxic potency (over a 30 min exposure).

IC HCl	100 ppm	LC$_{50}$ (30 min)	3700 ppm [10]
IC HBr	100 ppm	LC$_{50}$ (30 min)	3700 ppm [10]
IC HF	50 ppm	LC$_{50}$ (30 min)	900-3600 ppm [24]
IC SO$_2$	15 ppm	LC$_{50}$ (30 min)	300-500 ppm [24]
IC NO$_2$	25 ppm	LC$_{50}$ (30 min)	60-250 ppm [24]
IC acrolein	3 ppm	LC$_{50}$ (30 min)	140-170 ppm [24]
IC formaldehyde	25 ppm	LC$_{50}$ (30 min)	700-800 ppm [24]

There is, however, no toxicological evidence that incapacitation of exposed victims ever occurs as a function of a certain concentration of any toxicant. In consequence, the concept of "FEC" has no technical validity and has not been proven with experimental studies.

Moreover, this concept of incapacitation levels being lower than lethality levels, although logical on paper, is flawed in reality, when applied to irritants. It has been shown that irritants (such as hydrogen chloride or acrolein) do not cause incapacitation at dose levels so high that the victim eventually dies of inhalation toxicity after the exposure. This is a complex concept, but is critical: when primates have been exposed to doses of irritants at levels where they died a few days after exposure, they were still capable of performing the necessary avoidance responses to escape the exposure, thus not being incapacitated [25]. Interestingly, the concept of incapacitation is only applied to irritants; see Equation (2). Interestingly, it has also been found that incapacitation from asphyxiants occurs at levels very similar to those leading to lethality, and not at levels an order of magnitude lower [26].

The issue of decay of concentration of reactive combustion products (particularly hydrogen halides and other acids, most of which are included among typical irritants) has been studied in depth (e.g. [27-34]). This has shown that the concentration, of hydrogen chloride, for example, can be much lower than the initial emitted levels after it has travelled some distance from the fire source (in some cases becoming undetectable). This issue must be considered when dealing with toxicity of combustion products, especially regarding incapacitation by irritants.

The ISO DIS 13571 draft raises a different, very interesting, and valuable, issue: people in a fire environment are affected by convected heat and by being unable to see due to smoke obscuration, as well as being affected by the toxicity of the atmosphere.

PRACTICAL IMPLICATIONS OF INCAPACITATION THRESHOLDS

Under the assumption that a typical 50 kW fire requires 0.19 m^2 (2 ft^2) of burning surface [35], it is possible to calculate the amount of the critical toxicant that would be emitted from such a surface burning for four different materials. The estimates were made based on the yields of combustion products found in the literature [10, 14] and on fire test data [10, 36].

The results indicate the following:

1. A small amount of PVC (corresponding, for example, to a floor cove trim 6 ft long and 4 inches wide) weighing 0.6 kg could not be used in a room, because it would drastically exceed the recommended level for IC HCl (100 ppm). However, when the material burns, its heat release rate is only ca. 20 kW, a level smaller than a burning waste basket. Such small fires are usually not reported to the fire departments, but controlled in house.

2. A similar amount of a halogen-free cross-linked polyolefin material (perhaps intended for a similar application) releases ca. 2.5 times the level of irritants. However, in spite of generating a much higher incapacitating level, the irritants it generates are of unknown composition, and thus not usually assessed by Equation (2), although they should actually be included in the term that has the summation of irritant concentrations (if the IC levels were known). From the point of view of a realistic fire hazard (namely heat release) such a material releases only 30 kW, still less than a burning waste basket.

3. A similar surface and thickness of fire retarded wood (with smaller mass, because of its lower density, which could also be used as interior trim) releases CO and virtually no irritants, and is thus unaffected by the assessment in Equation (2). From the point of view of a realistic fire hazard (namely heat release) this material releases 60 kW, making it a slightly more severe problem than the two earlier materials (and one that is likely to be reported), but still a small fire.

4. A similar surface (but at 10 times the thickness, to account for logical use as foam) also releases only asphyxiants as measurable combustion products, and thus is unaffected by Equation (2) (unless measurements of other gases are made). If a quarter of the HCN released had been converted to NO_2, this material would have exceeded the corresponding Equation (1). However, this material has very large heat release rate, so that now it is likely that a large fire has occurred, and not only has the fire department been notified, but severe destruction may have followed, via burning of adjacent materials/products.

Table 2. What Happens When 0.19 m^2 (2 ft^2) of Four Different Materials Burn

Estimates	PVC	Non FR Polyurethane Foam	FR Douglas Fir	XL Polyolefin
RHR (kW)	20	350	60	30
Density (kg/m^3)	1490	100	550	1500
Thickness (mm)	2	20	2	2
Material Mass (kg)	0.6	0.4	0.2	0.6
Ht Combustion (MJ/kg)	12	25	15	20
Toxicant yield (g/g)	0.4 (HCl)	0.005 (HCN)	0.1 (CO)	> 1 * (irritant)
Burning rate (g/s)	1.5	14.9	3.7	1.4
Toxicant Emission (g/s)	0.6	0.07	0.4	1.7 *
Air Entrainment (L/s)	490	490	490	490
Toxicant Level (ppm)	900	100	500	2400 *
FED (Lethality) Toxicant	0.24	0.50	ca. 0.12	?
Exceeds ISO 13571 FEC?	Yes	No	No	No
Ht Hazard (Low is Best)	1	4	3	2

*: Based on the finding that the irritancy of the combustion products of such materials exceeds that of PVC combustion products by a factor of 3-5 [14].

This analysis indicates that a small amount of any material releasing notorious irritants (such as halogen acids, sulphur dioxide, nitrogen oxides, formaldehyde or acrolein) even if it causes a fire that is probably not even reported, would trigger the threshold for incapacitation of Equation (2). This would then indicate to a designer, architect, or specifier, that 1 kg of that material cannot be used in any compartment!

The preceding analysis has ignored the fact that draft ISO DIS 13571, at the same time it contains illogically small threshold values for irritants, also contains equally illogical threshold values for asphyxiants. Thus, the problems discussed here can be extended to other materials.

Dr. Fredric Clarke has been the intellectual author of the analysis in the following paragraph, consequent to the fact that fires with small amounts of PVC cause incapacitation.

> NFPA data shows that between 1989-1993 there have been 54,000 residential fires, reported to the fire departments, where the material first ignited is wire and cable insulation or a wall covering, many (if not most) of which are made of PVC. Some 14,000 of these fires were big enough to spread beyond the room of fire origin (and thus reach flashover). Flashover fires where upholstered furniture was the item first ignited kill at least 10 people for each 100 fires, and it is logical to suppose that other residential flashover fires cause similar fatalities, and expose at least 10 times as many people. As less than 1 kg of burning PVC is sufficient to cause incapacitation, it is logical to assume that virtually all exposed people in a flashover fire became incapacitated, and most died. However, the actual number of fatalities in these fires was not 14,000, as results from this analysis, but a *miraculously low* 343 fatalities, more than 40 times less.

The thresholds in draft ISO DIS 13571 will not result in credit to a material that has been adequately fire retarded since they do not address fire performance properties of a material or product, including ignition resistance, lower heat release rate, lower burning rate or lower flame spread. In consequence, it appears clear that the implications of using those threshold levels would be that products made with combustible materials should be removed from inhabited areas, and replaced by ones made with non combustible ones (steel, concrete, ceramics). Thus would, of course, be very welcome by hermits desirous of an ascetic life in a cave, but not by those wishing the comforts of modern life.

ASSESSMENT OF FIRE HAZARD IN POST-FLASHOVER FIRES

The procedure for conducting a fire hazard assessment of the toxic fraction of smoke in a post-flashover scenario requires developing fire safety objectives, choosing the detailed fire scenarios, applying the relevant additional assumptions, and then making calculations and incorporating all the calculations into an overall hazard assessment.

The primary fire safety objective in a calculation of toxic fire hazard in post-flashover fires is to ensure the safe (unharmed) evacuation of all occupants in a post-flashover fire scenario. Then, a second fire safety objective, is to maintain a safe working environment for safety personnel, including fire fighters.

The primary fire safety objective is achieved if the time required, in the event of a fire, to evacuate the people in compartments remote from the fire, is less than the time for the fire to create untenable conditions (preferably for the fire not to create conditions that cause harm to people, whenever possible). The evacuation time includes the time required for the people to reach, or be transported to, a safe location. The time to untenability is calculated based on the shortest time until untenable conditions are created for any occupant along the evacuation path. Tenability is assessed on the basis of fire effects on humans, including both direct effects, such as heat, toxic gases or oxygen deprivation, and indirect effects, such as reduced visibility due to smoke obscuration. A tenable environment will therefore prevent loss of life and reduce the likelihood of harm, including non-fatal injury to individuals. Levels of tenability must be set based on literature data that show: the maximum temperatures which human beings can withstand, the maximum convected heat humans can tolerate, the heat flux required to blister or burn skin, the restrictions to escape imposed by smoke obscuration, the effects of the primary toxic gases, the overall effects of smoke toxicity or various ways to combine one or more of these effects. The documentation for HAZARD I [37-38] contains data that can be used safely, if no specific information is available to suggest that some of the information needs to be changed.

This fire hazard assessment procedure does not assess incapacitation. Incapacitation must be inferred from lethal toxic potency values. Moreover, the effects of sensory irritation are not addressed by this procedure, as the above discussion indicated that such an assessment is flawed.

The two critical fire scenarios to be investigated are: a fire that originates in the room immediately next to the room of interest and a fire that originates in another room, further away from the room of interest, and endangers the evacuation route from the room of interest through the spread of flames or smoke into the evacuation route. This assumes that other fire scenarios either are less severe and therefore will lead to achievement of the fire safety objectives if the design achieves the objectives for the specified fire scenarios, or are sufficiently unlikely that they need not be considered as part of the overall fire hazard assessment, although they may be considered individually.

Additional assumptions must also be made. These must include the occupancy of the room of interest and any other relevant occupiable spaces to which occupants may move during evacuation. It is critical to set them, for analysis purposes, to levels that pose the greatest challenge to the fire safety objectives. Thus, a logical assumption would be occupancy to capacity and a mix of occupants of different abilities (where some will have various physical or mental disabilities) and capabilities (for example, some will be assumed to be impaired by alcohol or drugs or by age-related limitations). The assumptions regarding age distributions of the occupants must reflect data on age patterns relevant to the occupancy class based on patterns in the general population, or known applications, if they differ. Assumptions regarding alcohol or drug impairment among occupants should also be based on patterns in the general population, weighted to reflect the age and economic distribution of known occupants. If such data are not available, conservatively assume that 10 percent of adult occupants are impaired by alcohol.

The calculations for the toxic hazard fraction of post-flashover fires should be done as follows. For post-flashover fires, the toxic potency of materials of "normal toxicity" can be, as indicated above, assigned a value of 8 g/m^3 (for a 30 min exposure period) (see ASTM E1678) [39] or NFPA 269 [40]. The smoke layer in a post-flashover fire can be assumed to have endured a CO generation corresponding to 20% of the overall mass loss during the fire. The actual concentration of CO, and that of overall smoke, should be calculated, minute by minute, based on the fuel mass loss during the fire. The toxic potency of CO can also be assigned a value of 8 g/m^3 (for a 30 min exposure period). It can also be assumed that the concentration-time curve for smoke of "normal toxicity" is linear, so that lethality is associated with a toxic load of 240 g min/m^3, so that lethality would be expected once the exposure concentration exceeds 240 g/m^3. Using information on the fire itself (in particular the mass loss as a function of time) and of the fire scenario, the toxic load should be calculated in the room of fire origin and in the room of interest, in the absence and presence of the product being investigated.

The complete fire hazard assessment (which should preferably follow the guidelines shown in ASTM E1546 [41]) then involves using one or more additional calculation procedures to determine whether the fire safety objectives will be met. Such calculations assess the overall fire hazard, specifically those aspects of the tenability dealing with thermal exposure (both radiant and convected heat) and smoke obscuration. As explained before, choices can be made on tenability levels and calculation procedures for their assessment, as input to generate a valid fire hazard assessment. This must be followed by:

(a) Translation of the fire scenario specifications into a description of the fire in its initial stages, as a function of time in the initially involved space. The fire-test-response characteristics of the materials or products initially involved that should be considered for such a description are rate of heat release, rate of mass loss, total heat release (if burned to completion, or cumulative heat release to end of burning otherwise), flame spread, cumulative full-scale smoke obscuration and toxic potency of the products of combustion released. A thorough analysis of the actual fire scenario should result in a final decision on the properties required for the fire hazard assessment. The data to be used for this fraction of the calculation must come from test methods that both can represent the fire scenario being investigated and generate data in fire safety engineering units. Typically, such data is measured in heat release rate calorimeters. See, for example [42-56], guidance in ASTM E603, upholstered furniture testing in ASTM E1537, mattress testing in ASTM E1590, cable testing in cable trays in ASTM D5424 and ASTM D5537, interior finish testing in a room corner configuration in NFPA 265, NFPA 286 or ISO 9705, stacked chair testing in ASTM E1822, foam display testing in UL 1975, or small scale testing in ASTM E1354 (generic cone calorimeter) or its applications: ASTM E1474 (upholstered furniture or mattress composites), ASTM E1740 (wall covering composites), ASTM F1550 (vandalized mattresses in prisons), ASTM D6113 (electric materials).

(b) Translation of the design specifications into characteristics of the fuel load environment near the initial fire. These and the time-based description of the initial fire as a function of time should be used to calculate the spread of fire to secondary items and the ignition of those secondary items.

(c) For each space, the time at which the major fire events occur must be assessed. This should include the onset of flashover; and fire spread from one space to an adjacent space, whether through barriers or not, particularly from outside the room of interest. The calculation of fire spread from one space to another will require measurement of barrier fire resistance characteristics.

(d) For each potentially exposed occupant, calculations must be made of the time to reach safe refuge and this must be compared to the calculated time until exposure to an unacceptable potential for harm (hazard). The former requires calculation of occupant alerting, response, travel speed, and other behavior. For occupants requiring rescue, calculations will need to estimate the size, capabilities, and arrival time of fire department or other rescue personnel. The latter can be calculated as time to exposure to untenable cumulative doses of fire effects or conservatively calculated as time to first exposure to unacceptably hazardous fire conditions. Calculations will be required for the area of fire origin, any occupied spaces, and any spaces that are part of escape or rescue routes.

(e) It is critical to incorporate the activation and effects of fire protection systems, including automatic or manual fire suppression, detection, and smoke control systems.

(f) It is also critical to develop "safety factors" needed to offset the uncertainties and biases associated with the method or with the data used by the method. Any calculation method is valid only for certain applications and within the limits of its own uncertainties and biases and the uncertainties of its source data. Therefore, evidence of validity from the calculation method documentation will provide the basis for specifying safety factors.

In summary, the overall effect of the product being investigated on fire hazard is a combination of its effects on the toxic tenability and on other types of tenability investigated.

CONCLUSIONS

- Fire hazard (or the potential for harm associated with a fire) is associated with the critical fire properties of the materials and products contained in the fire scenario and that can prevent or inhibit the escape of exposed people. These are, primarily, heat release, burning rate, flame spread and smoke production tendency (of all materials or products) and ignitability (of materials or products adjacent to the material first ignited).
- The use of Fractional Effective Doses for assessment of lethal toxicity is a reasonable one, while that of Fractional Effective Concentrations (with threshold levels causing "severe

effects" for incapacitation, and no time component) is not based on scientific data but on speculative assumptions, which have been proven to be inadequate.

- The levels of combustion products causing incapacitating levels are known in some cases: they are marginally smaller than those levels causing lethality (for some asphyxiants) and higher than those levels that will eventually cause post-exposure lethality (for many irritants). Assumptions that make them orders of magnitude smaller than lethal levels have no basis in scientific fact.

- The analysis of combustion product yields shows that the concept of critical irritant concentrations, and the associated recommended threshold values, would lead to bans in the use of combustible materials and products generating the comforts with which modern life has been associated in recent years.

- A toxic fire hazard assessment in pre-flashover fires must consider lethal levels of toxic products, as they have been assessed adequately, and can be combined by the N-gas model, irrespective of whether they are asphyxiants or irritants.

- A toxic fire hazard assessment needs to consider first those scenarios that cause the majority of fire fatalities, namely post-flashover fires. In such cases, material selection should be such that mass loss, heat and smoke release are minimized, as toxicity is a direct result of mass loss: CO dominates post-flashover toxicity, and it is generated as 20% of the mass of the combustible materials burning.

- A detailed procedure has been presented to show how to conduct a fire hazard assessment for post-flashover fire scenarios, which emphasizes smoke toxicity, but within the context of fire safety engineering concepts. This subsumes smoke toxicity as one element, together with heat release and other fire properties, to assess a realistic time to escape.

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GBH Attachment 15

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Fire Testing of Electrical and Optical Fiber Cables for Transportation Vehicles, Especially in North America

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ABSTRACT: Cables for transmission of power and data are a large, and growing, part of the fuel load in public transportation vehicles. Unfortunately, the fire performance of electric cables has usually been neglected or based only on semi-mandatory guidelines of relatively low severity. Furthermore, optical fiber cables have usually been ignored. This paper discusses the most recent approaches taken by the various regulatory authorities in the US (US Coast Guard [USCG], Federal Aviation Administration [FAA], Federal Railroad Administration [FRA], and Federal Transit Administration [FTA]), together with the work of the applicable standards developing organizations (the National Fire Protection Association [NFPA] and the International Maritime Organization [IMO]).

The US Coast Guard regulates all ships in US ports, but, as a signatory to the International Convention of Safety to Life at Sea (SOLAS), the International Maritime Organization regulates US ships going into international waters. Ships that do not go into international waters (including those that just cross rivers or lakes and those that operate in amusement parks) do not have to meet SOLAS requirements and can meet USCG requirements only or can meet the voluntary requirements contained in NFPA 301, Code for Safety to Life from Fire on Merchant Vessels. While SOLAS has very mild regulatory requirements for cabling, NFPA 301 has a minimum requirement for cables to meet the vertical cable fire test in CSA FT4 or UL 1581-1164 (a fairly severe test). Cables meeting more severe fire test requirements are also permitted to be used as replacement for these tests.

The Federal Railroad Administration regulates intercity trains as well as trains that cross state lines. FRA does not have required cable fire tests for cables. However, NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems, has as a minimum fire test requirement of a slightly milder vertical cable tray fire test for cables, the one in UL 1581-1160, but a smoke obscuration test is also required.. Again, cables meeting more severe fire test requirements are also permitted to be used as replacement for these tests. NFPA 130 is widely used by many rail authorities, both in the US and abroad (particularly Canada and the Far East), as it is more severe than the FRA rules.

The Federal Transit Administration provides guidelines and no requirements, and its guidelines apply to subways and suburban trains that do not cross state lines. The guidelines do not include any information on fire safety of cables. NFPA 130 also applies to subways and all trains, of course.

The Federal Aviation Administration regulates both the wiring that is placed into airplanes by air frame manufacturers (those who build the airplanes) and the one put in afterwards by airlines (usually for entertainment systems). The requirements are the same for both: a small 60° angle Bunsen burner test. The issue that needs to be pointed out, however, is that the cabling used by air frame manufacturers has a fire performance that is greatly superior to that required to meet the test, while the cabling used in entertainment systems is often barely able to meet the fire test and may be unsuitable from the point of view of fire safety. FAA is aware of this and is undertaking a program to develop an adequate fire test for all cabling in airplanes.

NFPA has a committee, Hazard and Risk of Contents and Furnishings, which is developing a Guide on Methods for Evaluating Fire Hazard and Fire Risk of Vehicular Furnishings, to be called NFPA 556, which will address cabling. The Fire Protection Research Foundation is also looking into this issue with

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their new Research Advisory Council on Fire and Transportation Vehicles.

In summary, this is an area where fire safety is a potential concern, but where abundant activity is taking place.

KEYWORDS:

Introduction

NFPA statistics indicate that in the United States there have been approximately 1 823 000 fires in 1999, with 368 500 occurring in vehicles and 523 000 in structures [1]. The trends have been similar for years: there were, on average, between 1994 and 1998, a yearly total of 399 900 fires in vehicles and 567 100 fires in structures [1]. Between 1980 and 1999, reported vehicle fires decreased by only 22 %, while reported structure fires decreased by 51 % and fires of all types decreased by 39 % [2]. Fires in public transportation vehicle environments are rare: most fires occur in buildings, and those in vehicles (20 %) often occur in private road vehicles (road vehicles account for almost 75 % of all vehicle fires). However, when fires in public transportation vehicles occur, the results can be very severe, because of the multitude of passengers using public transportation: buses, trains, ships, or airplanes. Furthermore, there is a growing realization that the increase in communications and electronics has resulted in a vast increase in the amount of electrical wires and cables that are present in such environments and particularly in the fuel load that these products represent. Table 1 shows the proportion of fires caused by electrical faults and the proportion of fires started in electrical wire or cable insulation as the item first ignited in various types of vehicles [2]. As a further example, Table 2 shows some statistics of fires in rail transportation environments (0.2 % of vehicle fires), where traditional guidelines have focused mostly on upholstery contents [2–5]. In recent years, the fraction of rail transportation vehicle fires starting in electrical wiring has been over 10 % of all fires, a much greater proportion than the fraction of fires starting in upholstery, and the greatest single material source of fires other than the inevitable fuel used to power the rail cars.

TABLE 1—*Distribution of vehicle fires in the United States, 1994–1998. Also, percentage of vehicle fires where the ignition factor was electrical and where the material first ignited was electrical wire or cable insulation, by vehicle type [2].*

	% of All Vehicle Fires	% With Electrical First*	% With Wire & Cable First†
Passenger Road Vehicle	73.8	25.0	27.0
Freight Road Transport Vehicle	9.3	22.5	23.1
Heavy Equipment Vehicle	1.6	26.4	19.9
Special Vehicle	0.5	16.9	14.2
Water Transport Vehicle	0.4	21.0	14.7
Rail Transport Vehicle	0.2	13.5	11.1
Air Transport Vehicle	0.1	12.8	12.0
Unclassified Vehicle	14.2		

* Fires where the "ignition factor" was "short circuit, ground fault, or other electrical failure."

† Fires where the material first ignited was "electrical wire or cable insulation."

TABLE 2—*Material first ignited in rail vehicle fires [2–5].*

	1991-95 All Trains*	1992–96 All Trains†	1994–98 All Trains‡	1988–97 Passenger Trains§
Fuel	17 %	17 %	18 %	16 %
Electrical Wire	11 %	11 %	11 %	18 %
Trash	8 %	9 %	7 %	1 %
Upholstery	3 %	2 %	2 %	11 %
Unclassified	16 %	15 %	15 %	7 %
Other	45 %	46 %	47 %	47 %

* All Rail Transportation Fires - Averages for 1991–1995 [3].
† All Rail Transportation Fires - Averages for 1992–1996 [4].
‡ All Rail Transportation Fires - Averages for 1994–1998 [2].
§ Rail Passenger and Diner Car Fires - Averages for 1988–1997 [5].

Fire safety in mass transportation has been an issue in the United States for years. The 1973 Urban Mass Transportation Administration (UMTA) project on fire safety of transit vehicles resulted in the Transportation Systems Center "Guidelines for Flammability and Smoke Emission Specifications" for materials used in transportation vehicles [6]. These guidelines have developed to some extent over the years, and they became quoted, in various guises, by a number of organizations, including the Federal Railroad Administration (FRA) [7], the Federal Transit Administration (FTA, successor to UMTA) [8], and the National Fire Protection Association (NFPA), initially for fixed guideway transit systems (i.e., underground subways) [9]. A survey of these guidelines and recommendations was made by NIST in 1994 [10]. These guidelines covered a broad number of products (using various traditional fire safety test standards [11–18], including especially the traditional ASTM E 662 smoke chamber, shown in Fig. 1 [16]), but the only fire safety requirements for cables were included in NFPA 130, addressing fixed guideway systems. Eventually, NFPA 130 was expanded to address all passenger rail systems, and this brought wire and cable fire safety requirements into a broader transportation picture [19]. In 1999 the Federal Railroad Administration issued a rulemaking process to make the guidelines into regulatory requirements and included some requirements for rail cable fire safety [20]. Unfortunately, the FRA then chose to backtrack and to eliminate the requirements for rail cable fire safety [21], but NFPA 130 is continuing to regulate these products. The details of the FRA requirements are clearly spelled out in ASTM E 2061 [22], which also discusses ways of assessing fire hazard for cable fires.

The earliest concern about the introduction of combustible materials into trains was expressed following full-scale testing of the burning behavior of a real-scale mockup of a rail passenger coach compartment [23], and that started the strong emphasis on upholstery, which continued to be the trend until the 1990s. Early studies highlighted the fact that rail transit car assembly and transit bus interior assembly mock-ups could be built with standard (i.e., with minimal if any fire retardance) polyurethane foam seats, which met the requirements of FMVSS 302 [24], but caused room flashover in 6–7 min [25]. The same concerns were immediately expressed for buses, which were soon intended to meet the same guidelines as trains. Separate fire test requirements were developed for public transportation on water and air, some of which included tests for electrical cables.

Early Requirements for Rail

Fire testing requirements for wire and cable can be found in Amtrak specifications [26] and NFPA 130 [9]. Amtrak "high performance wire and cable" insulated conductors must meet the flame test in ICEA S-19 [27], the VW-1 test [28], and ASTM E 662 [16] limits. In NFPA 130 fixed guideway vehicles, wires for control, and other low voltage (i.e., less than 100 V ac and 150 V dc) functions had to meet the requirements of ICEA S-19, (with Amendment FR-1); or of UL 44 [29], for thermosetting insulation and UL 83 [30], for thermoplastic insulation. In NFPA 130 vehicles, power cables also had to meet the requirements of IEEE 383 [31], with the additional requirement that circuit integrity continue for 5 min after the start of the test (*even though circuit integrity is not defined in the IEEE 383 test*). There were also statements that all electrical systems must meet National Electrical Code [32] requirements.

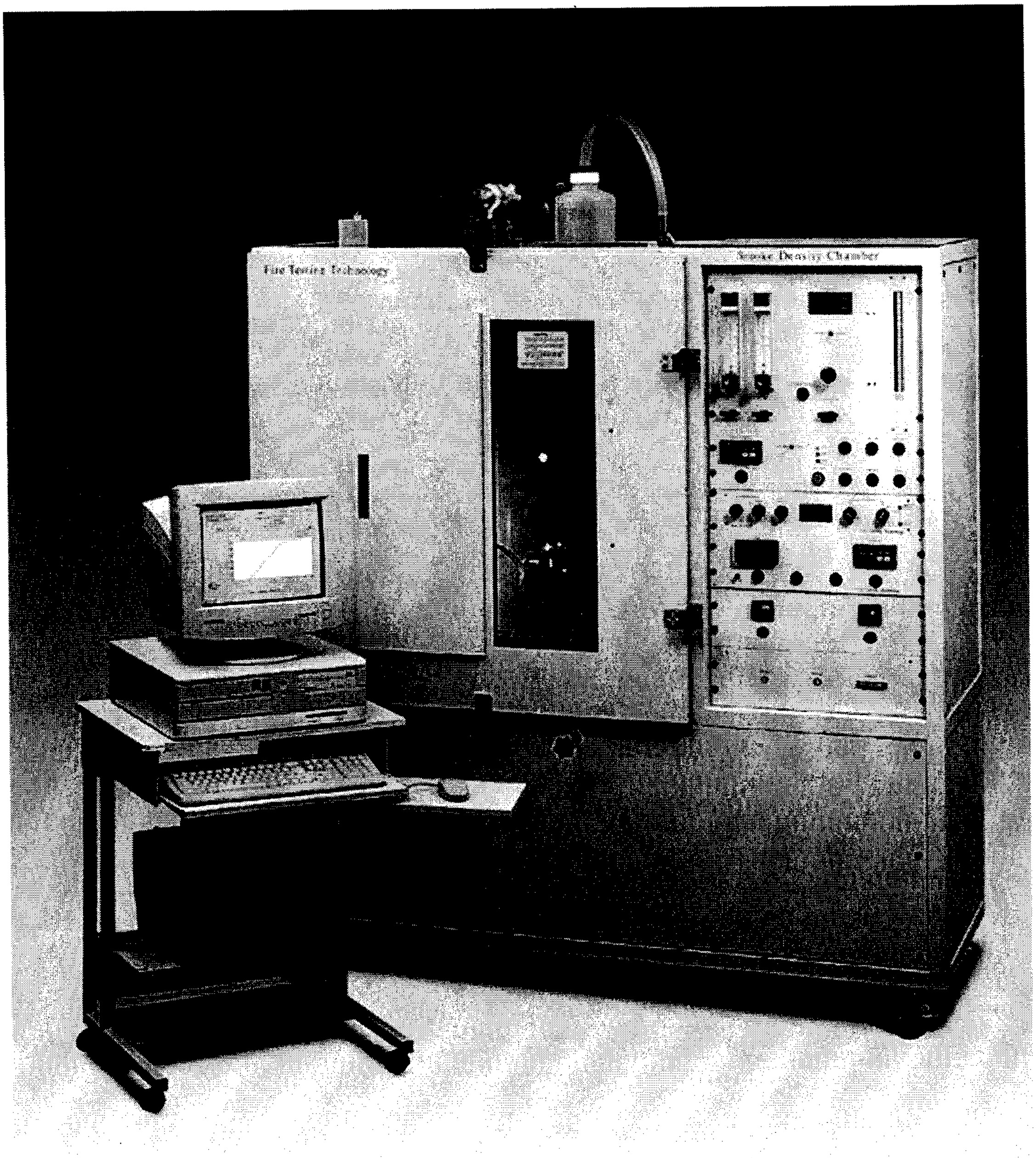

FIG. 1—*Smoke chamber fire test apparatus, in accordance with ASTM E 662 [16].*

Recent Requirements for Public Transportation

Passenger Road Vehicles, Including Buses and School Buses

There are almost no mandatory fire safety requirements for such vehicles. The National Highway Safety Transit Administration (NHTSA) has as its only mandatory fire safety test one that applies a small burner to interior materials (FMVSS 302 [24]). This test is very mild and has been replaced in most public transport applications by the FTA guidelines [8], which do not, however, contain information about electrical cables. Many manufacturers of passenger road vehicles do have some cable specifications of their own, which helps obtain a certain degree of fire safety, but this is an area where progress is needed. A recent white paper, discussed in more detail later, highlights the problems associated with such vehicles [33].

Aircraft

In aircraft, the regulatory authority is the Federal Aviation Administration (FAA), via Title 14 in the Code of Federal Regulations. All of their fire test requirements are published in a Fire Test Handbook [34]; found on the FAA website, with regular updates. Wire and cable needs to meet a relatively mild exposure to a Bunsen burner, at a 60° angle, for 30 s (Figs. 2 and 3), although the majority of the wire and cable actually used exhibits a fire performance that significantly exceeds the test requirements. The FAA has been actively pursuing the development of a new test for materials concealed outside of the passenger cabin, and wire and cable are prominent in that location. They have a test under development for that purpose, probably based on the flooring radiant panel (ASTM E 648, Fig. 4) [13], because that would be consistent with the FAA approach regarding thermal and acoustic insulation, which is also contained in concealed aircraft spaces and is regulated by a test based on ASTM E 648 (Handbook Chapter 23, Test Method To Determine the Flammability and Flame Propagation Characteristics of Thermal/Acoustic Insulation Materials). The FAA also has a test for wire and cable in a "designated fire zone" (based on MIL SPEC W 25038E or on ISO 2685) and one for smoke emission from wire and cable, using the NBS smoke chamber (ASTM E 662) [16]. The FAA prefers to develop test methods that are based on a fire hazard assessment and that are of specific use to the aircraft industry, and to work with the interested parties in the industry to complete the final test modifications and improvements.

Ships

All ships that engage in international trade and fly the flag of a country that has signed the International Convention for Safety of Life at Sea (SOLAS) [35], which includes the USA, must comply with the regulations of the International Maritime Organization (IMO). The IMO regulations are detailed in the SOLAS book, periodically amended by "Resolutions" of the IMO committees, and ratified by the signatory states. Details of the fire issues are given in the IMO Fire Test Procedures Code [36], also reissued regularly. Some special vessels are regulated separately: high speed craft that is never too far from shore is regulated by the IMO High Speed Craft Code [37]. All ships that sail in US waters must comply with the requirements specified by the US Coast Guard, laid out in US Federal Government - Coast Guard: Title 46, Shipping, Code of Federal Regulations, Parts 1–199 [38], and in NVIC (US Coast Guard Guide to Structural Fire Protection) [39].

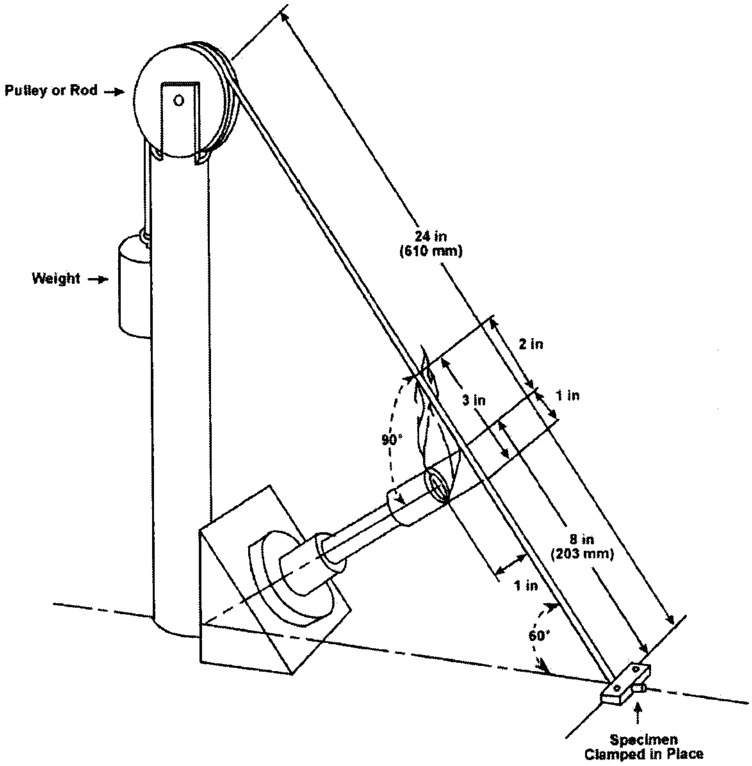

FIG. 2—*FAA 60° electrical wire bunsen burner test setup.*

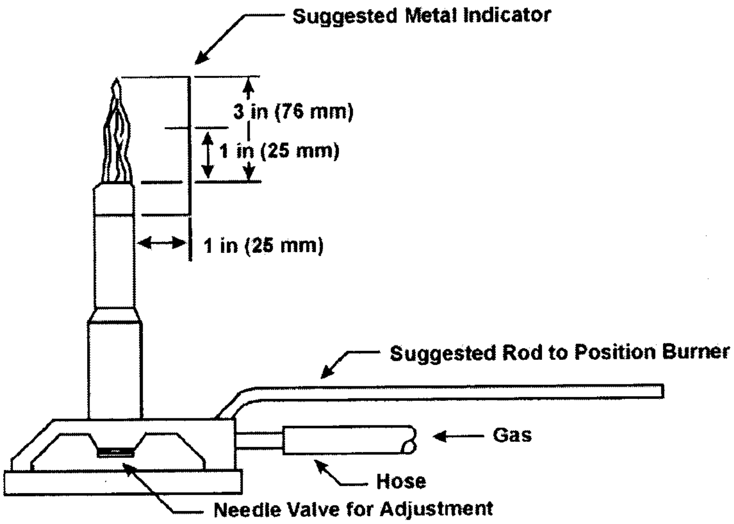

FIG. 3—*FAA wire bunsen burner plumbing and flame height indicator.*

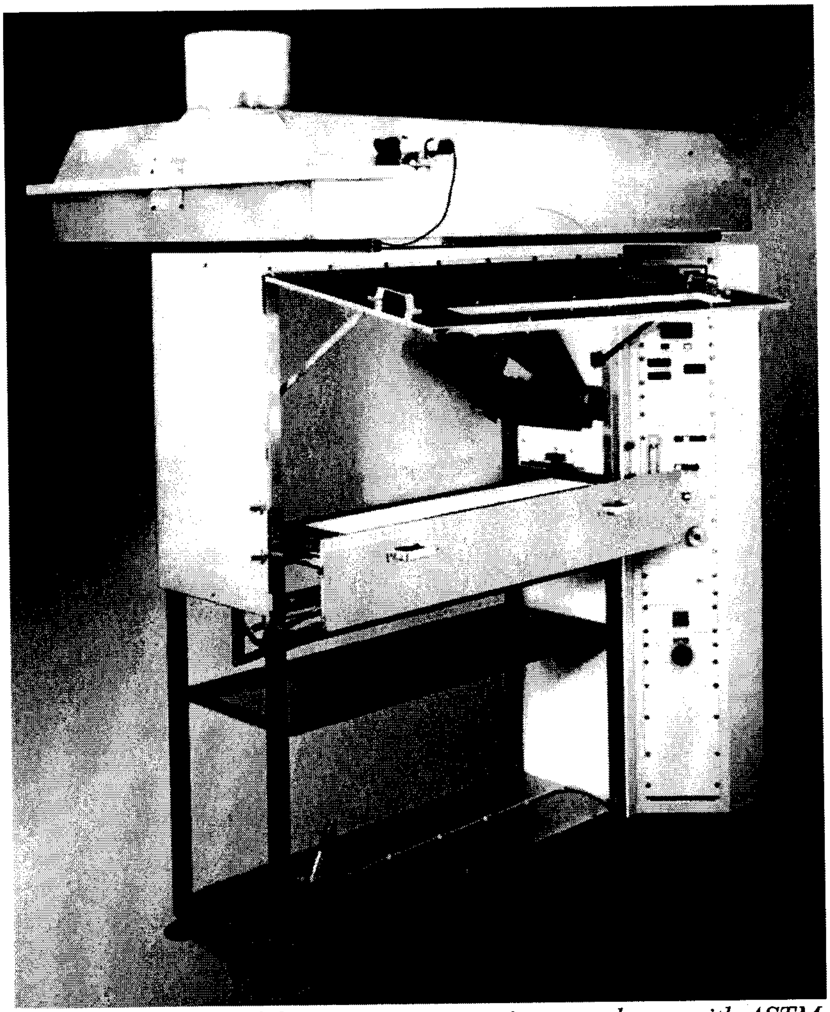

FIG. 4—*Flooring radiant panel fire test apparatus, in accordance with ASTM E 648 [13].*

The Coast Guard is also the authority having jurisdiction over ships engaging in international trade and sailing into US waters or US ports; such ships must comply with IMO regulations and need not also comply with separate Coast Guard requirements. With the instructions from the US federal government that standards should, whenever possible, be delegated to private organizations, the Coast Guard and NFPA agreed in the mid 1990s to develop NFPA 301 [40], to add to the existing NFPA 302 [41]. NFPA 301 applies to passenger vessels carrying more than 12 passengers, cargo and tank vessels, and towing vessels 12 m or more in length and greater than 500 hp; it does not apply to military ships (although military ships must comply with Coast Guard requirements). NFPA 302 applies to boats of less than 300 gross tons used for pleasure or commercial purposes that meet one of the following conditions: (a) motor craft; (b) boats that use cooking, heating, or auxiliary appliances; or (c) boats that have permanently installed ignition source(s); it does not apply to personal watercraft. In fact, passenger vessels carrying up to 12 passengers are covered by NFPA 302. In order for NFPA 301 or NFPA 302 to be a requirement, someone must choose to meet them, and that would typically be a shipbuilder in conjunction with ABS (American Bureau of Shipping, who certify ships in the USA). The market of ships that are not built to comply with IMO requirements is actually extremely large, because it encompasses all the ships sailing through rivers (e.g., Mississippi River), lakes (e.g., Great Lakes), and coastal waters (without reaching into international waters), as well as ships sailing in amusement parks. Typically, electrical installations in ships in the USA have always been regulated by military specifications included in CFR 46 (Subchapter J) and by the recommendations of IEEE 45 [42]. The most recent edition of IEEE 45 has taken the requirements for wire and cable out of IEEE 45 and placed them into IEEE 1580 [43]. The critical requirement is that all cables approved to IEEE 1580 must meet the flame spread requirements of a vertical cable tray test, namely IEEE 1202 [44]. IEEE 1202, which is very similar to other better-known tests: CSA FT4 [45], UL 1581- section 1164 [46] or ASTM D 5537 protocol B [47], requires that 2.44 m lengths of cables, at a specified cable loading, not spread flame more than 1.5 m vertically in a cable tray on exposure to a 20 kW gas burner, placed at a 20° angle (and not perpendicular to the cable; see Fig. 5) for 20 min. IEEE 1580 does not require all cables to meet smoke obscuration criteria, but it requires that cables that are described as "limited smoke" must meet the flame spread and smoke release requirements of UL 1685 (FT4 protocol) [48], and it contains requirements for a variety of low smoke materials to be used for cable insulation and cable jacketing. It also contains, by reference, smoke obscuration requirements based on MIL C24643A [49].

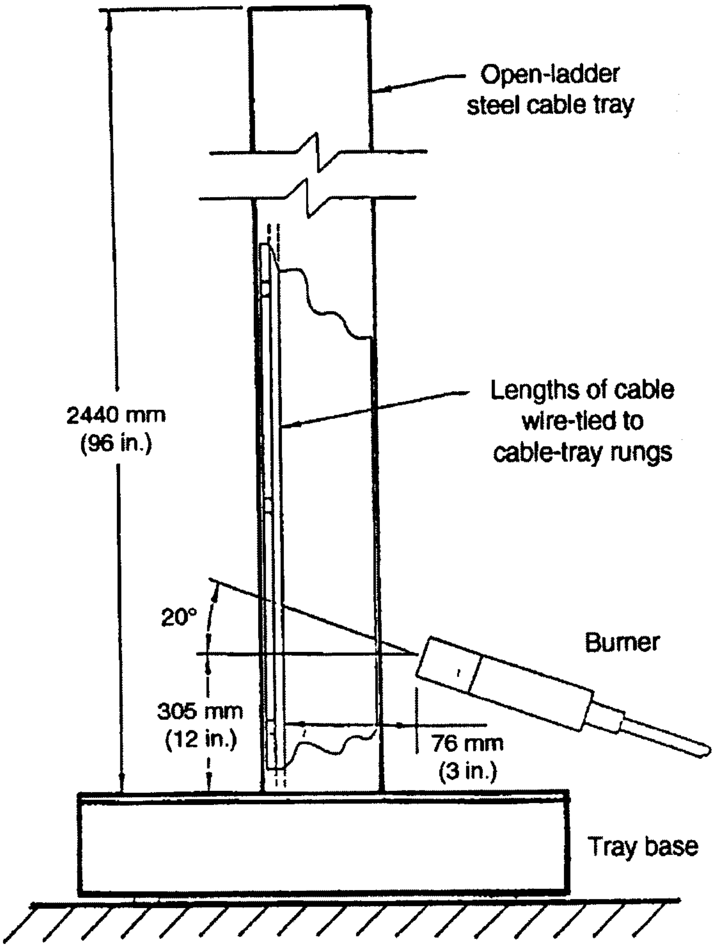

FIG. 5—*Vertical tray cable fire test apparatus, in accordance with ASTM D 5537.*

The older edition of IEEE 45 (1983 edition) required all shipboard cables to meet a test with a flame insult equivalent to the vertical tray test in IEEE 383 [31] or in UL 1581-1160 [50], and its jacket to be flame retardant (unspecified). This meant that large diameter cables had to meet the actual IEEE 383 test (a 2.44 m vertical cable tray test, with a 20 kW horizontal gas flame applied for 20 min, at a specified cable loading), and thin cables only had to meet a watered down version of that vertical cable tray test. The CSA FT4 standard differs from UL 1581-1160 in a few main aspects, as follows (see added details in [51]):

- The burner is at an angle of 20° from the horizontal, rather than vertical, and it is sited 30 cm (1 ft) from the floor rather than 45 cm (18 in.) from the floor.
- The burner is sited in front of cable tray rather than at the back.
- Cable loadings are different, the CSA FT4 test having significantly more cable, particularly for smaller diameters.
- Tray length is 3 m (10 ft) and not 8 ft (2.4 m); minimum cable length is 2.3 m (but it still is 2.4 m in IEEE 1202).
- Failure criterion is a char length of 1.5 m, rather than 8 ft (2.4 m).
- In summary, the CSA FT4 test is substantially more severe than UL 1581-1160.

NFPA 301 contains fire test requirements for cables by reference to 46 CFR Subchapter J (Electrical Engineering, Parts 110-113) [38] and to IEEE 45 [42], but also directly references the vertical cable tray fire tests discussed above (IEEE 1202, CSA FT4, UL 1581-1164) in the code. NFPA 301 does not require cables to meet the fire test criteria of UL 1666 (riser [52]) or NFPA 262 (plenum [53]), in spite of the fact that modern ships: (a) are multi-storied constructions, with many shafts communicating the various stories and concealed spaces and (b) have a multitude of communications cables critical for ship performance. However, now NFPA 301 does permit cables listed to these more severe fire test requirements, such as UL 1666 (riser [52]) or NFPA 262 (plenum [53]), to be substituted for the cables meeting vertical cable tray requirements. The National Electrical Code details the fire test requirements for cables. It contains four types of test requirements: UL 1581 VW-1, UL 1581-1160 or UL 1581-1164, UL 1666, and NFPA 262, in degree of increasing severity. Of these tests, the UL VW-1 test can usually be met by any cable that has a thick enough insulation, irrespective of the fire performance of the insulating material used. The NEC understands, too, that, as a cable meets more severe fire test requirements, it can replace one that meets less severe requirements. Thus, the NEC permits cables meeting the UL 1581 cable tray test, the UL 1666 riser test, or the NFPA 262 plenum cable test to be used in any application where the VW-1 test is required. This is particularly important in environments where space and weight are at a premium, such as a transportation environment (train or ship), where the "modern" trend is to develop cables with thinner walls. Figure 6 shows the NEC substitution scheme for flame spread of cables and Fig. 7 the equivalent one for smoke obscuration. This occurred by the addition of a section in NFPA 301 specific to fire performance of cables, that clarified the situation, and contains requirements for a fire performance hierarchy of cables, including having references to communications cables, which is the fastest growing application for cables, and where the most severe fire requirements are needed.

NFPA 301 now contains a direct reference to the substitution requirements of the National Electrical Code [32]. The National Electrical Code contains requirements for fire tests for a broad range of cables: all cables (including power) associated with information technology supply circuits, remote control, signaling and power limited circuit cables, fire alarm cables, optical fiber cables and raceways, communications wires and cables and raceways, community antenna television and radio cables, coaxial cables and network-powered broadband communications equipment, and cables. However, the NEC requires all cables to be grounded, and that requirement should not apply to cables in ships. Unfortunately, NFPA 301 does not contain mandatory requirements for smoke obscuration of the cables themselves.

Listing and certification of naval cables can also be accomplished via a joint UL/CSA standard (UL 1309 and CSA 245 [54]) and, internationally, via IEC 92-350 or IEC 92-353 [55,56], which are required by SOLAS. UL 1309 requires cables to meet a vertical cable tray test, either the one contained in UL 1581-1160 or the one in UL 1581-1164/IEEE 1202/CSA FT4. The international standards bodies have a set of three fire tests for electrical cables: IEC 60332-1, IEC 60332-2, and IEC 60332-3 [57–59], where the first two apply to a single insulated wire or cable, and IEC 60332-3 is also a vertical cable tray test, but it is somewhat less severe than CSA FT4 [45] and even UL 1581-1160 [50]. The US Coast Guard is recommending that electric installations listed to UL 1309, IEC 92-350, or IEC 92-353 be accepted as equivalent to those presently permitted.

In NFPA 302, electrical systems are described, but no specific fire test requirements are mentioned (other than the UL designations for various cables). Systems connected to electrical ac current in the marina must meet the National Electrical Code requirements for the application.

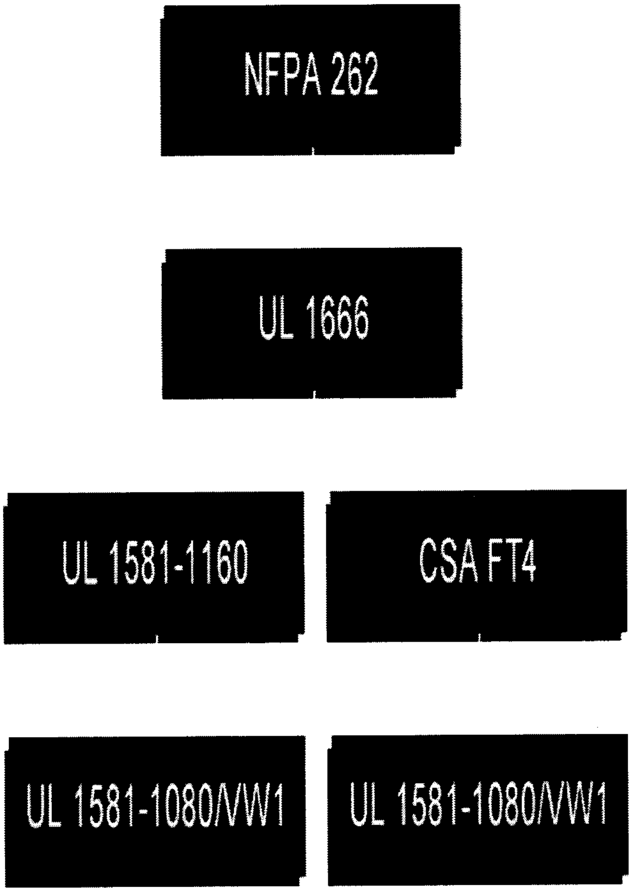

FIG. 6—*National electrical code substitution scheme for flame spread.*

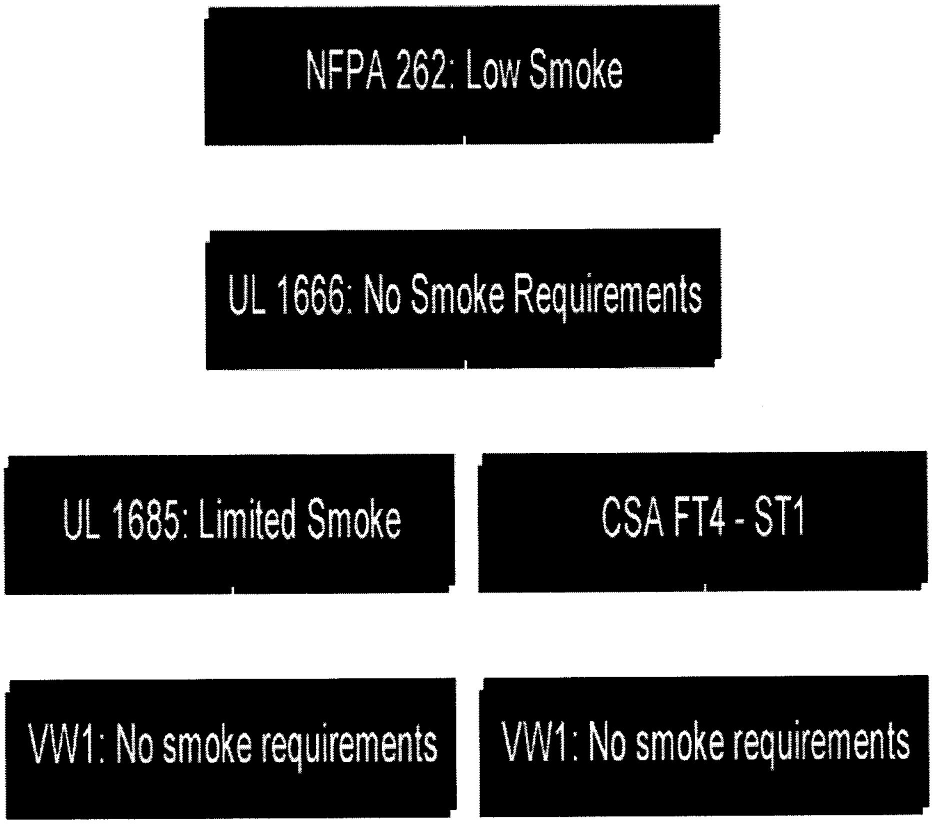

FIG. 7—*National electrical code substitution scheme for smoke obscuration.*

Rail

NFPA 130 has expanded its scope in the 2000 edition to address not just Fixed Guideway Transit Systems (i.e., underground city trains) but all passenger rail systems. There have been, however, no recent changes to the requirements for electrical cables or electrical installations. The 2000 edition of NFPA 130 also discusses the need to consider heat release rate as a critical component of fire hazard assessment and that the mandatory rules are simply one way of solving the fire safety problem. In 1999 two other major developments occurred: the Federal Railroad Administration published a new mandatory Rule [20], to be applied to all new rail passenger systems, and the ASTM committee on Fire Standards first issued a guide for the fire hazard assessment of rail transportation vehicles: ASTM E 2061 [22]. Both contain significant new concepts for fire testing of electrical cables.

The 1999 FRA Rule is a set of Mandatory Requirements, as opposed to the Guidelines and Voluntary Requirements of earlier vintages. The Table of mandatory requirements in that rulemaking included a section on electrical cables, absent before (see Table 3), with new notes. The fire tests for wire and cable were almost identical to those included in NFPA 130-2000, but were then not applied system wide. Another major change presented by the new FRA rule is the explicit assertion that alternative test methods can be used to replace existing test methods (The notes include some examples of these statements). Finally, the most important change is the fact that the FRA Rulemaking publication explicitly states that it is desirable to use overall systems approaches to fire hazard, including mentioning specifically the ASTM E 2061 guide.

TABLE 3—*FRA requirements for electrical cables for rail transportation vehicles from 1999 rulemaking [20].*

	Flammability		Smoke Emission	
Category Function of Material				
	Test Procedure	Performance Criteria	Test Procedure	Performance Criteria
Low voltage wire and cable	ICEA S-19	Pass	ASTM E 662	Ds (4.0) $\leq$ 200 (flaming)
	or			Ds (4.0) $\leq$ 75 (non flaming)
	UL 44 and UL 83 (Note # 17)			
Power cable	IEEE 383 (Note # 18)	Pass	ASTM E 662	Ds (4.0) $\leq$ 200 (flaming)
				Ds (4.0) $\leq$ 75 (non flaming)
	See also notes # 10, 11 and 12			

10. Materials used to fabricate miscellaneous, discontinuous small parts (such as knobs, rollers, fasteners, clips, grommets, and small electrical parts) that will not contribute materially to fire growth in end use configuration may be exempted from fire and smoke emission performance requirements, provided that the surface area of any individual small part is not $\geq$ square inches (100 cm^2) in end use configuration and an appropriate fire hazard analysis is conducted which addresses the location and quantity of the materials used and the vulnerability of the materials to ignition and contribution of flame spread.

11. If the surface area of any individual small part is less than 16 square inches (100 cm^2) in end use configuration, materials used to fabricate such small part shall be tested in accordance with ASTM E 1354, unless such small part has been shown not to contribute materially to fire growth following an appropriate fire hazard analysis as specified in Note 10. Materials tested in accordance with ASTM E 1354 shall meet the performance criteria of tig /q"max $\leq$ 1.5. Testing shall be at 50 kW/m2 applied heat flux. (Note the error in the criterion)

12. Assessment of smoke generation by small miscellaneous, discontinuous parts may be made by utilizing the results from the ASTM E 1354 test procedure conducted in accordance with Note 11, rather than the ASTM E 662 test procedure, if an appropriate fire hazard analysis is provided which addresses the location and quantity of the materials used and the vulnerability of the materials to ignition and contribution of smoke spread.

17. Testing shall be conducted in accordance with ICEA S-19/NEMA WC3, paragraph 6.19.6, or UL 44 for thermosetting wire insulation and UL 83 for thermoplastic wire insulation.

18. Testing shall be conducted in accordance with IEEE Standard 383, Section 2.5, with the additional requirement that circuit integrity shall continue for 5 min after the start of the test.

NFPA 130-2003 incorporated a complete restructuring of cable fire test requirements for rail transportation vehicles. What was incorporated is a requirement that all cables must meet the UL 1581-1160 vertical tray cable fire test flame spread criteria and must also meet smoke obscuration criteria, either in the same test or in combination with other tests. Control and low voltage cables must also meet the small individual wire tests. Fire alarm cables must now meet one of three types of circuit integrity tests, including the one from IEEE 383 contained in earlier editions. The relevant requirements are shown below and in Table 4:

"8.5.7.1 Electrical Insulation.
8.5.7.1.1 All wires and cables shall be listed as being resistant to the spread of fire and shall have reduced smoke emissions.
8.5.7.1.2 Cable shall be permitted to be listed by any of the following methods:
(1) The cable does not spread fire to the top of the tray in the vertical-tray flame test in UL 1581, Section 1160, and the cable exhibits a specific optical density of smoke at 4 minutes into the test that does not exceed 200 (in the flaming mode) or 75 (in the nonflaming mode) when tested in accordance with ASTM E 662.

(2) The cable exhibits damage (char length) that does not exceed 1.5 m (4.9 ft) when the vertical flame test, with cables in cable trays, is performed as described in CSA C22.2 No. 0.3, and the cable exhibits a specific optical density of smoke at 4 minutes into the test that does not exceed 200 (in the flaming mode) or 75 (in the nonflaming mode) when tested in accordance with ASTM E 662.

(3) The cable is listed as a limited smoke cable (/LS) by meeting the cable damage height, total smoke released, and peak smoke release rate criteria required when tested in the vertical tray flame test in the UL 1685. The following performance criteria shall be met when testing by UL 1685:

(a) When testing in the UL vertical tray flame exposure:

i. The cable damage height shall be less than 2.44 m (8 ft) when measured from the bottom of the cable tray.

ii. The total smoke released shall not exceed 95 m2 (1023 ft^2*).*

iii. The peak smoke release rate shall not exceed 0.25 m^2/s *(2.7* ft^2/s*).*

(b) Alternatively, when testing in the IEEE 1202 flame exposure:

i. The cable damage height shall be less than 1.5 m (4.9 ft) when measured from the lower edge of the burner face.

ii. The total smoke released shall not exceed 150 m^2 *(1615* ft^2*).*

iii. The peak smoke release rate shall not exceed 0.40 m^2/s *(4.3* ft^2/s*).*

(4) The cable is listed as having fire-resistant characteristics capable of preventing the carrying of fire from floor to floor, by being capable of passing the requirements of ANSI/UL 1666, and the cable exhibits a specific optical density of smoke at 4 minutes into the test that does not exceed 200 (in the flaming mode) or 75 (in the nonflaming mode) when tested in accordance with ASTM E 662.

(5) The cable is listed as having adequate fire-resistant and low smoke-producing characteristics, by having a flame travel distance that does not exceed 1.52 m (5 ft), generating a maximum peak optical density of smoke of 0.5 and a maximum average optical density of smoke of 0.15 when tested in accordance with NFPA 262.

8.5.7.1.3 Wires and cables for control and other low voltage (i.e., less than 100 V ac and 150 V dc) functions shall comply with 8.5.7.1.2 and either of the following:

(1) The physical, mechanical, and electrical property requirements of ICEA S-19/NEMA WC3

(2) UL 44 for thermosetting insulation and UL 83 for thermoplastic insulation

8.5.7.1.4 Wires and cables used for fire alarm cables shall comply with 8.5.7.1.2 and one of the following:

(1) Be capable of having 15 minute circuit integrity when tested in accordance with IEC 60331-11

(2) Demonstrate that, if circuit integrity is tested during the vertical flame test, a current continues operating for at least 5 minutes during the test

(3) Be fire alarm circuit integrity cable in accordance with NFPA 70"

TABLE 4—*NFPA 130-2003 requirements for electrical cables in rail transportation vehicles.*

Category	Function of Material		
		Test Method	Performance Criteria
Wire and cable	All	UL 1581, CSA C22.2,	Pass; see 8.5.7.1
		UL 1685, ANSI/UL 1666,	
		NFPA 262, ASTM E 662	
		See 8.4.1.5.16	
	Control and low voltage	ICEA S-19/NEMA WC3	Pass; see 8.5.7.1.3
		UL 44 and UL 83	
	Fire alarm cable	IEC 60331-11	Pass; see 8.5.7.1.4

8.4.1.5.16 All wires and cables shall be listed as being resistant to the spread of fire and shall have reduced smoke emissions. (See 8.5.7.1.1 for requirements.)

8.5.7.1 Contains all fire test requirements, including permitted substitutions.

8.5.7.1.3 contains fire test requirements for control and low voltage cables.

8.5.7.1.4 contains requirements for circuit integrity.

According to ASTM E 2061, the Standard Guide for Fire Hazard Assessment of Rail Transportation Vehicles, the procedure for conducting a fire hazard assessment on a product in a rail transportation vehicle is based on a series of explicit fire safety objectives, requiring the application of specific design considerations, in particular scenarios, where explicit assumptions are presented. The Guide provides lists of test methods from which the test methods to be used should be chosen, as well as appropriate calculation methods. It does not state which test method, model, or procedure is to be used. Documentation and validity checks are essential at every step. The final step in a fire hazard assessment procedure should be the development of a detailed procedure to ensure consistent quality control over time. Thus, if it is decided not to follow the series of prescriptive small-scale tests from the Federal Railroad Administration, which dictate the minimum fire-test response characteristics required for each material or product, alternative means should be described so that the fire safety of the rail transportation vehicle can be ensured without having to conduct full rail transportation vehicle burn tests. Examples of the use of this guide for assessing electrical cables were developed and are contained in the guide; significant data on fire performance of relevant electrical cables are also included. The ASTM E 2061 guidelines, the recommendations by FRA, and analogous sections in NFPA 130-2003 constitute a significant step forward in the development of fire safety assessments for an overall system.

Research Advisory Council on Fire and Transportation Vehicles

In view of the concern that insufficient attention was being placed on the problem of transportation vehicle fire safety, the NFPA Fire Protection Research Foundation (FPRF) created, in late 2002, a Research Advisory Council on Fire and Transportation Vehicles, with Marcelo Hirschler as Technical Coordinator. The Transportation Council was created to address fire safety in vehicles in five modes of transportation (road, rail, water, air, and underground fixed guideway). It decided to investigate requirements (or guidelines) and make recommendations for research in the areas of fire safety of interest to all transportation vehicles, including private cars, as they represent the mode of transportation with the highest fire losses. The issues studied are: reaction-to-fire (furnishings and contents), fire resistance (structural fire protection), detection and suppression, egress, ignition sources (including wiring and arson), propulsion systems (fuels and fuel tanks), and ventilation. A first white paper on the situation in 2004 was issued in September of that year [33]. Although the Transportation Council is focusing primarily on the US fire problem, it is apparent that: (a) most of the fire issues are the same, irrespective of where the vehicle operates, and (b) that many vehicles cross international borders continually, so that the fire problem is "exported" from one country to another. In some areas, this is already being addressed by international organizations or by "de facto" arrangements whereby a certain organization is known to develop rules which are followed by many (or most countries). The white paper also discussed all the fire tests for electrical and optical fiber cables.

NFPA 556 - Draft Guide for Identification and Development of Mitigation Strategies for Fire Hazard to Occupants of Road Vehicles

The NFPA Technical Committee on Hazard and Risk of Contents and Furnishings is in the process of developing a Guide that will address a number of issues associated with the fire safety of passenger road vehicles, including fire test requirements for electrical cables. A critical recommendation will be that all cables in the engine compartment should meet a fire test, which could be based on the vertical cable tray fire test in UL 1581-1160.

General Cable Fire Tests

Cable fire tests can be subdivided into four categories, as shown below. This has been addressed in detail in [51].

a) Old fashioned small scale tests, which generally address only ignitability or flame spread, but the results of which are rarely meaningful in terms of real fire performance. Such tests are often conducted on materials rather than cables themselves.
b) Vertical cable tray tests, of which there is a large variety, ranging in heat input from 20 kW up to 154 kW (in the case of riser cables), which address flame spread and sometimes also smoke and heat release.
c) The Steiner tunnel NFPA 262 test, which determines wind aided horizontal flame spread and smoke release, under a very high heat input (ca. 90 kW), with a relatively small mass load of cables.
d) Small scale cable tests, often originally designed for materials, directed at measuring fundamental fire properties, such as heat release or critical fluxes for ignition or flame spread and thermal heating properties. The most important of these tests is the cone calorimeter (ASTM E 1354 [60]), for which a version specific to electrical and optical fiber cables was issued by committee D09, namely ASTM D 6113 [61]. See schematic in Fig. 8.

Some recommendations that the author has made earlier [51] should be pointed out:

- Cable tray tests are well suited to measure many essential fire hazard assessment parameters, and not only flame spread.
- Peak and average heat release rate values are excellent indicators of overall cable fire performance in tray tests and are much better discriminators than char length or peak flame height.

- Cables that pass tray tests will release ≤ 50 % of their combustible mass, while those that fail release much more.
- Full scale heat release rate is a reasonable predictor of total smoke release, albeit mostly for passing cables.
- Large improvements in smoke obscuration in full scale fires can be achieved by improving cable fire performance, without necessarily decreasing the specific (per unit mass) amount of smoke emitted by the products.
- Trends found by the cone calorimeter are similar to trends found in full scale tests.
- Cone calorimeter heat release rate is a reasonable predictor of full scale rate of heat release and char length, particularly for passing cables.
- Cone calorimeter smoke factor correlates reasonably well with full scale total smoke release, at least in the first instance.
- The cone calorimeter, with the large number of parameters it measures, appears to be a very promising instrument for testing cable fire performance and predicting full scale results.
- For all correlations investigated, it appears that results for passing cables can be analyzed more adequately than those for failing cables.
- In the only case investigated where sheath and insulation materials were the same, the overall fire performance of the cables appeared similar. However, ignitability and propensity to flashover, in the cone calorimeter, still suggest that the sheath may be more important for overall fire performance than the primary insulation.

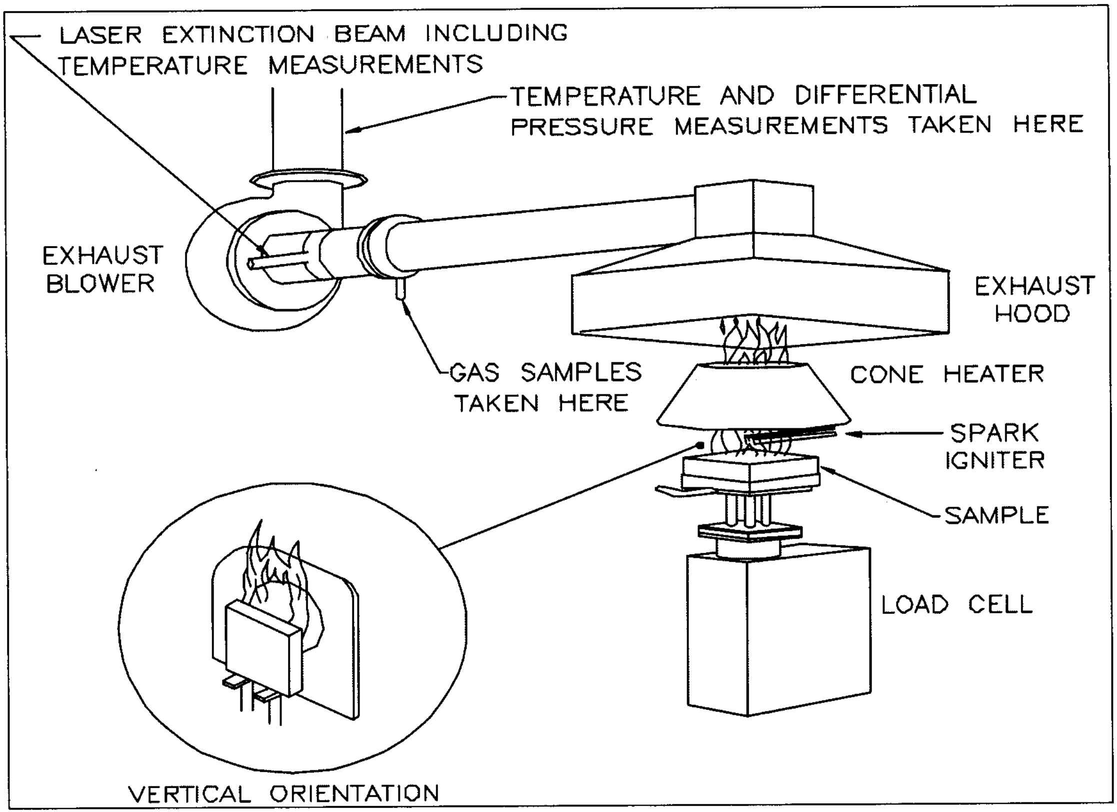

FIG. 8—*Schematic of cone calorimeter.*

Conclusions

Fires in public transportation are rare but can affect multiple people if they occur. Furthermore, statistics indicate that electrical cables are a critical and growing area in such environments. In recent years, this has led to more emphasis being placed on fire safety requirements for electric cables in various public transportation sectors: ships, trains, and aircraft (but not, unfortunately, in road passenger vehicles). In particular, the emphasis is moving toward the use of heat release and fire hazard assessment, so that tests can be chosen in order to obtain validated fire safety engineering test results, which can then be used as input into fire models.

It is also worth pointing out that smoke obscuration requirements are starting to be added in a variety of transportation vehicle environments, to ensure that egress can be effected in an orderly and safe manner.

A fire hazard assessment developed as a result of heat release data should be able to assess a new product being considered for use in a vehicle and conclude whether the new product considered is safer, in terms of predicted fire performance, than the one in established use. The result of such assessments will be the ability to design, with a high degree of confidence, public transportation vehicles which offer excellent fire protection to passengers, while incorporating as much comfort as is consistent with the fire safety required.

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GBH Attachment 16

AB59-COMM-7-16

FIRE SAFETY, SMOKE TOXICITY AND ACIDITY

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ABSTRACT

The question of the importance of smoke toxicity in relation to fire hazard or to the emission of acid gases in smoke is misdirected. Although roughly 2/3 of fire victims die as a direct effect of smoke toxicity, it is extremely rare that their deaths are caused by the inhalation of smoke from a specific very toxic material. In fact, probably well over 90% of fire deaths are the result of fires becoming too big (often so big that they extend beyond the room of origin) and thus resulting in too much toxic smoke. There is excellent correlation between blood CO concentrations in fire victims and the resulting fire fatalities; thus the toxic effects of other combustion products are negligible. More important than any individual combustion product is the fact that if a fire remains small it almost never causes fatalities. Therefore, fire hazard is directly related to the fire heat release rate (i.e. the fire intensity) with other issues (such as smoke toxicity) being of minor relevance. The toxic potency of the smoke of almost all individual polymers lies within a very small band, so that they are almost indistinguishable.

At flashover, every polymer will give off ca. 20% of its weight as CO: that is toxic enough to be lethal. The lethal toxic potencies of CO and HCl are similar and significantly lower than that of acrolein or HCN. In order to study the small toxic effects that can be added to the major heat release effect, the fractional effective dose of that toxicant must be calculated. It will be a function of the ratio of the concentration emitted and the lethal toxic potency. Studies show that CO concentrations regularly exceed its LC_{50}, while those of HCl and HCN rarely exceed a small fraction of their LC_{50} and those of acrolein rarely exceed its LC_{50}. In other words there is so much more CO than anything else in fire atmospheres that CO is the big toxic killer in smoke. The lethal toxic dose associated with the smoke of virtually all commercial polymers are very similar; and are within a factor of 3, while lethal toxic doses for poisons can be orders of magnitude higher. Therefore, measurement of toxic gases is of very little interest from the point of view of fire hazard. It only helps in material development and in understanding the fire performance of any material or product. There are very few actual fire cases where smoke toxicity can have an important contribution: when people die in very small fires (often smoldering) that destroy minimal amounts of material. Acidity of solutions formed from smoke in fires is a function of acid gas release and it is often used as a synonym for smoke corrosivity (even if that is not fully correct). However, there is no relationship whatsoever between acid gases (or acidity of solutions) and smoke toxicity. "Declarations" of acid gas emissions are not associated with fire hazard but with the development of so-called property protection guidelines and the use of halogen-free materials. In fact, most assessments of smoke toxicity via "indices" tend to be ways of ensuring that materials are free of halogens. This may have a logical rationale in some limited applications for specific reasons, but has no general validity in fire hazard.

Toxic potency is a minor contributor to fire hazard and it is most critically dominated by CO concentration. Fire hazard and life safety are best served by ensuring that fires remain small, meaning that they need to exhibit heat release rates as small as possible.

INTRODUCTION

The toxicity of smoke in a fire is a function of four factors; the amount of materials burnt; the distribution of combustion products within the smoke; the individual toxic potencies of each combustion product found in the vapor phase; and the duration of exposure.

Clearly, the greater the amount of longer material burnt the greater the toxicity of the smoke. In fact although roughly two-thirds of fire victims die from the effects of smoke inhalation, it is extremely rare for the root cause of their deaths to be that the smoke comes from a specific very toxic material. Fire fatalities are usually the result of inhaling too much smoke of average toxicity. More than 83 percent of fire deaths in building fires in the United States occur in fires that have become very large so that they extend beyond the room of origin, and thus generate too much toxic smoke [1]. This means that very few people actually die in fires that are small and that fire deaths are rarely due to burning or heat effects, even in small fires.

CARBON MONOXIDE

All combustible materials release carbon monoxide (CO) when they burn [2]. Once a fire has reached flashover – the moment when every combustible in the fire area is burning and the temperature exceeds 500°C – roughly 20 percent of the mass lost from the combination of any material has been converted into carbon monoxide (CO). This is almost irrespective of fuel composition or ventilation [3-5]. Most fire fatalities occur only after flashover.

Thus, the smoke from fires that have reached flashover contains a baseline toxicity from carbon monoxide. The smoke toxicity from fire effluents other than CO is of little consequence, since there is enough smoke toxicity from carbon monoxide to cause fatalities. Under conditions where flashover is not achieved, smoke toxicity is calculated (with the N-gas model [6]) by adding the contributions to overall smoke toxicity from each individual toxicant found in the smoke (or in the vapor phase).

MASS LOSS MODEL

In a simplified approach, the overall smoke toxicity can be calculated under the general assumption that all smokes are similar in toxicity. This means that the overall smoke toxicity of most materials or products is very similar, and not that every component in smoke has the same toxic potency. With this approach, it is sufficient to assess an overall mass loss, and the criterion for the concentration time product (Ct) for lethality can then be considered to be 900 g min/m^3 [7]. This is consistent with various calculations that have been made by summing up abundant data from multiple sources [8-10]. In general, the values of toxic potency of smoke have been found to range between 15 and 30 g/m^3, leading to Ct products of 450 to 900 g min/m^3 (for a 30 minute exposure, which is typically used in smoke toxicity tests). With the lesser toxicity (i.e. higher value) criterion in a normal size room that has a volume of about 36 m^3, lethality results following an exposure to the smoke resulting from burning no more than some 10 kg in just over 3 minutes (actually, a mass loss of exactly 10.8 kg over the 3 minutes).

N GAS MODEL

The overall smoke toxicity can also be calculated in more detail as a fractional effective dose (FED) using the formula shown in Equation 1. In Equation 1, $\sum_1$ (from 1 to n), corresponds to the summation of the effects of each one of n toxic gases, $\sum_2$ (from t_1 to t_2), corresponds to the summation of the relative concentration-time effects of the toxicants at each individual time increment (usually 1 min). C_i is the average concentration (in ppm) of the toxic gas "i" over the chosen time increment Δt and $(C\,t)_i$ are the specific lethal exposure dose (concentration-time product, in ppm•min).

Fractional Effective Doses (FEDs) can be determined for each toxic gas (from 1 to n) at each discrete increment of time. The time at which their accumulated sum exceeds the lethal toxic dose represents the time available until lethality sets in with the actual concentrations measured. With this analysis, smoke toxicity depends both on the concentrations of toxic gases and on the intrinsic toxic potency of each component of smoke. This analysis is also based on the concept that the effects of both asphyxiant gases and irritant gases are a function of their dose (i.e. concentration and duration of exposure) and not simply of their concentration (as shown in studies of baboons and rats) [11-13].

$$\text{FED} = \sum_1 \sum_2 [C_i \cdot \Delta t] / (C\ t)_i \qquad \{\text{Equation 1}\}$$

Typical lethal toxic potencies (in volumetric units of parts per million, ppm, for 30 minute exposures) for the major toxicants are [5, 14, 15]:

LC_{50} CO:	4,000-5,100	Units: ppm
LC_{50} HCN:	150-200	Units: ppm
LC_{50} HCl:	3,700	Units: ppm
LC_{50} HBr:	3,000	Units: ppm
LC_{50} HF	2,500-2,900	Units: ppm
LC_{50} Acrolein:	90-200	Units: ppm
LC_{50} O_2 (oxygen depletion):	- 54,000	Units: ppm

IRRITANT GASES

In one document, ISO TS 13571 [16] the issue of smoke toxicity of individual toxicants is incorrectly addressed by separating asphyxiants from irritants. Asphyxiants are properly addressed in that document by using the N-gas model, whereby the fractional effective dose (or FED) for toxicity by asphyxiants is the summation of the exposure dose of the individual toxic gases, based on their individual concentration at each time period, just as in Equation 1.. The concentrations used in that document are somewhat different from those shown above, but the general concept is reasonable. However, ISO TS 13571 assumes that heat and irritant gases have no effect on FED for asphyxiants, a statement which is patently incorrect and is not based on any published scientific work. Thus, ISO TS 13571 calculates an FED based on bioassay exposures of asphyxiants which looks at the concentrations of asphyxiants in isolation of everything else, particularly in isolation of irritant effects, heat effects and lack of visibility effects. Abundant work has shown that the N-gas model should not be limited to asphyxiants and that the effect of irritants is also dose-related and should be added to the FED equation, including work by the FAA [17-18], by NIST [6] and by SwRI [11,19-20]. However, ISO TS 13571 invents the bizarre concept of "incapacitating concentration" for dealing with irritants. This concept eliminates exposure time considerations, so that incapacitation occurs only after adding the effects of exposure to a toxic concentration at every time period. This means that as soon as a critical concentration of an irritant is reached, the victim is instantly incapacitated.

This approach is reminiscent of denigrated concepts in use many years ago when people talked about "instant clampdown" resulting from PVC [poly(vinyl chloride)] smoke and developed "correction" factors when dealing with the toxicity of PVC smoke to make it look worse [21-22]. The concept of "incapacitating concentration" is particularly unrealistic for people who have worked in a chemical research laboratory, where it is not uncommon for emissions of irritant gases (e.g. hydrogen chloride) to occur. However, there is no evidence that incapacitated researchers are found throughout chemical laboratories. It is worthwhile remembering also that human exposures to various toxic gases (especially including irritants) have been conducted in Europe, in the late 19th century and early 20th century [23-27]. All of that work was summarized in a modern publication [28]; it clearly showed how researchers were able to continue being active and alert during exposure to high concentrations of irritants. Some of the experimental results of that work on humans are worth repeating:

* Lehmann 1886 [23]: A 30 year old man was exposed for 12 minutes to 600 ppm min of HCl. He had available a gas mask which he could use to breathe if conditions became intolerable. He found working in the room absolutely impossible after 12 min, part of which was spent outside. He had some irritation of the respiratory system (nose, larynx), irregular respiration solely through his nose, chest pains (needle-like sensation), shortness of breath, no eye irritation and no acid taste.

- * Matt 1889 [24]: Three experiments were conducted, designed to address safe work-place concentrations of HCl and did not involve concentration which were incapacitating or lethal

  On 12/13/1888 three men were exposed to 100 ppm min of HCl for 10 min. They experienced cold and acid sensation in nose, mouth and throat, no effect on their eyes, a slight discomfort in their larynx, trachea and lung, as well as some secretion and coughing. One man had slight head and chest pains. All men recovered immediately on leaving the HCl atmosphere.

  On 12/18/1888 one man was exposed to 1,050 ppm min of HCl for 15 min. He experienced little eye irritation, some irritation on breathing through the mouth, somewhat artificial respiration, irritation in the nose, throat, larynx, trachea and sternum, including "scratching" feelings and coughing. he had to exit the room because of chest pains. He experienced slight headache on termination of the experiment, which disappeared very rapidly.

  On 12/13/1888 one man was exposed to 1,500 ppm min of HCl for 15 min. He experienced slight irritation in his eyes, abundant tear secretion, a strong feeling of coldness and irritation in the nose, mouth, throat, larynx and trachea. His respiration was enhanced and his salivation increased. He experienced strong coughing and a sensation of heat in the head, forcing him to exit the room. On reentry, he experienced abundant coughing and catarrh. After the experiment he felt a slight headache and catarrh, which disappeared soon.

  As a result, the author recommended the following **work-place** limits for HCl:

10 ppm	Work unhindered
10-50 ppm	Work possible but uncomfortable
50-100 ppm	Work impossible

- * Lehmann et al. 1908 [25]: A man (one of the authors, Dr. J. Yamada) breathed from a bottle containing progressively higher concentrations of HCl for periods of 20, 20 and 5 min respectively, and exhaled into another bottle. The inhaled doses were 4,021 ppm min, 4,107 ppm min and 5,170 ppm min. There were no ill effects whatsoever on the subject.

In more recent times, it has been shown that irritants (such as HCl or acrolein) do not cause incapacitation of baboons (primates very similar to humans) or of rats at dose levels so high that the victim eventually dies of inhalation toxicity after the exposure. This is a complex concept, but is critical: when animals have been exposed to doses of irritants at levels where they died a few days after exposure, they were still capable of performing the necessary avoidance responses to escape the exposure, thus not being incapacitated [11]. Interestingly, it has also been found that incapacitation from asphyxiants occurs at levels very similar to those leading to lethality, and not at levels an order of magnitude lower [29].

Thus, the type of statement frequently made regarding the inexistence of data on human exposure (or primate exposure) to irritants is misleading. This should not be used as excuse for presenting other concepts that have not been validated by experiments. Moreover, the pungent odor of most irritant gases (and their low odor detection level, often in the order of 1 ppm, [30]) means the warning appears at levels much lower than those at which any effect occurs. This is usually not being considered.

FLASHOVER

It is interesting to note that the toxic potency (LC_{50}) value of carbon monoxide assessed from experimental data is about 5 g/m^3, for a 30 minute exposure. Therefore, the LC_{50} of post-flashover smoke (20 percent by mass of which is CO) cannot be higher than a value of about 25 g/m^3, for a 30 minute exposure, irrespective of the other substances present in the smoke. It has been shown that bench-scale toxicity data will only reflect real-scale fires when the allowable error band is a factor of 3 [14]. Thus, if the toxic potency of flashover smoke is multiplied by a factor of 3 (since toxic potency cannot be predicted better than that), normal smoke toxicity materials have a smoke toxic potency not exceeding 8 g/m^3 (for 30 minutes) [14]. So, materials with a toxic potency lower than 8 g/m^3 (or an LC_{50} higher than 8 g/m^3) will become of no consequence at flashover since the toxicity of the flashover fire atmosphere itself is larger than that of those materials. In simpler language, this means that the only materials that need to be considered for toxicity at flashover are those with an LC_{50} lower than 8 g/m^3, and they are very uncommon.

FIRE FATALITIES, CARBOXYHEMOGLOBIN AND TOXIC GASES

A pair of studies were made in the United States involving more than 5,000 fatalities and covering:

- a period between 1938 and 1979 in a localized area (Cleveland, Ohio);
- and a broad countrywide study in the early 1990s [3-4].

The studies demonstrated that there is an excellent correlation between fire fatalities and levels of carbon monoxide absorbed in the blood as carboxyhaemoglobin (COHb) and that the distribution of COHb concentrations was identical (when comparing populations of the same type, following a statistical multi variant analysis) between fire and non-fire deaths (e.g. defective space heater) . The studies also showed that whenever high levels of hydrogen cyanide were found in blood, high levels of COHb were also found, indicating that hydrogen cyanide is of minor consequence in the overall study of fire fatalities. Finally, the studies showed that fatalities can be linked to COHb levels as low as 20 percent and that it is likely that any COHb level above 30-40 percent is lethal. The work also reconfirmed that any hydrogen chloride found during fire fatality studies cannot be assigned to fire gases (or smoke) as it cannot be distinguished from the stomach acid naturally present. The overall conclusion of this work, the most extensive ever conducted, is clear: fire fatalities are overwhelmingly associated with the carbon monoxide generated when fires become big, and other causes of fire deaths are of minor importance. Similar conclusions were obtained earlier by other authors, with smaller data bases [31-33].

Looking at toxic potency of smoke data, Figure 1 indicates that the toxic potency of the smoke of virtually all individual polymers is within such a narrow band (in toxicological terms) as to be almost indistinguishable [34]. In particular, the smoke toxicity of poly(vinyl chloride) has been studied extensively and found to be quantitatively similar to those of most other polymers [28]. As discussed earlier, that work reviewed also hydrogen chloride toxicity studies, including some done by exposure of animals and people, in the late 19th century and early 20th century to hydrogen chloride alone or by their exposure to smoke containing hydrogen chloride. The critical issue is that what was studied was the behavior, and whether incapacitation or lethality occurred, rather than looking for hydrogen chloride itself in autopsies (which cannot be detected). The exposures of rats and baboons made in the 1980s at Southwest Research Institute showed that both rats and baboons were not incapacitated at huge concentrations of hydrogen chloride (and in fact sometimes they died a long time after exposure, but they were able to perform the escape functions that they were taught to do, to escape from their exposure) [11, 28]. This means that the toxic potency of hydrogen chloride is, in fact, such that exposed primates are not incapacitated at concentrations that may eventually kill them.

Two investigations were conducted in the United States in the late 1970s, wherein fire fighters were sent into buildings equipped with gas monitors [34-36]. In the fires investigated, carbon monoxide was almost inevitably present, with the maximum concentration found being 7,450 ppm (approx. 150% of the 30 min LC_{50}). The three other most common gases found in fires in those studies were (in descending order of number of times the gas was found, and shown in relation to the 30 min LC_{50}):

- acrolein (with a maximum concentration of 100 ppm, approx. 50-80% LC_{50});
- hydrogen chloride (with a maximum concentration of 280 ppm, approx. 8% LC_{50}) and
- hydrogen cyanide (with a maximum concentration of 10 ppm, approx. 6% LC_{50}).

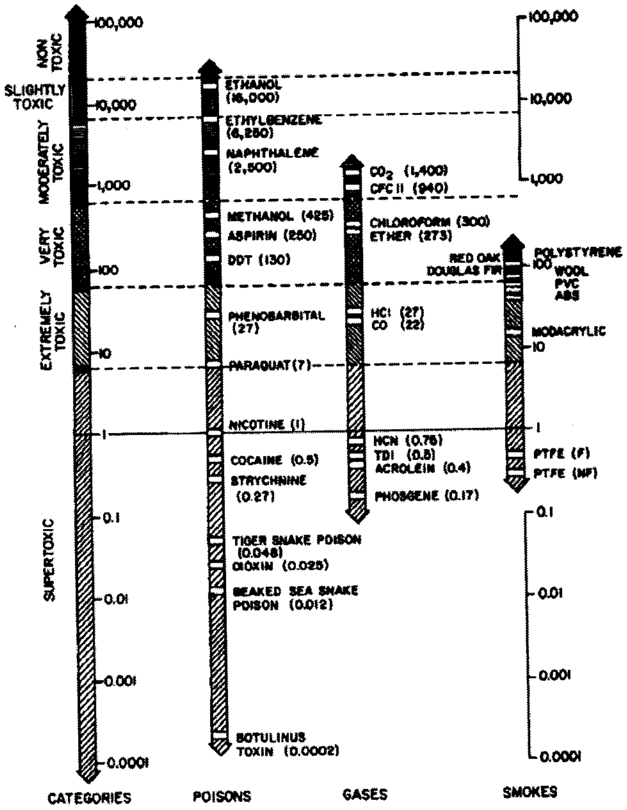

Figure 1: Toxicity Scales (inspired by Steven C. Packham)

FIRE HAZARD IMPLICATION

The analysis above indicates that all smoke is exceedingly toxic and fires can lead to lethality fairly rapidly if enough material burns. It also shows there is relatively little difference in values between the toxic potencies of some of the major gases in smoke, namely carbon monoxide (an asphyxiant gas formed by the combustion of all materials); hydrogen chloride (an irritant gas, and an acid gas, formed by the combustion of chlorine-containing materials); and hydrogen bromide (an irritant gas, and an acid gas, formed by the combustion of bromine-containing materials). However, some minor gases, including acrolein (a non-acidic irritant gas formed by the combustion of cellulosic materials, e.g. wood and paper, or polyolefins) or hydrogen cyanide (an asphyxiant gas formed by the combustion of nitrogen-containing materials) are significantly more toxic. This analysis also shows carbon monoxide is the major toxicant responsible for fire fatalities (and, in fact, no other toxicant needs to be searched for in post-flashover fires); and that hydrogen chloride from smoke cannot be identified in fire fatalities. Finally, this study again confirms that people will usually die in fires only after the fire has grown to be very big.

A conclusion to be drawn from this analysis is that fire hazard is directly related to the rate of heat release of the fire (i.e. the intensity of the fire) with other issues (such as smoke toxicity) being of much lesser relevance [37]. This is further enhanced by a study of fire hazard associated with several fire retarded and non fire retarded products [38]. In the study, the use of the fire retarded products was associated with an average 4-fold decrease in rate of heat release and led to a three-fold decrease in smoke toxicity in the room, and to a 10-fold increase in tenability time (even though the ignition source used was more than three times as intense). Insufficiently low levels of flame retardants that do not make a substantial difference to the heat release rate of the final product do not affect toxic hazard [39]. This clearly shows that considerable improvements in smoke toxicity will be obtained by decreasing the heat release rate of the materials/products considered, almost irrespective of the actual toxic potency of the materials/products involved. Toxic hazard is a direct function of heat release rate, therefore, any measurement of toxic gases is of relatively little interest from the point of view of fire hazard.

WHEN SHOULD TOXIC GASES BE MEASURED?

As has been discussed above, it is rarely important to measure individual toxic gases for hazard assessment purposes. The measurement of toxic gases is mainly helpful in material development and in understanding the fire performance of any material or product, especially before bringing it to market. There are some very rare cases where smoke toxicity can have an important contribution in fires. That is the case when people die in very small fires (often smoldering) that destroy minimal amounts of material. Fortunately, statistics indicate that such fire cases are extremely rare and a more complete investigation may be needed for each individual case.

There is another reason to measure gases emitted during burning, and it is not related to fire hazard or to fire safety, but to the ability to sell materials. Many specifications and requirements demand that materials be certified as lacking in a certain component, typically halogen elements. Thus, measurement of combustion products is often associated with "passing" certain specifications for material composition.

ACIDITY AND SMOKE CORROSIVITY

The acidity of solutions formed from smoke in fires is a function of the release of acid gases, typically hydrogen chloride, hydrogen bromide and hydrogen fluoride, as well as organic acids, such as acetic acid or formic acid. Acid gas emission (often assessed by measuring the pH, i.e. acid gas concentration, or the conductivity of aqueous solutions) is often used as a synonym for smoke corrosivity. That is, however, not fully correct as it has been shown that smoke corrosivity does not fully correlate with acid gas content of solutions.

* For example, it has been shown that solutions that are very alkaline (i.e. the opposite of acid on the pH scale) can be very corrosive [40], especially to copper (see Figure 2). The data in Figure 2 show that smoke from alkaline (nitrogen-containing) materials such as nylon and wool is significantly more corrosive to copper than smoke from halogenated materials (a standard PVC wire and cable compound, a low halogen PVC compound and a Neoprene compound). The data also shows a lack of correlation between the corrosion of the metal and the acidity of these three acid materials.

* In another example, it has been shown that soot deposits can cause bridging and corrosion of electrical and electronic circuit integrity [41], causing failures.

Thus, although high acidity is usually an indicator of some degree of propensity for corrosion, acidity does not correlate with smoke corrosivity. Moreover, most assessments of acidity are unable to take into account the effects of different realistic combustion conditions.

ACIDITY AND SMOKE TOXICITY

However, irrespective of the issue of whether acidity is a good surrogate for smoke corrosivity, suggestions have been made recently that acidity is a good surrogate for smoke toxicity. That is clearly not a technically defensible position. If this were true, that would mean that alkalinity (and the smoke from some nitrogen-containing materials forms alkaline solutions) must equate a lack of smoke toxicity (or perhaps even a favorable effect!).

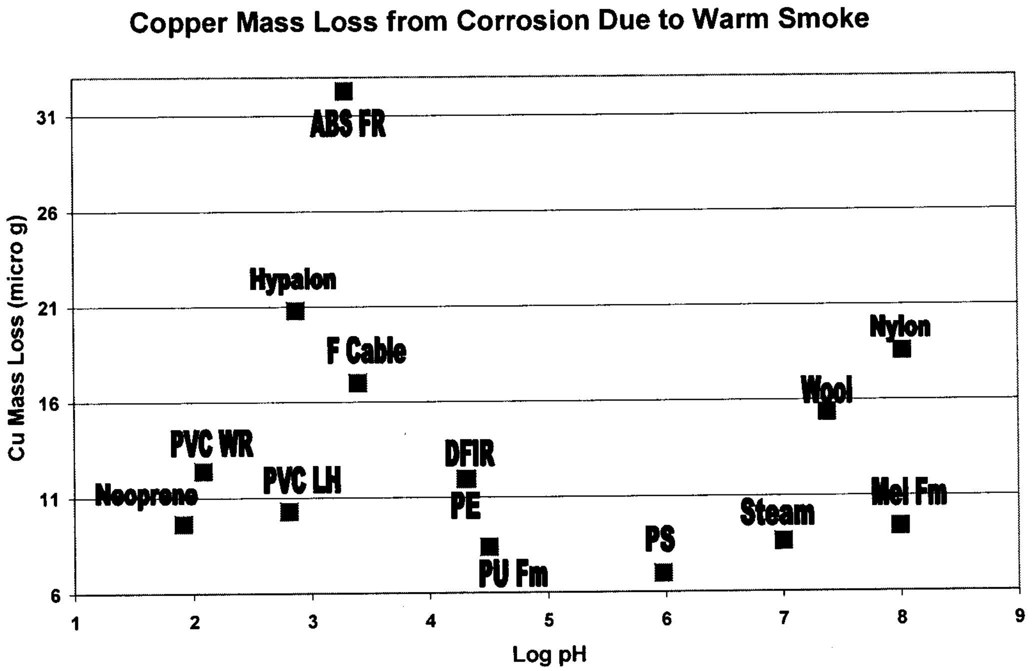

Figure 2: Exposure of Copper to Smoke from Various Materials [40]

As has been shown above, smoke toxicity is associated primarily with carbon monoxide, and secondarily with some other combustion products (including hydrogen chloride, hydrogen cyanide, acrolein, hydrogen bromide, hydrogen fluoride, carbon dioxide and low oxygen) while acidity is associated exclusively with the generation of acid gases. Of those gases listed above, only a few are acids, and two of the most prominent toxicants, carbon monoxide and acrolein, clearly are not. Thus, of course, any analysis of acidity will identify virtually only those materials that contain halogens in their composition (chlorine, fluorine, bromine). Therefore, it is worth pointing out some studies on one of the most widely studied polymeric materials, PVC.

* NIST work [6] showed that the FED contribution of HCl in PVC smoke is negligible in full scale studies, although it is significant in all toxicity test studies. It also showed that the average gas concentration of CO tended to be of the same order as that of HCl in one toxicity test and , and 2.5-3 times higher in another toxicity test. This indicates that the relative toxic importance of HCl in PVC smoke would be, at most, comparable to that of CO, and in full scale fires, much smaller than that of CO.

* Other work [20], which looked at 4 different PVC compounds and 3 test methods, found average HCl concentrations that were in most cases lower than those of CO. This again indicates that CO represents at least half the toxic load in PVC smoke.

These two examples alone show that the toxicity of the most notable material emitting acid gases cannot be directly related to the acidity of the resulting smoke. The same NIST work [6] also studied two other common combustibles: Douglas fir wood and a polyurethane foam. In both cases the yields of acid gas were negligible, and yet the toxic potency of the materials was broadly similar to that of PVC. Table 1 shows the results of a number of materials all using the same test method and it is clear that materials that have little if any acid gases can exhibit similar levels of toxic potency as those that are highly acidic, like some of the PVC materials tested. A small difference in toxic potency, as discussed above, is not really an indication of a higher degree of fire hazard.

Table 1. ASTM E 1678 Radiant Toxicity Test Results, in mg/L [5]

Material	LC_{50}	Material	LC_{50}
ABS	17.8	PVC Jacket	53.1
Acrylic Fabric + Melamine Foam	9.6	PVC Low HCl	146.9
Ceiling tile	30.5	PVC Med HCl	86.2
Composite	20	PVC Profile	26
Cork	ca. 40	PVC Profile	20-30
Douglas Fir	100-200	Particle board	120-138
Douglas Fir	56	Rigid PU Foam	22
Flexible PU Foam	52	Rigid PU Foam	20-30
Melamine Foam	12.5	Vinyl Fabric	32
Nylon	36.7	Vinyl Fabric + Melamine Foam	26
Nylon Rug (Treated)	28.5	Vinyl Flooring + Plywood	82
Nylon Rug (Treated)	42.9	PVC FR Low Smoke 1	18.2
Nylon Rug (Untreated)	> 41	PVC FR Low Smoke 2	45.9
PVC Cable	36	PVC FR Low Smoke 3	35.8
PVC Insulation	33.4		
PVC Insulation	29.2		

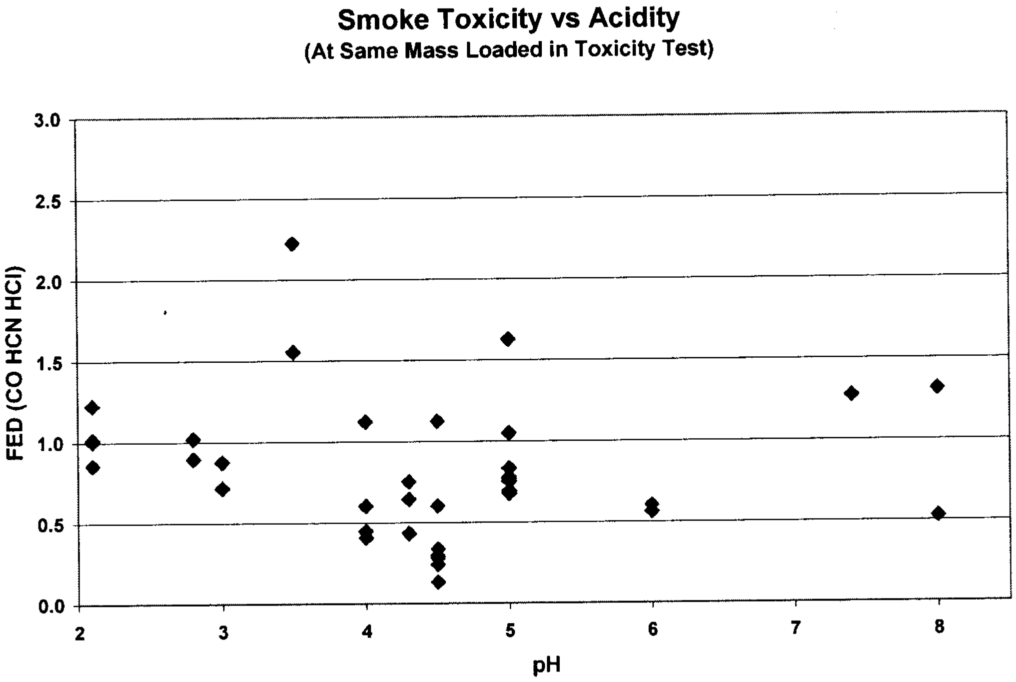

Figure 3: Comparison of Smoke Toxicity & Acidity for Various Materials

This work has clearly shown that an analysis of acidity cannot give a reasonable ranking or classification of materials or products in terms of smoke toxicity, since it will basically divide products among halogenated materials and non halogenated materials. As was shown above, this division is not a proper classification that is in any way related to smoke toxicity. It is even less associated with fire hazard.

Figure 3 shows a plot of a series of materials for which concentrations of CO, HCN and HCl were all measured in the same smoke toxicity test chamber (the one corresponding to the ASTM E 1678 test). The gas concentration data were taken from references 20, 38 and 42 and converted to a common mass of material loaded into the chamber: 40 mg/L. The acid gas data were taken from reference 40 and assessed by comparison for the materials not measured. The materials tested included halogen-free polyolefins, wood, styrenics and PVC. The Figure indicates that there is no correlation at all between smoke toxicity and acidity. The data also shows, just like Figure 1, that most polymeric materials have quite similar ranges of smoke toxicity, virtually irrespective of chemical composition.

IMPORTANCE OF ACIDITY

In summary, acidity is a poor representation of smoke corrosivity and is totally inadequate as a representation of smoke toxicity. In fact, even as a representation of smoke corrosivity, acidity simply looks at the "worst-case scenario" that can be associated with a material or product in that it does not consider differences in smoke emission or smoke decay (such as the well-known phenomenon of acid gas decay before transport through fire atmospheres [43]). Moreover, although smoke corrosivity (or acidity) may have some relevance to property damage it has no relation to life safety or even to smoke toxicity.

The use of acidity as the basis on which to assess toxicity of fire effluents may provide an illusion of life safety which is, in fact, incorrect, since the most common toxicant (carbon monoxide) is not taken into account.

CONCLUSION

As an overall conclusion, fire safety and fire hazard are associated primarily with the control of heat release and with ensuring that a fire remains small. On the other hand, smoke toxicity is, generally, no more than a small component of fire safety, except in some special circumstances. Therefore, fire safety is best served by monitoring and regulating heat release. Moreover, smoke toxicity is primarily identified with carbon monoxide, while several other gases are additional contributors: acrolein, hydrogen cyanide and hydrogen chloride primarily. Acidity (as an intended, albeit incomplete, surrogate for smoke corrosivity) may have potential utility as a property protection measure, but only when no thermal damage is to be expected. Acidity has no value as a monitor of improved life safety. Finally, acidity is totally unrelated to smoke toxicity and is not, in any way, to be looked at as a surrogate for smoke toxicity or as a fire hazard assessment measure.

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GBH Attachment 17

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10th European Meeting on Fire Retardancy and Protection of Materials
(10th European Conference on Fire Retardant Polymers)
FRPM '05, BAM, Berlin, Germany, 7th - 9th of September 2005

FULL SCALE FIRE TESTING OF CONSUMER PRODUCTS

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ABSTRACT

A number of consumer products exhibit very poor fire performance, to a large extent as a result of the lack of regulatory fire safety requirements for such products. Such products include, inter alia, television sets, upholstered furniture, mattresses, personal automobiles and playground structures for children.

The most accurate way to ensure that a consumer product exhibits proper fire performance is to conduct full scale tests in which all the interactions between the various materials and components have the opportunity to become manifest. Furthermore, the most critical property to be measured is the heat release in those tests.

In actual fact, it is likely that full scale fire tests will not form the basis for most fire safety regulation, unless the regulators are convinced that the predictive capability of the relevant regulatory small scale (or medium scale) tests is insufficient to allow them to be used reliably. In fact, a few small scale tests, typically the cone calorimeter, do provide proper predictability.

This article will discuss several series of tests conducted, in the United States, on: (a) mattresses (5 series, encompassing a broad range of performance and applications, residential and institutional), (b) residential upholstered furniture (including a product with good fire performance and a product where the paddings were slightly fire retarded), (c) wall coverings (with a wide range of chemical compositions), (d) automobiles (3 vans), (e) a typical plastic garbage can and (f) a children playground structure (which met a performance specification).

The full scale fire tests on mattresses, upholstered furniture, wall coverings and playground structure were conducted indoors, in standard rooms, and heat release (by oxygen consumption calorimetry) as well as smoke release was measured, while also making various other measurements and visual observations. The garbage can test was conducted in the same standard room, but only heat release was measured. The automobile (van) tests were conducted outdoors, and measurements involved exclusively thermocouples and visual observations.

Reference will also be made to work conducted on Christmas trees (both actual full scale tests and computer predictions), on television sets (comparison testing) and predictive work on computer housing fire performance.

The results clearly indicate that some of the consumer products in use in the United States (and in some cases in Europe) are permitted to be unsafe and that improved alternatives exist. Recommendations are presented for all cases. They include, for example, suggested code changes or improved fire test method requirements.

INTRODUCTION

Consumer products are usually not regulated for their fire performance, with a few exceptions. This is probably a mistake in the case of many of them. This work will address a few types of consumer products that can generate large amounts of heat when they ignite and burn. The fire performance of an individual furnishing item is often crucial in determining whether a room becomes untenable in a fire, thus resulting in fire fatalities [1-2]. This study will look at several sets of "large" consumer products and investigate the background, the likelihood of them producing a large fire and potential strategies for improving the fire performance and the safety of the consumers using them.

MATTRESSES AND UPHOLSTERED FURNITURE

Back in the 1970s it was established that upholstered furniture represented a potentially serious concern: a single item can yield a fire severe enough to engulf a whole room and take it to flashover. As a consequence of this, in the USA, the Boston Fire Department and the California Bureau of Home Furnishings (CBHF), independently, developed flaming ignition fire tests for full scale items of upholstered furniture, intended for medium or high risk applications, the most famous being the first edition of California Technical Bulletin 133 (CA TB 133) [3], which had as its principal pass/fail criterion the temperature increase in the test room, which can be correlated with heat release. The test was initially intended to be a "low-tech" tool for qualitative use by manufacturers. In other words, the simple application of the ignition source, with little instrumentation would permit a test user to assess whether the chair would burn vigorously or not. Unfortunately, the output was not usable for more comprehensive assessments of fire safety. CA TB 133 has been used for regulation in several US states, including California (and in codes: NFPA 101 [4], Life Safety Code, NFPA 301 [5], Life Safety Code for Ships, and the International Fire Code, IFC, [6] all require ASTM E 1537 [7], functionally identical), and for specifications since the early 1990s. CBHF soon later also developed a test for mattresses, which is analogous (but not identical) to CA TB 133: CA TB 129 [8] and, more recently, CA TB 603 [9]. However, CA TB 129 was never used for regulations by either the state of California, or any other US state (although it is also included in NFPA 101, NFPA 301 and the IFC, as ASTM E 1590 [10], again functionally identical). CA TB 129/ASTM E 1590 involves exposure of mattresses for 3 min to an 18 kW propane gas flame. CA TB 603, on the other hand, is a milder test with a double burner, and is now a requirement for all mattresses sold in the state of California, and is likely to form the basis for regulation throughout the United States by the Consumer Product Safety Commission (CPSC).

In the United Kingdom, a different simplistic test was the first serious attempt at developing a flaming ignition standard for upholstered furniture systems: British Standard (BS 5852 [11]). This test uses a variety of wood cribs, and it tests a combination of fabric and filling, made up into two standard cushions: bottom and back. The wood cribs in what was originally part 2 of BS 5852 range from # 4 (weighing 8.5 g), through # 5 (weighing 17 g) to # 7 (weighing 126 g). Less severe ignition sources (originally included in part 1 of BS 5852) address smokers' materials: cigarettes and butane flames simulating matches. An empirical study showed that the "rankings" resulting from testing fabric/foam combinations in this test correlated well with those that could be obtained from using the cone calorimeter at 25 kW/m^2 [12]. The cone calorimeter [13] has been shown to be an effective predictor of whether a product will cause flashover on its own [2], and it is particularly effective when used for upholstery composites with the ASTM E1474 protocol [14]. Following its initial adoption, BS 5852 has been modified somewhat, so that testing for qualification is now done effectively on separate items. Fillings are qualified when tested under a "standard" flame retarded polyester fabric and fabrics are qualified when tested over a filling deemed acceptable. Thus, it is not required to test the system actually proposed for use, which makes testing more accessible to materials manufacturers (and less costly for them), as they need not test the large variety of potential finished systems. The British government issued the Furniture and Furnishings Fire Regulations Act in 1988, which requires all fabric and polyurethane foams used in the construction of upholstered furniture to meet BS 5852, crib #5 fire test requirements, and all filling materials in mattresses, including cot mattresses, to meet the same regulations. In other words, no filling or padding materials sold for use in upholstered furniture or in mattresses in the United Kingdom is permitted to ignite and spread flame when exposed to a crib # 5, while covered by a standard fire retarded polyester fabric (the fabric does not actually protect from ignition).

Requirements to protect the public from smoldering fires have been in effect both in the USA and in the UK for a large number of years. In the USA, residential upholstered furniture components generally meet a voluntary smoldering ignition standard nationwide, as administered by the Upholstered Furniture Action Council, since the late 1970s, with mandatory requirements in place in California (where small flame ignition requirements also exist, although upholstered furniture that does not meet any open flame requirements can be sold in California, as long as it is labeled as not meeting the requirements) and in some other jurisdictions. All mattress and mattress pads (including residential) are required, since 1972, to comply with 16 CFR Part 1632 [15]: a smoldering ignition (by cigarettes) test method. This test method has been instrumental in heavily decreasing (and virtually eliminating) cases where a mattress undergoes flaming combustion resulting from ignition by a smoldering cigarette, usually by replacing cellulosic padding or filling materials (such as cotton) with non smoldering plastic materials. However, there are no requirements for flaming ignition of mattresses or mattress pads, or of their components, in the USA, other than requirements for ASTM E 1590 in some high risk applications in codes.

In the UK, the Department of Trade and Industry commissioned a study to look at the effects of the 1988 legislation in terms of lives saved, decreased number of injuries and economic impact [16] (based on the exchange rate, in 1992, of £1=$1.5). Some of the key improvements are shown in Table 1, based on an official UK government publication, for upholstered furniture only. The study indicates that 710 lives (and over £5 billion) were saved over a 10 year period, in spite of the relatively low smoke detector penetration into the UK. In fact, a follow-up UK study shows that neither smoke detector penetration nor the changes in smoking patterns can explain the improvement in fire losses [17]. Significant savings should also be expected from mattress and bedding fires. In both cases, the number of fire fatalities has been decreasing, and much more than in the US. A particularly important aspect of the UK study has been the economic analysis, included the cost to industry (which, by and large, was not passed on to the consumer) of developing and selling products with greatly improved fire performance.

This study presents results of 5 series of full scale fire tests of mattresses, and one series of full scale fire tests of upholstered furniture, involving the following products:

* Six US mattresses intended for institutional (detention) application
* US modern adult residential, US old adult residential and UK adult residential
* US baby residential and UK baby residential (without and with sheet)
* Two US adult mattresses suitable for residential use

- US adult residential and UK adult residential (without and with sheet)
- Four sofas (3 US modern residential and one UK modern residential).

Table 1 - Benefits Resulting From UK Upholstery Regulations

Benefit measure	Annual benefit 1992	Annual benefit 1997	Cumulative benefit 1988-1997
Number of dwelling fires	3,715	8,769	42,754
Total lives saved	169	362	1,856
Lives saved for upholstery as item first ignited	65	138	710
Total non-fatal injuries saved	1,548	3,315	17,000
Injuries saved for upholstery as item first ignited	526	1,126	5,774
Loss adjusted cost saving £m/yr	23	53	249
Final cost saving £m/yr	507	10,835	5,567
Total cost saving £m/yr	530	1,138	5,615

All six series of tests were conducted in a standard "ASTM" or "ISO" room. The room dimensions are: 2.4 m x 3.7 m x 2.4 m, with a door of 0.76 m, centered on one of the short walls, and with an exhaust duct just outside the room. Measurements were the type of measurements recommended for all large-scale heat release tests: heat release (by oxygen consumption calorimetry), smoke release in the duct and temperature measurements at various locations in the room and duct. Mass loss and heat fluxes were also measured in some cases.

Series 1 [18]: The fire tests involved six solid core mattresses (size: 1.9 m x 0.8 m x 76 mm thick), containing exclusively commercial materials, and designed for detention occupancies, all covered by a fluid resistant vinyl cover, 360 g/m^2. The mattress paddings are shown below:

(a) Cotton batting, fire retarded (FR Cotton)
(b) Combustion modified high resilient polyurethane cushioning A (FR PU A)
(c) Combustion modified high resilient polyurethane cushioning B (FR PU B)
(d) Densified polyester batting, fire retarded (FR Polyester)
(e) Polychloroprene compound cushioning, fire retarded (Neoprene)
(f) Commercial highly fire retarded foam (FR PU C)

All the mattresses had been shown to comply with the criteria of ASTM E 1590 as shown in NFPA 101 (namely 250 kW peak rate of heat release and 40 MJ maximum heat released after 10 min). They were tested in 1996 using a 50 kW exposure detention mattress test (designed specifically for detention mattresses [19], which is specifically recommended for such products in ASTM F 1870 [20]), and the main results are shown in Table 2. The test exposes mattresses from the top, with the burner simulating the heat release of a detention clothing ignition source (1 sweatshirt [50% cotton/50% polyester blend], 1 T-shirt [50% cotton/50% polyester blend], 1 pair of blue denim trousers [100% cotton] and 12 double sheets of newspaper: rough weight 1 kg). It should be noted that one mattress met the requirements based on ASTM E 1590 but failed similar requirements when the 50 kW exposure test from ASTM F 1870 was used, which prevents the mattress from passing the test by melting away from the flame (see Table 2).

Table 2. Test Results Obtained for Detention (Series 1) Mattresses With 50 kW Mattress Test

	Pk HRR	Time Pk	THR	Pk Room Temp	Time to Pk Temp	Wt Loss	Peak [CO]
	kW	s	MJ	°C	s	%	ppm
FR Cotton	89.3	96	18.80	152	36	1.6	381
FR PU A	138.5	114	42.90	175	156	10.9	234
FR PU B	119.6	102	27.90	160	72	6.2	981
FR Polyester	421.6	312	89.60	303	300	67.5	1818
Neoprene	76.7	246	19.40	138	72	2.4	72
FR PU C	81.6	186	19.90	125	222	0.7	87

	Pk Room Smoke	Time to Pk Smoke	Pk RSR	Time to Pk RSR	TSR	Time to 50 kW	CO Yield
	%	S	m^2/s	s	m^2	s	ppm min
FR Cotton	9.6	96	1.5	42	98.1	36	637
FR PU A	96.1	462	1.5	48	327.8	36	96
FR PU B	99.1	60	2.1	96	384.2	54	2171
FR Polyester	100	2.9	13.1	324	2251.6	48	4387
Neoprene	59.5	78	0.7	78	60.9	54	45
FR PU C	84.3	60	0.8	66	67.2	54	50

Series 2 [21]: Three commercial residential inner spring mattresses were obtained, all with a textile ticking: (a) a queen-size mattress, intended for residential use, purchased commercially in California (USA) in the 1990s; (b) a mattress made by the same manufacturer (in the USA) and built in 1937, constructed mostly with cotton materials (before the requirements for mattresses not to ignite from cigarette smoldering), and (c) a UK residential mattress purchased commercially in the UK in the year 1999. The modern US mattress was a typical mattress used throughout the country, and its cost was average for such mattresses; the UK mattress was a chosen as one of the most inexpensive mattresses available. The tests were conducted in the year 2000. The "old" mattress (made in 1937) failed the smoldering ignition test, so that a cigarette would have eventually caused it to catch on fire. However, when ignited by a simulated match (BS 5852 Ignition Source 1; flame applied for 20 s), its peak rate of heat release was only 114 kW, with maximum temperatures of ca. 180°C in the room (and that fire took well over an hour to get going). The new US mattress caused flashover on its own and released heat at a rate of well over 1.5 MW (with temperatures up to 920°C), when ignited simply by the simulated match. The fire had to be extinguished at that heat release level to prevent damage to the facility. The UK residential mattress was exposed to both the simulated match and to a 17 g wood crib (BS 5852, Ignition Source # 5): it did not release any significant amount of heat in either case. The major test results are shown in Table 3.

Table 3. Major Results of Series 2 Mattress Tests

	US Adult Residential Mattress Pre Requirement	UK Adult Residential Mattress (1990s)	US Adult Residential Mattress (1990s)
Peak HRR (kW)	113.9	1.3	1655 (water)
THR (MJ)	127.4	0.1	110.4
Avg HRR (kW)	25.4 (19.5)	0.2	128.8
THR 10 min (MJ)	0.3 (0.0)	0.1	86.7
Peak RSR (m^2/s)	1.14	0.0	18.10
TSR (m^2)	528	0.0	1074
Avg RSR (m^2/s)	0.11 (0.08)	0.0	0.74
TSR @ 10 min (m^2)	0.9 (0.0)	0.0	18.1
Peak OD	0.41	0.0	2.74
Avg OD	0.04 (0.03)	0.0	0.13
Flashover Time (s)	NA	NA	564
Time Peak HRR (s)	3048 (4578)	150	582 (water)
Mass Loss (%)	72.8	0.3	18.0
Peak Heat Flux (kW/m^2)	NM	NM	NM
Ignition source	Cigarette - BS 5852 # 1	BS 5852 # 5	BS 5852 # 1

Note 1: US Adult Residential Mattress Pre Requirement: values calculated from application of match; values in parentheses calculated from application of cigarette. Flaming ignition resulted from first match application.

Note 2: US Adult Residential Mattress (CA 1995): Values for peak rate of heat release and total heat release must be adjusted as the fire was extinguished within a few seconds of it reaching flashover, when less than 20% of the mattress had been burnt.

Note 3: NA: as flashover did not occur, flashover time is not applicable; NM: not measured.

Note 4: Both cigarette and simulated match were used. Match caused the propagation.

Series 3 [21]: Two commercial residential solid core baby mattresses (intended for use in baby cribs) were obtained: one purchased commercially in Texas (USA) in the 1990s; and one purchased commercially in the UK in the year 2000. The US baby mattress was constructed of solid core non fire retarded polyurethane foam (its size was, of course, only a fraction of the size of the modern residential queen-size mattress tested in Series 2, and weighed some 20 times less). Both mattresses were chosen among the most inexpensive mattresses available in the range. The tests were conducted in the year 2000. The US baby mattress ignited easily (although the vinyl cover resisted the simulated match ignition), released over 250 kW and gave a peak temperature of 226°C in the same standard room. Both mattresses were also tested with a baby sheet (50/50 polyester/cotton) and a cotton comforter; the ignition source used for these tests was the simulated match (BS 5852 Ignition Source # 1). The US baby mattress ignited easily again and gave off high levels of heat and smoke. On the other the UK mattress released no significant amount of heat, when tested both with and without sheet and comforter, but it did release some smoke when the sheet and comforter were used. The major results of the tests are shown in Table 4.

Table 4. Major Results of Series 3 Mattress Tests

	US Baby Residential Mattress	UK Baby Residential Mattress	UK Baby Mattress + Bedding
Peak HRR (kW)	255	2	10
THR (MJ)	29.6	0.4	2.3
Avg HRR (kW)	45.8	0.9	3.7
THR 10 min (MJ)	29.0	0.4	2.3
Peak RSR (m^2/s)	7.51	0.004	0.14
TSR (m^2)	815	0.22	22
Avg RSR (m^2/s)	1.26	0.00	0.04
TSR @ 10 min (m^2)	813	0.22	22
Peak OD	1.48	0.002	0.05
Avg OD	0.26	0.00	0.01
Flashover Time (s)	NA	NA	NA
Time Peak HRR (s)	405	165	270
Mass Loss (%)	91.8	0.0	14.6
Peak Heat Flux (kW/m^2)	2.1	0.0	0.1
Ignition source	BS 5852 # 5	BS 5852 # 5	BS 5852 # 1

Series 4 [22]: Two adult commercial mattresses were purchased commercially in the year 2001 in the United States. One of the mattresses (labeled FR Mattress) was a solid core foam mattress, with ticking, designed with fire retarded technology commercially available in the early 1990's; it had a medium-to-low price. Its size was approximately 1.5 m x 2.0 m x 0.18 m. The other mattress (labeled Non FR Mattress) was an air mattress, with foam surround pieces, manufactured between 1995 and 1997, at the luxury end of the mattress price scale. It was probably not fire retarded. Its size was approximately 1.9 m x 2.0 m x 0.20 m. The mattress was hooked up to pump and inflated prior to testing. Both tests used identical sheets: a top and a bottom sheet, both 50/50 polyester/cotton. The tests were conducted in the year 2001. In these tests, three thermocouples were placed inside the room: TC1 (center of room, 0.1 m below ceiling), TC2 (at foot of bed, on top of the sheets, i.e. by ignition source) and TC3 (center of doorway, 0.1 m below doorway top). The ignition source was a small cigarette lighter, applied at the middle of the foot of the bed, at a height corresponding to the base of the mattress. The major results of the tests are shown in Table 5. While the FR mattress caused a minimal fire, the Non FR mattress caused flashover in the room, which had to be extinguished manually.

Series 5 [23]: Four commercial adult residential inner-spring mattresses were purchased in the year 2001: 2 identical ones in the USA and 2 identical ones in the UK, all of them among the more inexpensive mattresses available. One pair of the mattresses was tested without sheets and the other pair with a single fitted 50/50 polyester/cotton sheet. The US mattress, both without and with a sheet, ignited with a simulated match (@ 8 s) and lost 90% of its mass within < 8 min (a bit slower with the sheet). The UK mattress, when tested without the sheet, did not ignite with a simulated match, and did not fully ignite either with a BS 5852 crib 4 or a BS 5852 crib 5 ignition source (peak heat release rate in the test: 5 kW, minimal mass loss). The UK mattress, when tested with the sheet, also did not ignite with the simulated match, but the sheet ignited after 1 min 40 s with a BS 5852 crib 5 ignition source, with the mattress ticking then igniting at 12 min 27 s after the start of the test. For the next 37 min, a very small fire continued, until 50 kW was reached at 49 min 50 s after the start of the test, with peak rate of heat release and 90% mass loss at 53-56 min after the start of the test.

Table 5. Major Results of Series 4 Mattress Tests

Property	Non FR Mattress	FR Mattress
Peak RHR (kW)	3,553	42
Smoke Obscuration (%)	98.0	21.5
Peak CO (ppm)	11,185	347
Time to Flashover (s)	264	Did not occur
Time to Extinguishment (s)	420	Not needed
Peak Temperature TC1 (°C)	516	20
Peak Temperature TC2 (°C)	305	312
Peak Temperature TC3 (°C)	557	16

Series 6 [24]***:*** Three sofas were manufactured in the US and were sectional sofas; two of them contained foam mildly fire retarded to CA TB 117 [25] and one did not (US Sofa 1). The other sofa was a standard residential sofa purchased in the UK. The ignition sources used for all tests were based on BS 5852. BS 5852 Ignition source 1 was used on all sofas, and the ignition was conducted in the seat section of one cushion (a section less prone to ignition than the side arm, the back or any edges). The ignition source is a butane gas flame with a 45 mL/min flow rate and a total application time of 20 s, simulating a match. Only US Sofa 1 ignited with this ignition source, and quickly developed a self-propagating fire. The other three sofas were then subjected to BS 5852 Ignition source 2, which is a butane gas flame with a 160 mL/min flow rate and a total application time of 40 s. Both the other US sofas ignited with this ignition source, and quickly developed a self-propagating fire. The UK sofa did not ignite with either ignition source. Table 6 contains the summary information of the principal data of all large scale tests. Three of the 4 tests had to be extinguished soon after flashover to prevent damaging the test facility. At the time of extinguishment none of them had reached their maximum rate of heat release and the values of peak rate of heat release reported in Table 6 are those just before extinguishment. Similarly, the total smoke released is reported at 540 s, shortly after extinguishment for the US sofas, at the same time for all tests. It is noteworthy that the time until a self-propagating fire was obtained differed only by about 1 minute among the three US sofas, with the sofas containing foam complying with CA TB 117 taking just somewhat longer time to become a fire that went out of control. The sofa purchased in the UK did not ignite (with either ignition source) and the small flame (on the surface) gave a maximum rate of heat release of ca. 2 kW, and virtually unmeasurable amounts of smoke and mass loss.

A series of six photographs showing the sequence of events with US Sofa 1, starting shortly after ignition (with BS 5852 source 1) and leading up to just before flashover, are attached at the end of this work.

Table 6. Major Data from all 4 Large Scale Furniture Tests

	US Sofa 1	**US Sofa 2**	**US Sofa 3**	**UK Sofa**
Ignition Source	BS 5852 1	BS 5852 2	BS 5852 2	BS 5852 2
Extinguishment@ (s)	485	480	486	No ignition
Pk HRR (kW) (before extinguishment)	4,802	2,641	4,394	2
Time to flashover (s)	410	465	447	No ignition
Time to Pk HRR (s)	440	498	485	No ignition
Time before self-propagating fire (s)	310	378	372	No ignition
Total Heat Release @ 600 s (MJ)	292	251	359	No ignition
Flashover HRR in Test Room (kW)	1,000	1,000	1,000	1,000
Total Smoke Release @ 540 s (in m^2)	889	2,535	6,389	No ignition
Maximum Smoke Release (per building code, in m^2)	1,000	1,000	1,000	1,000
Mass of Sofa (kg)	290	276	275	56
Mass Loss Before Extinguishment (kg)	6.1	4.6	9.1	No ignition
Maximum Toxic Smoke Concentration in Test Room Before Extinguishment (g/m^3) *	295	212	420	No ignition
Toxic Smoke Incapacitation Limit (g/m^3)	15	15	15	15
Time to Toxic Smoke Incapacitation Concentration in Test Room (s)	310	420	384	No ignition
Toxic Smoke Lethality Limit (g/m^3) *	30	30	30	30
Time to Toxic Smoke Lethality Concentration in Test Room (s)	340	441	411	No ignition

Note: * Based on smoke concentration for a 30 minute exposure period or the equivalent concentration-time product. This is calculated from the mass lost and the room volume and not from the measurements of toxic gases themselves, and includes all toxic species.

The series 2 mattress test data show how, while a typical US adult residential mattresses exhibits rapid ignition leading to flashover conditions with a small ignition source (a match), an inexpensive commercial alternative exists in the UK, which would not ignite under similar conditions. Both modern adult mattresses had polyurethane foam as filling material (however, whereas the one from the UK was fire retarded, the one from the US was not; also the modern US mattress had multiple layers in the filling, with the non FR polyurethane foam being the largest layer), while the old mattress had a cotton ticking and cotton filling. Thus, while the old mattress was able to be ignited by a smoldering cigarette, in a fire that smoldered very slowly but progressively, fast flaming ignition actually resulted only from the action of the simulated match. Smoke release in the room followed the pattern expected from the heat release data: if the mattresses released abundant heat, they also caused abundant smoke obscuration [26]. The series 4 mattress test data shows the exact same pattern as series 2 mattress tests, but for a comparison between a luxury US adult residential mattress and an inexpensive US alternative. The US FR mattress is most often used for institutional applications but is available for residential use. The difference in fire performance is, of course, considerable. For example, a European project (CBUF) investigating fire performance of upholstered furniture and mattresses does not even consider that "real ignition" has occurred until a product has released 50 kW [27]. Thus, while the FR mattress barely ignited (42 kW peak rate of heat release, including the sheet), the non FR mattress caused flashover in the room before the fire was manually extinguished. The series 3 mattress test data shows that US mattresses made for the infant market are equally poor in fire performance to those made for their parents. Thus, while flashover cannot be reached from a fire involving one baby mattress alone, due to its small size, differences in fire performance between the US and UK mattresses are as pronounced as those for adults. The series 1 mattress test data shows that the peak rate of heat release for five of the detention mattresses did not exceed 150 kW (and for 3 of them did not exceed 100 kW), while one mattress performed rather poorly, while losing about 60% of its mass in roughly 8 min. However, the severity of the ignition source must be taken into account: 50 kW for 5 min. Even the poorest performer would have released much less heat if exposed to the ASTM E 1590 ignition source: even the FR polyester mattress would have release < 250 kW. Clearly, the technology exists for making institutional mattresses with excellent fire performance, and that can resist extremely severe ignition sources. Even more importantly, the technology for achieving good mattress fire performance does not rely on a single type of material: modified polyurethane foams, polychloroprene foams and fire retarded cotton fillings can all be used to obtain excellent mattress fire performance. The series 5 mattress test data also shows that the UK legislation has led to significant improvements in mattress fire safety, since: (a) the US mattress tested ignited very rapidly (within 8 s) from a simulated match source, (b) the US mattress tested was 90% consumed within < 8 min from a simulated match source, (c) the UK mattress tested did not ignite from either a simulated match or a # 5 wood crib ignition source, (d) the US mattress tested ignited very rapidly (within 12 s) from a simulated match source, when covered by a sheet, (e) the US mattress tested was 90% consumed within < 12 min from a simulated match source, when covered by a sheet, (f) the UK mattress tested did not ignite from a simulated match ignition source, even when covered by a sheet, (g) the UK mattress tested did not ignite until > 12 min from a # 5 wood crib ignition source, when covered by a sheet and (h) the UK mattress tested took almost an hour to be 90% consumed after ignition from a # 5 wood crib ignition, when covered by a sheet. However, series 5 test data also shows that further protection of the entire UK mattress from severe ignition sources would still be desirable. The legislation in the UK on mattresses has been aimed primarily at ignition, and additional requirements based on fire performance (or perhaps heat release) of the entire mattress would result in even greater fire safety. Tests conducted using the cone calorimeter applications standard for upholstered fabric and mattress composites, ASTM E1474 [14] for mattresses in series 2 and 3 make it clear that the principal source of heat release is the filling, since the peak heat release rates of the two modern US mattresses (adult new series 2 and baby series 3) are virtually the same, in spite of the different cover materials. Of course, the total heat released by both mattresses was very different, and reflected the significant difference in mass. The peak and average rates of heat release in the cone tests of the new adult US residential mattress (series 2) were sufficiently high to clearly indicate that flashover was likely to occur [2], as it indeed did in the room test. The values for the US baby mattress (series 3) were borderline, with a very high peak and a smaller average (again due to the small mass), which is consistent with having had a high rate of heat release in the room test, but insufficient for flashover. Data analysis indicates that the other samples (UK mattresses series 2 and 3, or old US mattress series 2) were unlikely to cause flashover, as was indeed the case. Smoke release was significant for all samples, except for the old US mattress (series 2), indicating that smoke is more difficult to predict than heat release, confirming an earlier finding that the cover has a much larger effect in cone calorimeter tests than it has in full-scale tests. The poor fire performance of US residential mattresses has been well known for a number of years [28], particularly following a critical study conducted in 1991, at the California Bureau of Home Furnishings and Thermal Insulation (CBHF), on mattresses and bedding systems [29]. The study found that single mattresses could lead to rates of heat release of almost 2 MW (with room temperatures exceeding 1,000°C) in a small room (with the tests ending in manual extinguishment, to prevent fire damage to the facility). Mattresses similar to those that resulted in the high intensity CBHF fire tests can still be purchased commercially throughout the USA: solid core non fire retarded conventional polyurethane foam, 150 mm (6 in) thick, at 24 kg/m^3 density, with quilting and ticking. The CBHF study also showed that viable mattresses were available that released no more than 20-30 kW and caused room temperatures of < 100°C. Furthermore, CBHF had also conducted earlier studies (on detention facility mattresses) indicating that mattresses could be manufactured that caused very low temperature increases in the same room (maximum temperatures < 100°C), one of them being a cotton mattress [xx]. In spite of this information, which has now been available for over 20 years, residential mattresses are being sold in the USA with very poor fire performance; such mattresses endanger the lives of the people using them.

The upholstered furniture tests also led to similar conclusions: (a) residential upholstered furniture in the US often has very poor fire performance, (b) corresponding residential upholstered furniture in the UK has adequate fire performance, including excellent ignition performance, (c) the technology exists in the US (just like in the UK) to make upholstered furniture with excellent fire performance, (d) fire safety regulations addressing open flame ignition, exists in the UK, (e) fire safety of contract upholstered furniture in the US is governed by codes and specifications, but only for some institutional environments and (f) the use of appropriately fire-safe upholstered furniture in the US would result in considerable decreases in fire losses and probably economic savings (since that has occurred in the UK).

WALL COVERINGS (INTERIOR FINISH)

Ten construction materials were tested in a room-corner test configuration [30], using the NFPA 265 (40/150 kW ignition source test [31]), to study heat release and smoke obscuration. The materials were chosen to illustrate adequate fire performance, in terms of heat release and flame spread, together with a broad range of smoke release performances. The same materials were also tested using the ASTM E84 (Steiner tunnel,[32]) test. Only a single one of the materials chosen caused flashover in the room (with an ASTM E84 flame spread index exceeding 25). Similarly, only a single material failed to meet an ASTM E84 smoke development index of 450 (even though that material had a very low ASTM E84 flame spread index and very low heat release rate), and had very high room smoke release. The results indicated that: (a) limits for smoke release need to be set in the room-corner test and (b) that most materials performing well in the room-corner test release low smoke. Similar results were also obtained in a number of other studies, showing that, on average, about one tenth of the materials with low heat release can generate high smoke release.

The materials tested are described in Table 7. Six materials are typically used for wall interior finish: two vinyl wall coverings, a textile wall covering, a thermoplastic sheet, a varnished wood product, and a composite panel. One material is intended for use as ceiling interior finish (ceiling tile). Three materials are normally used as insulation: polyimide foam, phenolic foam and mineral wool.

The NFPA 265 room-corner tests were conducted in a standard "ASTM" or "ISO" room, similar to that for the mattress and upholstered furniture tests. The method uses a propane gas burner to produce a diffusion flame to expose the walls in the corner of the room with a rate of heat output of 40 kW for 5 min followed by 150 kW for 10 min, for a total exposure period of 15 min. The propane gas burner is located such that the edge of the diffusion surface is 51 mm from both walls, in a corner of the room, opposite the door. A total heat flux gauge (calorimeter) is mounted 26 mm above the floor, facing upward, in the geometric center of the test room. An initial volumetric flow rate of 0.94 m^3/s is established through the duct. Within 10 s following the 5 minutes 40 kW exposure, the gas flow is increased to a burner heat release rate of 150 kW, for 10 min. The ignition burner is shut off 15 min after start of the test and the test terminated.

Table 7. Materials Tested per NFPA 265 and ASTM E84

Material	Thickness (mm)	Density (kg/m^3)	Other Information
Ceiling Tile	15	500	Ceramic panel
FR Composite Panel	11	860	Multiple layers*
Mineral Wool	51	115	Unfaced
Phenolic Foam	38	35	Unfaced
Pine	10	32	Varnished plank
Polyimide Foam	51	6.4	Unfaced
Textile Vinyl Wall Covering, on Calcium Silicate Board	11	875	Surface layer: 400 g/m^2
Thermoplastic Sheet	3	1,180	Unfaced
Expanded Vinyl Wallcovering, on Gypsum Board	13	750	Surface layer: 850 g/m^2
Commercial Vinyl Wallcovering, on Gypsum Board	13	720	Surface layer: 480 g/m^2

* Top layer (face) is a high pressure decorative laminate, 0.76 mm thick, adhered with a resorcinol adhesive to a 10 mm FR particle board, adhered with the same adhesive to the back face, a high pressure laminate, 0.66 mm thick.

In the ASTM E84 test method a methane gas burner is set at a gas flow rate adequate to provide a flame extending 1.37 m, exposing the underside of construction materials for 10 min. This corresponds to flow rate of ca. 79 kW (300,000 BTU/hr). The fire test chamber consists of a horizontal duct, 7.6 m long and 448 mm wide. Its sides and base are lined with insulating masonry, and one is provided with a row of high temperature glass pressure-tight observation windows, located so that the entire length of the specimens being tested is observable from outside the fire test chamber. A removable noncombustible insulated top cover seals the chamber. Smoke obscuration is measured with a 12-V sealed beam, clear lens, auto spot lamp, operated from a dc light source, and mounted downstream of the chamber on a horizontal section of the exhaust duct at a point at which there is fully mixed flow. The light beam is directed upward along the vertical axis of the vent pipe. The vent pipe is insulated with high temperature mineral insulation from the vent end of the chamber to the photometer location. A photoelectric cell having an output directly proportional to the amount of light received is mounted over the light source with an overall light-to-cell path distance of 910 mm, 406 mm of which is taken up by the smoke in the exhaust duct. Both the light source and the photocell are open to the environment of the test room. The cylindrical light beam passes through openings at the top and bottom of the duct, with the resultant light beam centered on the photocell. The test method was developed by Al Steiner, at Underwriters Laboratories [33] for traditional building materials, and exposes samples 7.3 m long and 0.5 m wide (the sample is wider than the chamber, and sits on a ledge). The output is expressed in terms of relative indices for flame spread (flame spread index, FSI) and smoke obscuration (smoke developed index, SDI), based on the fire properties of inorganic reinforced cement board and red oak flooring, assigned arbitrary values of 0 and 100, respectively. It is common to find requirements (in building codes, such as the International Building Code (IBC, [34]) or NFPA 5000 [35], fire codes (such as the IFC [6] or the Uniform Fire Code [36]) and the Life Safety Code [4]) or in specifications, requirements for Class A (or Class I) performance, which corresponds to a flame spread index of 0-25 and a smoke developed index of 0-450.

Only one material caused flashover in the room-corner test, namely the varnished pine, for which all flashover criteria were exceeded. However, several materials released significant heat and smoke. Table 8 presents the major heat release results of the NFPA 265 tests conducted, and Table 9 presents the major smoke release results obtained during the same tests. Average optical density can be calculated by averaging all the OD values or (more correctly) by averaging rate of smoke release and volumetric flow rate; in the latter case average optical density is the average smoke release rate divided by the product of 2.303 and the average volumetric flow rate. Table 10 presents the FSI and SDI values for each material. It should be noted that the varnished pine planking did not qualify as a Class A material, based on its flame spread. Clearly, heat release is the most important property measured in the room-corner test, and only low heat release rates guarantee that flashover will not occur, since increased heat (or energy) release induces additional burning, and thus more heat release. Moreover, the premise that there is a rough correspondence between low heat release rate and low optical density (as a measure of smoke), is a reasonable first approximation: more smoke tends to be associated with more heat release rate.

Table 8. Major Heat Release Results for Materials Tested in NFPA 265

Material	Pk HRR	Av HRR	THR	Time to Peak HRR
	kW	kW	MJ	s
Ceiling Tile	22	0	0	822
FR Composite Panel	128	23	21	534
Mineral Wool	35	0	0	900
Phenolic Foam	153	63	57	840
Pine: **Flashover**	1460	122	52	354
Polyimide Foam	40	4	4	630
Textile Wall Covering, on Calcium Silicate Board	109	8	7	342
Thermoplastic Sheet	40	0.2	0.2	360

Expanded Vinyl Wall Covering, on Gypsum Board	359	14	13	336
Commercial Vinyl Wall Covering, on Gypsum Board	126	1	2	348

Table 9. Major Smoke Obscuration Results for Materials Tested in NFPA 265

Material	Av OD 1/m	Av V_s m^3/s	TSR m^2	Av RSR m^2/s	Pk RSR m^2/s
Ceiling Tile	0.063	1.21	165	0.18	0.3
FR Composite Panel	0.088	1.35	270	0.30	0.6
Mineral Wool	0.066	1.18	167	0.19	0.3
Phenolic Foam	0.060	1.27	180	0.20	0.4
Pine: **Flashover**	0.120	1.18	225	0.61	8.5
Polyimide Foam	0.071	1.27	193	0.21	0.4
Textile Wall Covering, on Calcium Silicate Board	0.037	1.78	139	0.15	0.3
Thermoplastic Sheet	0.295	2.00	1359	1.50	7.0
Expanded Vinyl Wall Covering, on Gypsum Board	0.160	1.92	664	0.74	8.9
Commercial Vinyl Wall Covering, on Gypsum Board	0.169	1.67	584	0.65	4.5

Table 10. ASTM E84 Steiner Tunnel Results for Materials Tested

Material	Flame Spread Index (FSI)	Smoke Developed Index (SDI)
Ceiling Tile	15	0
FR Composite Panel	15	15
Mineral Wool	0	0
Phenolic Foam	15	5
Pine	70	105
Polyimide Foam	0	0
Textile Wall Covering, on Calcium Silicate Board	10	10
Thermoplastic Sheet	10	1000
Expanded Vinyl Wall Covering, on Gypsum Board	25	120

Commercial Vinyl Wall Covering,on Gypsum Board	25	80

However, it is also clear that there are some materials that are both much better and others that are much worse in smoke than their heat release results suggest when compared to the general trend. For example, varnished pine causes flashover, but releases much less smoke than would have been expected from materials releasing that much heat. On the other extreme, the thermoplastic sheet releases negligible amounts of heat but high smoke levels.

Table 11 contains results of five series of room-corner tests conducted where heat and smoke were measured. The Table shows that a small fraction of the materials tested for use in construction, approximately 10%, can have adequate heat release (or fire growth) characteristics, but have very high smoke release. In each one of the five series of tests undertaken, there were 1 or 2 materials that would cause a problem if used in buildings; overall a total of 8 out of 84 materials tested were found to be severe outliers and have high smoke.

Table 11: Results of 5 Series of Tests Using Room-Corner Fire Tests

Room-Corner Test Series	Materials Reaching Early Flashover	Materials With Adequate Heat and Low Smoke	Materials With Adequate Heat and High Smoke	# Materials Tested
SwRI [37]	1	8	1	10
Eurefic [38]	14	12	2	28
SBI [39]	12	15	3	30
Coast Guard [40]	3	5	1	9
BFGoodrich [41]	1	5	1	7
Overall	31	45	8	84

References address a study conducted as Southwest Research Institute (San Antonio, TX: SwRI), one in Scandinavia for development of room-corner testing (Eurefic), one in the European Union for development of the Single Burning Item test (SBI), one by the US Coast Guard for analyzing smoke in comparison with heat release and one conducted in Ohio at the BFGoodrich company fire test lab.

NFPA developed a room-corner test specifically designed to assess heat and smoke release of all interior finish (wall and ceiling), other than textile wall coverings, namely NFPA 286 [42]. There is one main difference between NFPA 265 (for textiles) and NFPA 286: the burner. In NFPA 265 the burner is placed 51 mm away from each wall and set at 40 kW and then at 150 kW, while in NFPA 286 the burner is placed against both walls and set at 40 kW and then at 160 kW. This difference means that the flame in NFPA 265 does not reach the ceiling while that in NFPA 286 does. This makes NFPA 286 suitable for all wall and ceiling interior finish, while NFPA 265 is only intended for textile wall coverings. The smoke criterion normally used in the ASTM E84 tunnel test is a smoke developed index (SDI) of 450, and this has been correlated [37] with a total smoke release in a room-corner test of 1,000 m^2. Moreover, an investigation was made to assess the logical threshold criterion for smoke obscuration testing. Several authors have proposed smoke tenability limits as survival criteria. Smoke tenability limits have been measured based on the needed visibility to permit escape and prevent disorientation and, in one case, on the irritancy inherent in smoke. The idea is to allow people present in a fire situation to see far enough that they can escape the fire before being overcome by the effects, of heat or toxicity (or before their eyes become so irritated by smoke that they can no longer see properly). This is usually expressed in terms of visibility distances (in meters), which can then be easily converted to optical density. A value of 4 m visibility, as recommended by Dr. T. Jin for people familiar with their environment [43] seems reasonable and correlates with an average optical density of 0.22 m^{-1} and a total smoke release of 1000 m^2 (or an average smoke release rate of 1.1 m^2/s). This has been adopted by all codes in the USA. This requirement is also consistent with the requirement laid out by the International Maritime Organization (IMO) for testing interior finish materials using the ISO 9705 room-corner test [44]. The maritime requirement is a maximum average rate of smoke release of 1.4 m^2/s, with the ISO 9705 test, which is a more severe test than the NFPA 286 test ["Standard for Qualifying Marine Materials for High Speed Craft as Fire Restricting Materials", IMO Resolution MSC.40 (64) (December 5, 1994), International Maritime Organization, London, UK.)].

More recently, most US codes have made the NFPA 286 room-corner test more severe, by adding a requirement that a material not be permitted to release more than 800 kW, while also permitting textile wall coverings to be tested in the same way as other interior finish materials.

AUTOMOBILES AND VANS

Three vans were purchased and exposed to realistic fire scenarios [45]. In the first test, a van was positioned on a concrete pad, in an exterior location, and tested with the passenger and driver door windows rolled down 3/4 of the way. The test was followed with 26 K-type air thermocouples, positioned inside the van, and 4 video cameras. A shallow aluminum pan with gasoline (50 mL) was placed on the floor under the dash on the passenger side of the van. An additional 20 mL of gasoline were poured onto three sheets of crumpled newspaper. The newspapers were placed beneath the dash on the passenger side of the van. The gasoline pool was ignited with an ignitor. The second test simulated a post-collision fire inside a van, to look at the propensity of materials in the passenger compartment to ignite, burn and propagate fire, and to investigate time available until conditions inside the vehicle became untenable. The van was modified (by: 1) removing the front windshield, 2) removing the top portions of the rear side windows, 3) displacing the roof of the van forward so the front of the headliner was directly above the dash, 4) displacing the dash upward in the center, and 5) placing the engine cover approximately 15 mm back from the dash) to simulate a specific scenario and positioned on a concrete pad, at an exterior location. A small ignition source was placed below the dash area in the vicinity of the engine cover under the transverse HVAC duct. The test was followed with 24 K-type air thermocouples and 5 video cameras. The engine of the van was started and run for ca. 30 min before starting the demonstration. After stopping the engine, the fuel tank was filled with acetone and water to remove residual flammable gasoline and displace any vapors. A diffusion type burner was made from a 6 mm diameter flexible copper tube, extending outside the van, and mounted to the engine beneath the dash and engine cover. Propane gas was fed to the copper tube burner with Tygon tubing from a small cylinder. The propane gas flame was applied with a flame height of 25 mm from the burner surface. The propane supply was turned off once sustained burning was achieved. Eventually, the fire was manually extinguished. In the third test, a different post-collision fire scenario inside another van was investigated. The van was modified (by: 1) removing the front windshield, 2) removing the rear side windows, 3) displacing the roof of the van forward so the front of the headliner was directly above the dash, 4) displacing the dash upward in the center, and 5) placing the engine cover approximately 15 mm back from the dash) and positioned on a concrete pad, at an exterior location. A small ignition source was placed below the dash area in the vicinity of the engine cover. The test was followed with 25 K-type air thermocouples and 6 video cameras. The engine of the van was started and run for approximately 30 min before starting the demonstration. After stopping the engine, the fuel tank was filled with acetone and water to remove residual flammable gasoline and displace any vapors. A diffusion type burner was made from a 6 mm diameter flexible copper tube, extending outside the van, and mounted to the engine beneath the dash and engine cover. Propane gas was fed to the copper tube burner with Tygon tubing from a small cylinder. The propane gas flame was applied with a flame height of 25 mm (1 in.) from the burner surface. The propane supply was turned off once sustained burning was achieved. Eventually, the fire was manually extinguished.

The major qualitative results of the real-scale car tests are indicated below, with the time lines of events shown following each description.

Test 1: The temperature recorded at the headliner near the windshield rapidly increased to a maximum temperature of 782°C at 200 s after ignition while the back portion of the front bench seat reached a maximum temperature of 446°C at 340 s after ignition. The temperature profiles of the thermocouples in the HVAC vents show that fire spread through the central HVAC ductwork traversing the passenger compartment. Examination of the interior of the van after fire extinguishment showed that all combustible materials, including plastic dash components, HVAC duct, carpeting, seat fabric, door panels and the headliner, were damaged in the fire. The fire damage on the passenger door panel and seat was more extensive than the damage on the driver door and seat. The fabric on the exposed surfaces of the bench seats was burned and the exposed foam decomposed. The plastic components of the dash on the passenger side were totally consumed in the fire. The driver side dash components, including the instrument panel, were consumed or exhibited severe melting and charring.

Time line (min: s)	**Event**
0:00	Ignition of gasoline inside the van.
0:42	Flames are visible inside the center HVAC duct.
0:50	Smoke begins to vent from the two HVAC vents on the top and in the center of the dash.
1:52	Passenger compartment fills with smoke.
2:00	Flames emerge from HVAC vent on the face of the dash on the passenger side. Underneath the passenger dash is fully involved.
2:50	Smoke begins to vent from the air supply vents directly in front of the windshield on the exterior of the van.
3:10	Flames emerge from passenger side window.
3:40	Front windshield compromised.
4:00	Passenger compartment fully involved.
5:30	Van fire extinguished manually.

Test 2: The temperature on the headliner directly above the dash reached a temperature of 699°C at 230 s after ignition. The headliner thermocouple temperature data indicates that the fire spread from the front to the rear of the van in approximately 30 s, once the headliner became involved in the fire. The passenger compartment of the van was already fully involved approximately 160 s after the start of the demonstration.

Time line (min: s)	**Event**
0:00	Ignition.
1:56	Dash fire.
2:17	Fire from dash impinges on headliner. Headliner dripping.
2:40	Front portion of van fully involved.
2:54	Rear bench seat in flames.
3:03	Fire emerges from rear side windows.
3:20	Side window on driver's side compromised from heat.
3:27	Side door windows compromised from heat.
3:44	Van fire extinguished manually.

Test 3: The temperature on the headliner directly above the dash reached a temperature of 862°C at 335 s after ignition while the back and seat portions of the front bench seat reached a maximum temperature of 866°C at 380 s after ignition. The temperature on the passenger side edge of the dash reached a maximum of 460°C, at 335 s, and that on the HVAC vent, under the dash on the driver side, reached a maximum of 537°C at 360 s after ignition. The headliner thermocouple temperature data indicates that the fire spread from the front to the rear of the van in approximately 40-50 s, once the headliner became involved in the fire. The passenger compartment of the van was already fully involved approximately 5 min after the start of the demonstration.

Time line (min: s)	**Event**
0:00	Ignition.
2:00	Smoke emerges from passenger side HVAC vent.
3:30	Fire grows under dash and emerges from passenger side HVAC vent and out of space between engine cover and dash.
3:50	Top of the dash in flames.
4:20	Fire from dash impinges on headliner. Headliner debris falls from roof.
4:30	Dash fully involved.
4:40	Headliner on fire.
5:00	Front passenger seat in flames.
5:10	Flames out the side rear window space. Van fully involved.
5:34	Side door windows break.
5:45	Van fire extinguished manually.

Analysis of Real-scale Van Tests: In all 3 real-scale tests conducted, fires inside the passenger compartment consumed virtually all the combustible materials, leaving a rusted interior with seat frames and springs and the metal frame of the dash. They also burnt off the vehicle paint.

Considering that human tenability ceases when temperatures reach 60°C , heat fluxes reach 20 kW/m^2 and smoke layers get to 1.2 m from the ceiling, this happened no later than 1 min 52 s in test 1 (passenger compartment filled with smoke), or than 2 min 40 s in test 2 (front portion of vehicle fully involved) or than 4 min 40 s in test 3 (after dash is fully involved in fire, the headliner catches fire), so that clearly the vehicle interior became rapidly untenable in all cases. Figures 3 and 4 show traces of temperatures in the headliner, duct and front car seat, illustrating how rapidly high temperatures were reached. Thus, a vehicle occupant who may still be conscious, but is likely to be stunned or otherwise injured, has very little time left to exit or be rescued before receiving fatal injuries as a result of the fire. Such time available for escape or rescue could clearly be increased if the fire performance of the materials in the passenger compartment were improved, for example by better fire retardance [46].

The information presented expands on analyses conducted earlier, that showed that car interior materials exhibit poorer fire performance than average plastics [47-48]. The most interesting issue is that the median fire test data from those cone calorimeter tests conducted on automotive materials was much poorer than that of commercial plastic materials of the same vintage [26], in virtually all aspects of fire performance. Furthermore, car seats perform as poorly (or worse) than domestic fabric-foam seat composites, using non fire retarded foams. In fact, such padding materials would not be permitted for use even in homes in the United Kingdom [16]. Other products with poor fire performance are: the engine cover, the ducts and the headliner. The engine cover should offer a high degree of protection so that ignition, if it occurs at all, is delayed for very long periods and a fire does not penetrate from the engine compartment into the passenger compartment. Thus, it is interesting to note that the molded fiber reinforced plastic material comprising the engine cover in a car studied exhibited fairly poor fire performance. It consisted of two materials, one of which ignited in the cone calorimeter at ca. 2 min at an incident heat flux of 25 kW/m^2, and at ca. 1 min at an incident heat flux of 40 kW/m^2, with a high peak rate of heat release, close to 300 kW/m^2. This offers a simple passageway for flames from the engine compartment to enter the passenger compartment, which can result in a severe fire that traps the passengers, as they are often injured, as a result of collision, and have lower mobility. The fire performance of the duct materials, which was tested in every vehicle investigated, is very poor and could easily be improved by the use of existing fire retarded polyolefin materials. Ducts are surrounded by a large mass of other combustibles, most of which are easily ignitable. Thus, they can cause an untenable situation within a very short time. Vehicle headliners are typically coated fabrics, with a thin covering layer and a back coating (often a foam), perhaps mounted on plywood or fiberglass. This acts, of course, as the interior ceiling finish of the vehicle's passenger compartment. The headliners tested had times to ignition ranging from 9 to 62 s, at a cone calorimeter incident heat flux of 25 kW/m^2; so that they clearly offered little protective escape time! Moreover, in each of the three real-scale fires conducted, headliner temperatures quickly reached values that correspond to well over 50 kW/m^2 incident heat fluxes (approximately 695°C): headliner ignition would have resulted.

GARBAGE CANS

Typical garbage cans are made of polyethylene without fire retardants. In order to have a reasonable idea of what kind of fire safety issue is involved, the author conducted a full-scale test with a typical household garbage can. It was a polyethylene household garbage can, nominally designated at 30 gallons (114 Liters), which weighed 10.2 kg. The ignition source used was some paper and a match, and the test was conducted in a standard ASTM room (as described above). The test was terminated by manual extinguishment when flashover was reached. The test results indicate that a peak heat release rate of 1.342 MW was obtained at 11.35 min (which simply means that this is when the test was terminated, because the polyethylene was still burning vigorously), the total heat released was 201.4 MJ, the total smoke released was 202 m^2, the peak smoke release rate was 4.2 m^2/s, the mass loss (by weight after the test) was 61.05% and the peak optical density was 3.95 [49]. As a result of this test, and of tests with the cone calorimeter on polyethylene samples, codes in the United States have developed requirements that basically ban polyethylene garbage cans from hospital and other health care environments, by requiring the materials of construction of the cans to meet a heat release rate of 300 kW/m^2 at a flux of 50 kW/m^2 in the cone calorimeter. Table 12 shows some cone calorimeter data on the material (all tests were conducted on commercial polyethylene, non fire retarded, in the horizontal orientation, with sample thicknesses of 6 mm).

Table 12 - Cone Calorimeter Data on Polyethylene [26]

Incident Heat Flux (kW/m^2)	Time to Ignition (s)	Peak Heat Release Rate (kW/m^2)	Total Heat Released (MJ/m^2)
20	403	912	162
40	159	1408	221
70	47	2735	228

CHILDREN'S PLAYGROUND

In recent years there has been a proliferation of children's playground structures, constructed indoors, especially in shopping malls, fast food restaurants and transportation terminals (typically airports). These playgrounds are intended for young children, so that all exposed surfaces are soft and brightly colored. These structures can be fairly large and tend to contain large amounts of combustibles. The typical exposed combustibles are:

- Rigid plastics (usually non fire retarded polyethylene)
- Foam padding, for structural use, usually covered by a textile
- Foam padding for tubes and pipes
- Foamed ball pool balls
- Various fabrics

The potential for such children's playground structures to represent a serious fire hazard for the children using them was investigated by conducting fire testing of one such structure [49] in a standard "ASTM" room (as described above). The structure tested was a "mini children's playground structure", just small enough to fit into the room, constructed of materials all of which were described as complying with ASTM F 1918 [50] (although this was not independently verified by tests on the materials). The structure was erected over concrete floor, without placing any protective surfacing underneath. The test structure weighed approximately 215.5 kg and was built in place, with the following components, with most of the rigid plastics being non fire retarded polyethylene (other than the foams, the polycarbonate and the netting):

- 27.4 m of steel pipe, to construct the 1.2 m x 1.2 m frame
- 35 pipe fittings
- 17 m of "Tuff Pad" foam "post padding"

- 2.4 m of "No-climb" netting
- 1 elbow tube, 760 mm in diameter, 90 degree angle
- 1 T-tube, 760 mm in diameter
- 1 Hexagonal shoe rack
- 1 Triangle platform climb deck
- 1 Tower panel
- 1 Retro Flange
- 1 JC 30 Polycarbonate bubble window
- 160 in-line tie-wraps

The source of ignition used for the test was a standard over-the-counter disposable lighter and 750 g of a standard daily newspaper. The paper was placed sheet-wise in one corner of the test structure and two crumpled balls of paper were placed between the two tubes. No paper was placed inside any of the components and no paper was attached to any part of the structure using artificial means. No accelerants were used. The newspaper was quickly consumed and the hexagonal shoe rack spread the fire further. Abundant white smoke was generated within less than a minute of the ignition of the newspaper. The fire grew slowly over the first several minutes of the test in terms of visible flame spread. However, temperatures at the ceiling directly over the test specimen rose to over 100°C approximately 1 min into the test and never dropped below that level. As the polyethylene from the shoe rack dispersed and the heat of the fire grew, fire spread to the 90 degree elbow tube. Once the fire broke through the elbow tube, flaming drips soon followed, with fuel pools of molten polyethylene, creating a situation of imminent hazard As the pooling and dripping expanded from the consumption of the 90 degree tube, the fire breached that tube and jumped to the upper T-tube. Once this tube, a thinner walled part, ignited, the severity of the flames and the fire hazard increased very rapidly. Flashover occurred in approximately 16 min, roughly 4 min after the breach to the upper levels and thinner walled parts. When the test room flashed over, it produced upper layer and doorway temperatures in excess of 800°C and 700°C, respectively. The heat flux at the floor peaked at over 25 kW/m^2 and the carbon monoxide and carbon dioxide concentrations in the exhaust duct peaked at 43 and 308 g/s, respectively. The test was terminated after approximately 17 minutes. Smoke remained thin and white for the first third of the test; however, as more fuel became involved, oxygen levels dropped in the test room and the smoke developed quickly into a thick black cloud. See major test results in Table 13.

Flashover was observed because all 4 of the following criteria were met: rate of heat release exceeding 1 MW, flames out the door, floor heat flux exceeding 25 kW/m^2 and temperature rise exceeding 600°C. The test data highlighted are critical for fire hazard: (1) heat release rates above 1 MW correspond to flashover conditions; (2) human skin cannot tolerate temperatures above 65°C for any significant time period before causing irreversible damage and incapacitation; (3) temperatures above 100°C result in human lethality; (4) temperatures above 650°C ensure flashover; (5) total smoke release of 1,000 m^2 is the limit of acceptability for the smoke released by interior wall or ceiling finish in a room the same size in US codes, (6) visibility inside the structure soon fell below 1 m, and (7) survival by children in that structure would have been very difficult (if not impossible) after 1-2 minutes. Moreover, the melting and flaming drips, very early in the test, of structures usually placed on combustible rubber mats, increases the hazard to the children inside. Personal experience with these structures found people crawling through the tubes to reach small children stranded in a remote area of the structure because the child was unable to climb a rope, the only way to exit that area. In case of a fire, the plastics that these structures are built from would create hot fires and heavy smoke that would hinder egress by users and rescue by staff and/or parents. Typical sprinkler activation in such structures may not be enough to protect the children, because of the inability of sprinklers to penetrate zones "protected" by horizontal steel surfaces (needed for structural support). A recent fire in such a structure in a fast food restaurant (in the middle of the night) destroyed the entire restaurant, fortunately without loss of life as the place was closed.

Table 13 - Major Fire Test Results from Children's Playground Fire

Property Described	**Value and Units**	**time (min, s)**
Flashover	Flames Out Door	16 min 7 s
Peak Heat Release Rate	5209 kW	17 min 38 s
Average Heat Release Rate	458 kW	
Peak HRR (30 s average)	4732 kW	
Total Heat Released	467 MJ	
Peak Mass Loss Rate (30 s avg)	148 g/s	16 min 48 s
Average Mass Loss Rate *	13 g/s	
Total Mass Loss*	12 kg	
Peak Smoke Production Rate	16.11 m^2/s	17 min 8 s
Peak Smoke Production Rate (60 s avg)	10.41 m^2/s	
Average Smoke Production Rate	0.96 m^2/s	
Total Smoke Released	982 m^2	
Peak Optical Density	1.08 1/m	16 min 53 s
Exhaust Duct Flow at Pk OD	2.47 m^3/s	16 min 53 s
Average Optical Density	0.098 1/m	
Average Volumetric Exhaust Flow	1.96 m^3/s	
Peak Heat Flux to the Floor	25.8 kW/m^2	17 min 8 s
Peak Average Ceiling Temperature	805°C	17 min 13 s
Peak Doorway Temperature	741°C	17 min 18 s
Peak CO Production Rate	37.61 x 10-3 m^3/s	17 min 3 s
Peak CO Release Rate	43.07 g/s	
Peak CO_2 Production Rate	0.171 m^3/s	17 min 28 s
Peak CO_2 Release Rate	308 g/s	

* Load cell signal was lost prior to peak heat release rate due to burning on the floor

A standard performance specification, ASTM F 1918 [50], exists for these structures. Unfortunately there is no legal requirement that manufacturers comply with this performance specification. Moreover, there are, unfortunately, no code requirements as yet, since these playground structures are not considered to be kiosks, interior finish or decorations (all of which have to meet certain fire safety rules). Work is underway to try to include some appropriate requirements into some codes.

CHRISTMAS TREES AND DECORATIVE LIGHTS

Christmas trees can generate severe fires, and this has been investigated in detail by several projects, in particular work by Gordon Damant [51] and by David Stroup [52]. If the Christmas tree is either: (a) a natural Christmas tree which is wet (that is if the tree has been kept with plenty of water in the roots) or (b) if the tree is an artificial poly(vinyl chloride) (PVC) tree, the tree itself is very difficult to ignite. On the other hand, fire tests conducted on natural Christmas trees (ranging in height from 2.3 to 3.1 m, and dried after 2-3 weeks inside a house) showed that dry Christmas trees can ignite easily and result in fires with heat release rate values of 1.7- 5.2 MW [51], more than enough to ignite any item of upholstered furniture that is close by, for example an easy chair, a couch, or a bed. Moreover, with such a big fire, it is very likely that flashover will be reached in the room of any house very quickly, since 1 MW tends to be enough to cause flashover in a small room. Other fire tests have given similar results, including demonstrations showing that a natural Christmas tree can become fully involved within 7 to 10 s of starting the fire [53]. Of added interest is the fact that in many cases (and the United States has had an average of 8-14 fire fatalities per year from such Christmas tree fires [54]) the actual cause of Christmas tree ignition are the decorative lights which are almost always present [53]. Such lights tend to have very poor fire performance and, more importantly, are often made of materials with inadequate temperature ratings, so that they often thermally degrade after prolonged use, creating weak spots where fires can start. Many regulations exist for such decorative lights, but they are often manufactured in places where requirements are being flaunted and are incorrectly labeled. To compound the potential cause for concern with decorative trees, recently patents have been taken out to start manufacturing polyethylene trees, without using fire retardants. In response to this concern, the Uniform Fire Code (UFC/NFPA 1) [36] has added an annex note into the 2006 edition that recommends testing artificial Christmas trees in public occupancies by releasing < 100 kW when tested with a 340 g wood crib furniture calorimeter (UL 1975 [59]) or have small flames when exposed to 450 g of shredded newspaper (UL 411 [60], now withdrawn).

In terms of regulations for these products, this is well underway: (a) natural Christmas trees are not permitted (in the US) in most public occupancies, (b) decorative lights used in public occupancies must be listed (which ensures a high degree of safety if properly done) and (c) decorations (including natural and artificial vegetation) is starting to be considered as a key product the fire safety of which needs to be regulated (for example using a standard fire test being developed, based on the "furniture calorimeter".

TELEVISION SETS

This work was primarily conducted by Jürgen Troitzsch [55-56], who has shown that non fire retarded television sets, such as those commonly used in Europe, can quickly take a room to flashover. The key fire test was carried out with a TV set purchased in Germany, with a 20 x 20 mm hole cut in the lateral right front side of the backplate adjacent to the housing, where a solid fuel pellet (0.15 g, 40-55 W, 5-10 mm flame) was applied. After ignition, the solid fuel pellet flame impinged on the backplate on top of it and later on the edge of the housing, simulating an external and internal low intensity ignition source. Just 24 s after ignition of the pellet, the backplate began to burn. After 1 min, the flames were 8-10 cm high and after 2.5 min they were 1 m high. A pre-flashover situation developed in 4.5 min and complete room flashover, with all the furniture burning, after 7 min with flames 6-8 m high coming out of the front of the fire room. Temperatures rose to 800-900°C and reached over 1,100°C near the ceiling after 12 min. The fire safety requirements for the cabinet of that TV set was no more than a UL 94 HB test [57]. In contrast, TV sets purchased in the US and in Japan, where the cabinets have to meet UL 94 V requirements (Class UL 94 V2, V1, V0 or 5V), either did not ignite or extinguished quickly when exposed to ignition sources as high as 200 mL of isopropanol or cloth soaked in isopropanol (representing up to 40 kW insults).

PREDICTION OF COMPUTER HOUSINGS

In a recent study [58], five engineering thermoplastics were considered for use as computer housings, and a cone calorimeter was used to assess their fire performance. The plastics considered were all materials with the appropriate mechanical and electrical properties and they were all fire retarded to some extent, but their level of fire performance ranged widely. The results were used, by applying a simple zone fire model, to investigate the resulting fire hazard in three fire scenarios: (1), a home fire, with the fire starting at the computer, placed in the kitchen and (2) a home fire (in the same home), with the fire starting at the computer, placed in a bedroom, and (3) a small office building fire, with the fire starting at the computer, placed in one of four offices. The cone calorimeter tests were conducted at an incident heat flux of 50 kW/m^2, in the horizontal orientation. The first analysis assessed the time until the smoke layer reached a level that could be considered untenable. The second analysis conducted evaluated evacuation and tenability. It was very interesting that the relative rankings of four of the materials varied considerably depending on the analysis conducted, but that one of the materials was consistently the safest material in every case. The analysis permitted a ranking of the five materials on the basis of their fire safety as computer housing materials for real use.

REGULATORY UPDATE

A few requirements associated with the type of consumer products discussed in this work have recently been incorporated into codes and regulations in the United States, and some other issues are under discussion.

The 2006 editions of the International Fire Code (IFC, [6]) and of the Uniform Fire Code (UFC, NFPA 1, [36]) have both incorporated similar heat release requirements for garbage cans. The UFC-2006 reads: "*Nonmetallic rubbish containers exceeding a capacity of 5 ft3 [40 gal (0.15 m^3)] shall be manufactured of materials having a peak rate of heat release not exceeding 300 kW/m^2 at a flux of 50 kW/m^2 when tested in the horizontal orientation, at a thickness as used in the container but not less than of 0.25 in. (6 mm), in accordance with ASTM E 1354*". The criteria are intended to be similar to the way wood performs and to prevent the use of materials with very high heat release.

The IFC-2006 reads: "*Wastebaskets in Group I-3, detention and correction facilities. Wastebaskets and other waste containers, including their lids, located in Group I-3 detention and correction facilities shall be constructed of noncombustible materials or of materials that meet a peak rate of heat release not exceeding 300 kW/m^2 when tested in accordance with ASTM E 1354 at an incident heat flux of 50 kW/m^2 in the horizontal orientation. Metal wastebaskets and other metal waste containers with a capacity of 20 gallons (75.7 L) or more shall be listed in accordance with UL 1315 and shall be provided with a noncombustible lid.*" [61]

The International Building Code (IBC, [34]) agreed to add the following wording into its 2006 edition, in the section on malls:

"*Children's Playground Structures. Structures intended as children's playgrounds that exceed 10 ft (3.05 m) in height and 150 ft (14 m^2) in area shall comply with the following.*

Materials. Children's playground structures shall be constructed of noncombustible materials or of combustible materials that comply with the following:
(1) Fire retardant–treated wood.
(2) Light-transmitting plastics complying with Section 2606.
(3) Foam plastics (including the pipe foam used in soft-contained play equipment structures) having a maximum heat-release rate not greater than 100 kW when tested in accordance with UL 1975.
(4) Aluminum composite material (ACM) meeting the requirements of Class A interior finish in accordance with Chapter 8 when tested as an assembly in the maximum thickness intended for use.
(5) Textiles and films complying with the flame propagation performance criteria contained in NFPA 701.
(6) Plastic materials used to construct rigid components of soft-contained play equipment structures (such as tubes, window, panels, junction boxes, pipes, slides, and decks) meeting the UL 94 V-2 classification when tested in accordance with UL 94.
(7) Ball pool balls, used in soft-contained play equipment structures, having a maximum heat release rate not greater than 100 kW when tested in accordance with UL 1975. The minimum specimen test size shall be 36 in. by 36 in. (914 mm by 914 mm) by an average of 21 in. (533 mm) deep, and the balls shall be held in a box constructed of galvanized steel poultry netting wire mesh.
(8) Foam plastics shall be covered by a fabric, coating, or film meeting the flame propagation performance criteria of NFPA 701.
(9) The floor covering placed under the children's playground structure shall exhibit a Class I interior floor finish classification, as described in section 804, when tested in accordance with NFPA 253.

Fire protection. Children's playground structures located within the mall shall be provided with the same level of approved fire suppression and detection devices required for kiosks and similar structures.

Separation. Children's playground structures shall have a minimum horizontal separation from other structures within the mall of 20 ft (6090 mm).

Area limits. Children's playground structures shall not exceed 300 ft^2 (28 m^2) in area, unless a special investigation has demonstrated adequate fire safety." [62, 63]

The state of California adopted a requirement that came into effect on January 1, 2005: all mattresses (especially residential mattresses) sold in the state must meet the heat release requirements contained in California Technical Bulletin 603 (CA TB 603 [9]), which are as follows: a maximum heat release rate of no more than 200 kW during the 30 minute test and a total heat release rate of no more than 25 MJ during the first 10 minutes of test. This test is used on a complete mattress but is different from, and less severe than, the traditional CA TB 129 [8] test, which was intended for high risk applications. The 2006 IFC [6] contains requirements that mattresses in a few occupancies (board and care facilities, nursing homes and hospitals, and detention and correction facilities) must to comply with CA TB 129 [8] (or ASTM E 1590 [10]) with a maximum heat release rate of no more than 100 kW during the entire test and a total heat release rate of no more than 25 MJ during the first 10 minutes of test (which does not apply if the facility is fully sprinklered). CPSC has initiated a process of rulemaking to require all residential mattresses sold in the United States to meet a fire test similar to CA TB 603; that process is not complete. The 2006 IFC [6] also contains requirements that upholstered furniture in the same occupancies discussed for mattresses above must comply with CA TB 133 [3] (or ASTM E 1537 [7]) with a maximum heat release rate of no more than 80 kW during the entire test and a total heat release rate of no more than 25 MJ during the first 10 minutes of test (which does not apply if the facility is fully sprinklered). CPSC has also initiated a process of rulemaking to require all residential upholstered furniture sold in the United States to meet a fire test that CPSC designed; that process is also not complete.

CONCLUSIONS AND RECOMMENDATIONS

It is clear from the work discussed here, which covered a wide variety of products, that full-scale fire testing of consumer products is a worthwhile endeavor. In many cases, adequate fire safety information cannot be obtained unless such tests are conducted. When the results of full-scale tests are shown publicly, they can often open up the eyes of regulators and the public to the potential for fire safety concerns that most people never think of.

The advantage of conducting large-scale tests is that they are more likely to be convincing and to generate conclusive results, that can results in changes in requirements or in favorable outcomes in product liability cases (in the USA). Thus, whether it is through regulatory requirements or through self-policing by major manufacturers, it is important that steps be taken to attempt to improve the fire performance of the consumer products discussed here, several of which are known to be associated with particularly high fire losses.

Unfortunately, full-scale tests are very expensive and can usually be conducted only in special scenarios, which makes them lack some generality (it is always possible to argue that the scenario was not perfect or the ignition source too severe). It is usually critical to ensure that such full-scale tests are not conducted to try to replicate an exact situation, as they are never perfectly known, but to understand the real fire performance of the product under investigation.

It is now, of course, possible to make excellent predictions of results of full-scale fire tests (albeit in very simplified scenarios) from small scale fire tests (such as the cone calorimeter) and modeling. In the initial stages of a fire investigation or of research into a fire problem, it is always preferable to attempt to start conducting such small-scale tests and modeling, so that the full-scale tests are properly designed and give the answers needed (which are, of course, not always those that the researcher would have predicted or preferred). However, it is critical to use small scale fire test methods that can adequately predict full scale fire tests, and those will generally be tests which asses heat release.

In the United States, three major transport regulatory authorities have conducted full-scale fire tests in recent years: Federal Aviation Administration (which bases its regulation of aircraft materials on them), Coast Guard (which made recommendations to the International Maritime Organization for fire restricting materials based on them) and Federal Railroad Administration (which permits alternate approvals for passenger rail vehicle materials based on them).

In contrast, the National Highway Traffic Safety Administration (NHTSA) is responsible for the fire safety in cars and vans and it has not conducted any full scale fire tests for years. In fact, the sole material fire safety requirement for cars and vans in the United States (and also in most of the rest of the developed world) is that materials in the passenger compartment must meet the flame spread criteria of FMVSS 302 [64], a 1960s extremely mild and inappropriate test. As the work reported here indicates, this provides inadequate safety for driver and passengers and should be replaced by a more realistic test that fully addresses the realistic fire hazard.

In the European Union, three major projects have been conducted in recent years, including full-scale fire tests, looking at fire safety issues:

(1) construction products, which has led to regulation throughout the European Community;
(2) upholstered furniture, which has not led to regulation, and
(3) electrical cables, which is under discussion now for use in regulation.

It is hoped that authorities having jurisdiction will continue paying attention to full-scale tests conducted, either on their behalf or independently by others, and use the results obtained as the basis for regulation of consumer products.

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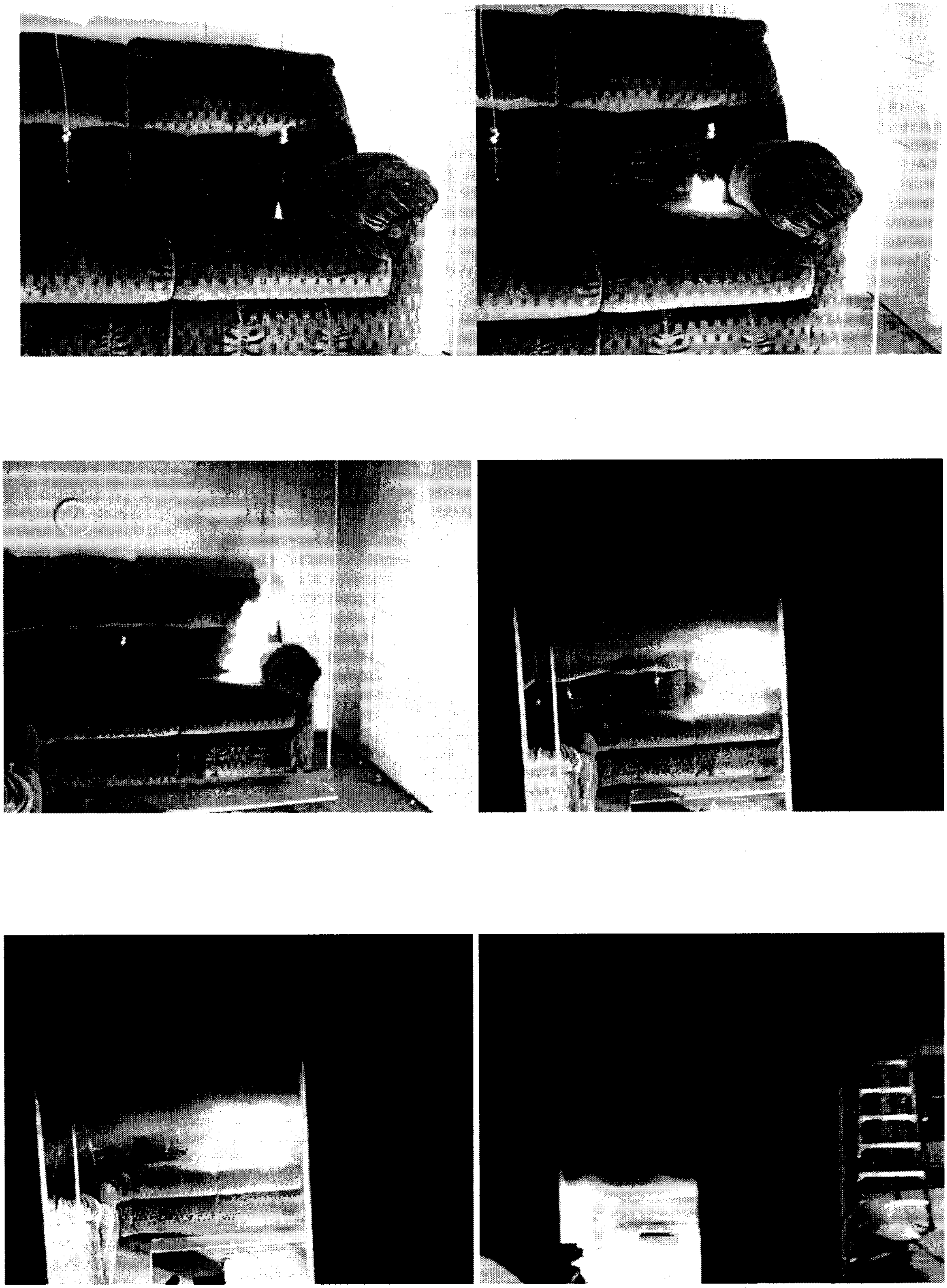
The figures below show the progression of fire on a non FR upholstered furniture item, from ignition with a BS 5852 Source 1 small flame until just before flashover occurs.



GBH Attachment 18

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Heat and Smoke Measurements of Construction Materials Tested in a Room-Corner Configuration According to NFPA 265

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ABSTRACT

Fire tests were conducted on 10 construction materials, in a room-corner test configuration, according to NFPA 265 (with a 40/150 kW ignition source), in order to understand the importance of smoke obscuration measurements. The materials were chosen to illustrate adequate fire performance, on the basis of heat release and flame spread, together with a broad range of performances in terms of smoke release. The same materials were also tested using the ASTM E84 test. Only 1 material caused flashover in the room (and had an E84 FSI > 25). Similarly, only 1 material failed to meet the E84 SDI limit of 450 (even though it had a very low E84 FSI and very low rate of heat release), and had very high smoke release in the room. The results indicate that: (a) it is important to set limits for smoke release in the room-corner test and (b) the majority of materials which perform well in the room-corner test will release low smoke. A discussion is included on the relevance of the data to fire safety, based on optical density.

INTRODUCTION

Once ignition has occurred, there are three main ways in which fire, whatever the materials burning, can cause harm to people, property or operations. These are, in decreasing order of their importance to fire hazard: (a) heat or flames spread from the item first ignited to other items, potentially resulting in thermal injury to people, destruction of property or loss of operations, (b) smoke generation, which obscures vision and can inhibit both the escape of trapped victims and the action of fire fighters and (c) toxic product generation (gases and particulates in smoke), which can be inhaled by victims and injure them.

For clarification purposes, the definition of smoke given by the ASTM Fire Standards Committee (in ASTM E176, [1]) is used in this paper. It states "smoke is the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis and combustion".

Test methods used to measure heat release from a fire can involve specimens of different sizes, so that bench-scale, intermediate-scale or full-scale tests can be conducted [2]. The theory inherent in such testing has been published [3] as has abundant information on test results in small and large scale [4]. It is now fairly common for such tests to include also measurements of smoke obscuration, although that was not the case originally, because the technology for smoke measurements lagged slightly behind that for heat measurements.

The best known small scale tests are the cone calorimeter (ASTM E1354, [5], with a 100 x 100 mm specimen) and the Ohio State University calorimeter (ASTM E906, [6], with a 150 x 150 mm specimen). In the intermediate scale, the ICAL has been standardized in recent years (ASTM E1623, [7], with a 1 x 1 m specimen). Finally, the large scale tests involve testing a full product (such as a chair, in ASTM E1537 [8] or mattress, in ASTM E1590 [9]) or a fully lined room (such as in NFPA 265 [10] or ISO 9705 [11]).

Test methods used to measure smoke obscuration accompanying a fire have been classified into five categories [12]:

(I) Static small scale smoke obscuration tests on materials
(II) Dynamic small scale smoke obscuration tests on materials
(III) Traditional large scale smoke obscuration tests on products
(IV) Full scale tests measuring heat release and smoke release
(V) Small scale tests measuring heat release and smoke release

Small scale tests are likely to be shunned for use in regulatory applications. They are most often used for screening purposes and for developing fire safety engineering calculations designed for fire hazard assessment calculations or for material or product development.

The present work uses two tests, one of category III (ASTM E84, the Steiner tunnel test, [13] measuring flame spread and smoke) and one of category IV (NFPA 265, a full scale room-corner test measuring heat release, as well as smoke release, a requirement added recently to the test, in view of the advances in measurement technology and fire hazard concepts). Both tests are intended to assess the suitability of the tested building materials for various applications. In fact, however, smoke release is assessed, in code applications, only by using the Steiner tunnel test and not by using the room corner test, for two basic reasons:

(a) There is fear that any restriction placed on smoke levels would result in preventing the use of some materials considered suitable.

(b) There is a tacit belief that materials which perform well in terms of their heat release will always perform well in terms of their smoke release [14].

This work was undertaken with the intent of investigating those reasons, by testing 11 building materials, using both the traditional flame spread and smoke obscuration test (ASTM E84) and the more novel heat release and smoke obscuration test. Smoke toxicity will not be investigated in this work, because it is best done by means of bioassay tests, if actual toxic potency is desired, since most materials tend to have similar smoke toxicities [15-19].

EXPERIMENTAL

The materials tested are described in Table 1.

Table 1. Materials Tested per NFPA 265			
Material	Thickness (mm; in)	Density (kg/m^3)	Other Information
Ceiling Tile	15; 0.60	500	Ceramic panel
FR Composite Panel	11; 0.45	860	Multiple layers*
Mineral Wool	51; 2.0	115	Unfaced
Phenolic Foam	38; 1.5	35	Unfaced
Pine	10; 3/8	32	Varnished plank
Polyimide Foam	51; 2.0	6.4	Unfaced
Textile Wallcovering, on Calcium Silicate Board	11; 3/8	875	Surface layer: 12 oz/yd^2 (400 g/m^2)
Thermoplastic Sheet	3; 1/8	1,180	Unfaced
Expanded Vinyl Wallcovering, on Gypsum Board	13; 0.5	750	Surface layer: 25 oz/yd^2 (850 g/m^2)
Commercial Vinyl Wallcovering, on Gypsum Board	13; 0.5	720	Surface layer: 14 oz/yd^2 (480 g/m^2)

* Top layer (face) is a high pressure decorative laminate, 30 mil thick, adhered with a resorcinol adhesive to a 3/8" FR particle board, adhered with the same adhesive to the back face, a high pressure laminate, 26 mil thick.

Fire Tests Used:

1. NFPA 265:

This method uses a propane gas burner to produce a diffusion flame to expose the walls in the corner of a room 8 ft x 12 ft x 8 ft (2.4 m x 3.7 m x 2.4 m). The burner produces a rate of heat output of 40 kW for 5 min followed by 150 kW for 10 min, for a total exposure period of 15 min. The contribution of the construction material to fire growth is measured by constant monitoring of the incident heat flux on the center of the floor, the temperature of the gases in the upper part of the room, the rate of heat release, the smoke release, and the time to flashover (if it occurs). The test is conducted with natural ventilation to the room provided through a single doorway of 30 in. x 80 in. (0.76 m x 2.03 m). The combustion products are collected in a hood feeding into a plenum connected to an exhaust duct in which measurements of the gas velocity, temperature, and concentrations of selected gases are made.

Flashover is determined to have occurred when any two of the following conditions has been reached:

(a) Heat release rate exceeds 1 MW.
(b) Heat flux at floor exceeds 20 kW/m^2.
(c) Average upper layer temperature exceeds 1112°F (600°C).
(d) Flames exit doorway.
(e) Autoignition of paper target on floor.

The test compartment is placed indoors in an essentially draft-free, heated space, large enough to ensure that there is no influence of the surroundings on the test fire. The test compartment used is a framed (with wood studs) block structure, with an inside surface of calcium silicate board of 46 lb/ft^3 (736 kg/m^3) density, and nominal thickness of 0.5 in. (12 mm).

Test specimens are mounted on a substrate, appropriate to the intended application. The test specimen assembly is installed on the interior wall surfaces of the test room so as to cover fully both 8 ft x 12 ft (2.44 m x 3.66 m) walls, and the 8 ft x 8 ft (2.44 m x 2.44 m) wall not having the door. Prior to testing, the mounted specimen is conditioned to approximate equilibrium in an atmosphere at a temperature of 70 ± 5 °F (21 ± 3°C) and a relative humidity of 50 ± 5 %. The materials were screwed on to three of the compartment walls. Backing materials were used for the textile wallcoverings and the vinyl wallcoverings, simulating a support system comparable to that intended for their actual field use, using commercial adhesives intended for the application, and representing a typical value of thermal resistance for the wall system. Care was taken that the materials should not delaminate or fall during testing.

Room Instrumentation. The room instrumentation used for this test is as follows. The ignition source is a propane gas burner with a nominal 12 in. x 12 in. (nominal 0.3 m x 0.3 m) porous top surface of a refractory material, through which the gas is supplied, namely a minimum 4 in. (102 mm) layer of Ottawa sand, over a 6 ± 0.2 in. (152 ± 5 mm) plenum. The top surface of the burner through which the gas is applied is located horizontally 12 ± 2 in. (0.30 ± 0.05 m) above the floor. The burner enclosure is located such that the edge of the diffusion surface is 2.0 ± 0.1 in. (51 ± 0.3 mm) from both walls, in a corner of the room, opposite from the door. A total heat flux gauge (calorimeter) is mounted at a height of 1.1 ± 0.9 in. (26 ± 25 mm) above the floor surface, facing upward, in the geometric center of the test room. Seven bare Type K Chromel Alumel thermocouples, 20 mil (0.5 mm) in diameter, are used: one at the doorway (on the interior plane of the door opening on the door centerline, 4.0 ± 0.8 in. (100 ± 2 mm) from the top), and six inside the test room, at positions 4 in. (100 mm) below the ceiling. The room thermocouples are located at the center of the ceiling, at the center of each of the four ceiling quadrants, and directly over the center of the ignition burner. The thermocouples are not attached to the test specimens. Two paper target flashover indicators are placed on the floor of the test room, consisting of a single piece of newsprint crumpled into an approximate 6 in. (152 mm) diameter ball.

Canopy Hood and Exhaust Duct. A hood is located immediately adjacent to the door of the fire room. The bottom of the hood is level with the top surface of the room. The face dimensions of the hood are 8 ft x 8 ft (2.44 m x 2.44 m), and the depth is 3.5 ft (1.1 m). The hood feeds into a plenum having a 3 ft x 3 ft (0.92 m x 0.92 m) cross section, and a height of 3-6 ft (0.9-1.8 m). The exhaust duct connected to the plenum is 22 3/4 in. (0.578 m) in diameter, horizontal, and has a circular aperture at its entrance. The hood has a sufficient draft to collect all of the combustion products leaving the room, with an air flow starting at 2,000 standard ft^3/min (0.94 m^3/s) at the beginning of the test and increasing if needed. Inside the exhaust duct there is a collection system with: a blower, steel hood, duct, bidirectional probe, two thermocouple(s), oxygen measurement system, smoke obscuration measurement system (white light photocell lamp/detector or laser) and combustion gas (carbon monoxide and carbon dioxide) sampling and analysis system. Two bare Type K Chromel Alumel thermocouples are placed 11 ft (3.4 m) downstream of the entrance to the horizontal duct, straddling the center of the duct and separated 2 in. (50 mm) from each other.

Oxygen concentration, for heat release determinations, is derived from a stainless steel gas sampling tube located 11.5 ft (3.5 m) downstream from the entrance to the duct at the geometric center of the duct to obtain a continuously flowing sample, fed to a paramagnetic oxygen analyzer capable of measuring oxygen concentration in a range of 21 percent to 15 percent, with an accuracy of 50 ppm in this concentration range. An optical system for measurement of light obscuration is installed across the centerline of the exhaust duct. The optical density of the smoke is determined by measuring the light transmitted with a photometer system consisting of a white light source and a photocell/detector across the centerline of the exhaust duct. The photometer system consists of a lamp, lenses, an aperture, an optical filter, to match the sensitivity of the human eye, and a photocell.

Photography. Photographic and video equipment is used to record the spread of fire in the room and the fire projection from the door of the room. The camera is located outside the doorway so as to avoid interference with airflow. The interior wall surfaces of the test room adjacent to the corner in which the burner is located are marked with a 12 in. (0.3 m) grid. A clock appears in all photographic and video records, showing the time to at least the nearest 1 s from the start of the test. Color photographs are taken at appropriate times for the duration of the test, and a continuous video recording is made.

Test procedure. An initial volumetric flow rate of 2,000 ft^3/min (0.94 m^3/s) through the duct is established. All sampling and recording devices are started, so as to determine steady-state baseline readings for 3 min. The propane gas burner and the clock are started simultaneously, to give a gas flow rate adequate to provide a rate of heat release of 40 kW ± 1 kW by the burner, which is continued for 5 min. Within 10 s following the 5-min exposure, the gas flow is increased to provide a rate of heat release by the burner of 150 kW ± 5 kW exposure for 10 min. The ignition burner is shut off 15 min after start of the test and the test terminated at that time, unless safety considerations dictate an earlier termination.

Calculations. Equations 1-9 describe all the calculations needed. The mass flow rate through the duct is obtained from the velocity, measured with a bidirectional probe, using equation (1), the oxygen depletion factor is calculated with equation (2), the heat release rate with equation (3), and the total heat release with equation (4), while equations 5-9 describe the extinction coefficient, the optical density per unit path length, the volumetric flow rate at the smoke meter, the rate of smoke release and the total smoke released, respectively. The non dimensional absolute optical density (labeled OD m) is calculated by multiplying the optical density by the light path length.

The symbols used here, including equations 1-9, (with the corresponding units) are:

* C: Calibration factor for orifice plate or bidirectional probe (in $kg^{1/2}$ $m^{1/2}$ $K^{1/2}$)
* E: net heat released per unit mass of oxygen consumed (13.1 MJ/kg)
* E_{CO}: net heat released per unit mass of oxygen consumed, for carbon monoxide (17.6 MJ/kg)
* I_o: Light intensity for a beam of parallel light rays, measured in a smoke free environment, with a detector having the same spectral sensitivity as the human eye and reaching the photodetector
* I: Light intensity for a parallel light beam having traversed a certain length of smoky environment and reaching photodetector
* k: Extinction coefficient (in 1/m)
* L_p: light path length of beam through smoky environment, which is equal to the duct diameter (0.578 m)
* $\dot{m}_e$: Mass flow rate in exhaust duct (in kg/s)
* M_{O2}: Molecular weight of oxygen (32 kg/kmol)
* OD : Optical density per unit light path length (in 1/m)
* OD m: Absolute optical density (product of OD and unit path length) (non dimensional)
* Δp: pressure drop across the orifice plate or bidirectional probe (in Pa)

- $\dot{q}$: rate of heat release (kW)
- RSR: Rate of smoke release (in m^2/s)
- Δt: scan period (in s)
- T_e: gas temperature at the orifice plate or bidirectional probe (K)
- THR: Total heat released (in MJ)
- TSR: Total smoke released (in m^2)
- V_s: Volumetric flow rate at location of smoke meter (value adjusted for smoke measurement calculations) (in m^3/s)
- X_{CO} : Measured mole fraction of CO in exhaust flow (non dimensional)
- X_{CO2}: Measured mole fraction of CO_2 in exhaust flow (non dimensional)
- X^{o}_{CO2}: Measured mole fraction of CO_2 in incoming air (non dimensional)
- X_{O2}: Measured mole fraction of O_2 in exhaust flow (non dimensional)
- X^{o}_{O2}: Measured mole fraction of O_2 in incoming air (non dimensional)
- $\propto$: Combustion expansion factor (non dimensional; 1.105)
- Φ: Oxygen depletion factor (non dimensional)
- ρ_0: density of air at 273.15 K: (1.293 kg/m^3)

2. ASTM E84:

This method uses a methane gas burner to produce a flame exposing the underside of construction materials. It is a test method, developed in the 1940's for traditional building materials [20], which exposes samples 7.3 m (24 ft) long and 0.5 m (20 in) wide to a ca. 79 kW (300,000 BTU/hr) methane flame and generates relative indices for flame spread (flame spread index, FSI) and smoke obscuration (smoke developed index, SDI), based on the fire properties of inorganic reinforced cement board and red oak flooring, assigned arbitrary values of 0 and 100, respectively. It is very common to find requirements (in model building codes [21-24] or the Life Safety Code [25]) requiring Class A performance, which corresponds to a flame spread index of 0-25 and a smoke developed index of 0-450.

RESULTS

Only one of the materials reached flashover in the room-corner test, namely the varnished pine planking, which exceeded all the flashover criteria: it released > 1 MW (1,460 kW) of heat, flames came out of the doorway, the peak floor heat flux was > 20 kW/m^2 (> 34 kW/m^2), all 5 upper layer room thermocouples exceeded 1,200°F and the paper targets burst into flame. However, significant heat and smoke release was obtained from several of the materials. Table 2 and Figures 1-10 present the major heat release results of the NFPA 265 tests conducted, while Table 3 and Figures 11-20 present the major smoke release results obtained during the same tests. Table 4 presents the FSI and SDI values for each one of the materials. It is interesting to note that the varnished pine planking did not qualify as a Class A material, based on its flame spread.

DISCUSSION

Clearly, heat release is the most important property measured in the room-corner test, and only a low rate of heat release guarantees that flashover will not occur, since increased heat (or energy) release can induce additional burning, and thus more heat release.

The premise that there is a rough correspondence between low heat release rate and low optical density (as a measure of smoke), is a reasonable first approximation, as can be seen from Figure 21. The Figure indicates that, very broadly speaking, for many of the materials, more smoke is associated with more heat release rate. However, it is also clear from the same Figure that there are materials that are both much better and much worse on smoke than the general trend indicates. For example, the varnished pine material (on the bottom right of the diagram) causes flashover, but releases much less smoke than would have been expected from materials releasing that much heat. On the other extreme, the thermoplastic sheet (on the top left of the diagram) releases negligible amounts of heat but generates high levels of smoke.

Table 2. Major Heat Release Results for Materials Tested in NFPA 265

Material	Pk RHR	Av RHR	THR	Time to Peak RHR
	kW	kW	MJ	s
Ceiling Tile	22	0	0	822
FR Composite Panel	128	23	21	534
Mineral Wool	35	0	0	900
Phenolic Foam	153	63	57	840
Pine: **Flashover**	1460	122	52	354
Polyimide Foam	40	4	4	630
Textile Wallcovering, on Calcium Silicate Board	109	8	7	342
Thermoplastic Sheet	40	0.2	0.2	360
Expanded Vinyl Wallcovering, on Gypsum Board	359	14	13	336
Commercial Vinyl Wallcovering, on Gypsum Board	126	1	2	348

Table 3. Major Smoke Obscuration Results for Materials Tested in NFPA 265

Material	Av OD	Av OD m	TSR	Av RSR	Pk RSR
	1/m	-	m^2	m^2/s	m^2/s
Ceiling Tile	0.063	0.037	165	0.18	0.3
FR Composite Panel	0.088	0.051	270	0.30	0.6
Mineral Wool	0.066	0.038	167	0.19	0.3
Phenolic Foam	0.060	0.035	180	0.20	0.4
Pine: **Flashover**	0.120	0.069	225	0.61	8.5
Polyimide Foam	0.071	0.035	193	0.21	0.4
Textile Wallcovering, on Calcium Silicate Board	0.037	0.022	139	0.15	0.3
Thermoplastic Sheet	0.295	0.171	1359	1.50	7.0
Expanded Vinyl Wallcovering, on Gypsum Board	0.160	0.092	664	0.74	8.9
Commercial Vinyl Wallcovering, on Gypsum Board	0.169	0.098	584	0.65	4.5

Table 4. ASTM E84 Steiner Tunnel Results for Materials Tested

Material	Flame Spread Index (FSI)	Smoke Developed Index (SDI)
Ceiling Tile	15	0
FR Composite Panel	15	15
Mineral Wool	0	0
Phenolic Foam	15	5
Pine	70	105
Polyimide Foam	0	0
Textile Wallcovering, on Calcium Silicate Board	10	10
Thermoplastic Sheet	10	1000
Expanded Vinyl Wallcovering, on Gypsum Board	25	120
Commercial Vinyl Wallcovering, on Gypsum Board	25	80

It is important to compare the results obtained from the room-corner test, NFPA 265, with those obtained from the Steiner tunnel test, ASTM E84, on smoke obscuration. There are two reasons for that comparison: (1) building materials are regulated so that if SDI exceeds 450, the material is not permitted in a number of applications, and (2) data exist that assesses smoke hazard based on the optical density measured (see Table 5).

Table 5 - Tenability Values Proposed for Smoke

	Extinction Coefficient	OD
T. Jin (for people familiar with the environment, 4 m visibility) [26]:	0.50 m^{-1}	0.22 m^{-1}
T. Jin (for people unfamiliar with the environment, 13 m visibility) [26]:	0.15 m^{-1}	0.06 m^{-1}
D. Rasbash (for 10 m visibility) [27]:	0.18 m^{-1}	0.08 m^{-1}
D. Purser (from irritancy) [28]:	1.2 m^{-1}	0.52 m^{-1}
V. Babrauskas (for 2 m visibility) [29]:	1.2 m^{-1}	0.52 m^{-1}

Jin (in Japan) has worked with people exposed to smoke, in the absence of fire [26]. He found that if people are familiar with the environment in which they are exposed, they have little trouble finding the exits and leaving the smoky area when they have 4 m (just over 13 ft) visibility. On the other hand, people unfamiliar with their environment require 13 m (just over 43 ft) visibility to have the same ease in finding the exits and escaping. A smoke hazard limit of 10 m (just over 33 ft) visibility has also been suggested [27] but that appears probably too severe. Purser, based on the irritant effect of smoke, has suggested that the limit should be equivalent to a minimum visibility of 2 m (approximately 6 ft 7 in), in terms of maximum optical density, and Babrauskas has suggested the same minimum visibility [29], also in terms of peak optical density. In summary, it appears reasonable to set visibility limit ranges, that permit escape from a fire situation, of between 3 m and 5 m (approximately 10 ft to 17 ft), corresponding to average optical density levels of between 0.31 and 0.18 1/m. This paper does not recommend threshold limit requirements.

Figure 22 shows the average optical density measured in the NFPA 265 room-corner test as a function of the ASTM E84 Steiner tunnel test SDI. The flow rates used in NFPA 265 at high smoke emissions were at the maximum level that the system allows. On the same Figure 22 it is possible to incorporate the safety range limits for smoke discussed here, namely an SDI of 450 and an average optical density of between 0.18 and 0.31 1/m. If that is done, a "safe zone", in terms of smoke obscuration, can be seen in the diagram, when neither the optical density nor the SDI are excessively high, i.e. in the bottom left of the diagram. This zone is consistent with the ISO 9705 room-corner test [11] requirement of an average rate of smoke release of no more than 1.4 m^2/s of the IMO High Speed Craft Code [30].

With this safety zone, only one of the building materials tested would potentially fall outside: the thermoplastic sheet (which is a reasonable finding, in view of its very high SDI, and its generally high smoke numbers). If the extremes of the range are used, the same material would exceed the limit of 0.18 1/m (for 5 m visibility) but would not exceed the other limit of 0.31 1/m (for 3 m visibility). It is particularly interesting that a textile wallcovering should be near the threshold of smoke safety, since it has been shown that the Steiner tunnel is inappropriate for testing such materials [31], and they are now required to be tested by the NFPA 265 room-corner test, in all the model building codes [21-24] and in the Life Safety Code [25]. Moreover, they now no longer have to meet smoke obscuration requirements. It is critical to note that a material can be unable to "pass" the ASTM E84 Class A material, because of smoke development, and yet "pass" the more severe NFPA 265 room-corner test requirements, which do not include smoke obscuration criteria, like one of the materials found in this work.

CONCLUSIONS

This work (which was based on choosing materials with good fire performance) has shown that a variety of building materials can be tested in the room-corner test, yielding excellent results in terms of both heat release and smoke release. Moreover, the majority of the materials tested are of that type. In fact, at least in a very rough sense, materials giving low heat release usually give low smoke release. However, this work has also shown that some materials can release very low heat, but such high smoke that escape would be severely hindered in a fire. As a consequence, it is important to add some type of threshold on smoke release to the heat release requirements now in existence for room-corner tests.

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Equations

$$\dot{m}_e = C * \sqrt{[\frac{\Delta p}{T_e}]} \tag{1}$$

$$\varphi = \frac{X^{\circ}{}_{O_2} * [1 - X_{CO_2} - X_{CO}] - X_{O_2} * [1 - X^{\circ}{}_{CO_2}]}{X^{\circ}{}_{O_2} * [1 - X_{O_2} - X_{CO_2} - X_{CO}]} \tag{2}$$

$$E * \varphi - [E_{CO} - E] * \frac{1 - \varphi}{2} * \frac{X_{CO}}{X_{0_2}}] * \frac{M_{0_2}}{M_e} * \frac{\dot{m}_e}{1 + \varphi * (\alpha - 1)} * \tag{3}$$

$$THR = \int \dot{q}\ dt \tag{4}$$

$$k = \frac{1}{L_p} \ln(\frac{I_0}{I}) \tag{5}$$

$$OD = \frac{1}{L_p} \log\ [\frac{I_0}{I}] \tag{6}$$

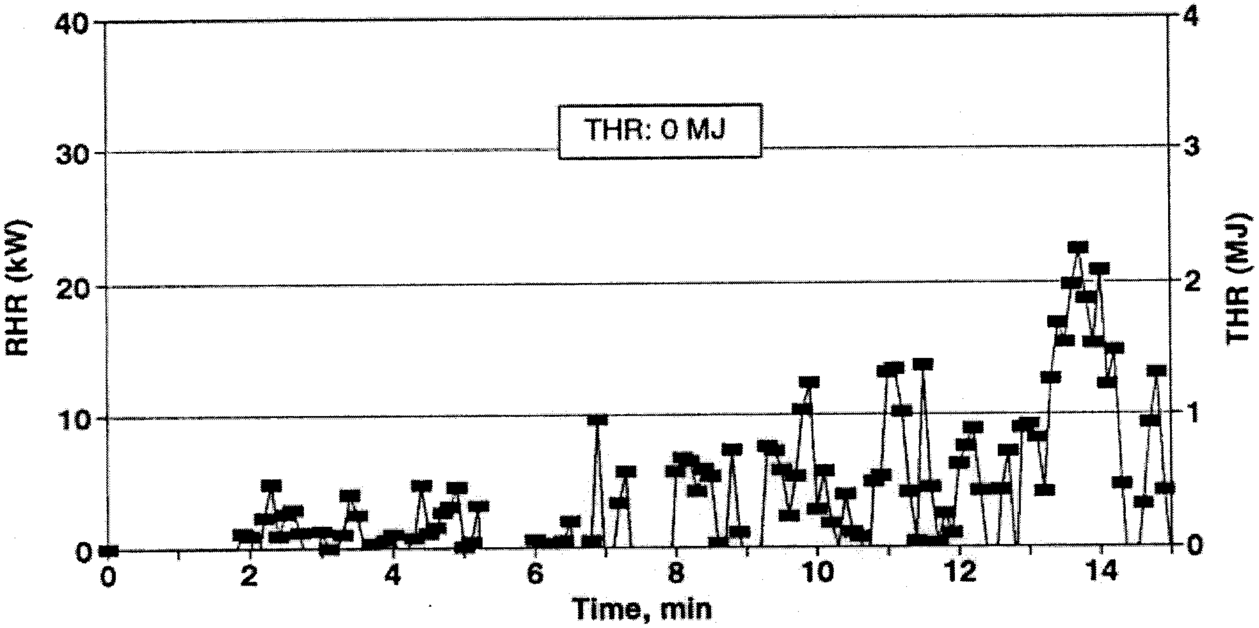
$$\dot{V}_s = \dot{m}_e * (\frac{T_e}{\rho_0 * 273.15}) = \frac{\dot{m}_e * T_e}{353} \tag{7}$$

$$RSR = [\dot{V}_s * k] \tag{8}$$

$$TSR = \int RSR\ dt \tag{9}$$

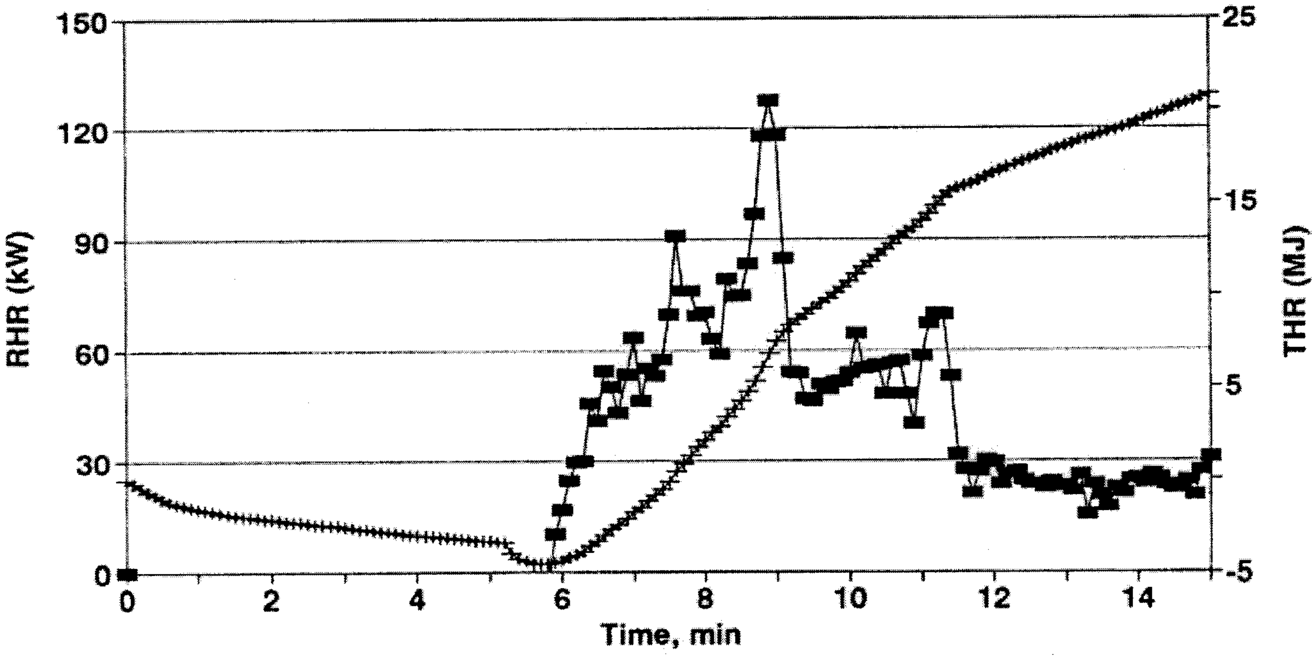
NFPA 265 Heat Release (Rate & Total)

Ceiling Tile (Fig. 1)



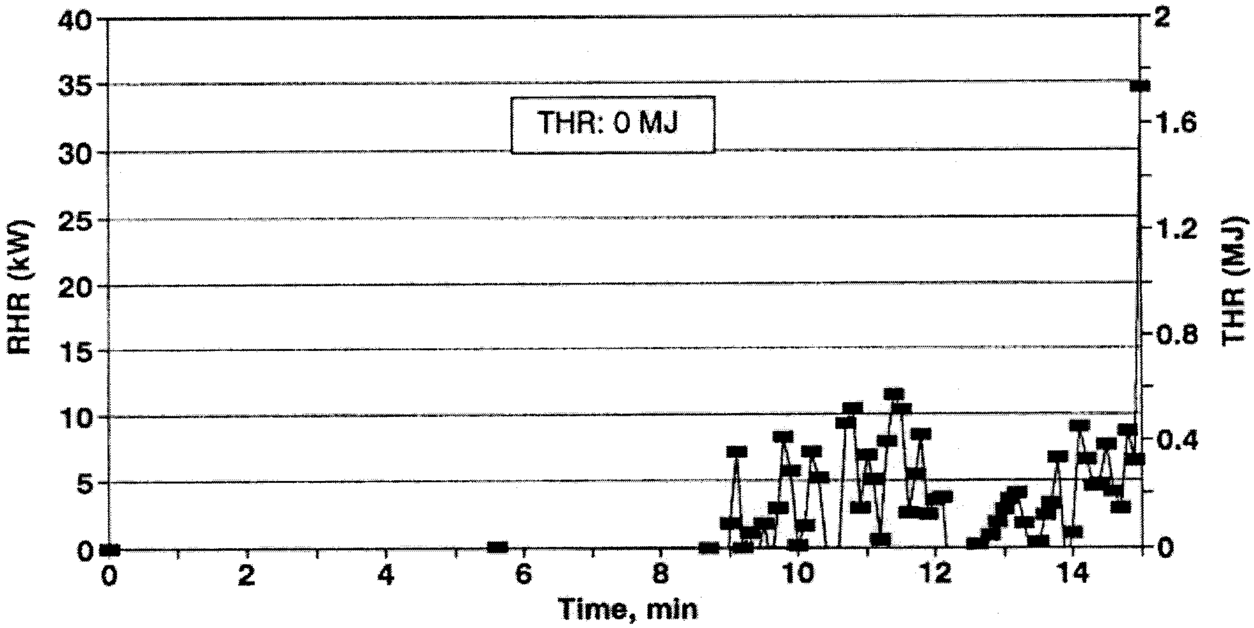
NFPA 265 Heat Release (Rate & Total)

FR Composite Panel (Fig. 2)



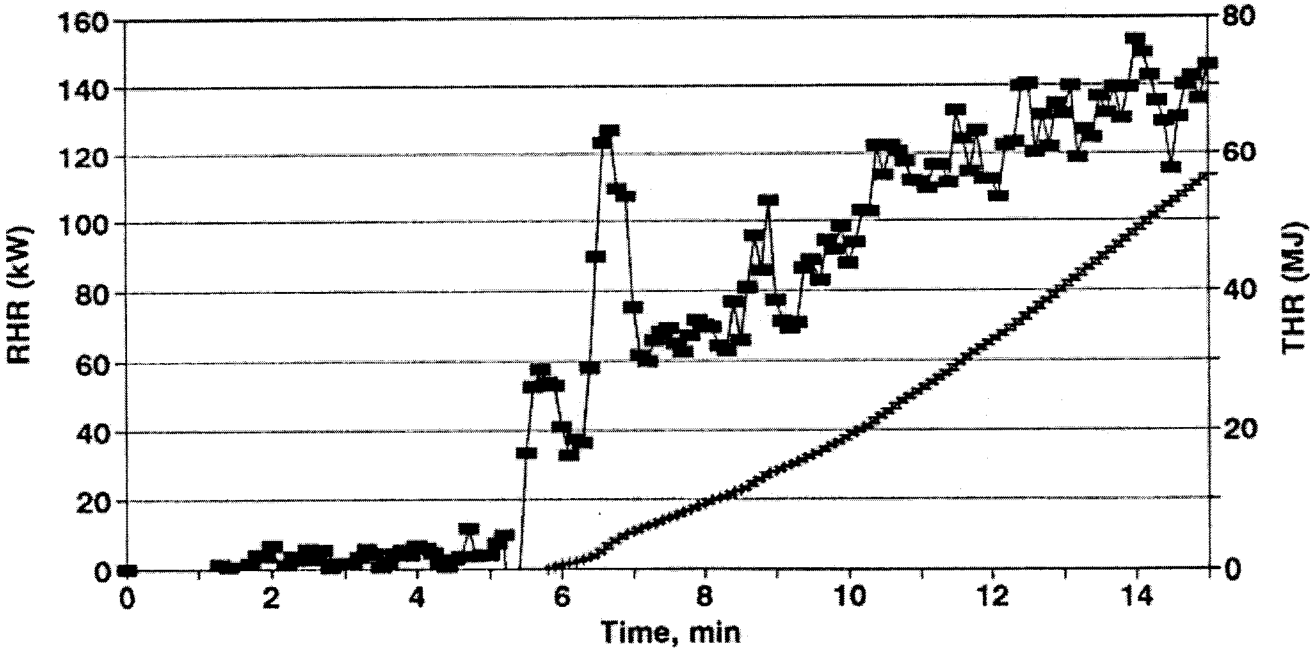
NFPA 265 Heat Release (Rate & Total)

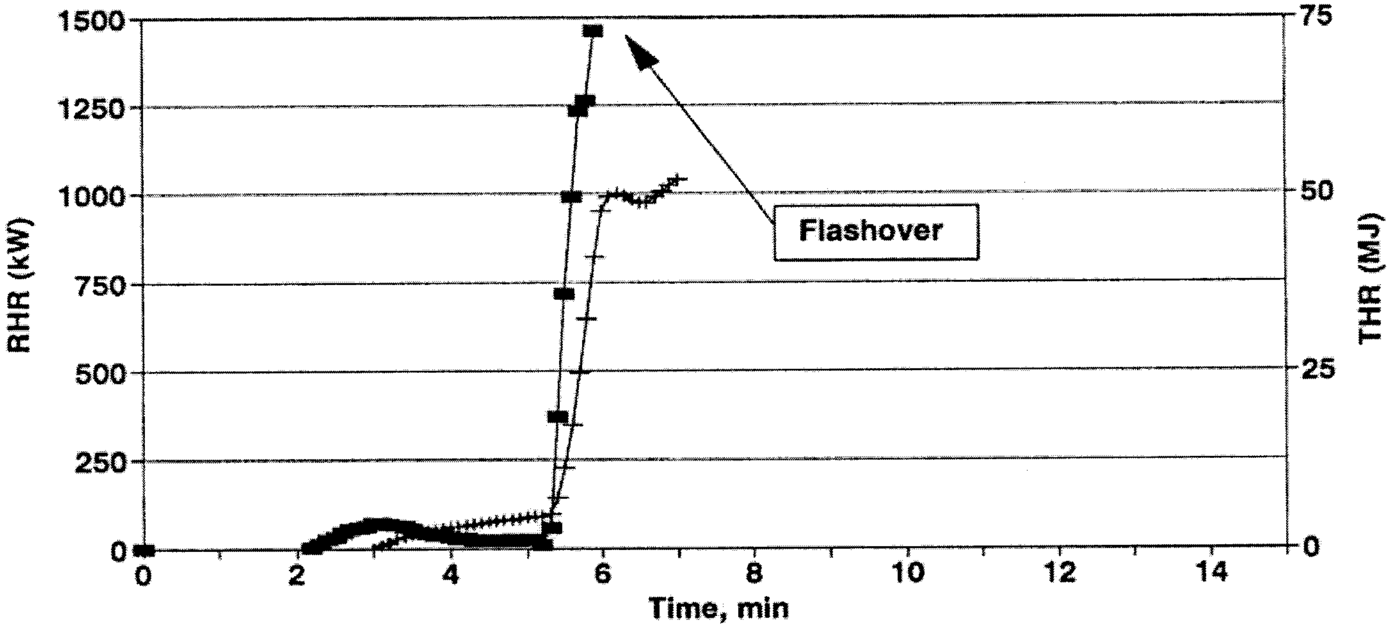
Mineral Wool (Fig. 3)



NFPA 265 Heat Release (Rate & Total)

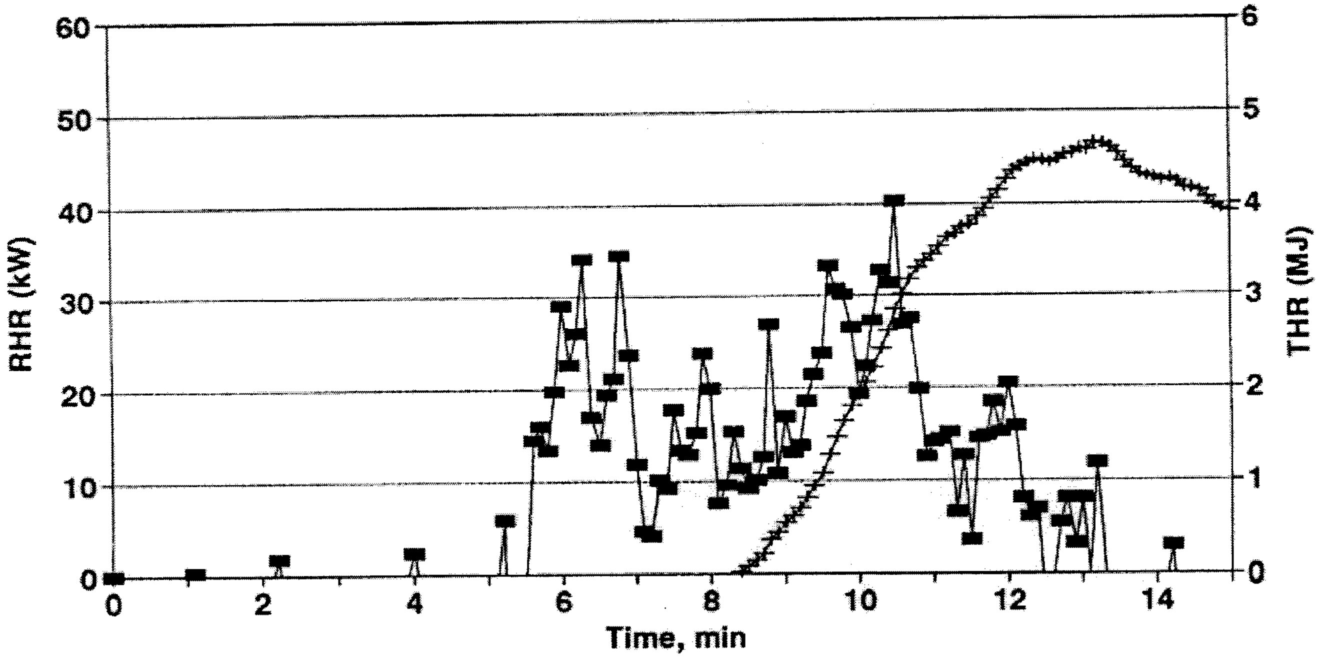
Phenolic Foam (Fig. 4)





Rate of Heat Release in NFPA 265

Pine, Varnished (Fig. 5)

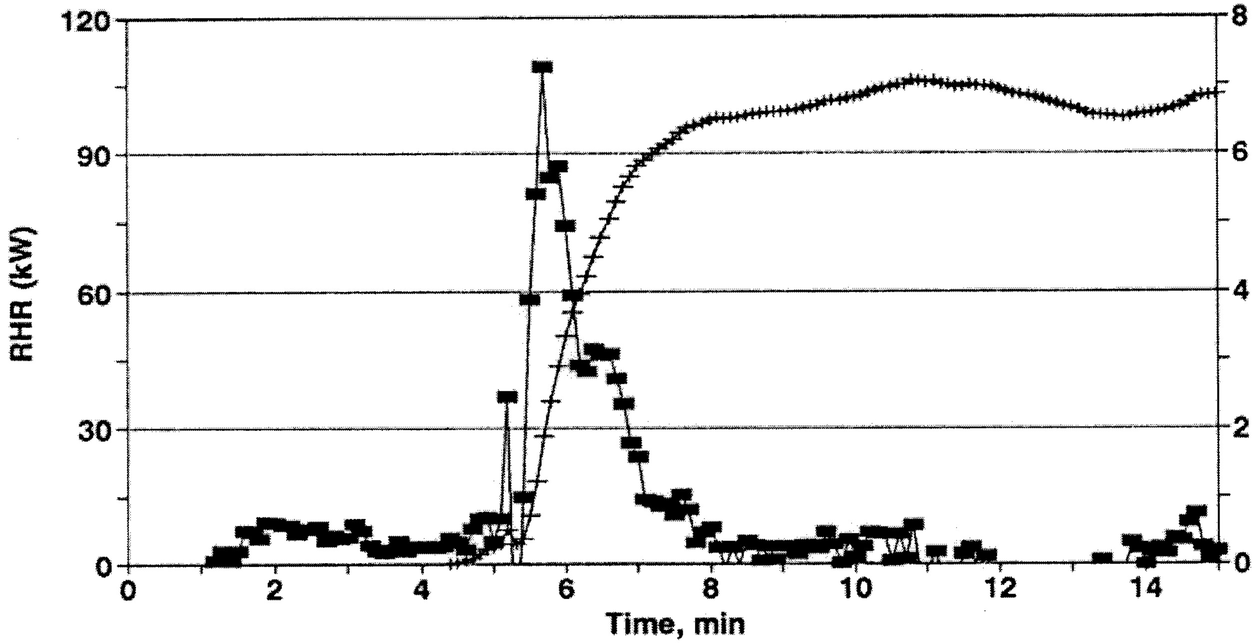


NFPA 265 Heat Release (Rate & Total)

Polyimide Foam (Fig. 6)

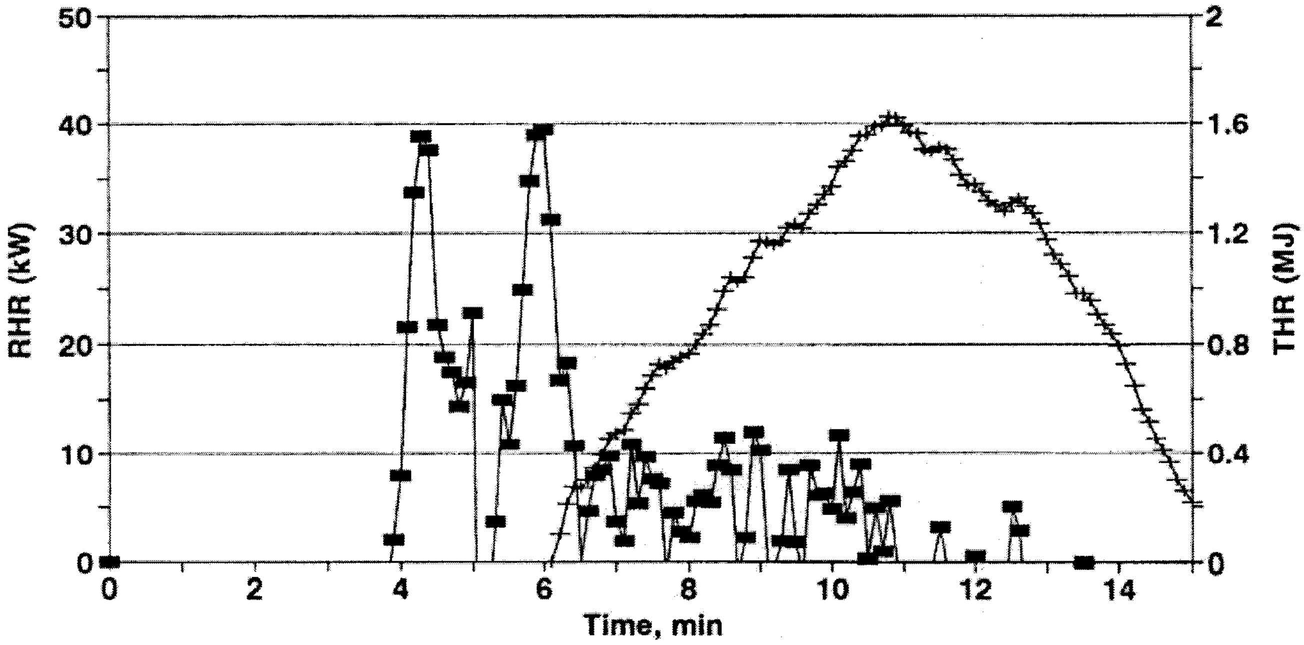
NFPA 265 Heat Release (Rate & Total)

Textile Wallcovering (Fig. 7)



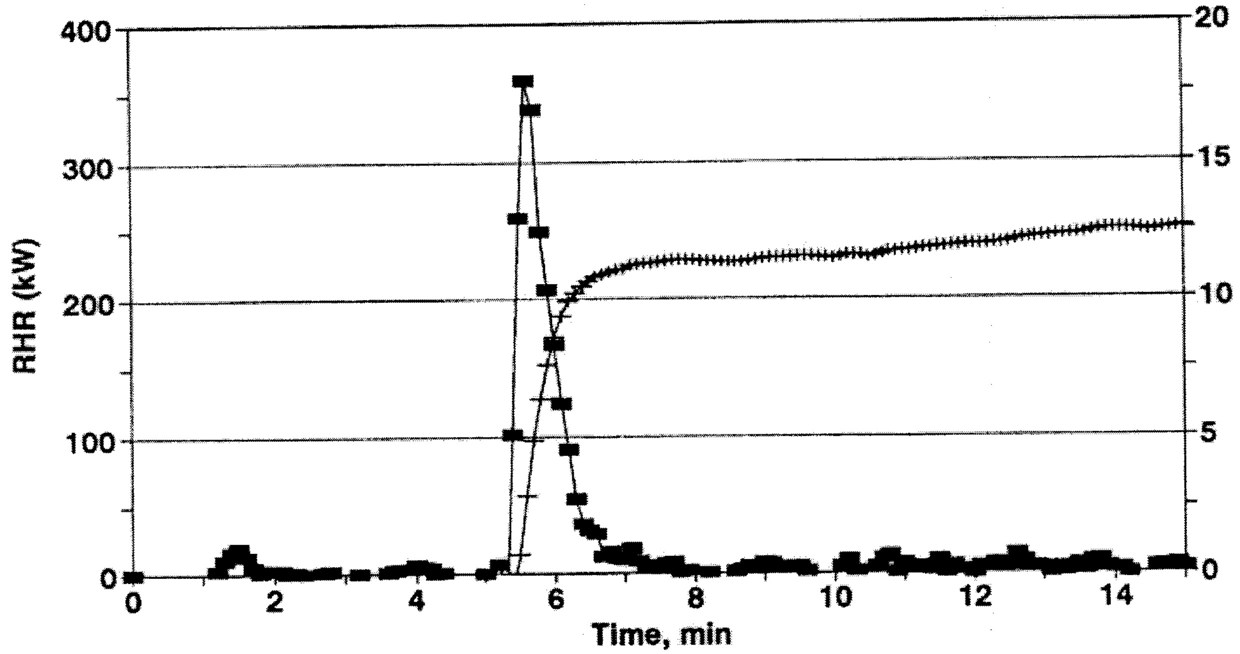
NFPA 265 Heat Release (Rate & Total)

Thermoplastic Sheet (Fig. 8)



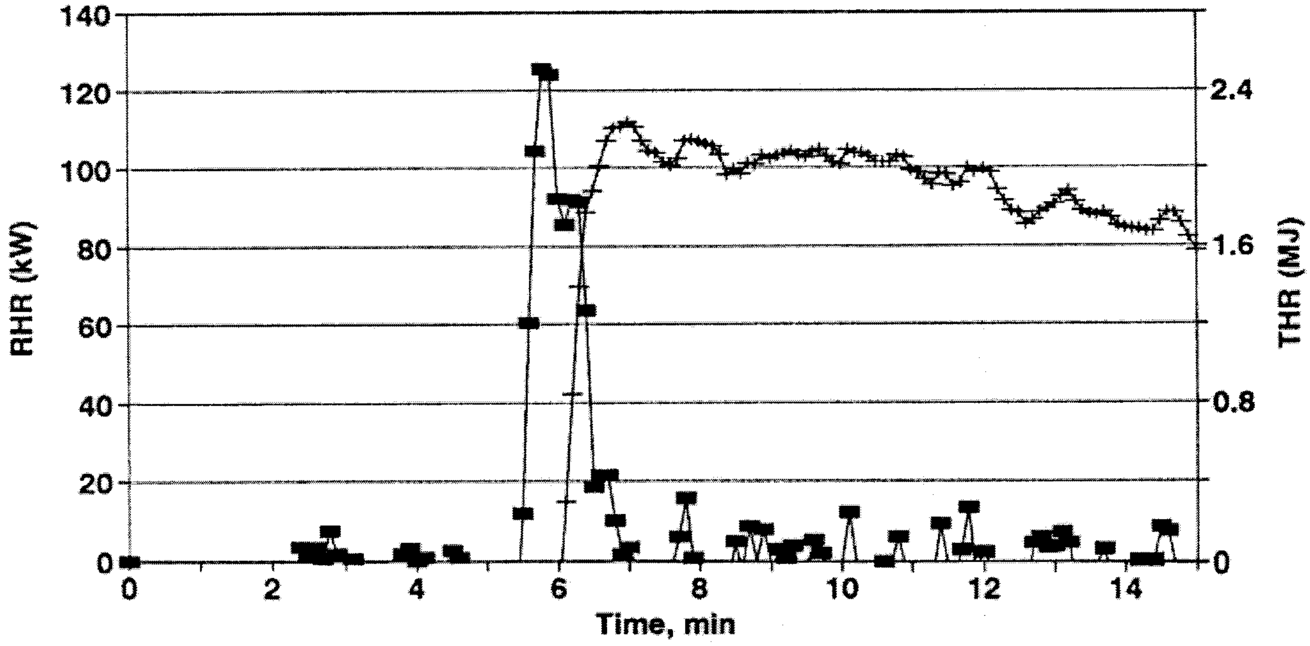
NFPA 265 Heat Release (Rate & Total)

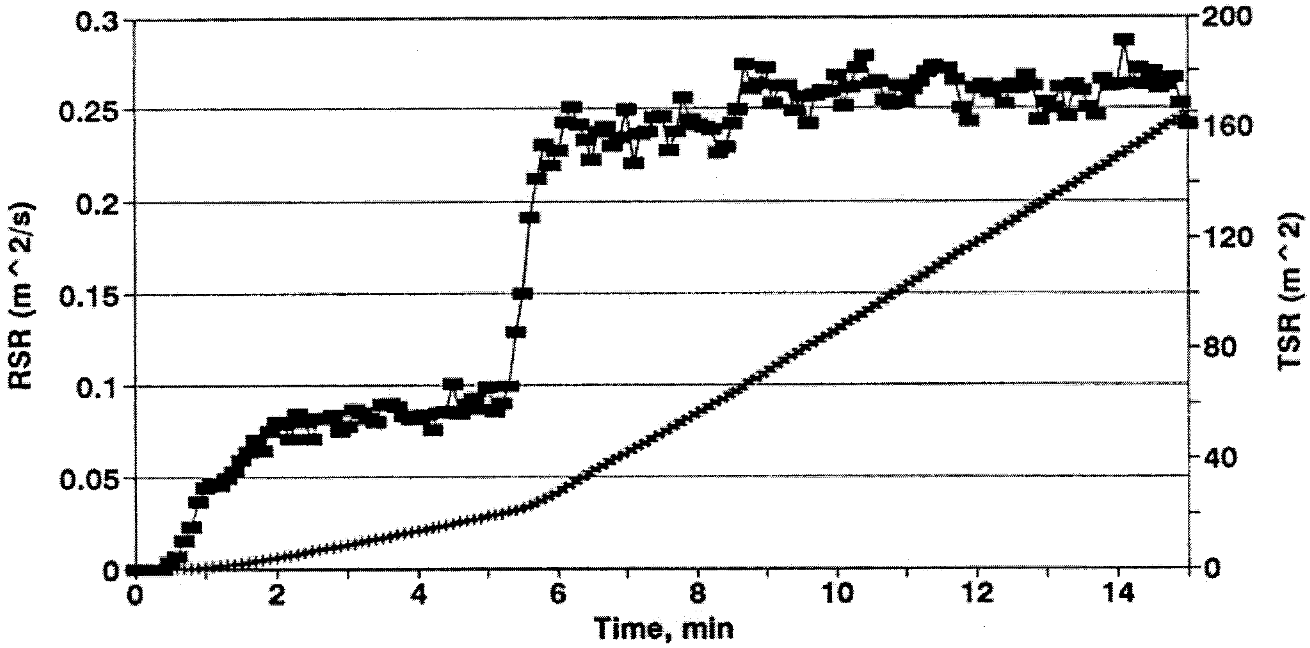
Expanded Vinyl Wallcovering (Fig. 9)



NFPA 265 Heat Release (Rate & Total)

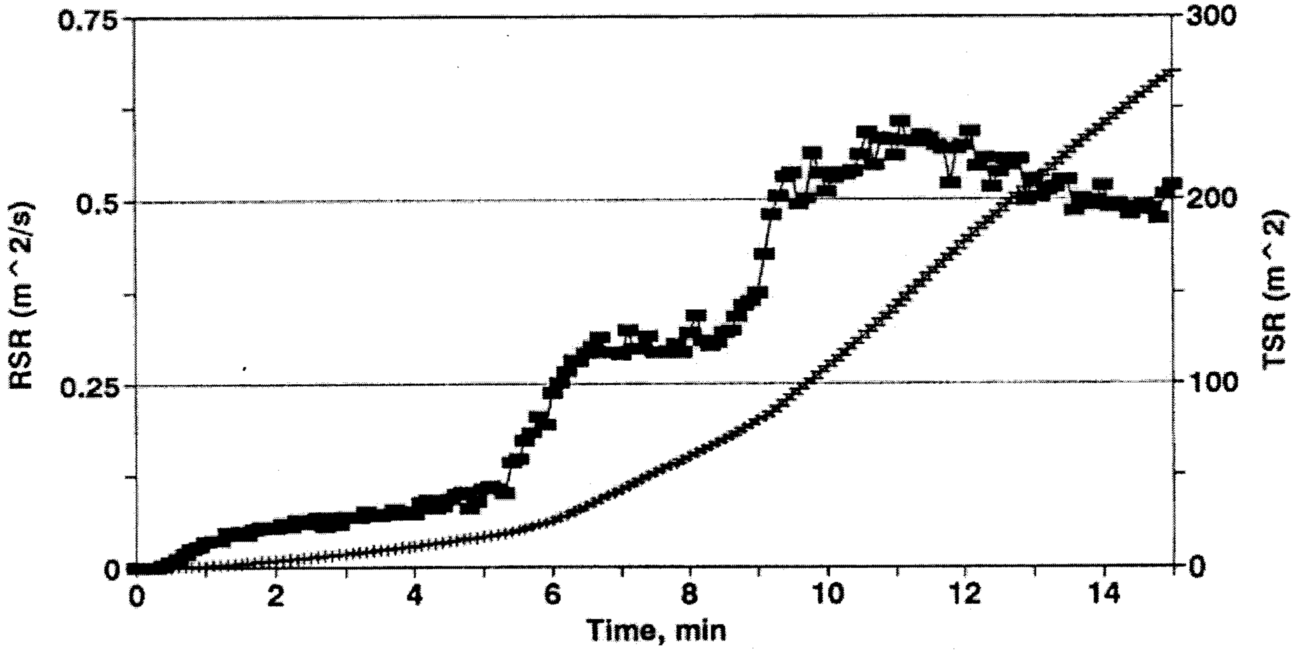
Commercial Vinyl Wallcovering (Fig. 10)





NFPA 265 Smoke Release (Rate & Total)

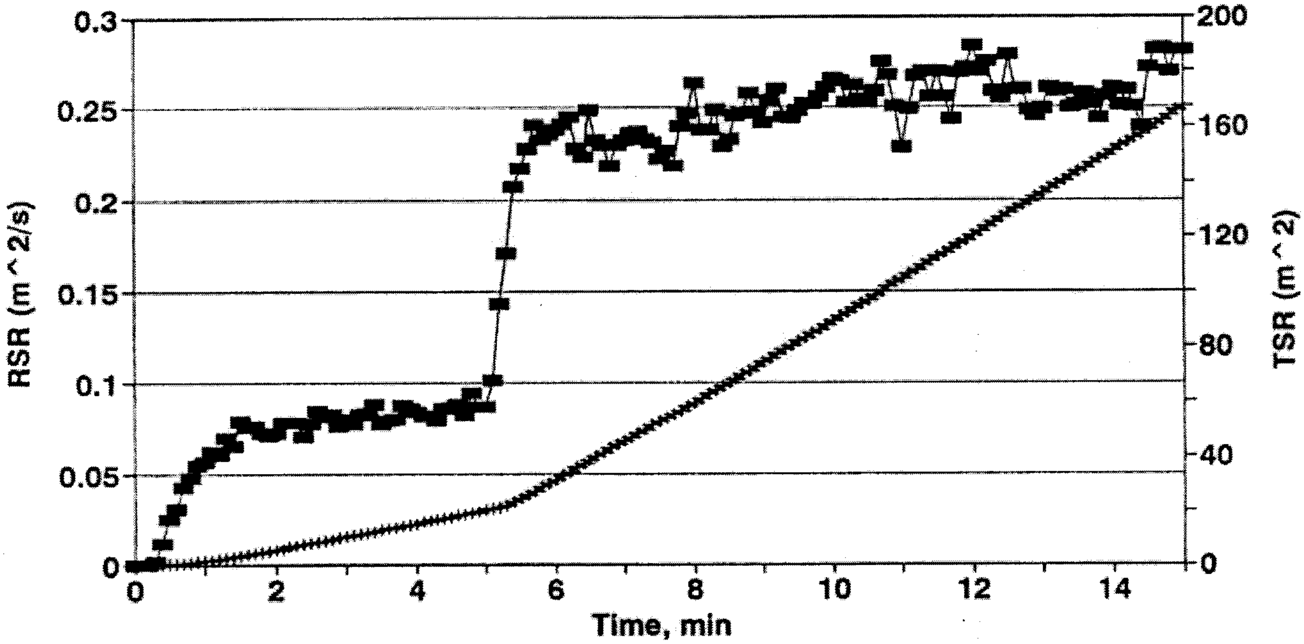
Ceiling Tile (Fig. 11)



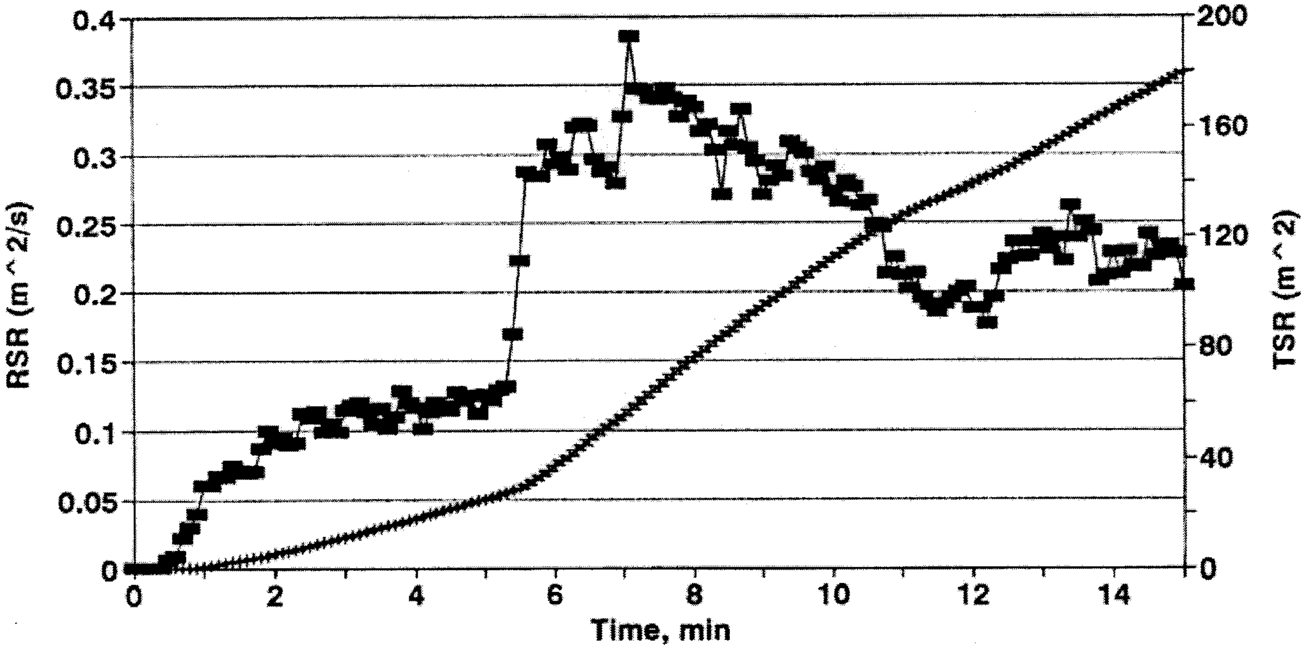
NFPA 265 Smoke Release (Rate & Total)

FR Composite Panel (Fig. 12)

NFPA 265 Smoke Release (Rate & Total)
Mineral Wool (Fig. 13)

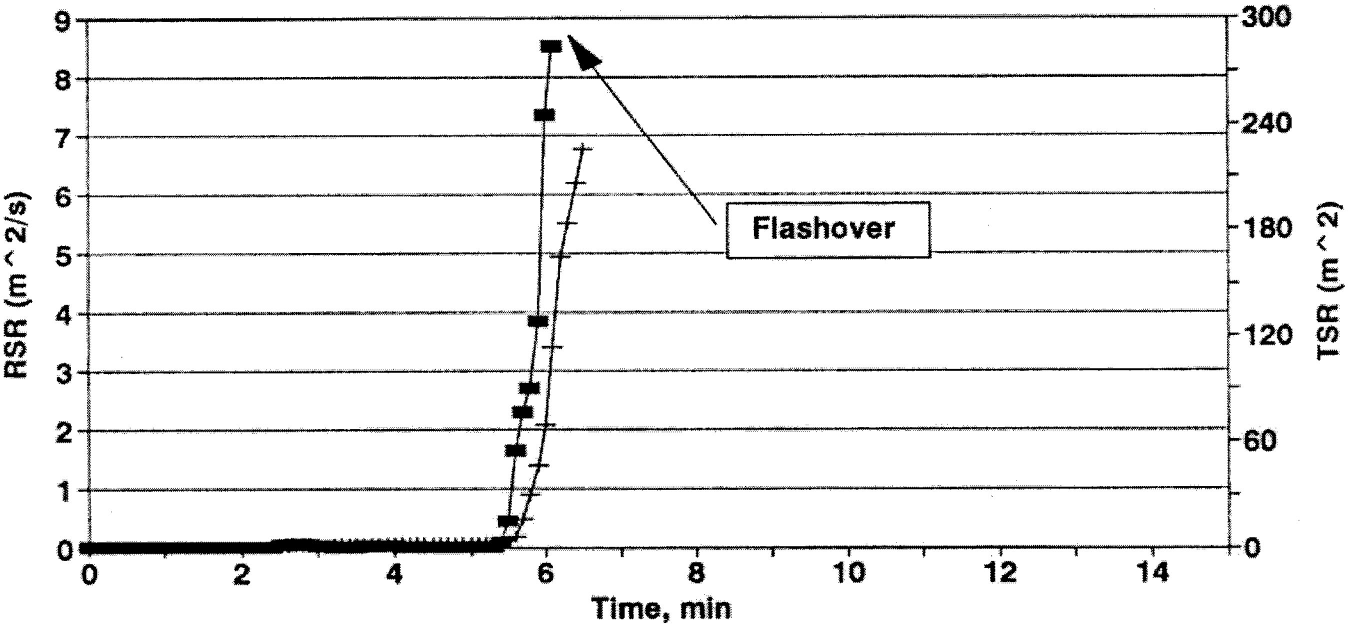


NFPA 265 Smoke Release (Rate & Total)
Phenolic Foam (Fig. 14)



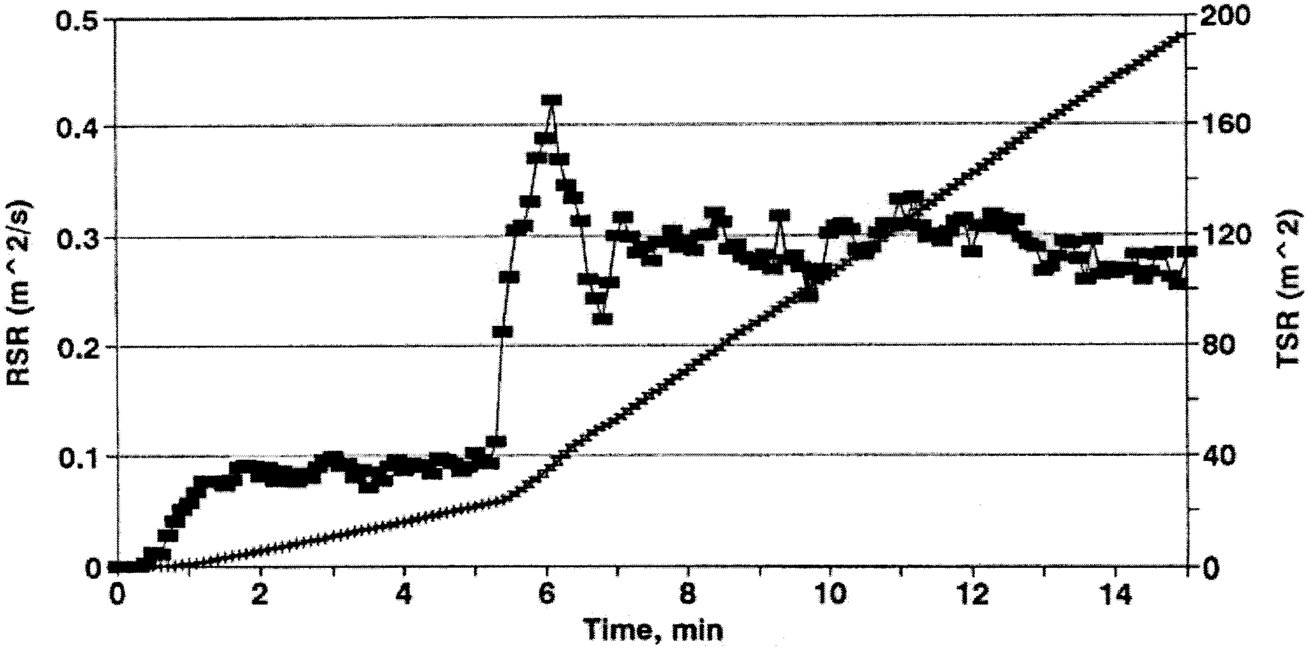
Rate of Smoke Release in NFPA 265

Pine, Varnished (Fig. 15)



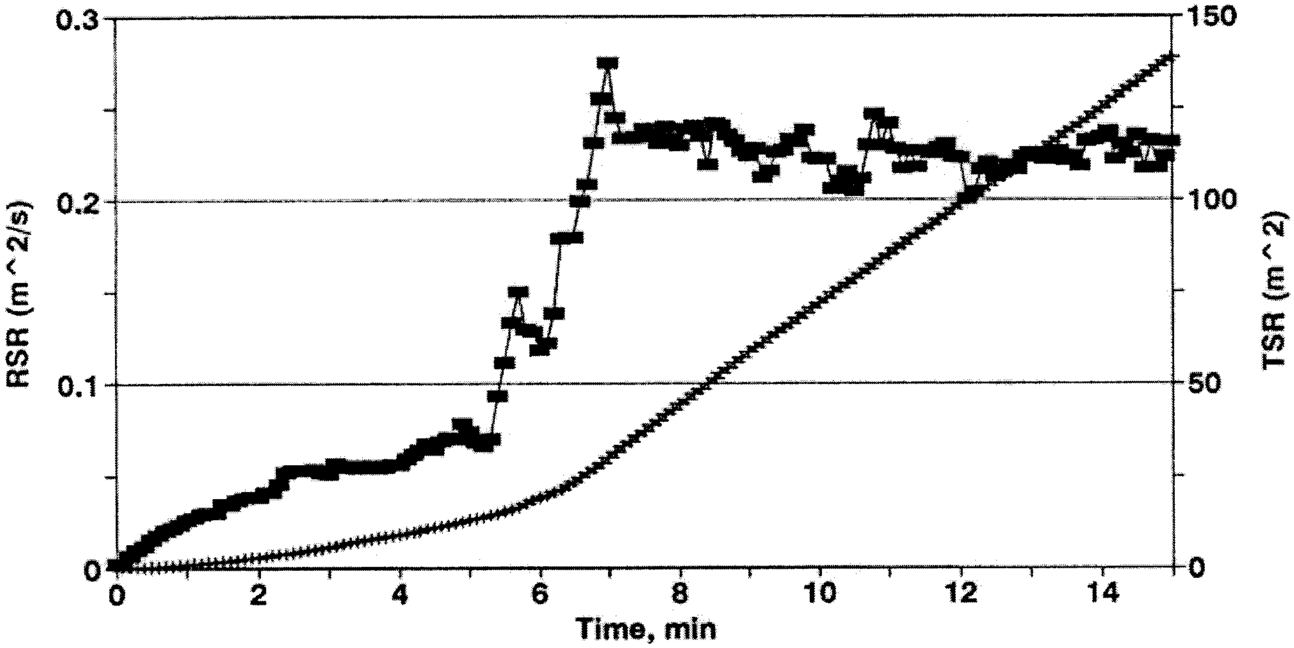
NFPA 265 Smoke Release (Rate & Total)

Polyimide Foam (Fig. 16)



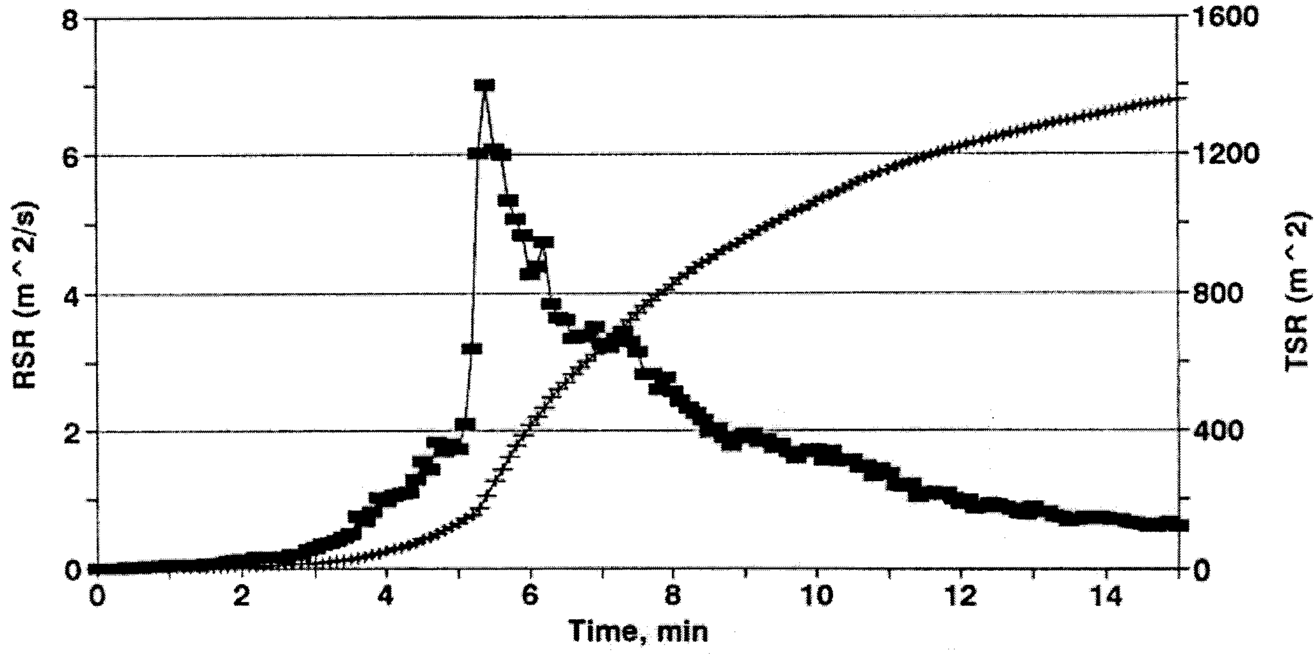
NFPA 265 Smoke Release (Rate & Total)

Textile Wallcovering (Fig. 17)



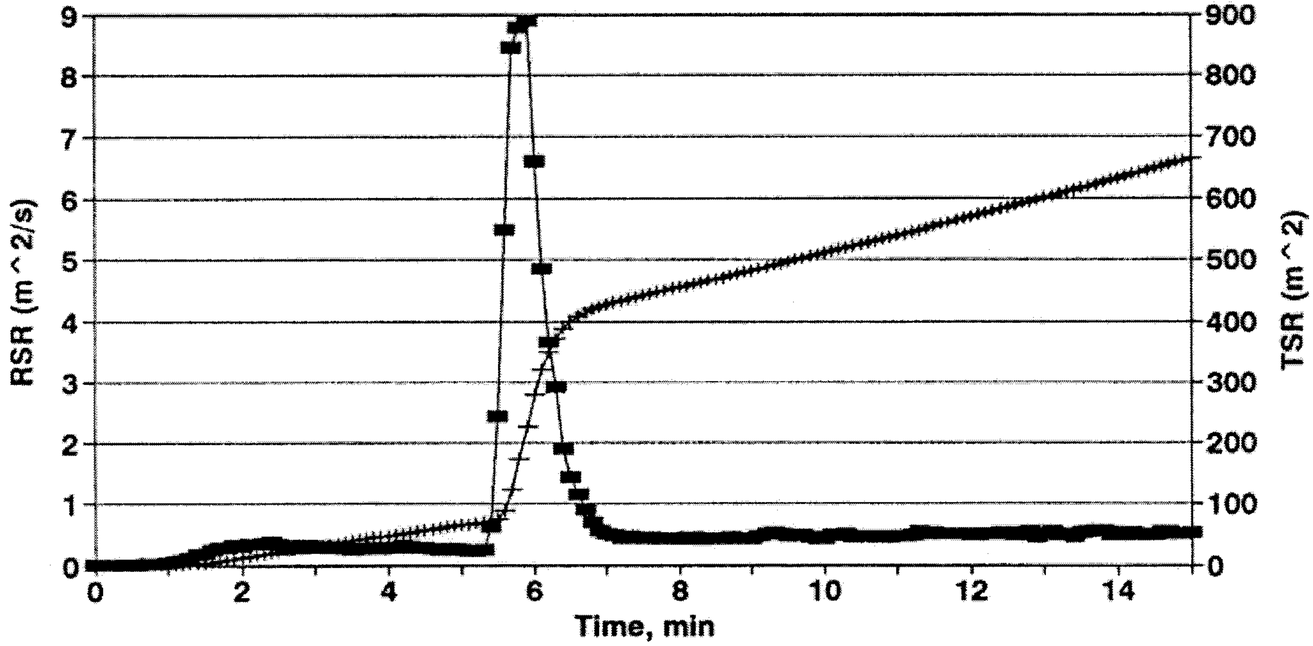
NFPA 265 Smoke Release (Rate & Total)

Thermoplastic Sheet (Fig. 18)



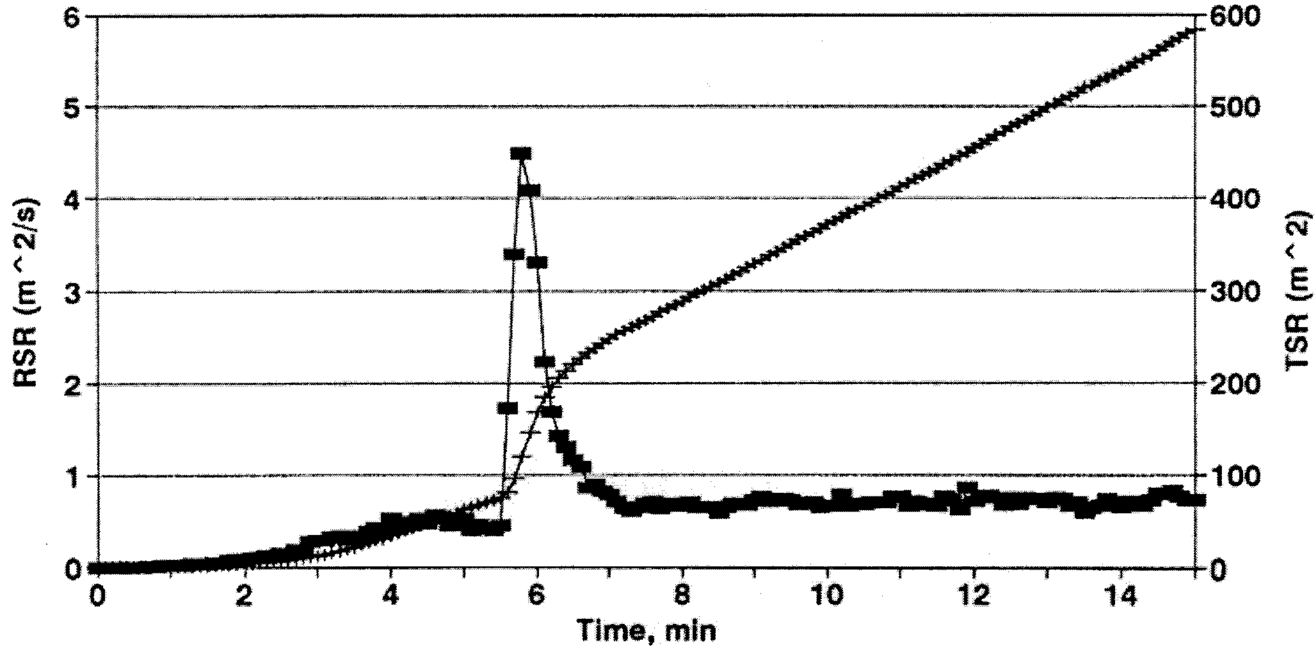
NFPA 265 Smoke Release (Rate & Total)

Expanded Vinyl Wallcovering (Fig. 19)



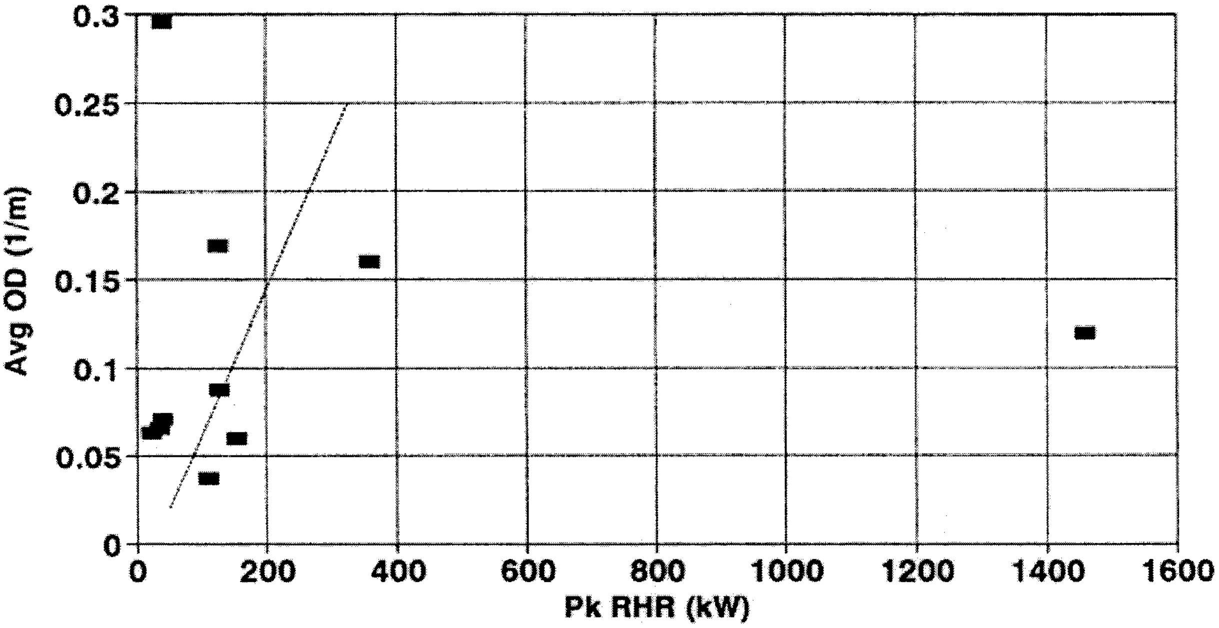
NFPA 265 Smoke Release (Rate & Total)

Commercial Vinyl Wallcovering (Fig. 20)



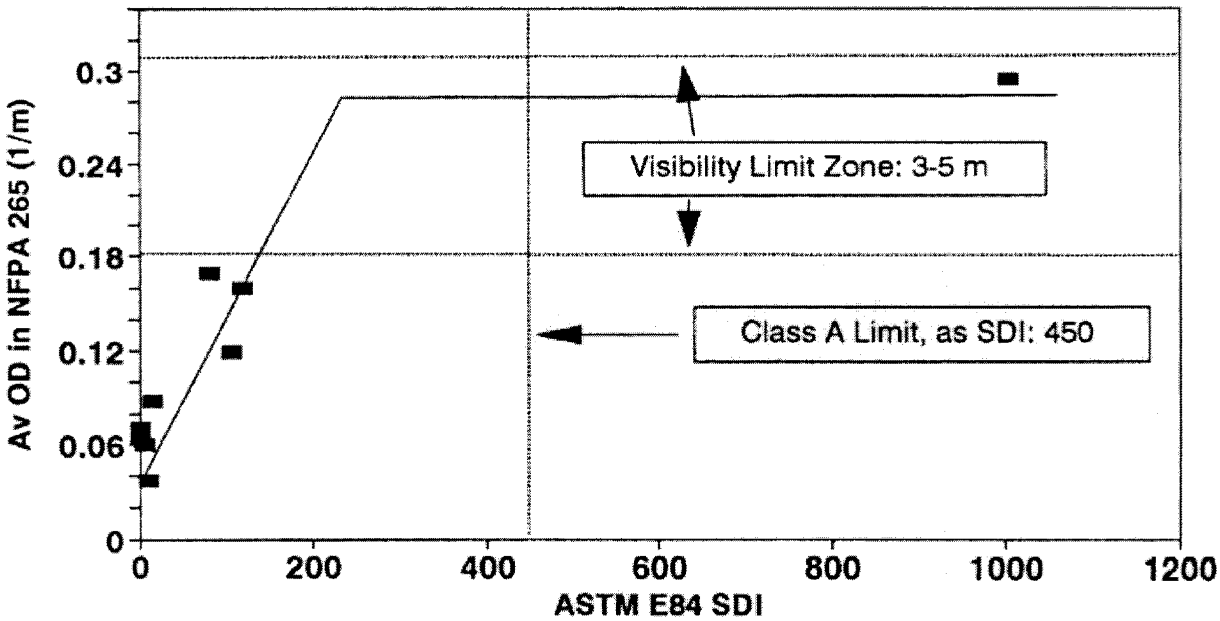
NFPA 265 Heat vs. Smoke Release

Av. OD (1/m) vs. Pk RHR (kW) (Fig. 21)



NFPA 265 and ASTM E84 Steiner Tunnel

Smoke Measurements (Fig. 22)



GBH Attachment 19

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BCC Flame Retardancy Conference 1999 - May 24-26 1999, Stamford, CT

PLENUM CABLE FIRE TEST METHOD:

HISTORY AND IMPLICATIONS

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"Plenum Cable Fire Test Method: History and Implications", M.M. Hirschler, Business Communications Company Tenth Ann. Conference on Recent Advances in Flame Retardancy of Polymeric Materials, May20-22, 1999, Stamford, CT, Ed. M. Lewin, pp. 325-349, Norwalk, CT, 1999.

ABSTRACT

The Steiner tunnel has been used since the late 1970's to list data and communications cables for use in plenums, without requiring enclosure in metal conduit. Originally, plenum cables had to have fluoropolymer materials for both insulation and jackets. The rapid increase in use of communications tools led to fast market growth. More recently vinyl materials and polyolefins have become capable of partially, or completely, replacing fluoropolymers as coating materials. With this active market activity, there has been extensive research and codes and standards activity around the test, in the USA and internationally, including proposals to replace it by alternative means of approving plenum cables. There have not yet been any demonstrated fire safety problems with plenum cable.

INTRODUCTION

All electrical installations and cables are regulated in the USA by the National Electrical Code, NFPA 70 (NEC), issued by the National Fire Protection Association (NFPA) every 3 years. The National Electrical Code subdivides cables required to exhibit a degree of fire performance into four categories: limited use "flame retardant" cable, general purpose cable "resistant to the spread of fire", riser cable "having fire-resistant characteristics capable of preventing the carrying of fire from floor to floor" and plenum cable "having adequate fire-resistant and low-smoke -producing characteristics". Within each category there are different applications and, thus, various physical and electrical property requirements. This paper addresses only plenum cables.

Plenum Cables - Background

The National Electrical Code restricts the wiring permitted for use in air handling spaces so as to control fire safety. The NEC defines plenum as "Plenum: A compartment or chamber to which one or more air ducts are connected and that forms part of the air distribution system."

Before the 1975 edition, cables installed in plenums had to be enclosed in metal raceways or metal conduits. Three types of metal sheathed cables were permitted: mineral-insulated metal-sheathed cables (Type MI), metal-clad cables (Type MC) and armored cables (Type AC, now no longer permitted), based on their presumed similarity to a conduit or raceway system. The 1975 edition incorporated, for the first time, exceptions for cables permitted to be used without enclosure in a metal raceway or conduit, if they were listed as having "adequate fire resistant and smoke producing characteristics." The first cables that had these exceptions were those in communications circuits and power-limited circuits and fire alarm cables. However, the NEC did not initially set up a test to list such cables, nor construction details. Therefore, an alliance of Bell Labs (AT&T, now Lucent) and Underwriters Laboratories (UL) developed a test method for that purpose [1]. A set of seven objectives were set for the test development by the consortium:

1. High heat flux, characteristic of actual fires: 60-70 kW/m^2 was deemed the correct range.
2. High flame coverage of the test samples, so as to apply to the cables a high heat insult.
3. The test sample to be mounted horizontally simulating actual plenum cable conditions.
4. Samples to contain multiple cables (and not single cables), all of sufficient length to both simulate actual plenum installation and provide a realistic amount of combustible fuel.
5. The test chamber to be insulated to provide conservation of heat energy.
6. Air flow over cables to be dynamic, providing sufficient oxygen for combustion and to enhance flame propagation.
7. The test must be of sufficient duration to ensure a peak value flame spread is reached.

The objectives virtually ensured the test method would be based on the Steiner tunnel.

The tunnel test, developed by Al Steiner in 1943 for use with flat construction products (typically wood products and gypsum board) involves testing a 24 ft x 20 in (7.3 m x 0.5 m) specimen laid horizontally under the test chamber (tunnel) ceiling. The sample is exposed to a gas flame of 300,000 BTU/h (87.9 kW) for 10 min, at an air flow rate of 240 ft/min. The fuel source ensures that the first 4.5 ft (1.37 m) are completely destroyed, whatever the material used. The test measures flame spread (beyond the first 4.5 ft, assessed visually) and smoke obscuration (measured via a light source and photocell installed in the exhaust duct) and both magnitudes are reported as indices related to arbitrary performance indices for inorganic reinforced cement board [0] and red oak flooring [100]). Unfortunately, soon after it was developed (it was first standardized by ASTM in 1950 as ASTM E84 [2)) it was discovered that it suffered from some serious deficiencies. Perhaps the most important of them addressed the problem of melting away of those newer materials that are not self-sustaining (i.e. not capable of remaining in place during the test), so that false "passes" could be obtained with materials which fell to the floor of the tunnel before the flame reached them. This was the basis for the renowned FTC action whereby a variety of plastics manufacturers (and several standards making bodies) were censured in the 1970's [3]. Later, it was found that tunnel test results were unable to adequately predict whether a textile wallcovering would flash over a room [4]. However, the tunnel test is the most popular fire test for construction products, and it is entrenched in a number of codes and specifications. Thus, it is not surprising that, when the need for a severe fire test for cables was felt the idea of the tunnel sprung to mind immediately. Test development resulted in standards development: UL 910 [5], followed by NFPA 262 [6], which is the test actually referenced in the NEC.

NFPA 262 differs from ASTM E84 in that a tray 24 ft x 12 in (7.3 x 0.3 m) is placed in the tunnel and a single layer of cables is laid on it. The test is conducted for 20 min. In order to "pass", cables must have a flame spread distance < 5 ft, beyond the gas flame itself, a peak smoke optical density ≤ 0.5 and an average optical density ≤ 0.15, both measured in the exhaust duct. This test is, by far, the most severe fire test for cables in existence anywhere in the world.

It is critical to understand the need (or perceived need) for the test. The cable test requirements did not result from a fire hazard assessment or a fire risk assessment, based on a reported increase in plenum fires or plenum fire fatalities, but from two sets of market forces.

(1) The NEC requirement for cables in plenums to be in metal conduit created a problem for installers because of the high cost of the metal conduit and the "awkwardness"

of having to install metal raceways. Cable makers looked for ways to have alternative cables which did not cause added fire hazard (based on either flame spread or smoke obscuration, the only properties measured in the NEC).

(2) Moreover, materials and cables had been developed which outperformed the most severe fire test requirements. Bell Labs had developed cables and restrictive in-house specifications for the Bell System. The cables were based almost exclusively on cable coatings with highly fluorinated polymeric materials (both jacket and insulation). Bell/AT&T were, consequently, manufacturing plenum cables with a very high degree of fire performance. Computer manufacturers were generally producing cables only to meet the requirements imposed by codes and standards, (usually based on actual fire experience: i.e. fires that had occurred) and were not manufacturing or specifying such high-performance products. Thus, the NFPA 262/UL 910 test ensured a market was created for the high performance cables.

Shortly after the development of the UL 910/NFPA 262 test, required for listing plenum cables, papers were published by an alliance of UL/Bell/DuPont, describing the "fire testing leading to the Classifications" by UL [7-8] (results are shown in Table 1). The cables tested included different types of data cables: telephone inside wiring cable, telephone station wire, power limited signal/fire alarm cable and coaxial cable. The coating materials included two classes: (a) those for traditional cables intended for use enclosed in metal conduit (aluminum rigid metal conduit, rigid steel electrical metallic conduit [EMT] or flexible steel metal conduit): poly(vinyl chloride) (PVC) and polyethylene (PE) and (b) fluorinated materials: fluorinated ethylene-propylene copolymer (FEP). Results were very clear: FEP cables, with no metal conduit, could outperform traditional cables enclosed in metal conduit (Figure 1).

Thus, pass-fail criteria were easy to invent: they must ensure that the systems tested passed, or at most barely failed. This is not untypical of the way listing criteria are often generated, in that they recognize the products on the market.

Of interest, too, was later work [9], including a UL fact finding report [10], studying the relation between plenum fire tests (in the tunnel) and simulated plenum fires. In this work a very large fire source (60 lb [27 kg] wood crib, equivalent to 1,200,000 BTU/h [360 kW]) was used in a plenum. The fuel source took roughly 30 min to burn and achieved temperatures of >500 °C at the ceiling. The work also investigated several air drafts and mounting methods, and used the one that caused the most severe conditions. In spite of these design constraints, such a test was found to be less severe than the tunnel test. Cables which failed the tunnel test, had "relatively low flame spread" in the simulated plenum. Moreover, the fire performance of cables with improved fire performance was barely distinguishable from that of standard cables. The results were attributed to the insulation in the tunnel. Similar warnings were presented in results from IBM [11-12], showing that standard cables caused relatively low flame spread and smoke output depending on the arrangement in the cable tray and plenum. They also showed, with simulated plenum tests, that the UL 910/NFPA 262 tunnel test caused more extensive flame spread.

The conclusions to be drawn from this early work are as follows:

(1) A profitable niche market was created, fulfilling the needs of some manufacturers of materials and products.

(2) The new products offered increased fire safety, and were thus unobjectionable.

(3) No fire hazard or fire risk assessments were made to generate this new market, so that its justification was simply based on the existence of a product to serve it.

Market Development

The activities described above created a niche market for fluorinated polymeric materials, and the cables manufactured from them, for several years. However, the communications cable market grew extremely rapidly, in fact much faster than had been predicted by most experts; the growth level was so significant, that the worldwide capacity was insufficient to produce the fluoropolymer materials the market required. A major reason for this growth, of course, is the rapid expansion of electronic communications (information superhighway), particularly the growth in personal computer use in the business environment and their linking into networks. In parallel, many homes today have one or more computers, several telephone lines (with multiple phone hook-ups), mobile phones, and cable TV, all of which require wiring via data cables.

In 1991, EIA/TIA (Electronics Industry Association/Telecommunications Industry Association) published EIA/TIA standard 568, to create standardized performance specifications for data and communications wires and cables. The standard did not include Category 5 (Cat 5) cables, which have since become the most popular communications cables, and are overwhelming all other cables (Figure 2, based on data by C. Glew [12]). A Technical Service Bulletin, just a few months later (TSB 36) described Category 3, 4 and 5 cables (see applications in Table 2).

Cat 1 cables handled POTS (plain old telephone voice-grade copper cables), Cat 2 cables handled IBM mainframe and minicomputer terminal transmissions, both of low interest today, and worked at transmission rates of less than 10 megabytes per second (Mbs). Cat 3 cables were designed to start handling local area network (LAN) and Ethernet technologies at transmission rates of 10-20 Mbs. Cat 5 cables handle 100 Mbs transmissions; applications with transmission levels of 155 Mbs have now been introduced: an > 10 fold increase in transmission rates in < 8 years! Figure 2 shows that Cat 5 cables have grown at levels of 40-50% per year (or higher); at least one prediction suggests they will continue growing at that rate. The US communications cable market (22×10^9 ft in 1998; 40% of which is plenum cable) has grown 46%/yr since 1991, according to one estimate, with installed plenum cable having increased 9 fold since 1991.

Table 1. Flame Spread and Optical Density in UL/AT&T/DuPont Original Tests

Cable	Jacket	Insulation	# Cables	Conduit	Flame Spread (ft)	Peak Optical Density	Average Optical Density
Inside wiring	PVC	PVC	18	Rigid Aluminum	2.0	-	-
Inside wiring	PVC	PVC	18	Rigid Aluminum	2.0	0.20	0.045
Inside wiring	PVC	PVC	18	Steel EMT	2.5	0.14	0.069
Inside wiring	PVC	PVC	18	Steel EMT	2.5	0.38	0.094
Inside wiring	PVC	PVC	10	Flexible Steel	2.0	0.06	0.008
Inside wiring	PVC	PVC	10	Flexible Steel	2.0	0.04	0.005
Inside wiring	PVC	PVC	10	Flexible Aluminum	2.5	0.56	0.084
Inside wiring	PVC	PVC	10	Flexible Aluminum	2.5	0.31	0.051
Inside wiring	FEP	FEP	18	None	3.0	0.35	0.121
Inside wiring	FEP	FEP	18	None	3.0	0.25	0.047
Station wire	PVC	PE	70	Flexible Aluminum	3.5	0.85	0.222
Station wire	PVC	PE	70	Flexible Aluminum	3.5	0.66	0.157
Station wire	FEP	FEP	70	None	3.5	0.08	0.069
Station wire	FEP	FEP	70	None	3.5	0.07	-
Station wire	FEP	FEP	70	None	3.5	0.08	-
Fire alarm	PVC	PVC	30	Steel EMT	4.0	0.70	0.17
Fire alarm	PVC	PVC	30	Steel EMT	3.5	0.50	0.09
Fire alarm	PVC	PVC	12	Flexible Aluminum	6.0	0.60	0.22
Fire alarm	PVC	PVC	12	Flexible Aluminum	5.5	1.20	0.19
Fire alarm	FEP	FEP	36	None	3.0	0.10	0.028
Fire alarm	FEP	FEP	36	None	3.0	0.15	0.043
Coaxial	PVC	PE	30	Steel EMT	7.0	1.85	0.37
Coaxial	PVC	PE	30	Steel EMT	4.5	1.00	0.11
Coaxial	PVC	PE	12	Flexible Aluminum	13.5	1.85	0.45
Coaxial	PVC	PE	12	Flexible Aluminum	19.5	2.15	0.32
Coaxial	FEP	FEP	12	None	3.0	0.12	0.015
Coaxial	FEP	FEP	21	None	3.0	0.25	0.067
Coaxial	FEP	FEP	30	None	3.0	0.45	0.13
Coaxial	FEP	FEP	30	None	3.0	0.60	0.15

Table 2. Communications Cables

Category	Application
Cat. 1 and 2	Voice Only
Cat. 3	Voice and Data up to 16 MHz
Cat. 4	Voice and Data up to 20 MHz
Cat. 5	Voice and Data up to 100 MHz

As transmission speeds increase, a major issue to be solved is transmission quality, i.e. lower scrambling of messages or lower cross-talk. This affects the materials that can be used. For example, some fluoropolymer materials (such as FEP, with excellent fire performance) and polyolefins (without fire retardants, with very poor inherent fire performance) have very low dielectric constant (which helps for data transmission and makes them ideal insulation materials for Cat 5 cables, when fire properties are ignored). However, adding fire retardants or smoke suppressants to polyolefins increases their dielectric constant, and they become less efficient as insulation materials (perhaps only good enough for Cat 3 cables) but more likely to meet the fire test requirements for plenum cable, at least when surrounded by a fluoropolymer jacket. FEP is not the only fluoropolymer used in this market: ethylene chlorotrifluoroethylene (ECTFE), with a fairly high dielectric constant, making it unsuitable as insulation for communications cables at the high Cat 5 level, has excellent performance as jacket material for any cable, and may even be used as insulation in Cat 3 cables. Polyvinylidene fluoride (PVDF) is suitable for Cat 3 cable jackets. Standard PVC materials tend to have better fire performance than polyolefins but not as good as fluoropolymers. Neither their dielectric constant, probably too high, nor their fire and smoke properties, too mediocre, allowed them to be used in plenum cables, until the late 1980's.

Activities in the late 1980's and early 1990's

As a consequence of the growing market and the increasing scarcity of fluoropolymer materials, manufacturers worked hard to break the monopoly of fluoropolymer producers. The first breakthrough came with vinyl materials: the use of intrinsically fire retarded plasticizers and flexibilizers (often containing specialized phosphate esters [13]) and complex combinations of fire retardants and smoke suppressants (including novel materials such as zinc stannates or molybdenum compounds [14]) produced fire retarded and smoke suppressed PVC compounds with fire performance comparable to that of fluoropolymers. Once these materials were built into cables, in the late 1980's, cables were made that were shown to be able to meet the NFPA 262 fire test requirements. The initial types of PVC plenum cables contained PVC jacket materials only, while still retaining fluoropolymer (mainly FEP) insulations. Some creative compounding (by several manufacturers, including some cable companies making their own materials) also permitted the development of some plenum cables fully insulated with PVC.

As PVC material technology for plenum cables improved, their lower production costs, and easier processability (low flexural modulus and greater ease of stripping), eroded into the fluoropolymer plenum market, so that the typical plenum cable of the mid 1990's had a PVC jacket and an FEP insulation, causing consternation for the loss of market share by fluoropolymer materials. FEP materials also started changing: to improve processability, new FEP materials have higher melt flow indices, which may cause easier melting and dripping during fire testing.

Later still, creative cable manufacturers (and > 30 companies manufactured plenum cables by the late 1990's) making cables with multiple pairs of insulated conductors, investigated the possibility of substituting different insulation materials on some of the conductors. Some cable manufacturers eliminated costly FEP materials by replacing them with polyolefins (often not fire retarded), much less expensive, while still meeting the plenum cable fire test requirements. As this trend progressed, not only partial replacements but total replacements were investigated. Thus, the state-of-the-art appeared to have shifted, by the late 1990's, from all fluoropolymer cables (in the early 1980's) to cables with PVC jacket and fluoropolymer insulations, with some that are partially fluoropolymers and partially polyolefins. This affords very small margins of error in manufacturing practices (materials used and cable constructions) and in testing.

Errors in testing became particularly important since no published precision study exists for NFPA 262, and the smoke obscuration precision reported for ASTM E84 is rather poor [15].

Codes and Standards Activities

Outside the United States (and Canada), fire testing of cables follows the International Electrotechnical Commission (IEC) standards. The most severe international standard cable fire test is IEC 332-3 (a vertical cable tray fire test, with a 70,000 BTU/hr, or 20 kW, input heat source [16]): much milder than NFPA 262/UL 910, with no smoke component. The test intensity is similar to the UL 1581 vertical cable tray test [17], exceeded, in the NEC hierarchy of cable fire tests, by the riser test, UL 1666 [18], and the plenum test, NFPA 262. Therefore, the most common fire retarded cables available in Europe are ones that would be listed as general purpose cable "resistant to the spread of fire", in the NEC. The corresponding regulatory smoke requirement results from testing via IEC 1034 (a cubical closed smoke chamber, with sides of 3 m each and a liquid fuel pan fire, [19]). This requirement is often met by using "low smoke zero halogen" (LSZH) cables, due to widespread European concern about halogenated materials.

The rapid communications growth is a worldwide phenomenon, at least in the developed world: Western Europe and Japan. Office buildings and many other public buildings in the USA commonly are constructed with plenums. Many such American buildings are relatively new, fairly large and air conditioning systems are very prevalent. In Western Europe and Japan, building space is at a premium (more than even in the more populated American cities) and older buildings exist, with the use of air conditioning still less widespread than across the ocean.

This background explains a spurt in international activity in the 1990's to promote the use of the NFPA 262/UL 910 test internationally, by the same coalition which was successful in the USA in the late 1970's: UL/Lucent (ex AT&T, ex Bell Labs)/DuPont, working both at IEC and in the research arena. Their extensive research work, with some additional partners in some instances, included testing communications cables common in Europe and in the USA, in several fire tests: NFPA 262, IEC 332-3, an amended (to make it more severe) version of IEC 332-3, the cone calorimeter (ASTM E1354 [20]), the single burning item test (SBI [21]) and a simulated room-plenum facility, constructed in the UK [22-25]. The work showed that the fire performance of plenum cables was indeed much better than that of cables built to meet either IEC 332-3 or a small scale fire test, whatever the test used. Moreover, the work also showed that cables listed to the NFPA 262 test performed well in the room-plenum test, but cables meeting IEC 332-3 burnt completely in the room-plenum test and gave both flame spread and smoke beyond the pass-fail criteria in the NFPA 262 test. At IEC level, descriptions of the Steiner tunnel test were proposed into existing standards (descriptions of ignition sources), into new guidance documents (test methods for flame spread) and as a new international standard (within IEC TC20), but have been strongly resisted by European interests.

A major reason for the opposition was the absence of Steiner tunnels outside North America. This was remedied by American interests helping in the construction of 2 tunnels in the UK and 1 in Japan. Furthermore, the National Fire Protection Research Foundation is managing a precision round robin for the NFPA 262 test, using 5 tunnels, 2 in the USA and 3 overseas. Another reason for international opposition to NFPA 262 was a concern as to whether the test severity is excessive. This view is reinforced by the fact that plenums are rare in Europe, even though communications cables, often in concealed spaces, are a fast growing phenomenon. There is, however, a new European search for a way to distinguish the better performing cables from the merely adequate ones, something which the IEC 332-3 cannot do. Pre-normative research funded by the European Commission to solve this problem led to the FIPEC project (Fire Performance of Electric Cables, [26]). The FIPEC coalition was commissioned to develop 2 tests, simultaneously measuring heat and smoke release. The intent is that the larger scale test should be based on a modification of the IEC 332-3 apparatus allowing more severe pass-fail criteria to be developed, and the smaller scale one should be the cone calorimeter [20], which should serve as a predictor of the larger one. Part of the rationale for this approach is that such tests have been shown to reasonably assess fire hazard [27-28].

In the USA, standard Steiner tunnel test descriptions have always been fairly vague (e.g. in ASTM E84 [2]), giving laboratories leeway in both test procedure and equipment construction. In fact, no North American tunnels contained, as far along as 1997, 2 features characteristic of the UL Northbrook tunnel: an inlet chamber (upstream of the gas burners, used mostly during the period between tests) and an extended transition piece (downstream of the end of the tunnel itself). This caused concern among manufacturers as UL saw a high level of failures on retest of listed plenum cables, and various meetings of TAPCOM, a UL Technical Advisory Panel on Communications Cables. Interestingly, Figures 3-5 plot results of tests on 22 cables generated by Tom Chapin (Lucent [29]) which show differences between results for the same cables tested at UL and at another lab, with a variation in tunnel configuration. The reason that this work highlights differences with UL is that UL is the most prominent listing organization, and the one that has set the pass-fail requirements. The most critical discrepancy is at the level of the average optical density, where the UL data are much higher than the data from the other laboratory.

As a consequence, the NFPA Technical Committee on Fire Tests modified NFPA 262, and a new edition was issued in late 1998 by NFPA. It contains major changes: the inlet chamber and transition piece from UL are now mandatory for NFPA 262, as are construction and procedural details. Some issues to be highlighted: (a) calibration will now cease using red oak flooring and be based on a plastic rod, based on a fluorinated (polyvinyilidene fluoride) material for plenum communications cables, manufactured by Lucent Technologies, (b) data acquisition scan periods are set at 2 s, and (c) details have been incorporated on all averaging and smoothing of data. A technically identical standard is likely to be issued as the new edition of UL 910, and probably also by the corresponding ASTM Committee (ASTM D09.21). A related potential conflict may arise since ASTM E84 is unlikely to be changed to require the same construction details as NFPA 262. Thus, laboratories may be forced to choose whether to run ASTM E84 (construction materials) or NFPA 262 (plenum cables) in future. Laboratories involved in the NFPA 262 round robin have built their tunnel as required by the new version of the standard.

The contents of plenums are, at least in principle, controlled by NFPA 90A [30] and by the model building codes. As is fairly common in codes, in NFPA 90A, plenum cables which are not enclosed in metal, are permitted to be included based on an "exception". The exception allows the use of such cables if they have met the flame and smoke requirements from the NFPA 262/UL 910 test, as follows (taken from the 1996 edition of NFPA 90A):

"The following materials shall be permitted in the ceiling cavity plenum where listed as having a maximum peak optical density of 0.5 or less, an average optical density of 0.15 or less, and a maximum flame spread distance of 5 ft (1.5 m) or less when tested in accordance with the specified test method:

(a) Electrical wires and cables NFPA 262, Standard Method of Test for Fire and Smoke Characteristics of Wires and Cables

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(c) Optical-fiber cables NFPA 262, Standard Method of Test for Fire and Smoke Characteristics of Wires and Cables"

Alternatively, plenum cables would have to meet requirements for "non-combustible" or "limited combustible" materials, defined as materials having a maximum potential heat (heat content) of 3500 BTU/lb (ca. 8 MJ/kg), with materials having a smoke developed index of 50 in ASTM E84. Only perfluoropolymer materials, among common wire coating materials, can meet these requirements: the potential heat for polyolefins ranges between 25 and 40 MJ/kg and that for vinyls between 15 and 25 MJ/kg; not even all fluorinated coating materials meet the limit.

At present, as plenum cables are installed in existing buildings, it is rare for the cables already there to be taken out; they are usually simply cut off at the ends and left in place. Moreover, installers try to foresee the inevitable growth in communications requirements and install excess cable capacity. Thus, the NFPA 90A committee proposed, early in 1998, to eliminate the above "exception", that permits plenum cables to be used based on NFPA 262/UL 910 testing. At the comment period stage, the proposal was softened to incorporate a clause that allows the use of plenum cables, but states that abandoned electrical wire and cable, that complies with the Exception, and is not also listed as being limited combustible, and having a maximum smoke developed index of 50, shall not be permitted to remain. If approved by NFPA in May 1999, this would: (a) create a plenum cable market with 2 categories of cables (listed plenum cables and limited-combustible perfluoropolymer cables, with their concomitant limits in production capacity, and for which no listing exists yet) or metal conduit, (b) it would confuse inspectors, who would be unable to distinguish between the existing plenum cables and (c) it would still allow the older (non plenum-rated) cables to remain in the plenum.

The decision will have been taken by the time the present paper is being delivered verbally. The American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) has now commissioned the National Research Council of Canada (NRC) to research whether a fire hazard exists in plenum cables: the outcome will be known after the decisions.

Potential heat test methods (oxygen bomb calorimeters) differ from heat release rate test methods (heat release calorimeters). This represents the crucial difference between complete heat of combustion and effective heat of combustion. Heat release calorimeters determine effective heat of combustion, normally lower than the complete heat of combustion (determined by oxygen bomb calorimeters) but which represent (in a properly chosen fire scenario) the expected heat generated in the real fire. It is, of course, always possible to extract the "last ounce" of heat from a specimen in a heat release calorimeter test, but that defeats the actual purpose which is to assess the expected fire hazard. Moreover, both the accuracy [31] and the precision [32] of oxygen bomb calorimeters have been shown to be poor, especially at low heat levels.

The rationale for the proposals based on heat content is that the fire safety in plenums is being compromised by the additional fuel introduced via communications cables. However, neither when plenum cables were first introduced into plenum areas nor at this stage, has a fire hazard assessment or a fire risk assessment of the situation been made.

CONCLUSIONS

The area of plenum cables is one where there are extensive marketing implications of any technical decision made. Fire testing is based on a variation of a very traditional test: the Steiner tunnel, as a result of changes brought about in the late 1970's. It is clear that all cables meeting plenum test requirements undoubtedly have excellent fire performance, since they have complied with the most severe cable fire test in the world. However, considerations are being raised as to whether the fire test should be replaced by a more severe oxygen bomb calorimeter test. This is being proposed without a clear fire hazard or fire risk rationale for making the change, just as the original requirements were not introduced following a fire hazard or fire risk assessment. Rather, the original change showed that technology existed to meet new requirements.

Thus, it is not known whether a fire safety problem exists in plenums, or whether a solution is being sought simply to a series of marketing concerns.

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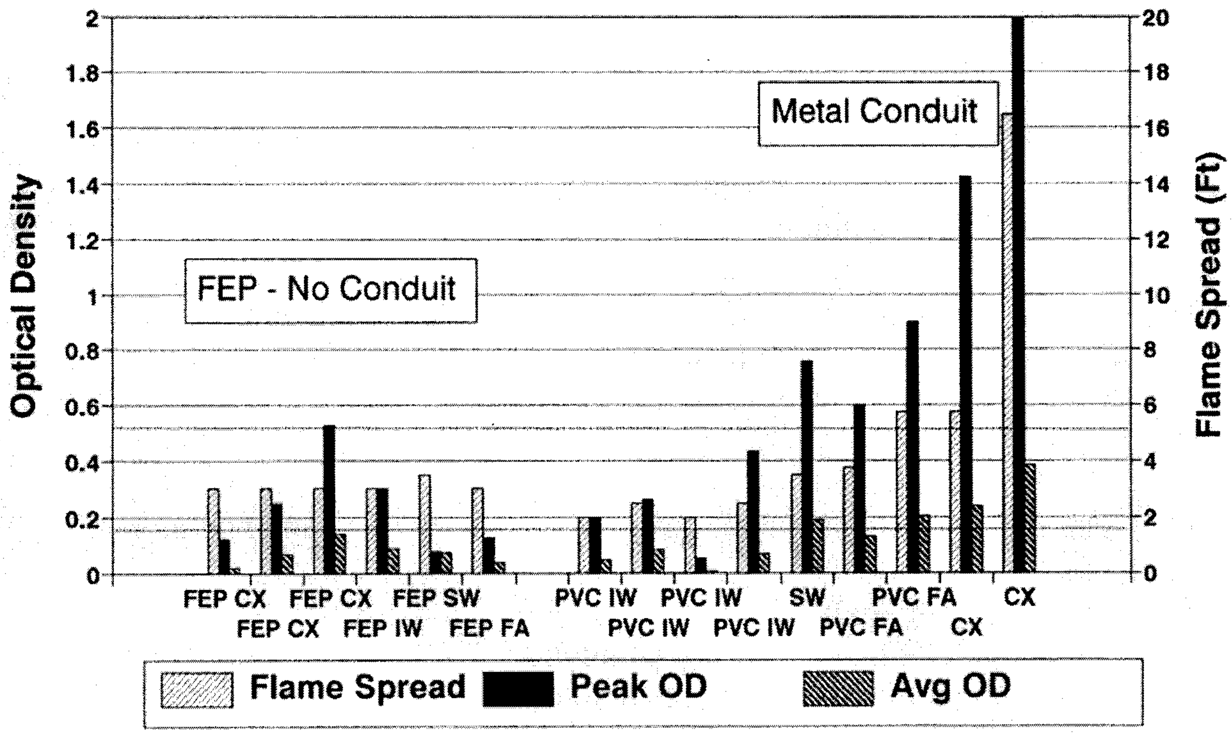
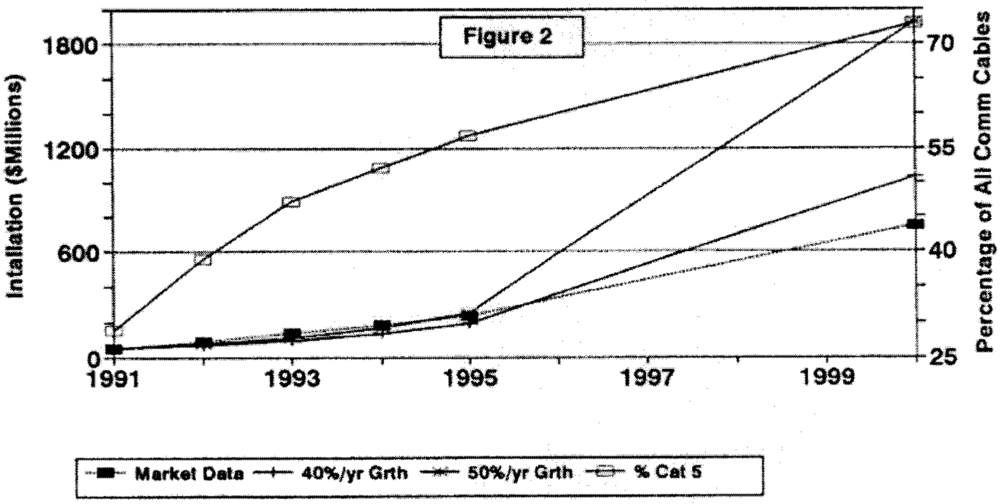
Initial Data on Flame Spread and Smoke

NFPA 262 Test - Fig. 1



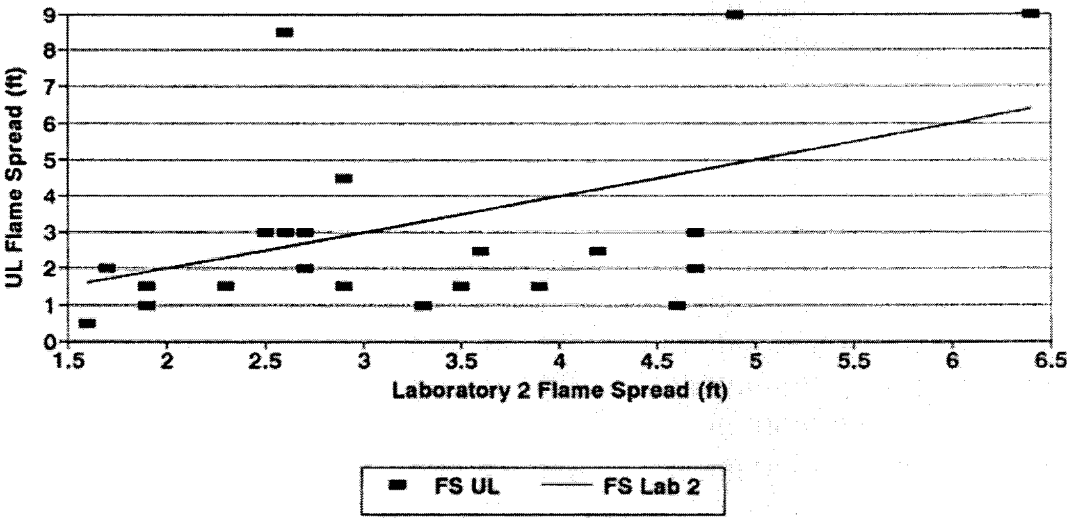
Category 5 UTP Communications Wiring

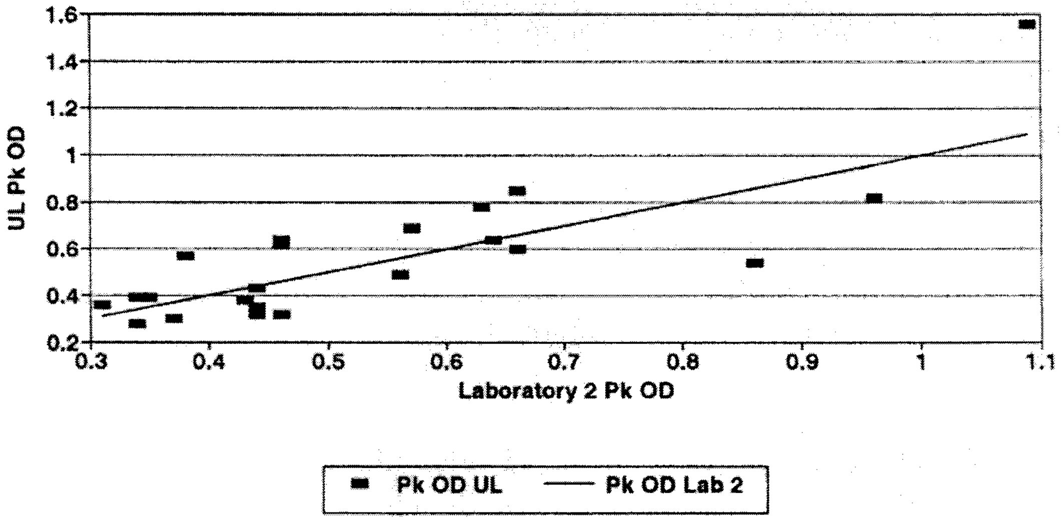
Growth of North American Market - 1990s



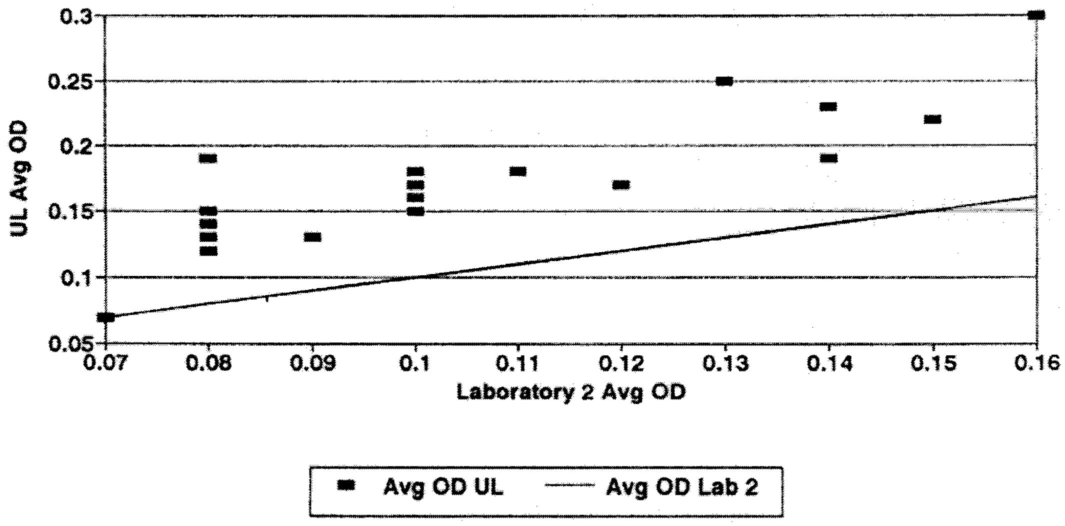
NFPA 262 Flame Spread @ 2 Laboratories

Comparison With UL Data - Fig. 3




NFPA 262 Peak Optical Density @ 2 Labs

Comparison With UL Data - Fig. 4


NFPA 262 Avg. Optical Density @ 2 Labs

Comparison With UL Data - Fig. 5

GBH Attachment 20

AB59-COMM-7-20

13 Flammability and Fire Performance

MARCELO M. HIRSCHLER

13.1 Introduction

All organic polymers are combustible. When sufficient heat is supplied to any organic polymer, it will thermally decompose, and its thermal decomposition products will burn. However, poly(vinyl chloride) (PVC) is among the polymers that tend to have superior fire performance. This chapter will discuss issues associated with fire performance and will show how PVC compares with other polymers.

13.2 Thermal Degradation and Thermal Decomposition

All polymers react adversely to excessive heat, resulting in both physical and chemical changes. In this chapter, thermal degradation is the result of physical (mechanical or electrical property) changes only, while thermal decomposition involves also chemical species changes [1]. In terms of fire, only thermal decomposition is relevant, because the chemical decomposition of a solid material generates gaseous fuel vapors, which can burn above the solid material. Therefore, thermal degradation will not be addressed further here.

In order for burning to occur, the gases resulting from thermal decomposition must undergo combustion and then feed back sufficient heat to the material to continue the production of gaseous fuel vapors or volatiles. Therefore, if the material continues burning, we have a self-propagating process, since the heat transferred back to the polymer causes further thermal decomposition (i.e., further generation of flammable volatiles). In the next step, these decomposition products react exothermally with an oxygenated species in the atmosphere (normally $OH\cdot$ or $O_2H\cdot$ free radicals) surrounding the polymer condensed phase to generate heat. In the last step, to complete the cycle, part of the heat generated by the burning materials is transferred back to the polymer and causes more thermal decomposition [2–5]. Burning gaseous products usually generate flames (most likely with light emission and soot).

Polymer + Heat → Thermal Decomposition Products
Decomposition Products + Oxygenated Radicals → Combustion Products + Heat

The formation of volatile products from polymers is a complex process, as the condensed phase material itself is essentially non-volatile, and chemical breakdown into smaller molecules that can vaporize is essential. In most cases, a solid polymer breaks down into smaller molecular fragments made up of a number of different chemical species. The lighter fragments vaporize immediately, while heavier molecules remain in the condensed phase (solid or liquid) for some time. The species that remain in the condensed phase can undergo further thermal decomposition to lighter fragments, which are, in turn, more easily vaporized. A few polymers break down completely so that virtually no solid residue remains. Most polymers, however, leave behind solid residues, which can be organic (char), inorganic (based on the heteroatoms (non-carbon atoms) from the original polymer resin or compound) or a combination of both. Charring materials, such as wood or PVC, for example, leave much of the original carbon content as a residue, often as a porous char. When thermal decomposition of the deep layers of a charring material continues, any volatiles produced must travel through the char layer above the virgin material to reach the surface. During this process, secondary reactions may occur within the volatiles. Char layers are almost always beneficial from the point of view of fire performance. On the one hand, organic (carbonaceous) char layers can be intumescent and thus slow down further decomposition. On the other hand, inorganic layers can be glassy and become virtually impenetrable to volatiles, thus also protecting the underlying layers from further thermal breakdown. However, it must be pointed out that all purely organic chars can always be "burned off" by oxidation at higher temperatures.

It is important to discuss how PVC is classified as a polymer, because that is critical in understanding its thermal decomposition and fire properties. PVC is:

1. a synthetic polymer (i.e., not a naturally-occurring material),
2. a plastic (i.e., not an elastomer or a fiber, according to its physical properties: elastic modulus and degree of elongation),
3. a thermoplastic (as it deforms reversibly at elevated temperature, between its melting point and chemical decomposition point) and not a thermoset,
4. a carbon-carbon chain polymer (as it contains no heteroatoms in the chain itself)
5. a vinyl polymer (its repeating unit is vinylic: $-[CH_2-CH_2]-_n$), and
6. a chlorine-containing polymer (as it contains chlorine in its chemical structure).

PVC has carbon-carbon chains with a chlorine atom substituting one hydrogen atom attached to the polymer backbone. It is unique in that it is used both as a rigid material (unplasticized) and as a flexible material (plasticized). Flexibility is achieved by incorporating plasticizers or flexibilizers into the polymer compound (so that flexible PVC often contains less than 50% actual PVC). Through the additional chlorination of PVC, another member of the family of vinyl materials is made: chlorinated poly(vinyl chloride) (CPVC). CPVC exhibits different physical and fire properties than PVC, and it needs to be distinguished from poly(vinylidene chloride) (PVDC). In CPVC, two chlorine atoms replace hydrogen atoms attached to the polymer backbone, one on each (successive) carbon atom. In PVDC, two chlorine atoms also replace hydrogen atoms, but on the same carbon atom. In the case of PVC, more perhaps than in the case of many other polymers, the distinction between "resin" and "compound" is critical. A "resin" is a commercially manufactured polymer, without additives, but which may still contain residues from the polymerization process. A "compound" is a material that is used to fabricate a product commercially, and which contains one or more "resins" and additives. The fire performance of PVC "resin" (or of virtually homopolymer PVC) is often considerably superior to that of many PVC "compounds", but it is often the compounds that possess the added properties needed for the proper use of the material. Additives contained in a PVC "compound" include the same type of materials as for other polymers, namely: copolymers, fillers, flame retardants, smoke suppressants, synergists, plasticizers, colorants, and processing aids, where often additives have more than one function. However, "flexible PVC compounds" will inevitably have a plasticizer or a flexibilizer as one or more of their ingredients. In many "flexible PVC compounds", the result of introducing this flexibility is that the fire performance will suffer, as easily combustible fuel may have been added.

Many materials (most cellulosic materials, many thermosetting plastics, as well as PVC and some other thermoplastics) produce carbonaceous chars when they decompose thermally. The physical structure of the char itself markedly affects the continued thermal decomposition process. The characteristics of the char (including density, continuity, coherence, adherence, oxidation-resistance, thermal insulation properties, and permeability) often dictate the thermal decomposition rate of the rest of the polymer. The most important combination of char properties is low density and high porosity. Such chars tend to be good thermal insulators so that they can significantly inhibit heat flow from the gaseous combustion zone back to the condensed phase behind it, and thus slow down thermal decomposition. This is an excellent means of decreasing polymer flammability (which can also be done by incorporating additives or reactive flame retardants). As the char layer thickens, the heat flux to the uncharred material decreases, and the thermal decomposition rate is reduced. Thermal decomposition of polymers may be enhanced by the presence of oxidants (such as is the case for poly(vinylidene fluoride) [6]) or be unaffected by them and be purely effected by heat. In many polymers, thermal decomposition is accelerated by oxidants (such as air or oxygen), but oxidants seem to have relatively little effect on PVC thermal decomposition [7].

There are a number of general classes of chemical mechanisms important in the thermal decomposition of polymers: (1) random chain scission, in which chain scissions occur at random locations in the polymer chain; (2) end chain scission, in which individual monomer units are successively removed at the chain end; (3) chain-stripping, in which atoms or groups not part of the polymer chain (or backbone) are cleaved; and (4) cross-linking, in which bonds are created between polymer chains [5]. Thermal decomposition of PVC occurs mostly by chain stripping, whereby hydrogen chloride (HCl) species are given off, but that is often followed by some cross-linking. Chain stripping involves the loss of small, usually volatile, molecules (in the case of PVC the molecule released is HCl) by reactions that "strip" side-chain substituents from the main chain and form small molecules. The residue, as the reaction scheme shows, is much richer in carbon than the original polymer. However, while chain stripping in PVC leads to a hydrogenated char:

$$\text{–CH}_2\text{–CHCl–} \rightarrow \text{–CH=CH–} + \text{HCl}$$

chain stripping in PVDC leads to an almost graphitic purely carbonaceous char:

$$\text{–CH}_2\text{–CCl}_2\text{–} \rightarrow \text{–C=C–} + 2\ \text{HCl}$$

These chars will tend to continue breaking down by chain scission, but only at high temperatures, during the carbon burn-off stage. Thus, again, chain stripping involves principally side-chains or groups, while chain scission involves mostly atoms in the main polymer chain. In PVC thermal decomposition, chain stripping is often followed by cross-linking, whereby there is a creation of bonds between two adjacent polymer chains. This process also enhances char formation, because it generates a more compact, less easily volatilized structure.

While char formation is a chemical process, its significance is principally due to the physical properties of the residual solid phase, which will give off lower amounts of flammable gases during thermal decomposition and form a barrier between the source of heat and the virgin polymer material. As such, the flow of heat to the virgin material is reduced as the char layer thickens, and the rate of decomposition is reduced, depending on the properties of the char [8]. If the heat source is the combustion energy of the burning volatiles, not only will the fraction of the incident heat flux flowing into the material be reduced, but the incident heat flux as a whole will be reduced as well.

In PVC thermal decomposition, HCl is evolved nearly quantitatively between 225 and 275 °C. It is very important to point out, however, that the temperature at which HCl starts being evolved to any significant extent depends heavily on the stabilization package used, and any commercial material will be stabilized. Thus, commercial PVC "compounds" (as defined earlier) have been shown to start evolving HCl at temperatures in excess of 245 °C and to have a dehydrochlorination stage starting at 325 °C [9]. Unstabilized poly(vinyl chloride) polymer samples used for academic research have, in some work, released hydrogen chloride at lower temperatures, but such materials are not commercially available. In fact, a recent study on five commercial PVC compounds showed details of its long-term stability [10]. Between 425 °C and 475 °C, hydrogen is evolved during carbonization, following cyclization of the species evolved. At higher temperatures, cross-linking between chains results in a fully carbonized residue. The rate of dehydrochlorination depends on molecular weight, crystallinity, presence of oxygen, hydrogen chloride gas, and stabilizers. The presence of oxygen accelerates the dehydrochlorination process, produces main-chain scissions, and reduces cross-linking. At temperatures above 475 °C, the char (resulting from dehydrochlorination and further dehydrogenation) is oxidized, leaving no residue. The rate of dehydrochlorination increases as the molecular weight decreases. Dehydrochlorination stabilizers include zinc, cadmium, lead, calcium, and barium soaps and organotin derivatives. The stability of model compounds indicates that weak links are important in decomposition.

PVC is one of the polymers whose thermal decomposition process has been most exhaustively studied. There has been considerable controversy, particularly in terms of explaining the evolution of aromatics in the second decomposition stage. Some evidence [9] seems to point to a simultaneous cross-linking and intramolecular decomposition of the polyene segments resulting from dehydrochlorination, via polyene free radicals, although more recently it appears that the mechanism is ionic (see, e.g., [11]). Earlier evidence suggested Diels-Alder cyclization (which can only be intramolecular, if the double bond ends up in a "cis" orientation [12]). Evidence for this was given by the fact that smoke formation (inevitable consequence of the emission of aromatic hydrocarbons) was decreased by introducing cross-linking additives into the polymer [13]. Thus, it has now become clear that formation of any aromatic hydrocarbon occurs intramolecularly. The chemical mechanism for the initiation of dehydrochlorination has also been reviewed a few years ago [11, 14]. More recently, a series of papers has been published investigating the kinetics of chain stripping, based on PVC [15].

The work by Starnes and his team has been key in explaining these mechanisms and the ways in which reductive coupling cross-linking can be used to decrease smoke release from PVC [16–18].

Chlorinated poly(vinyl chloride) (CPVC) needs to be mentioned, because it is often used where higher in-use temperatures make it a replacement for PVC. It results from post-polymerization chlorination of PVC and although it decomposes at a much higher temperatures than PVC, it does so by the same chain-stripping mechanism. The resulting solid is a polyacetylene, which gives off much less smoke than PVC and is also more difficult to burn [19].

13.3 Thermal Decomposition and Fire Properties

One of the major reasons why thermal decomposition of polymers is studied is because of its importance in terms of fire performance. This issue has been studied extensively. Very early, Van Krevelen [20, 21] showed that, for many polymers, the oxygen index (or limiting oxygen index, LOI, an early flammability measure, see below) could be linearly related to char yield, as measured by thermogravimetric analysis under specified conditions. After Van Krevelen showed how to compute char yield to a good approximation from structural parameters, LOI values became predictable, in theory; in fact they can be predicted to some extent for those pure polymers having substantial char yields. Since then, however, comparisons have been made between the minimum decomposition temperature (or the more meaningful temperature for 1% thermal decomposition) and the LOI. The conclusion was that, although in general low flammability resulted from high minimum thermal decomposition temperatures, no easy comparison could be found between the two, with some notable cases of polymers with both low thermal stability and low flammability [3, 22]. This type of approach has since fallen into disrepute, particularly in view of the lack of confidence remaining today in the LOI technique [23]. There is now significant consensus that LOI values are of interest mainly as an indication of ease of extinction (see below) and relate to very low heat inputs rather than to those inputs associated with most fires. Work by Lyon [24], however, indicates predictability of heat release (see below) information from thermoanalytical data obtained on a new piece of equipment. Mechanisms of action of fire retardants and potential effectiveness of fire retardants can be well predicted from thermal decomposition activity [3, 4], but it is often necessary to also have an understanding of the chemical reactions involved. Camino [25, 26] and Bourbigot [27] have recently used thermal decomposition techniques to understand the mechanism of fire retardance and to synthesize new polymers. The newest approach is the use of the mass loss cone, which uses heat fluxes and sample sizes typical of fires [28–30]. However far science has progressed in understanding how to predict fire performance from thermal decomposition data, it is clear that this remains a critical goal, as polymers cannot burn if they do not break down.

13.4 Fire Performance: General

When gaseous fuels burn in a gaseous oxidant, flames of two basic but extreme types are produced. Flame reactions are either controlled by chemical kinetics or by physical mixing processes such as diffusion or flow. Premixed flames are kinetically controlled, with the fuel, oxidant, and product uniformly distributed in the gas phase; gas explosions are typical examples. Diffusion flames have sizeable gradients of chemical species and temperatures with reactants diffusing into the flame zone and products and heat diffusing out: the combustion is diffusion-controlled. In practice, however, many flames are intermediate between the two extreme types. A burning organic polymer constitutes a highly complex combustion system, generating its own fuel at a rate which must satisfy the equilibrium condition for maintenance of the burning process. As condensed phase fuel generation is closely coupled with gas phase fuel consumption, the rates of these processes must be in equilibrium to maintain a steady state of combustion. Acceleration or deceleration of either process will lead to non-equilibrium and eventually to collapse or blow-off of the flame. In general, however, polymer combustion flames are much more similar to gaseous diffusion flames than to premixed flames. However, with certain polymers, air may be in contact with the polymer surface so that the flame is at least partly premixed (in the case of PVC, where the effect of oxygen is small, the flame is very similar to a diffusion flame). The most important species in all flames are simple free radical species such as $H^\bullet$, $0^\bullet$, and $OH^\bullet$, and to a smaller extent $HO_2^\bullet$, $HCO^\bullet$, and $CH_3^\bullet$ [22]. The larger species initially formed rapidly break down to give smaller species, such as $CH_3^\bullet$. The latter radicals, therefore, tend to be involved in the flames of all hydrocarbons, with the result that the chain-propagating species are largely independent of the initial fuel. Thus, the chemistry of most flames is effectively the high-temperature chemistry of a small number of free radicals. In practice, therefore, the number of relevant reactions is limited to perhaps five or six times the number of fuel species rather than to the square of the number of these species, as would be expected if every molecule reacted with every other molecule. However, the nature of the chemical reactions in hydrocarbon flames does depend on the fuel-to-oxidant ratio. Other elements may also be present in the final products of the combustion of organic polymers, especially in fuel-rich flames. The most important of these are nitrogen, sulfur, chlorine, and bromine, and some of the products are derived from those hetero-elements contained in the polymers. Most of the nitrogen appearing as nitrogen oxides is, however, formed mainly by reaction of molecular nitrogen in the atmosphere, a process called nitrogen fixation. In contrast, chlorine and bromine in organic polymers are converted during combustion almost exclusively into the corresponding hydrogen halides (although bromine-containing polymers sometimes result in volatilization of the bromine-containing additive rather than in generation of hydrogen bromide) and sulfur appears as oxides of sulfur, mainly sulfur dioxide, especially at high temperatures.

The nature of the fuel supplied to the flame when an organic polymer burns is clearly related to the structure of the original polymer. It also depends on the extent to which the polymer or its breakdown products react with the oxidant prior to entering the flame zone. Nevertheless, the chemistry of the flames of hydrocarbons and that of other organic compounds in a given oxidant are remarkably similar, involving largely the same chain-propagating radicals. In fact, because large hydrocarbon radicals are thermally unstable and thus usually decompose to give smaller radicals, such as methyl radicals, chain propagation normally involves the same simple species. Any hydrocarbon flame can thus be viewed as a reaction leading to a carbon monoxide-hydrogen-oxygen flame. In the same way, a flame above an organic polymer can be thought of as a chemical reaction taking place at a solid or liquid surface yielding a hydrocarbon flame. Flames above different burning organic polymers therefore do not differ greatly, from the chemical point of view, from one polymer to another, although they are highly dependent on the nature of the gaseous oxidant.

Fire performance involves a combination of fire properties including ignitability, ease of extinction, flammability of the products generated, amount of heat released on burning, rate of heat release, flame spread, smoke obscuration, and smoke toxicity. In order to combine that into an analysis of the fire hazard in a certain scenario, it is critical to understand the fire environment as well. The reader is encouraged to look at Appendix 1 of this chapter, which contains a number of the relevant definitions, most of them originating in ASTM E 176 [1].

Subsequent sections will discuss:

- Fire properties,
- Methods that can be used to assess each fire property (traditional and advanced), and
- How PVC materials compare with other materials made of other polymers.

Compliance with one or more fire properties is often required by various codes (typically by the National Electrical Code, Life Safety Code, or any of the Building Codes, Fire Codes, or Mechanical Codes) or by regulations. In such cases, the requirements usually apply to finished products, but they may occasionally also apply to materials. Specifications also often include requirements for certain fire properties, and they are then often applied to materials. Advances in fire science and in materials technology are responsible for better understanding of critical fire properties and of improved methods to assess them. Therefore, traditional fire tests are often no longer considered appropriate for some applications (or at all) by fire scientists, but are still used, because of three factors: (1) the inertia associated with changes in requirements, (2) the need to demonstrate that the new techniques are an improvement, and (3) the commercial interests associated with the existing materials or products.

13.5 Individual Fire Properties and Associated Test Methods

13.5.1 Ignitability

Unless a material ignites, there is no fire. Therefore, low ignitability is the first line of defense in a fire. All organic polymers do ignite, but the higher the temperature a material has to reach before it ignites, the safer it is. Therefore, measures of ignition are of three types:

1. the minimum temperature for ignition (in the absence or presence of a pilot source of ignition),
2. the time to ignition under a certain applied thermal insult (typically a heat flux or a flame of a particular size), and

3. the minimum (or critical) heat flux required to reach ignition (because temperature and heat flux can be correlated with the Stefan-Boltzman constant and black-body radiation).

The traditional method of assessing ignition temperatures is done with a test, such as the Setchkin chamber (ASTM D 1929 [31]), which has been used for many years to determine self ignition temperatures and flash ignition temperatures (with an applied pilot flame) of many polymers. ASTM D1929 uses small pieces (typically pellets) as specimens, exposed inside a vertical furnace tube, heated electrically, under a slow air flow. Its results are no longer considered very indicative of fire hazard, because the exposure is not truly representative of real fires. However, results from this test are frequently required in specifications and quoted in data sheets, and the test is referenced in building codes to determine the suitability of some plastics for use in construction, because it represents an easily understandable single number. The time to ignition at a certain incident heat flux is an excellent way of comparing material properties, but it will give a numerical result only, of course, if the heat flux is high enough to cause ignition. The advantage of the critical heat flux for ignition is that it can always be assessed; it results from extrapolation after measurements made at a variety of heat fluxes.

Beyond the Setchkin test (ASTM D 1929), three other test methods are common specific ignition tests: a radiant cone heater with an intermittent gas flame igniter (ISO 5657 [32], sometimes called the dipping duck test, Fig. 13.1) and two tests for materials coated onto wires: IEC 60695-2-2 (needle flame test, [33]) and IEC 60695-2-10 (glow wire test, [34]) are applied to coated electrical wires. The glow wire test involves bringing an electrically heated wire in contact with the material and simulates the thermal stresses resulting from faults or overload conditions during cable use. The needle flame test simulates the flame that can result from a fault or overload condition. The IEC 60695-2-2 test can also be used to obtain information on flame spread. Other methods that can be used for assessing ignitability are: the cone calorimeter (ASTM E1354, Fig. 13.2 [35]); whose primary purpose is heat and smoke release [36]; the Ohio State University calorimeter (ASTM E906, Fig. 13.3), whose primary purpose is also heat and smoke release [37]; and the Lateral Ignition and Flame Spread Test (LIFT, Fig. 13.4, ASTM E1321); whose primary purpose is flame spread [38].

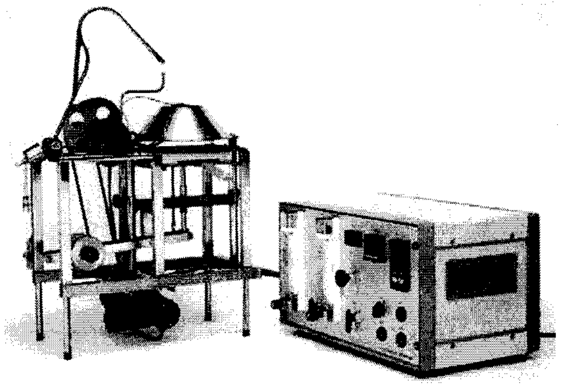


Figure 13.1 Radiant cone – ignitability test method (ISO 5657)

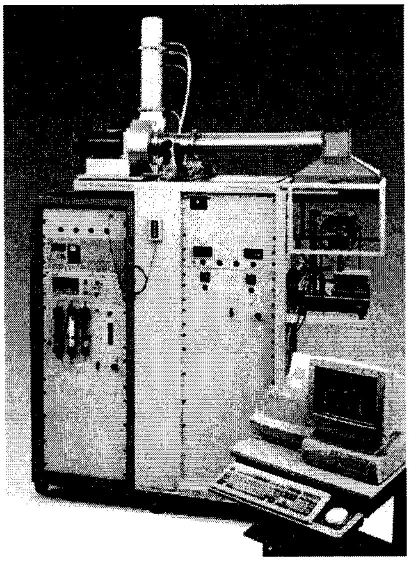


Figure 13.2 Cone calorimeter (ASTM E1354)

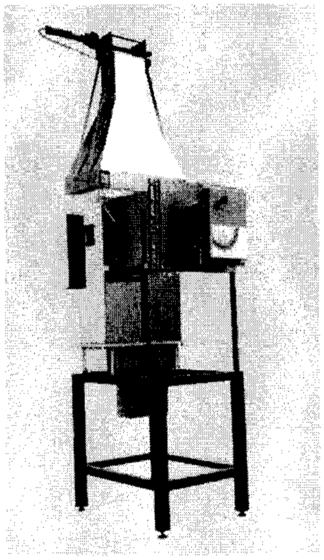


Figure 13.3 The Ohio State University calorimeter (ASTM E906)

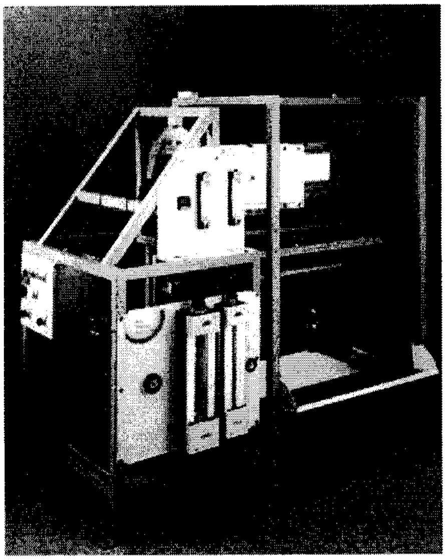


Figure 13.4 The Lateral Ignition and Flame Spread Test (LIFT, ASTM E1321)

Table 13.1 presents the self-ignition and flash-ignition (with a pilot flame) temperatures of many common materials, including PVC, as assessed by the Setchkin ignition test [5, 39–41]. Fire performance improves as either one of these ignition temperatures becomes larger.

Table 13.1 Flash Ignition and Self Ignition Temperatures (in °C) for Polymeric Materials Assessed with the ASTM D 1929 Test Method

Material	Flash ignition (°C)	Material	Self ignition (°C)
Polyethersulfone	560	Melamine, glass fiber laminate	634
Poly(vinylidene chloride)	532	Polycarbonate	580
Phenolic, glass fiber laminate	530	Phenolic, glass fiber laminate	575
Polyetherimide	520	Polypropylene fiber	570
Nylon 6	490	Polyacrylonitrile	560
Nylon 6,6	490	Polyethersulfone	560
Melamine, glass fiber laminate	487	Poly(phenylene sulphide)	540
Polyacrylonitrile	480	Polyetherimide	535
Polycarbonate	467	Poly(vinylidene chloride)	532
Polyamide (nylon)	421	Nylon 6,6	530
Poly(vinyl fluoride)	420	Polytetrafluoroethylene	530
Poly(vinyl chloride)	391	Polystyrene	492
Polyester, glass fiber laminate	372	Polystyrene beads	491
Styrene-acrylonitrile	366	Polystyrene foam (beadboard)	491
SBR	360	Polyester, glass fiber laminate	485
Polystyrene	352	Poly(vinyl fluoride)	480
Polyethylene	349	Cellulose acetate	475
Polystyrene foam (beadboard)	346	ABS	466
Acetal homopolymer	323	Poly(methyl methacrylate)	456
Polyurethane, polyether rigid foam	310	Poly(vinyl chloride)	454
Cellulose acetate	305	Styrene-acrylonitrile	451
Polystyrene beads	296	Nylon 6	450
Ethyl cellulose	291	SBR	450
Poly(methyl methacrylate	290	Polyamide (nylon)	424
Douglas fir	260	Polyurethane, polyether rigid foam	416
Cellulose nitrate	141	Red oak	416
		Acetal homopolymer	376
		Polyethylene	349
		Ethyl cellulose	296
		Cellulose nitrate	141

Table 13.2 presents a set of 35 materials used in a series of experiments (Series I) [36]. The materials (34 plastics and Douglas fir wood) were all commercial materials in the late 1980s and early 1990s and included 12 vinyls (labeled as "V" in this table and in several of the subsequent tables).

Table 13.2 Materials Used in Series I of Experiments
(Samples are 6 mm Thick Unless Noted Differently)

#	Abbreviation	V or NV	Description and source (including trade name)
1	PTFE	NV	Polytetrafluoroethylene sheet (samples were two sheets at 3 mm thickness each, Du Pont)
2	VTE 3	V	Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of the third of several families of VTE alloys
3	VTE 2	V	Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of the second of several families of VTE alloys
4	VTE 4	V	Semi flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of a family of VTE alloys containing CPVC
5	PCARB	NV	Polycarbonate sheeting (Lexan 141-111, General Electric)
6	VTE 1	V	Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of the first of several families of VTE alloys
7	CPVC	V	Chlorinated poly(vinyl chloride) sheet compound (BFGoodrich)
8	PVC CIM	V	Poly(vinyl chloride) general purpose rigid custom injection molding compound with impact modifier additives (BFGoodrich)
9	PVC WC FR	V	Flexible wire and cable poly(vinyl chloride) compound (containing fire retardants) (BFGoodrich)
10	PVC LS	V	Poly(vinyl chloride) rigid experimental sheet extrusion compound with smoke suppressant additives (BFGoodrich)
11	XLPE	NV	Black non-halogen flame retardant, irradiation crosslinkable, polyethylene copolymer cable jacket compound (DEQD-1388, Union Carbide)
12	PVC WC SM	V	Flexible wire and cable poly(vinyl chloride) compound (containing minimal amounts of fire retardants) (BFGoodrich)
13	PVC EXT	V	Poly(vinyl chloride) rigid weatherable extrusion compound with minimal additives (BFGoodrich)
14	PVC WC	V	Flexible wire and cable poly(vinyl chloride) compound (non fire retarded) (BFGoodrich)

Table 13.2 (continued)

#	Abbreviation	V or NV	Description and source (including trade name)
15	ACR FR	NV	Kydex: fire retarded acrylic panelling, blue (samples were 4 sheets at 1.5 mm thickness each, Kleerdex)
16	PCARB B	NV	Commercial polycarbonate sheeting (Commercial Plastics)
17	PPO GLAS	NV	Blend of polyphenylene oxide and polystyrene containing 30% fiberglass (Noryl GFN-3-70, General Electric)
18	PPO/PS	NV	Blend of polyphenylene oxide and polystyrene (Noryl N190, General Electric)
19	ABS FV	NV	Polymeric system containing acrylonitrile butadiene styrene and some poly(vinyl chloride) as additive
20	ABS FR	NV	Cycolac KJT acrylonitrile butadiene styrene terpolymer fire retarded with bromine compounds (Borg Warner)
21	FL PVC	V	Standard flexible poly(vinyl chloride) compound (non-commercial; similar to a wire and cable compound) used for various sets of testing (including Cone Calorimeter RHR ASTM round robin; it contains PVC resin 100 phr; diisodecyl phthalate 65 phr; tribasic lead sulphate 5 phr; calcium carbonate 40 phr; stearic acid 0.25 phr
22	DFIR	NV	Douglas fir wood board
23	PS FR	NV	Fire retarded polystyrene, Huntsman 351 (Huntsman)
24	ACET	NV	Polyacetal: polyformaldehyde (Delrin, Commercial Plastics)
25	PU	NV	Polyurethane flexible foam, non fire retarded (Jo-Ann Fabrics)
26	PMMA	NV	Poly(methyl methacrylate) (25 mm thick, lined with cardboard, standard RHR sample)
27	THM PU	NV	Thermoplastic polyurethane containing fire retardants (estane, BFGoodrich)
28	NYLON	NV	Nylon 6,6 compound (Zytel 103 HSL, Du Pont)
29	ABS	NV	Cycolac CTB acrylonitrile butadiene styrene terpolymer (Borg Warner)
30	PS	NV	Polystyrene, Huntsman 333 (Huntsman)
31	EPDM	NV	Copolymer of ethylene propylene diene rubber (EPDM) and styrene acrylonitrile (SAN) (Rovel 701)
32	PBT	NV	Polybutylene terephthalate sheet (Celanex 2000-2 polyester, Hoechst Celanese)
33	PET	NV	Polyethylene terephthalate soft drink bottle compound
34	PE	NV	Polyethylene (Marlex HXM 50100)
35	PP	NV	Polypropylene (Dypro 8938)

Table 13.3 shows the time-to-ignition (at 3 incident heat fluxes) in the cone calorimeter, using ASTM E1354 (cone calorimeter) [35], for the 35 materials shown in Table 13.2. Materials that do not ignite under the heat flux to which they have been exposed are shown as having an (arbitrary) time to ignition of 10,000 s. Table 13.3 also shows the minimum ignition flux to cause ignition within 100 s or 600 s, from the same test method. While a higher time to ignition represents better ignitability performance, the opposite is true for the critical ignition flux: the higher the better. It should be noted that the value presented for the extrapolation of the critical flux for ignition is not reliable under 15 kW/m^2, so all such data are shown as "≤ 15 kW/m^2".

Table 13.4 shows a set of wire and cable materials used in Series II of experiments, which included a number of fire tests [42, 43]. This series of tests was intended to compare the results of halogenated and non-halogenated materials, and included six PVC materials (again labeled as "V"). The ignitability results are shown in Tables 13.5 through 13.8.

In Table 13.5 are presented the Setchkin ignition test results (temperatures for both self-ignition and flash ignition, similar to what was shown in Table 13.1). Table 13.6 shows the IEC glow wire and needle flame tests. In the case of the glow wire ignition test (IEC 60695-2-10), the information shown is the temperature (in °C) at which the coated wire ignites, and the thickness of the coating required for ignition (either 1 or 3 mm). In the case of the needle flame ignition test (IEC 60695-2-2), the information shown is whether ignition occurred and whether it happened with edge flames (E) or with facing flames (F), as well as the thickness of the coating required for ignition (either 1 or 3 mm). The edge flames are a more severe ignition source than the facing flames, so that if there is no ignition with edge flames, ignition will not occur with facing flames. Similarly, ignition becomes more likely the thinner the sample, so that if ignition does not occur at 1 mm, it will not occur at 3 mm thickness, but the reverse is not the case. Table 13.7 shows the time to ignition at five different incident heat fluxes in the ISO 5657 radiant cone test (10, 20, 30, 40, and 50 kW/m^2). Just like for the cone calorimeter (Table 13.3), longer times correspond to better fire performance. Table 13.8 contains the critical ignition heat flux and the times to ignition at three incident heat fluxes in the cone calorimeter for the materials of Series II; the heat fluxes are 30, 40, and 50 kW/m^2. This data is similar to the data shown in Table 13.3 for other materials, but the critical flux for ignition is reported at low heat fluxes, even though this data is not very reliable.

Table 13.3 Ignitability of Materials from Series I (Table 13.2) in the Cone Calorimeter

	Time to ignition (in s) at heat flux			Heat flux (in kW/m^2) for a time to ignition of	
	20 kW/m^2	40 kW/m^2	70 kW/m^2	600 s	100 s
PTFE NV	10,000	10,000	252	63	83
VTE 3 V	10,000	1,212	17	45	64
VTE 2 V	10,000	1,253	424	60	110
VTE 4 V	10,000	10,000	1,583	86	115
PCARB NV	10,000	182	75	34	43
VTE 1 V	10,000	1,271	60	47	65
CPVC V	10,000	621	372	42	90
PVC CIM V	5,159	73	45	30	39
PVC WC FR V	236	47	12	≤ 15	31
PVC LS V	5171	187	43	33	44
XLPE NV	750	105	35	22	40
PVC WC SM V	176	36	14	≤ 15	27
PVC EXT V	3591	85	48	30	39
PVC WC V	117	27	11	≤ 15	22
ACR FR NV	200	38	12	≤ 15	28
PCARB B NV	6400	144	45	32	42
PPO GLAS NV	465	45	35	18	33
PPO/PS NV	479	87	39	17	38
ABS FV NV	5198	61	39	30	38
ABS FR NV	212	66	39	≤ 15	33
FL PVC V	102	21	15	≤ 15	20
DFIR NV	254	34	12	≤ 15	29
PS FR NV	244	90	51	≤ 15	38
ACET NV	259	74	24	≤ 15	35
PU NV	12	1	1	≤ 15	≤ 15
PMMA NV	176	36	11	≤ 15	27
THM PU NV	302	60	38	≤ 15	34
NYLON NV	1,923	65	31	27	37
ABS NV	236	69	48	≤ 15	34
PS NV	417	97	50	15	40
EPDM/SAN NV	486	68	36	18	36
PBT NV	609	113	59	20	41
PET NV	718	116	42	22	42
PE NV	403	159	47	≤ 15	50
PP NV	218	86	41	≤ 15	37

Table 13.4 Wire and Cable Materials Used in Series II of Experiments

#	Abbreviation	V or NV	Description	Tradename, manufacturer
36	PVC WC FRRA	V	Fire Retarded Reduced Acid Emission Cable Grade PVC	FRiLA VN 383/1, Hydro
37	PVC WC FRRA 2	V	Fire Retarded Reduced Acid Emission Cable Grade PVC	Evicom (EV2/410), EVC
38	PVC WC FR2	V	Fire Retarded Cable Grade PVC	Evicom (EV2/100), EVC
39	PVC WC FRRA 3	V	Fire Retarded Reduced Acid Emission Cable Grade PVC	FRiLA VN 381, Hydro
40	PVC WC	V	Flexible PVC, Conventional Cable Grade	Hyvin VN 336/3, Hydro
41	CSPE	NV	Chlorosulphonated Polyethylene	Hypalon, Du Pont
42	PTFE	NV	Polytetrafluoroethylene	Teflon, Du Pont
43	LDPE	NV	Low Density Polyethylene, Standard Cable Grade	DFDS 1169, Neste
44	EVA ATH+	NV	EVA Copolymer + Low Level Alumina Trihydrate Filler	NEWS 1386, Neste
45	EPR ATH++	NV	EPR Copolymer + High Level Alumina Trihydrate Filler	D 2983 FR sheathing grade, BP
46	EVA ATH++	NV	EVA Copolymer + High Level Alumina Trihydrate Filler	Megolon S2 UV stabilised, Lindsay & Williams
47	EVA ATH Si	NV	EVA Copolymer + Alumina Trihydrate Silane Cross-linked	500/424, AEI
48	ECA ATH Perox	NV	EVA Copolymer + Alumina Trihydrate Peroxide Cross-linked	G-328, STK
49	FEP	NV	Fluorinated Ethylene Propylene	FEP, Du Pont
50	EMA	NV	EMA Copolymer + Alumina Trihydrate (Thermoplastic)	WCZ 628, DuPont
51	PPO PS Cab	NV	Polyphenylene Oxide Polystyrene Copolymer Cable Grade	Noryl PX 17/166, General Electric
52	EVA ATH+++	NV	EVA Copolymer + High Level Alumina Trihydrate Filler	Megolon S300, Lindsay & Williams
53	VTE Cab	V	Fire Retarded Smoke Suppressed PVC Cable Grade Alloy	Flexel 1010, BFGoodrich
54	XLPO Inorg	NV	Polyolefin Copolymer + Inorganic Filler (Cross-Linked)	DQDB 1388, Union Carbide
55	PO Mg	NV	Polyolefin Copolymer + Magnesium Hydroxide Filler	DEFD 1736, Union Carbide
56	PEEK	NV	Polyether Ether Ketone	PEEK, ICI

Table 13.5 Flash Ignition and Self Ignition Temperatures (in °C) for Wire and Cable Compounds in Series II (Table 13.4), Assessed with the ASTM D 1929 Test Method

Material #	Flash ignition (°C)	Self ignition (°C)
36 V	400	410
37 V	375	410
38 V	400	430
39 V	340	385
40 V	330	385
41 NV	400	415
42 NV	530	540
43 NV	350	370
44 NV	400	420
45 NV	390	420
46 NV	390	420
47 NV	405	420
48 NV	400	435
52 NV	706	No ignition

Table 13.6 Ignition Test Results for Coated Wires from Cable Compounds in Series II (Table 13.4), as Assessed with IEC 60695-2-10 and IEC 60695-2-2

Material #	Glow wire ignition		Needle flame ignition			
	Temperature (°C)	Thickness (mm)	Edge	Thickness (mm)	Face	Thickness (mm)
37 V	960	3	NI	1.3		
38 V	960	1.3	NI	1.3		
39 V	960	1.3	NI	1.3		
40 V	960	3	NI	1.3		
41 NV	960	3	I	1.3	I	3
42 NV	960	1.3	NI	1.3		
43 NV	960	1.3	NI	1.3		
44 NV	850	1.3	I	1.3	I	1.3
45 NV	850	1	I	1.3	I	1.3
46 NV	850	1	I	1.3	I	1
47 NV	960	1.3	I	1	I	
48 NV	850	1	I	1.3		
49 NV			I	1		
52 NV	750	1	I	3		
53 V	960	3	NI	1.3		

Table 13.7 Ignition Test Results for Coated Wires from Cable Compounds in Series II (Table 13.4), as Assessed with the ISO 5657 Radiant Ignitability Cone

	Time to ignition (in s) at heat flux				
	10 kW/m^2	20 kW/m^2	30 kW/m^2	40 kW/m^2	50 kW/m^2
37 V	NI	150	62	35	23
38 V	NI	130	48	30	17
39 V	NI	170	75	42	26
40 V	NI	125	53	32	19
41 NV	NI	125	58	35	23
42 NV	NI	160	83	53	28
43 NV	NI	NI	NI	330	193
44 NV	NI	250	127	78	54
45 NV	NI	250	137	85	63
46 NV	NI	195	128	78	56
47 NV	NI	650	230	135	100
48 NV	NI	424	181	98	74
49 NV	NI	300	143	83	60
52 NV	NI	NI	NI	NI	1,766
53 V	NI	NI	NI		

Table 13.8 Ignitability of Materials from Series II (Table 13.4) in the Cone Calorimeter

Material #	Critical flux for ignition (kW/m^2)	Time to ignition (in s) at heat flux		
		30 kW/m^2	40 kW/m^2	50 kW/m^2
36 V	9.4	110	59	38
37 V	9.2	75	44	29
38 V	15.1	82	63	39
39 V	7.7	68	38	20
40 V	5.9	64	30	23
41 NV	12.9	99	58	42
42 NV	25.4	10,000	439	250
43 NV	9.8	103	67	50
44 NV	16.4	123	80	52
45 NV	12.9	105	60	48
46 NV	5.5	346	144	110
47 NV	13.6	231	139	97
48 NV	21.2	155	93	53
53 V	86	10,000	10,000	1,000

Table 13.9 also shows times to ignition of two series of materials in the cone calorimeter, with the data corresponding to seven wall lining materials, also tested in a room corner configuration (Series III).

Table 13.10 contains another series of wire and cable compounds (Series IV), used for cone calorimeter testing, for which the ignition data is presented in Table 13.11.

The abundant data presented makes it clear that PVC materials tend to be difficult to ignite, unless they have been extensively plasticized and not fire retarded. Summary of ignition properties for PVC:

Rigid PVC:

- Flash ignition temperature: 391 °C
- Self ignition temperature: 454 °C
- Time to ignition, ASTM E 1354 @ 20 kW/m^2: 450–10,000 s
- Time to ignition, ASTM E 1354 @ 40 kW/m^2: 47–187 s
- Time to ignition, ASTM E 1354 @ 70 kW/m^2: 12–45 s
- Critical heat flux, ASTM E 1354 30–33 kW/m^2

Flexible PVC:

- Flash ignition temperature: 330–400 °C
- Self ignition temperature: 385–430 °C
- Time to ignition, ASTM E 1354 @ 20 kW/m^2: 102–10,000 s
- Time to ignition, ASTM E 1354 @ 40 kW/m^2: 21–10,000 s
- Time to ignition, ASTM E 1354 @ 70 kW/m^2: 12–424 s
- Critical heat flux, ASTM E 1354 < 15–86 kW/m^2

Table 13.9 Time to Ignition (in s) in the Cone Calorimeter of Wall Lining Materials from Series III

		Heat flux			
		20 kW/m^2	**25 kW/m^2**	**40 kW/m^2**	**70 kW/m^2**
Rigid PVC	57 V	451	152	47	20
Wood panel	58 NV	276	135	39	17
Low smoke PVC	59 V	4,280	1,019	49	12
CPVC	60 V	10,000	344	170	60
Polycarbonate	61 NV	2,167	993	80	26
FR ABS	62 NV	690	77	38	12
FR acrylic panelling (with PMMA and PVC)	63 NV	986	83	23	10

Table 13.10 Wire and Cable Materials Used in Series IV of Experiments (Samples Are 3 mm Thick)

#	Abbreviation	V or NV	Description and source (including trade name)
64	XLPO Hydr	NV	Cross linked olefin elastomer with a metal hydrate (BP Exp. 839)
65	HDPE/Cl	NV	Blend of high density polyethylene and chlorinated polyethylene elastomer (Dow 5435-30-11)
66	CPE Fill	NV	Chlorinated polyethylene with fillers (Dow 5348-40-1)
67	EVA ATH	NV	Ethylene vinyl acetate polyolefin with aluminum trihydrate filler (Exxon EX-FR-100)
68	PPO/PS	NV	Polyphenylene oxide/polystyrene blend (General Electric Noryl® PX1766)
69	PEI	NV	Polyetherimide (General Electric Ultem® 1000)
70	PEI/Si	NV	Polyetherimide/siloxane copolymer (General Electric Siltem® STM 1500)
71	PP Int	NV	Intumescent polypropylene (Himont Exp. 127–32-6)
72	PO Fill	NV	Polyolefin copolymer with mineral filler (Union Carbide Unigard RE® DFDA 1735 NT)
73	XLPO Min Fill	NV	Cross-linked polyolefin copolymer with mineral filler (Union Carbide Unigard RE® HFDA-1393 BK)
74	XLPO ATH1	NV	Cross-linked polyolefin copolymer with aluminum trihydrate filler (Quantum Petrothene® XL 7403)
75	XLPO ATH2	NV	Cross-linked polyolefin copolymer with aluminum trihydrate filler (Quantum Petrothene® YR 19535)
76	EVA Min Fill	NV	Ethylene vinyl acetate polyolefin copolymer with mineral filler (Quantum Petrothene® YR 19543)
77	PO Min Fill	NV	Polyolefin with mineral filler (Union Carbide Ucarsil® FR-7920-NT)
78	XLPE/Cl	NV	Cross-linked polyethylene copolymer with chlorinated additive (BP Polycure® 798)
79	PVDF	NV	Commercial polyvinylidene fluoride material
80	PTFE	NV	Commercial polytetrafluoroethylene material
81	PVC Flex	V	Commercial FR flexible wire and cable poly(vinyl chloride) material
82	PE	NV	Polyethylene homopolymer (Union Carbide DGDK – 3364 NT)
83	DFIR	NV	Douglas fir wood
84	EVA PO	NV	Ethylene vinyl acetate polyolefin copolymer (Quantum Ultrathene® UE 631)
85	NYLON 2	NV	Nylon 6,6 (Nylet P50)
86	XLPO Br	NV	Cross-linked polyethylene copolymer with brominated additive (Union Carbide Unigard HP® HFDA-6522-NT)
87	PVC Flex 2	V	Commercial non FR flexible wire and cable poly(vinyl chloride) material
88	PVC Flex 3	V	Commercial non FR flexible wire and cable poly(vinyl chloride) material

Table 13.11 Time to Ignition (in s) in the Cone Calorimeter of Wall Lining Materials from Series IV (Table 13.10)

Material #	Heat flux	
	25 kW/m^2	50 kW/m^2
64 NV	392	94
65 NV		51
66 NV	179	34
67 NV		89
68 NV		60
69 NV	10,000	191
70 NV		173
71 NV	127	25
72 NV		110
73 NV	410	117
74 NV	618	135
75 NV		72
76 NV		60
77 NV		91
78 NV		83
79 NV	10,000	10,000
80 NV	10,000	227
81 V	10,000	31
82 NV	220	56
83 NV		22
84 NV	195	52
85 NV		80
86 NV	448	108
87 V	108	29
88 V	498	63

13.5.1 Ease of Extinction

Once ignited, the easier it is to extinguish a material, the lower the fire hazard a product made from it will cause. ASTM D 2863 [44] is used to determine the oxygen index (or LOI, Fig. 13.5), which is the minimum oxygen concentration (in a flowing mixture of oxygen and nitrogen) required to support candle-like downward flaming combustion.

Thus, in principle, a material with limiting oxygen index values above 25–7 should only burn under extreme conditions. In reality, the test serves as a measure of the ease of extinction of the material. The small specimen is placed vertically inside a glass column and ignited at the top with a small gas flame. This test method has excellent repeatability and reproducibility and can generate numerical data covering a very broad range of fire performance. However, once more, the test method is inappropriate as a predictor of real scale fire performance, mainly because of the low heat input and the artificiality of the high oxygen environments used. It is widely required in specifications and quoted in data sheets and is suitable as a quantitative quality control tool during manufacturing, and as a semi-qualitative indicator of the effectiveness of additives, during research and development, for low incident energy situations.

Table 13.12 shows results on a number of common materials [41] and Table 13.13 shows results of the wire and cable materials in Series II. Table 13.13 also contains the results of ISO 4589-3 [45], a method which assesses the LOI at a variety of temperatures. The combination of these results allows a prediction of the flammability temperature, at which the LOI has a predicted value of 21, and the percentage of ash remaining after the test.

It is of note that PVC materials exhibit extremely high LOI values (again, unless plasticized and not fire retarded). Summary of ease of extinction properties for PVC:

Rigid PVC:
LOI: 45–48

Flexible PVC:
LOI: 25–49

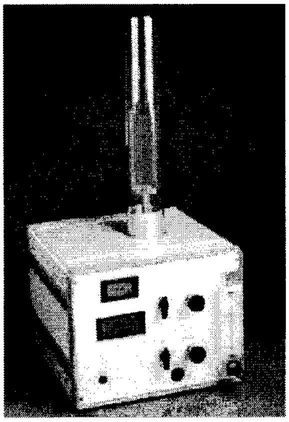


Figure 13.5 Limiting oxygen index test (LOI) (ASTM D 2863)

Table 13.12 Limiting Oxygen Index (ASTM D 2863) of a Variety of Materials

Material – Description and #	V or NV	LOI
Polyoxymethylene	NV	15.7
Polyacetal # 24	NV	15.8
Cotton	NV	16.5
Polyethylene # 34	NV	17.0
Polypropylene # 35	NV	17.1
Natural Rubber	NV	17.2
ABS # 29	NV	17.6
Polystyrene # 30	NV	17.7
PMMA # 26	NV	17.9
Polyacrylonitrile	NV	18.0
SAN	NV	18.0
Rayon	NV	18.8
Cellulose	NV	19.0
PET	NV	20.0
PVF	NV	22.6
Nylon 6,6	NV	25.1
Wool	NV	25.2
Polycarbonate	NV	26.2
Neoprene rubber	NV	26.3
Modacrylic	NV	26.8
Nomex	NV	28.5
Polysulphone	NV	31.1
Leather (FR)	NV	34.8
Polyimide	NV	36.5
PVDF	NV	43.7
PVC (rigid)	V	47.0
VTE 2 # 3	V	48.0
VTE 4 # 4	V	49.4
Carbon black rod	NV	59.9
PVDC	NV	60.0
CPVC # 7	V	62.2
PTFE # 1	NV	95.0

Table 13.13 Oxygen Index of Wire and Cable Materials in Series II (Table 13.4)

Material #	Abbreviation	V or NV	ASTM D 2863 LOI	ISO 4589-3					
				Oxygen Index @ Indicated Temperature (in °C)				Flammability temperature (°C)	Ash content (%)
				100	200	300	400		
36	PVC WC FRRA	V	32	30	26	23	19	350	28.2
37	PVC WC FRRA 2	V	32	30	26	21		300	28.6
38	PVC WC FR2	V	36	33	30	25		370	27
39	PVC WC FRRA 3	V	29	26	23	21		300	30.5
40	PVC WC	V	25	23	20	17		180	29.6
41	CSPE	NV	30.5	28.5	25	21.5		330	42.4
42	PTFE	NV	99	85	62	49	367	400	0
43	LDPE	NV	17						
44	EVA ATH+	NV	35	29	24	19		250	38.3
45	EPR ATH++	NV	37	33	25	20		290	39.5
46	EVA ATH++	NV	46	42	35	25	20	380	45.2
47	EVA ATH Si	NV	30	27	23	18		240	35.8
48	ECA ATH Perox	NV	36	31	26	22		310	42.8
49	FEP	NV	95	81	65	50	35	490	0
50	EMA	NV	34	31	25	21		300	40.4
51	PPO PS Cab	NV	34	32	30	26	18	360	1.3
52	EVA ATH+++	NV	37.5	33	30	21.5	16	310	43.5
53	VTE Cab	V	49						
54	XLPO Inorg	NV	48						18.6
55	PO Mg	NV	50	41	37	30	23	430	45.8
56	PEEK	NV	35	31	26.5	20.5		280	46.6

13.5.2 Flammability

Once ignited, the greater the flammability of a material, the greater will be the hazard associated with it. Small-scale flammability tests extensively used for plastic materials are the family of UL 94 tests ([46] also standardized in ASTM, ISO and IEC, but most widely known from the UL standard, Figure 13.6).

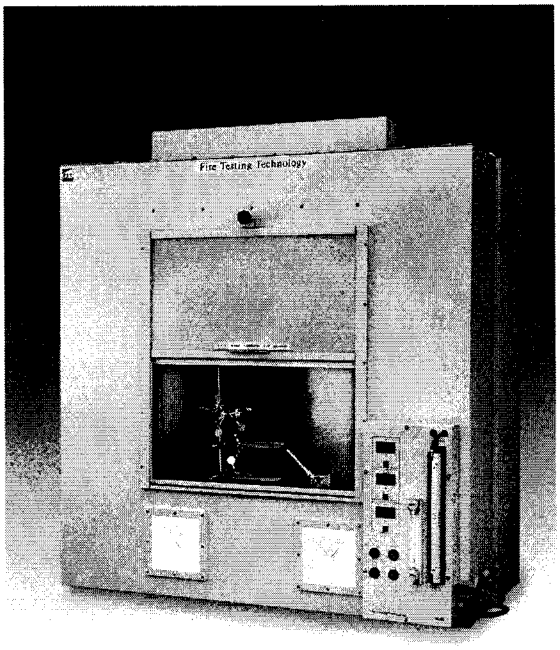


Figure 13.6 UL 94 flammability test cabinet

In this test, a small sample of material (127 mm × 13 mm, or 5 in × 0.5 in) is exposed vertically to a small Bunsen-burner type flame from underneath (in the UL 94 V test) and the results show a rating, ranging from V-0 (best), through V-1, V-2 to "B" (for Burn). Materials with a "B" rating on the UL 94 Vertical test can also be tested in the less severe UL 94 HB (for Horizontal burning), where the assessment is whether a flame spread rate of 4 inches per minute is achieved. It is the most widely used fire test specification for plastic materials, especially fire retarded ones, and forms the basis of the famous "Yellow Card" used by Underwriters Laboratories to list plastic materials. Results from these tests are almost invariably found in a variety of specifications and in data sheets.

Table 13.14 presents some UL 94 fire test results for wire and cable materials from Series II. Rigid PVC materials present a UL 94 V-0 rating down to the least thickness usually measured, typically 1 mm. Flexible PVC materials almost invariably will get a UL 94 V-1 rating, although it may get as low as a UL 94 V-2 rating for some non fire retarded materials. Many other materials will, of course, fail (or "Burn").

Rigid PVC:
UL 94: V-0

Flexible PVC:
LOI: V-2 to V-0

Table 13.14 UL 94 Flammability Test Results of Wire and Cable Materials in Series II (Table 13.4)

Material #	UL 94			
	V-0 @ 1 mm	V-0 @ 2 mm	V-0 @ 3 mm	HB (in/min)
36 V	V-0	V-0	V-0	
37 V	V-0	V-0	V-0	
38 V	V-0	V-0	V-0	
39 V	V-0	V-0	V-0	
40 V	V-1	V 2	V-0	
41 NV	V-1	V-0	V-0	
42 NV	V-0	V-0	V-0	
43 NV	B	B	B	2
44 NV	B			
45 NV	B			
46 NV	V-1	V-0	V-0	
46 NV	B	B	B	
48 NV	V-0	V-0	V-0	
51 NV	B	B	B	
52 NV	B	B	V-0	
53 V	V-0	V-0	V-0	

13.5.3 Flame Spread

The tendency of a material to spread a flame away from the fire source is critical to understand the potential fire hazard. Flame spread tests may refer to organic polymers themselves or to materials in diverse applications (such as textiles or electrical insulation sleeving), or to whole structures (such as furniture or building components). Most of the tests can be classified in terms of the angle between the exposed surface and the horizontal. Thus this angle may vary between 0°, for a horizontal material burning on its upper surface, through 180°, for a horizontal material burning on its lower surface, and 240°, for a material burning on its lower surface but rotated a further 60° from the horizontal, up to 270°, for a material burning vertically downwards [22]. This surface angle is closely related both to the extent to which the gaseous products of combustion heat the surface before the flame front reaches it and to the extent to which the hot gases penetrate into the polymer. Sample sizes range widely, from very small to quite large (7.3 m × 0.56 m, or 24 ft × 22 in, ASTM E 84 [47], Steiner tunnel, a test very widely used for specifications and building code requirements, see Fig. 13.7).

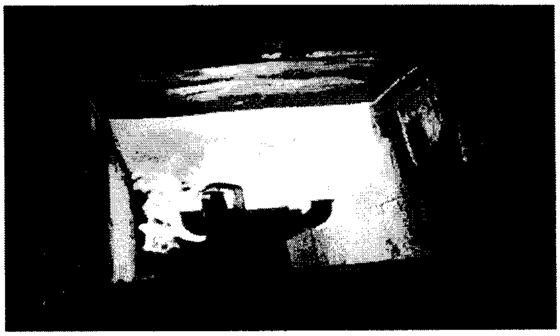


Figure 13.7 Burner for Steiner tunnel test (ASTM E 84)

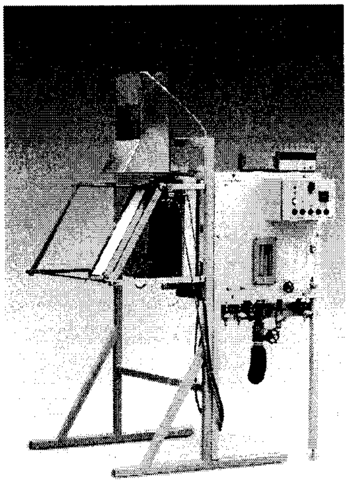


Figure 13.8 Radiant panel test (ASTM E 162)

Two other test apparatuses are also suitable to assess flame spread of materials: the ones in ASTM E 162 [48], radiant panel (Figure 13.8) (which is also used for cellular plastics in ASTM D 3675 [49]) and in ASTM E 1321 [38], also known as the Lateral Ignition and Flame Spread Test, or LIFT.

The Steiner tunnel test method (ASTM E 84 [47]) was developed by Al Steiner for building materials [50], such as wood or gypsum board. It has been adopted by every building and fire code in the USA. It is perhaps the most widely accepted test for surface flammability in North America, and there are a large number of applications tests developed from it. The most famous is the one used for electrical cables needed for plenum use (NFPA 262, formerly also known as UL 910 [51]), and there are also application tests for pneumatic tubing, sprinkler piping, and so on. The specimen in ASTM E 84 is a building material (normally up to 0.15 m thick), either in one unbroken length or in separate sections joined end to end, which is mounted face downwards so as to form the roof of a horizontal tunnel 305 mm high. The fire source, two gas burners, ignites the sample from below with an 89 kW fire source. When plastics started being used in construction, this test was applied to them, in spite of the fact that it is not always appropriate. For example, samples that cannot be retained in place above the tunnel floor, or which melt and continue burning on the tunnel floor (typical behavior for most thermoplastics) are still being tested with this equipment in spite of the results being misleading. It can also produce wrong results for thin materials [52]. The normal output is a flame spread index (FSI), calculated based on the area under the flame spread distance vs. time curve. The FSI index is a relative number based on an FSI = 0 for cement board and FSI = 100 for red oak flooring. Results are used, in the codes, as classes, with Class A being an FSI of up to 25, Class B being an FSI of 26 up to 75 and Class C being an FSI of 76 up to 200. The test method also assesses smoke obscuration, and assigns a smoke developed index (SDI), based on a similar concept to the FSI. To be classified as Class A, B, or C, a material must have an SDI not exceeding 450. Results of a variety of materials in the Steiner tunnel test are shown in Table 13.15; the results are presented on the basis of the "flame spread index" (or FSI).

ASTM Test Method E 162 [48] is also used to determine a flame spread index, albeit different from the one assessed by the Steiner tunnel, which is why it is now known as the radiant panel index. The flame spread index is calculated as the product of a "flame spread factor" and a "heat evolution factor", using techniques described in the standard. The test apparatus consists of a gas-fed radiant panel in front of which an inclined (at a 30° angle) specimen (150 × 460 mm) is exposed to a radiant flux equivalent to a black body temperature of 670 °C (943 °K), namely approx. 45 kW/m^2, in the presence of a small gas pilot flame. The maximum thickness that can be tested in the normal specimen holder is 25 mm, but alternative specimen holders can accommodate thicker specimens. The ignition is forced near the upper edge of the specimen and the flame front progresses downward. The radiant panel index (I_s) (formerly flame spread index) is calculated as the product of a flame spread factor, which results from the measurements of flame front position and time, and a heat evolution factor, which is proportional to the maximum temperature measured in the exhaust stack. This test has also not been shown to be an adequate predictor of real scale fire performance. If the specimen melts or causes flaming drips, this is likely to affect the flame spread in a way that is uneven. The test method simply requires that such events be reported. Moreover, if flame spread is very rapid, the flame spread value is potentially lost unless recording is continuous. This apparatus is often referred to as the radiant panel, and results from this test are frequently required in regulations, particularly for transportation environments (both foamed and rigid materials) and detention environment specifications (foamed materials) and are quoted in data sheets. Results from this test for some materials are shown in Table 13.16 [41].

The LIFT apparatus (Lateral Ignition and Flame Spread Test, ASTM E 1321 [38]) was developed as an improvement on the apparatus in ASTM E 162 [53]. The specimen size for flame spread studies is 155 × 800 mm by a maximum thickness of 50 mm (and a smaller specimen is used for ignition studies). The test method determines the critical flux for flame spread, the surface temperature needed for flame spread, and the thermal inertia or thermal heating property (product of the thermal conductivity, the density, and the specific heat) of the material under test.

Table 13.15 Flame Spread Index Test Results from the ASTM E 84 (Steiner Tunnel) Test

Material/Product	Flame spread index range	
	Low	High
ABS	200	275
Douglas fir/cedar plywood	190	230
Ponderosa pine A	170	230
Acrylic plastic	220	
Northern white pine A	190	215
Southern yellow pine	130	195
Hemlock/cedar plywood	190	
Red oak flakeboard	70	190
Poplar	170	185
Particleboard	135	180
Northern white pine B	120	180
Modified polyphenyl oxide	170	
Lauan hardwood	150	170
Ponderosa pine B	105	170
Red Gum (25 mm)	140	155
Cypress (25 mm)	145	150
Plywood panelling over gypsum	130	150
Red pine	140	
Walnut	130	140
Douglas fir overlay	110	140
Vinyl faced plywood	110	130
Polycarbonate	80	120
Cottonwood (25 mm)	115	
Polyether imide	110	
Yellow birch (25 mm)	105	110
Maple flooring	105	
Western spruce	100	
Red oak flooring (20 mm)	100	100
Douglas fir (25 mm)	70	100

Table 13.15 (continued)

Material/Product	Flame spread index range	
	Low	**High**
ABS FR	10	100
Lodgepole pine	95	
Eastern white pine	85	
Pacific yellow cedar (25 mm)	80	
Cellulose fiberboard ceiling tile	70	80
Western white pine	75	
Western red cedar (25 mm)	70	
Pacific silver fir (25 mm)	70	
Varnished pine (10 mm)	70	
Redwood	65	70
West coast hemlock (25 mm)	60	70
Fire retarded polycarbonate	10	65
FR Polyester B	35	45
FR Treated plywood (6 mm)	40	
Vinyl faced wallboard	20	35
FR Polyester A	20	30
PVC wallcovering on gypsum board	10	25
PVC rigid profile	15	20
Polypropylene scrim foil	15	20
Cellulosic ceiling tile (15 mm)	15	
Phenolic foam (38 mm)	15	
Gypsum wallboard	10	20
Polypropylene scrim kraft paper	10	15
PVC siding (1 mm)	10	15
PVC vapor barrier	10	15
PVC sheet (3 mm)	5	10
Polyimide foam (51 mm)	0	
Mineral wool unfaced (51 mm)	0	0
Asbestos cement board	0	0

Table 13.16 Radiant Panel Index Test Results from the ASTM E 162 Test

Material	Thickness (mm)	Flame spread index
Chlorinated PVC	3	4
Polyether sulphone	3	5
PVC (rigid)	4	10
Polyester	3	43
FR polystyrene	3	59
FR polycarbonate	6	73
Modified polyphenylene oxide	6	84
Polycarbonate	3	88
Red oak	19	99
Phenolic resin	2	114
ABS	6	131
Plywood (fir)	6	143
Hardboard	6	185
GRP polyester (21%)	2	239
FR acrylic	3	316
Polystyrene	2	355
Acrylic	6	416
Polyurethane foam (flexible)		1490
Polyurethane foam (rigid)		2220

These properties are mainly used for assessment of fire hazard and for input into fire models. A flame spread parameter, Φ, is also determined, and this can be used as a direct way of comparing the responses of the specimens. This test method appears well-suited for materials (or composites), which are non-melting and which can be ignited without raising the incident flux to potentially dangerous limits. It has been used successfully for predictions of full-scale flame spread performance [54].

Rigid PVC:
ASTM E 84: FSI: < 25
ASTM E 162: I_s: 10–25

Flexible PVC:
ASTM E 84: FSI: < 25–40
ASTM E 162: I_s: 10–50

13.5.4 Heat Release

The key question to ask in a fire is: "How big is the fire?" The critical fire property that presents the answer to that question is the maximum rate of heat release. A burning product will spread a fire to nearby products only if it gives off enough heat to ignite them. Moreover, the heat has to be released fast enough not to be dissipated or lost while traveling through the cold air surrounding any product that is not on fire. Therefore, fire hazard is dominated by the rate of heat release [55–58]. In fact, the rate of heat release has been shown to be much more important than either ease of ignition, smoke toxicity, or flame spread in controlling the time available for potential victims of a fire to escape [59]. In the late 1960s, Professor Edwin Smith, at The Ohio State University (OSU), developed the first bench-scale test instrument, the OSU rate of heat release (RHR) calorimeter (ASTM E 906 [37]), to measure rates of heat release [60].

Table 13.17 contains peak rate of heat release results for a variety of materials, at an incident heat flux of 20 kW/m^2, as measured in the OSU calorimeter [39, 61]. In the early 1980s, the National Institute of Standards and Technology (NIST, then National Bureau of Standards) developed a more advanced test method to measure rate of heat release: the cone calorimeter (ASTM E1354 [35, 61]). This fire test instrument can also be used to assess other fire properties, the most important of which are the ignitability (as discussed above), the mass loss, and the smoke released. Appendix 2 to this chapter contains the major fire properties from this test method, and a short explanation of each one of them. Moreover, results from this instrument correlate with those from full-scale fires [62–66]. In order to obtain the best overall understanding of the fire performance of materials, it is important to test the materials under a variety of conditions. Therefore, tests are often conducted at a variety of incident heat fluxes. The peak rates of heat release (and total heat released) of the materials in Series I at each incident flux are shown in Table 13.18.

Table 13.19 shows the fire performance index (FPI) for the same materials at all three fluxes; fire performance index (the ratio between the time to ignition and the peak rate of heat release) has been shown to be a reasonable first-order indicator of propensity to flashover [66, 67]. Similar to the time to ignition, better results in the fire performance index correspond to those materials with higher numbers. Equivalent heat release data for the materials in Series II, III, and IV are shown in Tables 13.20 through 13.22 and in Tables 13.23 through 13.25 for the fire performance index data.

A number of modern full-scale fire test methods have been developed for products, relying on rate of heat release measurements, such as those involving testing of upholstered furniture (ASTM E 1537 [68]), mattresses (ASTM E 1590 [69], stacking chairs (ASTM E 1822 [70]), electrical cables (ASTM D 5424 [71] and ASTM D 5537 [72]), plastic display stands (UL 1975 [73]), or wall lining products (NFPA 265 [74], NFPA 286 [75], ASTM E 2257 [76], and ISO 9705 [77]). In fact, room-corner tests (Figs. 13.9 to 13.11) are being used in the newest editions of the codes, as alternatives to replace the ASTM E 84 Steiner tunnel test, thus generating more useful results. Figure 13.9 shows a room-corner test layout, Fig. 13,10 shows the intensity of a flame once the test material has started to get involved, in a room corner test, and Fig. 13.11 shows a test material that has reached flashover and where flames are coming out of the doorway. The cone calorimeter fire performance index (with tests conducted at 50 kW/m^2) [78] was shown to be a good predictor of time to flashover in Federal Aviation Administration (FAA) full aircraft fires [67, 79] and in the ISO 9705 room-corner test [80].

Table 13.17 Ohio State University (ASTM E 906) Peak Rate of Heat Release Results at a Heat Flux of 20 kW/m^2

Material (#)	Peak RHR (kW/m^2)
PMMA (26)	586.8
PE (34)	476.9
PP (35)	451.2
EPDM (31)	402.8
PS (non FR) (30)	398.9
ABS (non FR) (29)	391.1
Polystyrene	376.7
ABS (non FR)	344.5
Polyester PBT (32)	316.0
Hardboard	227.1
Polycarbonate (5)	192.5
Polystyrene (FR)	189.3
PPO Glas (17)	170.4
THM PU (27)	158.1
ABS FV (19)	152.4
PPO/PS (18)	136.4
Polycarbonate	132.5
Plywood	113.6
PS (FR) (23)	103.8
Pine (25 mm)	79.5
Oak (25 mm)	79.5
Vinyl tile	75.7
ABS (FR) (20)	70.7
FL PVC (21)	56.8
Gypsum board	47.3
PVC CIM (8)	43.0
PVC EXT (13)	40.0
LS PVC (10)	39.3
VTE 4 (4)	17.5

Table 13.18 Heat Release of the Materials in Series I (Table 13.2) in the Cone Calorimeter (ASTM E 1354) at Three Incident Heat Fluxes

#	Material	Flux 20 kW/m^2		Flux 40 kW/m^2		Flux 70 kW/m^2	
		Pk RHR (kW/m^2)	T THR (MJ/m^2)	Pk RHR (kW/m^2)	THR (MJ/m^2)	Pk RHR (kW/m^2)	THR (MJ/m^2)
1	PTFE	3	0.3	13	11.7	161	69.1
2	VTE 3	4	5.1	43	31.5	70	48.8
3	VTE 2	9	5.7	64	66.1	100	39.0
4	VTE 4	14	13.2	87	25.9	66	57.4
5	PCARB	16	0.1	429	119.2	342	121.7
6	VTE 1	19	12.2	77	48.1	120	63.4
7	CPVC	25	14.7	84	37.4	93	44.9
8	PVC CIM	40	3.0	175	24.3	191	93.0
9	PVC WC FR	72	36.5	92	51.7	134	65.5
10	PVC LS	75	6.6	111	73.6	126	75.5
11	XLPE	88	87.6	192	126.2	268	129.2
12	PVC WC SM	90	49.0	142	75.4	186	73.4
13	PVC EXT	102	2.9	183	90.8	190	96.5
14	PVC WC	116	47.3	167	95.7	232	94.4
15	ACR FR	117	20.5	176	86.7	242	77.2
16	PCARB B	144	35.4	420	134.7	535	143.5
17	PPO GLAS	154	111.0	276	125.8	386	125.7
18	PPO/PS	219	103.6	265	128.5	301	134.3
19	ABS FV	224	80.7	291	108.5	409	114.1
20	ABS FR	224	38.3	402	70.3	419	61.0
21	FL PVC	233	116.4	237	98.2	252	86.3
22	DFIR	237	46.5	221	64.1	196	50.0
23	PS FR	277	93.0	334	94.5	445	82.0
24	ACET	290	143.9	360	141.3	566	167.1
25	PU	290	9.4	710	13.2	1221	13.3
26	PMMA	409	691.5	665	827.9	988	757.1
27	THM PU	424	110.0	221	119.3	319	120.1
28	NYLON	517	188.0	1313	226.3	2019	233.8
29	ABS	614	160.0	944	162.5	1311	162.5
30	PS	723	202.6	1101	210.1	1555	197.8
31	EPDM	737	213.1	956	199.8	1215	215.7
32	PBT	850	96.7	1313	169.9	1984	197.4
33	PET	881	93.3	534	113.7	616	125.5
34	PE	913	161.9	1408	221.0	2735	227.5
35	PP	1170	231.3	1509	206.9	2421	231.1

Table 13.19 Fire Performance Index of the Materials in Series I (Table 13.2) in the Cone Calorimeter (ASTM E 1354) at Three Incident Heat Fluxes

#	Material	Flux 20 kW/m^2	Flux 40 kW/m^2	Flux 70 kW/m^2
		FPI (s m^2/kW)	FPI (s m^2/kW)	FPI (s m^2/kW)
1	PTFE	6780	839	1.56
2	VTE 3	2850	36.4	0.24
3	VTE 2	1301	21.4	6.01
4	VTE 4	1027	115	24.3
5	PCARB	5173	0.43	0.22
6	VTE 1	591	16.7	0.49
7	CPVC	392	7.44	4.06
8	PVC CIM	1343	0.42	0.24
9	PVC WC FR	3.49	0.50	0.09
10	PVC LS	72.4	1.65	0.34
11	XLPE	8.08	0.55	0.13
12	PVC WC SM	1.96	0.25	0.07
13	PVC EXT	31.4	0.46	0.25
14	PVC WC	1.00	0.16	0.05
15	ACR FR	1.70	0.22	0.05
16	PCARB B	474	0.34	0.08
17	PPO GLAS	3.03	0.16	0.09
18	PPO/PS	2.45	0.33	0.13
19	ABS FV	66.3	0.21	0.10
20	ABS FR	0.93	0.16	0.09
21	FL PVC	0.44	0.09	0.06
22	DFIR	1.10	0.15	0.06
23	PS FR	0.90	0.27	0.11
24	ACET	0.90	0.20	0.04
25	PU	0.04	0.0014	0.0008
26	PMMA	0.43	0.05	0.01
27	THM PU	0.72	0.28	0.12
28	NYLON	3.85	0.05	0.02
29	ABS	0.38	0.07	0.04
30	PS	0.58	0.09	0.03
31	EPDM	0.66	0.07	0.03
32	PBT	0.75	0.09	0.09
33	PET	0.82	0.22	0.07
34	PE	0.44	0.06	0.02
35	PP	0.19	0.06	0.02

Table 13.20 Heat Release of the Wire and Cable Materials in Series II (Table 13.4) in the Cone Calorimeter (ASTM E 1354) at Three Incident Heat Fluxes

Material #	Flux 30 kW/m²		Flux 40 kW/m²		Flux 50 kW/m²	
	Pk RHR (kW/m²)	THR (MJ/m²)	Pk RHR (kW/m²)	THR (MJ/m²)	Pk RHR (kW/m²)	THR (MJ/m²)
36 V	182.4	52.8	220.2	68.2	170.2	35.8
37 V	143.0	30.8	170.6	39.2	153.6	32.8
38 V	221.7	42.9	208.2	39.2	252.4	39.2
39 V	235.2	46.6	98.5	41.7	276.9	53.8
40 V	189.1	53.6	282.7	81.6	250.2	63.2
41 NV	139.6	33.1	151.5	55.8	150.2	57.1
42 NV	10.0	2.0	63.5	13.8	62.6	13.1
43 NV	868.8	137.6	1162.4	136.5	1532.1	155.8
44 NV	256.3	94.5	300.1	106.5	275.9	87.9
45 NV	196.4	88.0	275.5	89.6	342.3	98.9
46 NV	189.2	57.4	225.9	89.4	191.8	53.3
47 NV	505.4	129.8	548.3	108.4	365.8	89.2
48 NV	206.0	50.9	172.3	59.9	196.0	68.3
53 V	20.0	2	87.0	25.9	100.0	27

Table 13.21 Heat Release of the Wall Lining Materials in Series III (Table 13.9) in the Cone Calorimeter (ASTM E 1354) at Four Incident Heat Fluxes

Material #	Flux 20 kW/m²		Flux 25 kW/m²		Flux 40 kW/m²		Flux 70 kW/m²	
	Pk RHR (kW/m²)	THR (MJ/m²)	Pk RHR (kW/m²)	THR (MJ/m²)	Pk RHR (kW/m²)	THR (MJ/m²)	Pk RHR (kW/m²)	THR (MJ/m²)
57 V	109	12	105	21	224	26	270	31
58 NV	385	85	367	78	435	140	661	139
59 V	62	21	54	34	91	27	95	49
60 V	17	23	42	15	54	20	94	29
61 NV	363	38	351	52	233	59	297	74
62 NV	158	10	165	18	264	36	341	46
63 NV	62	20	124	13	109	45	183	56

Table 13.22 Heat Release of the Wire and Cable Materials in Series IV (Table 13.10) in the Cone Calorimeter (ASTM E 1354) at Two Incident Heat Fluxes

Material #	Flux 25 kW/m^2		Flux 50 kW/m^2	
	Pk RHR (kW/m^2)	THR (MJ/m^2)	Pk RHR (kW/m^2)	THR (MJ/m^2)
64 NV	118.9	77.7	109.3	120.0
65 NV			165.2	152.4
66 NV	100.1	102.8	111.8	122.2
67 NV			150.4	138.4
68 NV			478.5	130.5
69 NV	8.2	1.6	120.0	82.9
70 NV			154.9	84.4
71 NV	54.3	29.0	84.4	42.3
72 NV			111.8	122.3
73 NV	86.0	74.1	125.7	110.2
74 NV	167.3	160.3	270.8	154.7
75 NV			179.1	152.7
76 NV			322.9	160.7
77 NV			118.1	139.1
78 NV			517.0	177.4
79 NV	20.2	12.9	32.4	38.6
80 NV	8.2	2.2	118.7	52.9
81 V	21.1	15.3	55.3	38.8
82 NV	451.7	66.7	799.5	130.6
83 NV			157.0	117.3
84 NV	488.3	107.3	1194.2	153.4
85 NV			836.3	157.9
86 NV	508.9	109.1	480.4	126.5
87 V	150.5	84.0	189.4	88.0
88 V	29.6	12.5	73.5	59.7

Table 13.23 Fire Performance Index of the Wire and Cable Materials in Series II (Table13.4) in the Cone Calorimeter (ASTM E 1354) at Three Incident Heat Fluxes

Material #	Flux 30 kW/m^2	Flux 40 kW/m^2	Flux 50 kW/m^2
	FPI (s m^2/kW)	FPI (s m^2/ kW)	FPI (s m^2/kW)
36 V	0.603	0.268	0.220
37 V	0.524	0.255	0.186
38 V	0.368	0.300	0.155
39 V	0.287	0.381	0.072
40 V	0.338	0.104	0.090
41 NV	0.706	0.383	0.276
42 NV	1000	6.905	3.992
43 NV	0.118	0.058	0.032
44 NV	0.480	0.267	0.188
45 NV	0.535	0.218	0.140
46 NV	1.826	0.638	0.574
47 NV	0.457	0.253	0.264
48 NV	0.752	0.540	0.270
53 V	500	115	10,000

Table 13.24 Fire Performance Index of the Wall Lining Materials in Series III (Table 13.9) in the Cone Calorimeter (ASTM E 1354) at Four Incident Heat Fluxes

Material #	Flux 20 kW/m^2	Flux 25 kW/m^2	Flux 40 kW/m^2	Flux 70 kW/m^2
	FPI (s m^2/kW)	FPI (s m^2/kW)	FPI (s m^2/kW)	FPI (s m^2/kW)
57 V	4.154	1.445	0.207	0.072
58 NV	0.717	0.367	0.090	0.025
59 V	68.982	18.943	0.536	0.126
60 V	600	8.177	3.118	0.640
61 NV	5.970	2.832	0.341	0.086
62 NV	4.358	0.463	0.142	0.035
63 NV	15.925	0.667	0.207	0.055

Table 13.25 Fire Performance Index of the Wire and Cable Materials in Series IV (Table 13.10) in the Cone Calorimeter (ASTM E 1354) at Two Incident Heat Fluxes

Material #	Flux 25 kW/m^2	Flux 50 kW/m^2
	FPI (s m^2/kW)	FPI (s m^2/kW)
64 NV	3.29	0.86
65 NV		0.31
66 NV	1.79	0.30
67 NV		0.59
68 NV		0.12
69 NV	1216	1.59
70 NV		0.47
71 NV	2.33	0.29
72 NV		0.98
73 NV	4.76	0.93
74 NV	3.69	0.50
75 NV		0.40
76 NV		0.18
77 NV		0.77
78 NV		0.16
79 NV	495	309
80 NV	1220	1.91
81 V	475	0.56
82 NV	0.49	0.07
83 NV		0.14
84 NV	0.40	0.04
85 NV		0.10
86 NV	0.88	0.22
87 V	0.71	0.15
88 V	16.81	0.85

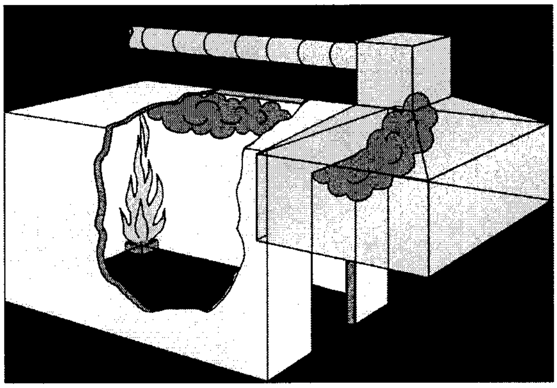


Figure 13.9 Layout of room-corner test

Figure 13.10 Room-corner test: intensity of flame once the test material has started to get involved

Figure 13.11 Room-corner test: material that has reached flashover

In addition, the same cone calorimeter tests, but using only heat release criteria, have been shown to have almost perfect predictability of ISO 9705 room-corner test rankings [80]. This is important because of the data shown in Table 13.26, where the wall lining materials in Series III (Table 13.9) were tested in a room corner test: all rigid PVC materials give very low heat release and they do not cause flashover.

Table 13.26 Room Corner Test Heat and Smoke Release of Wall Lining Materials in Series III (Table 13.9), compared with ASTM E 662 Smoke Data

Material #	Avg. RHR (kW)	THR (MJ)	Smoke yield (g)	ASTM E 662 Dm
57 V	2.6	29.9	368	780
58 NV	73.2	85.2	868	106
59 V	0.0	25.6	202	94
60 V	3.0	30.2	26	53
61 NV	135.6	133.9	4,218	247
62 NV	54.0	70.2	3,432	900
63 NV	10.9	36.6	483	435

The table also contains total smoke yield in the full scale tests as well as additional small scale smoke obscuration data, to be discussed later.

It is not possible to give easy summaries of heat release data for PVC materials, but it is clear that such materials exhibit extremely low heat release, and have high fire performance indices, leading to low propensity for flashover.

13.5.5 Smoke Obscuration

Smoke obscuration (reduction in light transmitted) is a serious concern in a fire, because a decrease in visibility reduces the light available, thus hindering both escape from the fire and rescue by safety personnel. The main way in which a fire causes visibility decreases is through smoke emission. This decrease in visibility is the result of a combination of two factors: how much material is burnt in the real fire (which will be less if the material has better fire performance) and how much smoke is released per unit material burnt.

Despite the understanding that smoke obscuration ought to be measured in a large scale, or by a method which can predict large scale smoke release, the most common small scale test method for measuring smoke from burning products is the traditional smoke chamber in the vertical mode (ASTM E 662 [81], Fig. 13.12).

The test results are expressed in terms of a quantity called "specific optical density", which is defined in the test standard. This test has now been shown to have some serious deficiencies. The most important problem is misrepresentation of the smoke obscuration found in real fires and found for melting materials, such as thermoplastics [82–86]. When those materials, which melt or drip when exposed to flame, are exposed vertically in the smoke chamber test, the molten portions will have escaped the effect of the radiant heat source [87]. This means that some of the material does not burn during the test (and does not give off smoke), suggesting a low test result. In a real fire, all of the molten material will burn and generate smoke. If these dripping products are exposed horizontally, the entire sample will be consumed. Smoke chamber test results for a number of materials are shown in Table 13.27.

Table 13.27 Maximum Specific Optical Density Data from Materials in ASTM E 662

Material, F or NF	V or NV	Dm	Thickness (mm)
ABS F	NV	780	6
Polystyrene F	NV	780	6
ABS NF	NV	780	6
Polypropylene NF	NV	780	6
Natural rubber foam F	NV	660	6
PVC rigid F	V	535	6
PVC rigid NF	V	470	6
Polyethylene NF	NV	470	6
Black walnut NF	NV	460	6
Polystyrene NF	NV	395	6
Red oak NF	NV	395	6
Douglas fir NF	NV	380	6
Natural rubber foam NF	NV	372	6
White pine NF	NV	325	6
Nylon rug NF	NV	320	8
Nylon rug F	NV	269	8
Douglas fir F	NV	156	6
White pine F	NV	155	6
Polyethylene F	NV	150	6
Polypropylene F	NV	119	6
Black walnut F	NV	91	6
Red oak F	NV	76	6
PTFE F	NV	53	6
PTFE NF	NV	0	6

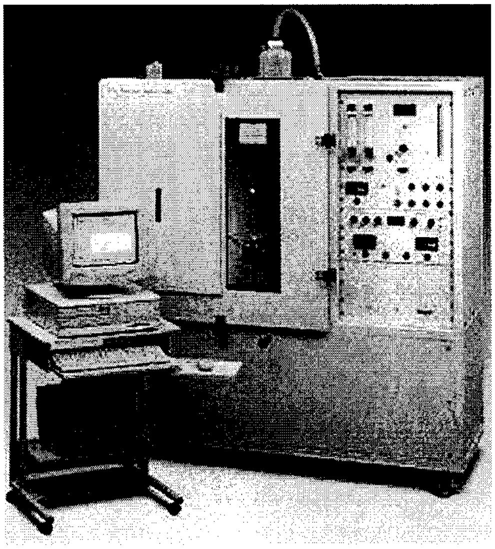


Figure 13.12 NBS smoke chamber test (ASTM E 662)

The cone calorimeter, which is a dynamic flow-through fire test, can also be used to assess smoke obscuration. The rankings tend to be quite different from those found with the static smoke chamber. Tables 13.28 to 13.31 show smoke obscuration data from the cone calorimeter for the materials in Series I through IV.

Several empirical parameters have been proposed to make this compensation for incomplete sample consumption, including one called the smoke factor (SmkFct), determined in small-scale rate of heat release calorimeters [88]. It combines the two aspects mentioned above: the light obscuration (as the total smoke released) and the peak rate of heat release. An alternative parameter is the smoke parameter (SmkPar) based on the specific extinction area (another measure of smoke release in the cone calorimeter) and the peak rate of heat release. Results are shown in Tables 13.28 to 13.31. The results show that PVC materials, when assessed properly, can release smoke in the same range as most other materials, or even less in some cases, when properly formulated.

The majority of materials with low flame spread (or low heat release) also exhibit low smoke release. However, it has been shown in several series of room-corner test projects (with the tested material lining either the walls or the walls and the ceiling), that approx. 10% of the materials tested (8 out of 84) exhibited adequate heat release (or fire growth) characteristics, but have very high smoke release [89, 90]. These materials would cause severe obscuration problems if used in buildings. A combination of this work, and the concept that a visibility of 4 m is reasonable for people familiar with their environment [91], has led all US codes to include smoke pass/fail criteria when room-corner tests are used as alternatives to the ASTM E 84 Steiner tunnel test. This needs to be considered when using PVC materials in products that occupy large surfaces, because PVC materials have intrinsically high smoke release, when the entire material is forced to burn.

Table 13.28 Smoke Obscuration Data in the Cone Calorimeter for Series I Materials (Table 13.2) at Three Incident Heat Fluxes

Material #	Flux 20 kW/m^2			Flux 40 kW/m^2			Flux 70 kW/m^2		
	SEA (m^2/g)	TSR (–)	SmkFct (MW/m^2)	SEA (m^2/g)	TSR (–)	SmkFct (MW/m^2)	SEA (m^2/g)	TSR (–)	SmkFct (MW/m^2)
1	0	200	0.4	673	376	0.3	33	764	4.4
2	305	730	0.4	319	1571	13.5	302	2077	42.4
3	94	422	0.6	358	2253	24.9	266	1725	80.3
4	131	417	1.1	246	670	35.9	174	945	25.7
5	3	15	0.1	993	3620	733.2	978	3900	728.4
6	331	1249	4.3	547	3198	76.1	572	4888	239.1
7	51	225	1.3	18	200	3.8	33	405	7.9
8	96	934	13.7	569	6653	298.2	1041	6920	701.8
9	440	2149	27.7	566	2391	104.6	664	3754	283.9
10	54	465	9.3	591	1937	78.6	528	2285	148.6
11	607	387	1.5	93	837	24.0	198	1427	133.8
12	645	4127	77.6	937	5880	473.0	1020	6512	872.6
13	186	1227	24.3	3459	7027	459.6	1130	8917	1143.8
14	676	3608	100.4	939	5652	503.5	1046	6419	969.7
15	512	1409	65.0	839	6825	535.0	951	7786	1368.9
16	415	1033	2.7	814	3142	616.0	879	4784	1124.1
17	0	4145	1.8	1342	5550	853.8	1334	6160	1830.5
18	0	7830	25.9	1731	8056	1143.3	1627	7830	1519.0
19	0	6650	22.3	1527	9692	1499.2	1243	8612	2561.8
20	0	9053	456.2	1772	9705	3740.9	1331	8222	3438.2
21	914	4912	481.6	1053	6075	914.5	1156	6809	1277.0
22	114	318	30.4	65	287	42.9	96	307	59.7
23	865	12090	290.1	1870	12799	3461.7	1445	10575	4490.1
24	74	249	13.0	10	198	17.5	25	477	103.3
25	225	138	33.1	572	301	134.4	545	297	239.9
26	67	2506	51.6	77	3646	429.0	97	3009	1012.1
27	0	3970	216.3	566	3592	367.6	684	4037	746.1
28	118	1966	2.7	217	3088	887.9	251	2130	4003.4
29	0	5520	793.3	885	4773	4457.4	666	3897	5035.5
30	107	6653	44.6	1293	7738	6791.5	852	5906	9152.8
31	0	7795	28.6	1014	7570	5785.4	1162	8586	10375.9
32	7	41362	1.4	466	3941	4711.2	660	4704	9656.5
33	1	2308	2.8	286	2837	1207.9	503	4009	2355.9
34	1982	892	29.9	299	1870	1822.0	275	4009	3975.8
35	0	2700	536.0	475	2503	3416.5	429	2317	5509.4

Table 13.29 Smoke Obscuration Data in the Cone Calorimeter for Series II Wire and Cable Materials (Table 13.4) at Three Incident Heat Fluxes

	Material		Flux 30 kW/m²		Flux 40 kW/m²		Flux 50 kW/m²	
			SEA (m²/kg)	SmkPar (MW/kg)	SEA (m²/kg)	SmkPar (MW/kg)	SEA (m²/kg)	SmkPar (MW/kg)
36	PVC WC FRRA	V	1089	199	1240	273	1415	241
37	PVC WC FRRA 2	V	1013	145	1187	202	1258	193
38	PVC WC FR2	V	1278	283	1411	294	1533	387
39	PVC WC FRRA 3	V	1342	316	1627	160	1654	458
40	PVC WC	V	1073	203	1665	471	1663	416
41	CSPE	NV	289	40	406	62	2511	377
42	PTFE	NV	66		9	4		1
43	LDPE	NV	525	456	511	594	483	740
44	EVA ATH+	NV	367	94	334	100	364	101
45	EPR ATH++	NV	242	48	336	93	411	141
46	EVA ATH++	NV	307	58	390	88	358	69
47	EVA ATH Si	NV	515	260	328	180	479	175
48	ECA ATH Perox	NV	37	8	59	10	198	39
53	VTE Cab	V	160	3	246	21	320	32

Table 13.30 Smoke Obscuration Data in the Cone Calorimeter for Series III Wall Lining Materials (Table 13.9) at Four Incident Heat Fluxes

Material #	TSR (–)	Pk RSR (1/s)	SmkFct (MW/m^2)	SEA (m^2/kg)
Flux 20 kW/m^2				
57 V	691	9.93	11	279.17
58 NV	871	6.53	45	122.80
59 V	159	0.92	2	34.95
60 V	115	0.36	0.4	27.66
61 NV	1938	16.40	16	129.69
62 NV	2123	22.46	124	831.23
63 NV	225	2.51	4	53.22
Flux 25 kW/m^2				
57 V	1241	9.62	85	420.45
58 NV	638	2.35	73	101.23
59 V	148	0.50	3	27.33
60 V	59	0.89	2	17.15
61 NV	1569	14.01	1	32.50
62 NV	4234	33.51	559	1221.50
63 NV	682	10.61	49	205.55
Flux 40 kW/m^2				
57 V	1613	26.15	336	457.50
58 NV	359	6.95	121	54.91
59 V	326	6.56	24	81.22
60 V	124	2.82	6	36.36
61 NV	1612	8.21	159	455.85
62 NV	4941	50.41	1290	1039.50
63 NV	1617	13.99	145	349.60
Flux 70 kW/m^2				
57 V	2171	42.66	577	560.10
58 NV	645	4.11	369	89.64
59 V	1074	11.65	90	241.45
60 V	409	4.11	30	112.70
61 NV	2072	14.40	499	493.30
62 NV	5878	73.07	1945	1174.00
63 NV	2232	38.21	385	432.23

Table 13.31 Smoke Obscuration Data in the Cone Calorimeter for Series IV Wire and Cable Materials (Table 13.10) at Two Incident Heat Fluxes

#	Abbreviation	V or NV	Heat flux (kW/m^2)	SEA (kg/m^2)	TSR (–)	SmkFct (MW/m^2)	Pk RSR (1/s)
64	XLPO Hydr	NV	25	0.086	388	6.7	1.21
66	CPE Fill	NV	25	0.437	2076	50.1	5.25
69	PEI	NV	25	0.364	56	0.1	0.22
71	PP Int	NV	25	0.174	348	2.8	1.05
73	XLPO Min Fill	NV	25	0.035	148	1.1	0.65
74	XLPO ATH1	NV	25	0.234	1317	3.5	2.51
79	PVDF	NV	25	0.076	509	0.3	0.68
80	PTFE	NV	25	0.278	122	0.2	0.35
81	PVC Flex	V	25	0.102	443	2.3	1.85
82	PE	NV	25	0.152	399	9.2	4.23
84	EVA PO	NV	25	0.424	1642	68.9	7.62
86	XLPO Br	NV	25	0.953	5000	5.9	26.03
87	PVC Flex 2	V	25	0.767	4433	168.3	9.44
88	PVC Flex 3	V	25	0.050	178	2.7	1.14
64	XLPO Hydr	NV	50	0.200	1307	32.5	1.85
65	HDPE/Cl	NV	50	1.113	6633	346.4	11.05
66	CPE Fill	NV	50	0.562	3407	146.0	6.09
67	EVA ATH	NV	50	0.396	2398	46.1	4.29
68	PPO/PS	NV	50	1.331	8235	2746.3	31.16
69	PEI	NV	50	0.202	862	31.2	4.47
70	PEI/Si	NV	50	1.096	5186	291.6	11.85
71	PP Int	NV	50	0.231	351	7.6	1.42
72	PO Fill	NV	50	0.347	1959	22.8	2.87
73	XLPO Min Fill	NV	50	0.104	549	28.4	1.69
74	XLPO ATH1	NV	50	0.349	2164	83.8	5.06
75	XLPO ATH2	NV	50	0.296	1782	73.0	2.91
76	EVA Min Fill	NV	50	0.268	1438	167.0	4.13
77	PO Min Fill	NV	50	0.103	517	23.6	1.17
78	XLPE/Cl	NV	50	0.967	6139	1544.5	17.79
79	PVDF	NV	50	0.061	540	8.1	3.24
80	PTFE	NV	50	0.040	481	5.8	1.33
81	PVC Flex	V	50	0.144	786	13.4	2.91
82	PE	NV	50	0.686	2430	746.5	9.05
83	DFIR	NV	50	0.044	370	11.0	1.35
84	EVA PO	NV	50	0.446	2298	1761.6	13.82
85	NYLON 2	NV	50	0.253	1334	375.6	9.56
86	XLPO Br	NV	50	0.978	6138	2167.5	27.03
87	PVC Flex 2	V	50	0.920	5540	582.7	13.82
88	PVC Flex 3	V	50	0.107	669	16.0	1.30

13.6 Fire Retardance and Smoke Suppression

The heat release of any material, including PVC materials, can be decreased by adding fire retardants. This is the way in which flexible PVC materials are developed that have extremely low heat release, as shown, for example, in Tables 13.32 and 13.33 for wall covering materials and plenum cable materials based on PVC.

Table 13.32 Properties of PVC Wall Covering Formulations Containing Various Fire Retardant Systems (Cone Calorimeter @ 50 kW/m^2; 6 mm Thickness)

Additives	Pk RHR (kW/m^2)	Avg. RHR (kW/m^2)	SEA (m^2/g)	TSR (–)	SmkFct (MW/m^2)	Ht Comb (MJ/kg)
DOP 40 + Ca 20 (base material)	228	146	1198	71	16.2	16.9
DOP 30 + Ca 20 + Sb_2O_3 8	167	116	876	63	10.5	14.0
DOP 40 + Ca 20 + Sb_2O_3 8	191	127	1011	73	13.9	11.2
DOP 50 + Ca 20 + Sb_2O_3 8	203	132	1070	76	15.4	13.0
DOP 40 + MgOH 20 + Sb_2O_3 8	135	104	842	48	6.5	10.8
IDDPP 40 + MgOH 20	90	83	775	34	3.4	11.9
IDDPP 35 + MgOH 20	91	89	723	36	3.9	11.3
IDDPP 40 + $MgCO_3$ 30	102	84	695	36	3.7	9.8
IDDPP 40 + $MgCO_3$ 30 (alt. PVC)	94	79	661	30	2.8	10.7
EHDPP 40 + MgOH 20	102	83	719	32	4.0	11.7
TARP 40 + MgOH 20	99	81	834	44	4.3	9.9
TARP 50 + MgOH 20	99	82	805	41	4.0	10.1
TIPPP 40 + MgOH 20	107	85	872	48	5.1	9.3
TIPPP 50 + MgOH 20	109	90	908	52	5.6	9.6
IDDPP 40 + MgOH 20 + ClPar 30	95	77	596	33	3.2	8.5
IDDPP 40 + MgOH 20 + ClPar 20	91	73	640	34	4.0	8.3
IDDPP 40 + MgOH 20 + ClPar 10	81	69	692	33	2.7	8.8
IDDPP 40 + ZS 10	159	102	855	56	8.9	10.5
IDDPP 40 + ZS 30	165	101	861	53	8.7	13.0
IDDPP 40 + MgOH 20 + AOM 10	105	80	574	26	2.8	10.6
IDDPP 40 + MgOH 20 + AOM 30	83	63	375	14	1.2	11.0
IDDPP 40 + MgOH 20 + AOM 50	98	67	301	12	1.2	10.4

Table 13.33 Properties of PVC Plenum Cable Formulations Containing Various Fire Retardant Systems (Cone Calorimeter @ 40 kW/m^2; 3 mm Thickness)

Additives	Pk RHR (kW/m^2)	Avg. RHR (kW/m^2)	SEA (m^2/g)	TSR (–)	SmkFct (MW/m^2)	Ht Comb (MJ/kg)
Non FR PVC W&C cpd w/DOP	283	170	1,665	6,000	1,000	15.7
IDDPP 30	161	47	788	3,339	477	12.9
IDDPP 30 + ATH 30	132	76	777	2,944	278	11.5
IDDPP 30 + ATH 30 + Sb2O3 10	134	64	538	2,315	235	12.0
IDDPP 30 + ATH 30 + ZnH 10	158	83	555	1,617	158	10.7
IDDPP 30 + ATH 30 + ZnSn 10	128	80	719	2,485	214	10.8
IDDPP 30 + ATH 30 + AOM 10	127	94	488	1,449	116	11.4
IDDPP 30 + ATH 30 + AOM 5 + ZnSn 5	117	76	565	1,758	136	11.4

The following additives are mentioned in the compounds used in Tables 13.32 and 13.33:

- Alumina trihydrate (ATH)
- Ammonium octamolybdate (AOM)
- Antimony oxide (Sb_2O_3)
- Calcium carbonate ($CaCO_3$)
- Chlorinated paraffin (ClPar)
- Dioctyl phthalate (DOP)
- 2-Ethylhexyl diphenyl phosphate (EHDPP)
- Isodecyl diphenyl phosphate (IDDPP)
- Magnesium carbonate complex ($MgCO_3$)
- Magnesium hydroxide (MgOH)
- Triaryl phosphate (TARP)
- Triisopropyl phenyl phosphate (TIPPP)
- Zinc hydroxystannate (ZnH)
- Zinc stannate (ZnSn)
- Zinc sulphide (ZS)

The most interesting new flexible (plasticized) types of PVC compounds are the plenum cable compounds and Tables 13.33 and 13.34 show some heat release properties of a few (experimental) materials, as data for most commercial materials is not publicly available.

It is clear that these flexible (plasticized) PVC materials perform as well as rigid PVC compounds, or even better. Thus, there is still abundant room for innovation in the development of PVC compounds with excellent fire properties.

Table 13.34 Properties of Experimental PVC Plenum Cable Formulations Containing Various Fire Retardant Systems (Cone Calorimeter @ Two Heat Fluxes; 6 mm Thickness)

	Heat flux (kW/m^2)	TTI (s)	Pk RHR (kW/m^2)	THR (MJ/m^2)	Avg. 3 RHR (kW/m^2)	SEA (m^2/g)
Plenum X1	40	175	60.2	28	37.5	57
Plenum X2	40	51	32.4	19	18.2	195
Plenum X3	40	44	75.0	38	50.7	132
Plenum X4	40	64	62.5	35	41.6	108
Plenum X5	40	72	46.2	24	24.1	79
Plenum X6	40	73	65.5	32	43.5	89
Plenum X7	40	65	93.8	53	58.6	135
Plenum X8	40	65	68.9	36	53.1	103
Plenum X9	40	62	60.1	37	36.6	67
Plenum X10	40	65	50.4	37	34.6	115
Plenum X11	40	73	64.8	34	50.1	136
Plenum X1	70	24	126.2	79	85.8	166
Plenum X2	70	15	68.5	44	47.0	93
Plenum X3	70	16	127.3	82	93.9	389
Plenum X4	70	23	120.6	82	76.9	246
Plenum X5	70	20	117.9	86	77.0	209
Plenum X6	70	24	104.1	78	76.9	191
Plenum X7	70	21	132.2	87	86.6	262
Plenum X8	70	19	119.2	85	83.6	276
Plenum X9	70	20	99.5	85	79.5	262
Plenum X10	70	19	101.6	83	71.4	290
Plenum X11	70	20	124.7	84	83.2	285

13.6.1 Smoke Toxicity

The majority of fire fatalities are a result of inhalation of smoke and combustion products, rather than being the consequence of burns. Various organizations have been trying for many years to develop test methods and guidance documents on smoke toxicity, but emotional responses arise from discussions on interpretation of results or requirements for the use of animals as test surrogates. The following is now accepted by many fire scientists [92–99], and is critical to understanding how to assess fire hazard:

1. Most fire fatalities occur in fires that become very large. In fact, US statistics indicate that such fires account for over six times more fatalities than all other fires. This is illustrated by NFPA statistics of US fires in the 1986 to 1990 time period (Table 13.35 [100, 101]).

Table 13.35 Statistics of Average Yearly Fire Fatalities in Post-Flashover Structure Fires in the United States in the Period 1986 to 1990

Details	Number of fire fatalities	Percentages of total numbers
Post-flashover fires		
Civilians killed by smoke inhalation only	621	78.3
Civilians killed by burns only	125	58.1
Civilians killed by combination of smoke inhalation and burns	2,406	83.3
Combination of all of the above	3,152	80.9
Other data, presented for comparison		
Total civilian fire fatalities in structure fires	3,896	
Total civilian fire fatalities in structure fires, intimate with ignition	670	17.2
Total civilian fire fatalities	5,696	

2. Carbon monoxide concentrations in the atmospheres of flashover fires (the fires most likely to produce fatalities) are determined by geometric variables and oxygen availability, but are virtually unaffected by chemical composition of fuels.

3. CO yields in full-scale flashover fires are approx. 0.2 g/g, which can be calculated to correspond to a toxicity of 25 mg/l [98, 99]. This consistent yield of CO is illustrated by a set of 24 studies where such results are shown is in Table 13.36 [102–107].

Table 13.36 Yields of Carbon Monoxide in Fires Found in Literature

Material	Yield	Reference	Organization
Plywood walls, wood fiberboard ceiling	0.35	Budnick 1978	HUD
FR plywood walls, wood fiberboard ceiling	0.42	Budnick 1978	HUD
Plywood walls, no ceiling	0.10	Budnick 1978	HUD
Upholstered chair, bed FR plywwod walls	0.36	Budnick et al. 1978	HUD
Plywood walls, bed	0.31	Budnick et al. 1978	HUD
Plywood walls, wood cribs, cellulosic ceiling tile	0.29	Levine and Nelson 1990	NIST
Non FR chair, TV cabinets, cables, etc	0.22	Babrauskas et al. 1988	FRCA
FR chair, TV cabinets, cables, etc	0.23	Babrauskas et al. 1988	FRCA
PMMA walls	0.28	NIST unpublished	NIST
Wood cribs	0.15	Gottuk et al. 1992	VPI
Flexible PU foam	0.25	Gottuk et al. 1992	VPI
PMMA	0.30	Gottuk et al. 1992]	VPI
Hexane	0.23	Gottuk et al. 1992	VPI
Propane	0.23	Beyler 1986	Harvard
Propene	0.20	Beyler 1986	Harvard
Hexanes	0.20	Beyler 1986	Harvard
Toluene	0.11	Beyler 1986	Harvard
Methanol	0.24	Beyler 1986	Harvard
Ethanol	0.22	Beyler 1986	Harvard
Isopropanol	0.17	Beyler 1986	Harvard
Acetone	0.30	Beyler 1986	Harvard
Polyethylene	0.18	Beyler 1986	Harvard
PMMA	0.19	Beyler 1986	Harvard
Pine	0.14	Beyler 1986	Harvard
Average CO yield	**0.236**	24 Cases	5 Studies

4. Toxic potency values from the most suitable small-scale smoke toxicity test (NIST radiant test, using rats as the animal model, but only for confirmatory purposes, standardized in ASTM E 1678 [108] and NFPA 269 [109]) have been well validated with regard to toxicity in full-scale fires. However, such validation cannot be done to a better approximation than a factor of 3. This is illustrated by the fact that the range of the toxic potency of the smoke of almost all materials (including PVC) is so small that it pales in comparison with the ranges of toxic potencies of typical poisons [41]. Consequently, all smoke is extremely toxic, virtually irrespective of the material that is burning.
5. The consequence of this is that any toxic potency (LC_{50}) higher than 8 mg/l will be subsumed within the toxicity of the atmosphere, and is of no consequence. Thus, values 8 or greater should be converted to 8 mg/l for reporting purposes. Moreover, therefore, almost all common materials have virtually the same smoke toxicity; their associated fire hazard will not be a function of smoke toxic potency.
6. A comprehensive study of fire (and non-fire) fatalities associated with CO showed that carbon monoxide inhalation statistically tracks fire fatalities [97, 98, 102].

13.6.2 Fire Modeling and Fire Hazard Assessment

Overall fire safety is generally achieved by deciding if materials meet certain pre-set safety objectives. However, it is usually necessary to combine various properties and calculate results based on certain fire models. Field models and zone models make calculations based on a fundamental understanding of the fire and its environment. On the other hand, correlation fire models now exist [e.g., 110], and new ones are being developed continually, which take fire test results, developed in fire safety engineering units, and predict full-scale fire outcomes. This is particularly true for those products most often associated either with fires or with strong commercial interests. Upholstered furniture, mattresses, wall linings, floor coverings, and electric cables are the most widely studied consumer products from the point of view of fire.

Many of the prescriptive techniques used most often for fire safety requirements (standard fire tests) were developed many years ago, and tend to have some deficiencies when applied to materials not commonly used when the test was developed. The typical example is the case of thermoplastics and their melting problem. As PVC does not normally melt away from flames, it often appears to perform less well in traditional tests than typical melting thermoplastics, when the test involves vertical or ceiling mounting, both of which can generate misleading results with melting materials.

This has resulted in the development of techniques (some of them national standards and guides, such as for rail transportation vehicles [111], health care occupancies [112], and prevention of flashover [113]) where all relevant fire properties and the entire fire scenario are considered, instead of pass/fail criteria based on individual tests. Such a process, a fire hazard assessment, if properly conducted, permits the introduction into the market place of innovative designs, which can then compete with established technologies. When a performance-based fire hazard assessment is used, it is still important to retain a certain number of prescriptive approaches as acceptable alternatives, so that materials or products are "grandfathered in", at least for a short period.

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Appendix 1 – Fire Safety Definitions

The following definitions have been transcribed verbatim from ASTM E176 [1], unless indicated otherwise:

Burn:	to undergo combustion.
Char:	*v*: to form carbonaceous residue during pyrolysis or during incomplete combustion.
Char:	*n*: a carbonaceous residue formed by pyrolysis or incomplete combustion.
Combustion:	a chemical process of oxidation that occurs at a rate fast enough to produce temperature rise and usually light either as a glow or flame.
Ease of extinction:	facility of quenching of combustion occurring with a material, product, or assembly.
Fire:	destructive burning as manifested by any or all of the following: light, flame, heat, and smoke.
Fire hazard:	the potential for a fire to cause harm to people or property *Discussion:* A fire may pose one or more types of hazard to people, animals, or property. These hazards are associated with the environment and with a number of fire-test-response characteristics of materials, products, or assemblies including but not limited to ease of ignition, flame spread, rate of heat release, smoke generation and obscuration, toxicity of combustion products, and ease of extinguishment.
Fire performance:	response of a material, product or assembly in a particular fire, other than in a fire test involving controlled conditions (different from fire-test- response characteristic). *Discussion:* The ASTM Policy on Fire Standards distinguishes between the response of materials, products or assemblies to heat and flame under controlled conditions, which is a fire-test-response characteristic, and under actual fire conditions, which is called fire performance. Fire performance depends on the occasion or environment and may not be measurable. In view of the limited availability of fire-performance data, the response to one or more fire tests, appropriately recognized as representing end-use conditions, is generally used as a predictor of the fire performance of a material, product, or assembly.
Fire resistance:	the ability of a material, product, or assembly to withstand fire or give protection from it for a period of time (contrast to fire resistance rating). *Discussion:* As applied to elements of buildings, fire resistance is characterized by the ability to confine a fire or to continue to perform

	a given structural function or both. More specific examples of this ability include retention of stability (loadbearing capacity), integrity, or thermal insulation. Once a measure of time is defined for fire resistance, and exposure conditions specified for that measure, the result is a fire resistance rating.
Fire resistance rating:	a measure of the elapsed time during which a material, product, or assembly continues to exhibit fire resistance under specified exposure conditions (contrast to fire resistance). *Discussion:* This term is defined because it is used in codes. As applied to elements of buildings, it is commonly measured by the methods and to the criteria defined in ASTM E 119 or ASTM E 1509.
Fire risk:	an estimation of expected fire loss that combines the potential for harm in various potential fire scenarios with the probabilities of occurrence of those scenarios. *Discussion:* Risk may be defined as the probability of having a certain type of fire, where the type of fire may be defined in whole or in part by the degree of potential harm associated with it, or as potential for harm weighted by associated probabilities. However it is defined, no risk scale implies a single value of acceptable risk. Different individuals presented with the same risk situation may have different opinions on its acceptability.
Fire scenario:	a detailed description of conditions, including environmental, of one or more of the stages from before ignition to the completion of combustion in an actual fire, or in a full scale simulation. *Discussion:* The conditions describing a fire scenario, or a group of fire scenarios, are those required for the testing, analysis, or assessment that is of interest. Typically they are those conditions that can create significant variation in the results. The degree of detail necessary will depend upon the intended use of the fire scenario. Environmental conditions may be included in a scenario definition but are not required in all cases. Fire scenarios often define conditions in the early stages of a fire, while allowing analysis to calculate conditions in later stages.
Fire-test-response characteristic:	a response characteristic of a material, product, or assembly, to a prescribed source of heat or flame, under controlled fire conditions. Such response characteristics may include, but not be limited to, ease of ignition, flame spread, heat release, mass loss, smoke generation, fire endurance, and toxic potency of smoke. *Discussion:* A fire-test-response characteristic can be influenced by variables of exposure, such as ignition source intensity, ventilation, geometry of item or enclosure, humidity, or oxygen concentration. It is not an intrinsic property such as specific heat, thermal conductivity, or heat of combustion, where the value is independent of test variables. A fire-test-response characteristic may be described in one

	of several terms. Smoke generation, for example, may be described as smoke opacity, change of opacity with time, or smoke weight. No quantitative correlation need exist between values of a fire-test-response characteristic for different materials, products, or assemblies, as measured by different methods or tested under different sets of conditions for a given method.
Flame:	a hot, usually luminous zone of gas that is undergoing combustion. *Discussion:* The luminosity of a flame is frequently caused by the presence of glowing particulate matter suspended in the hot gases.
Flame spread:	the propagation of a flame away from the source of ignition.
Flashover:	the rapid transition to a state of total surface involvement in a fire of combustible materials within an enclosure. *Discussion:* Flashover is a fluid-mechanical combustion instability within an enclosure that occurs when the surface temperatures of an enclosure and its contents rise rapidly, producing combustible gases and vapors, and the enclosure heat flux becomes sufficient to heat these gases and vapors to their ignition temperatures. At flashover, the volume occupied by hot combustion gases rapidly increases and ends up comprising more than 50% of the enclosure's volume. Experimentally it is found that flashover occurs when the upper gas layer temperature surpasses 600 ⌒C or when the radiant heat flux at the floor surpasses 20 kW/m^2. Visually, flashover often corresponds to a transition from flaming on a few surfaces to flames throughout the volume of the enclosure.
Heat release rate:	the heat evolved from the specimen, per unit of time.
Ignition:	the initiation of combustion. *Discussion:* The combustion may be evidenced by glow, flame, detonation, or explosion. The combustion may be sustained or transient. **Flash ignition temperature:** the minimum temperature at which, under specified test conditions, sufficient flammable gases are emitted to ignite momentarily upon application of a small external pilot flame. *(Contained in ASTM D1929)* [51] **Ignition temperature:** the lowest temperature at which sustained combustion of a material can be initiated under specified test conditions. *Discussion:* While the phenomenon of combustion may be transient or sustained, in fire testing practice, the ignition temperature is reached when combustion continues after the pilot source is removed. **Piloted ignition:** ignition of combustible gases or vapors by a pilot source of ignition. **Pilot source of ignition:** a discrete source of energy, such as, for example, a flame, spark, electrical arc, or glowing wire

	Self ignition: the minimum temperature at which the self-heating properties of the specimen lead to ignition or ignition occurs by itself, under specified test conditions, in the absence of any additional flame ignition source. *(Contained in ASTM D1929)* [51]
	Unpiloted ignition: ignition caused by one or more sources of energy without the presence of a pilot source of ignition
Oxygen consumption principle:	the expression of the relationship between the mass of oxygen consumed during combustion and the heat released.
Smoke:	the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion.
Smoke obscuration:	reduction of light transmission by smoke, as measured by light attenuation.
Smoke toxicity:	the propensity of smoke to produce adverse biochemical or physiological effects.
Toxic potency:	as applied to inhalation of smoke or its component gases, a quantitative expression relating concentration and exposure time to a particular degree of adverse physiological response, for example, death, on exposure of humans or animals. *Discussion:* The toxic potency of the smoke from any material, product, or assembly is related to the composition of that smoke which, in turn, is dependent upon the conditions under which the smoke is generated.

Appendix 2 – Meaning of Major Cone Calorimeter Fire Properties

Pk RHR:	Peak value of the heat release rate vs. time curve, in $\mathrm{kW/m^2}$, of the sample. Heat release rate is measured by the principle of oxygen consumption.
TTI:	Time to ignition, at each flux, in s. The time to ignition is determined visually and taken to be the time to a sustained combustion of at least 10 s duration. If no ignition is observed after 1 h of exposure, time to ignition is assumed to be 10,000 s, for calculations.
THR:	Total heat released by the sample, at the end of the test, in $\mathrm{MJ/m^2}$. It is calculated by integrating the curve of heat release rate over time. The individual report also includes the average value over the entire test. The standard report would only include the absolute value, in kJ, which is related to this one by the sample surface area.
FPI:	Ratio of the time to ignition to the peak heat release rate (in $\mathrm{s\,m^2/kW}$). This parameter has been shown to give an indication of propensity to flashover, because it relates to the time to flashover.
Ht Comb:	Effective heat of combustion, in MJ/kg. The report contains the average value for the entire test (the most useful number) and the peak instantaneous value.
3 Min RHR:	Average heat release rate during the period between ignition and 3 min after ignition, in $\mathrm{kW/m^2}$. If the sample did not ignite this value would be taken to be zero.
Av RHR:	Average rate of heat release over the entire test, in $\mathrm{kW/m^2}$.
SmkFct:	Smoke factor, in $\mathrm{MW/m^2}$. It is the product of the peak heat release rate and the total smoke released. It has been shown that it can be an indication of the relative propensity of materials to generate smoke in full-scale tests. The peak, average, and 5 min values are reported.
Pk RSR:	Peak value of the rate of smoke release vs. time curve, in 1/s. The rate of smoke released is the product of the extinction coefficient and the volumetric air flow rate divided by the sample surface area and the light path length (with the appropriate corrections).
TSR:	Total smoke released by the sample, at the end of the test (non dimensional). It is calculated just like the THR, from the curve of RSR vs. time.
Av SEA:	Average extinction area, in $\mathrm{m^2/kg}$.
SmkPar:	Smoke parameter, peak, average, and 5 min values, in MW/kg. It is the product of the specific extinction area and the peak rate of heat release, and can also be used as a first order prediction of full-scale smoke obscuration.

GBH Attachment 21

AB59-COMM-7-21

BCC Flame Retardancy Conference - May 24-26, 1999 - Stamford, CT

SMOKE TOXICITY: YIELDS OF TOXICANTS IN FIRES AND IMPLICATIONS FOR LETHALITY AND INCAPACITATION

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ABSTRACT

This work presents some data on yields of common toxicants (combustion products) in fires and fire tests and analyzes the implications of those yields to consider lethality and incapacitation limit levels. Recent limits, based on incapacitation concepts, have been suggested and analysis of actual fire data indicates that it is essential to replace them by realistic criteria that do not require severe and unreasonable building contents limitations. This information will be combined with a toxic fire hazard assessment for those fires that cause the vast majority of fatalities: the ones reaching beyond the room of fire origin and associated with flashover.

INTRODUCTION

Fire fatalities are often reported as resulting from smoke inhalation. However, the real cause of the overwhelming majority of fire fatalities is the fire, generating enough combustion products to create a lethal atmosphere. In order to understand, and put into perspective, the smoke toxicity of materials and products in actual fires, it is essential to follow a pattern of research that has led to the level of knowledge of fire, smoke and toxicity in the 1990's.

Many smoke toxicity test methods have been proposed over the years to investigate the toxic potency of the smoke from materials, both involving bioassay and analytical tests [e.g. 1-7]. Abundant published data exists on the smoke toxic potency resulting from many materials, using one or more of these methods. Unfortunately, much published information is not specific (mainly due to commercial confidentiality needs) as to formulation details of the material tested. Thus, as new materials are developed by a manufacturer, more testing is often required by specifiers, at high added expense. This is very often unproductive, for one of three reasons:

- It may lead to data statistically indistinguishable from existing information: new testing was then a waste of money.

- It may lead to data statistically distinguishable but toxicologically indistinguishable: new testing then leads to supporting marketing ploys which add nothing to fire safety.
- It may lead to new data showing improvements in one fire property (smoke toxicity) at the expense of (often hidden) deterioration in another fire property (e.g. heat release or flame spread): new testing then resulted in lower fire safety.

The fire performance and the smoke toxicity of materials have been the focus of so many investigations that work can, and should, now focus on the fire properties most applicable to fire hazard assessment. Some of the critical work conducted in this area was conducted at the US National Institute for Standards and Technology, in various stages: comparison of products made with fire retarded and non-fire retarded materials [8], analysis of the carbon monoxide (CO) yields in large full scale fires [9], study of full scale testing of materials (including a rigid PVC compound) and a comparison with small scale test results [10] and finally development of a small scale radiant test for toxic potency measurement [11]. The work must be understood combined with an analysis of the effects of carbon monoxide, the most hazardous toxicant affecting fire victims in real fire atmospheres, as shown in a comprehensive study of fire and non fire fatalities [12-13]. In consequence, many fire scientists now accept that:

- Most fire fatalities occur in fires that become very large. In fact, US statistics indicate that such fires account for over six times more fatalities than all other fires combined.
- Carbon monoxide concentrations in the atmospheres of flashover fires (the fires most likely to produce fatalities), are determined by geometric variables and oxygen availability, but are virtually unaffected by chemical composition of fuels.
- All small scale fire tests underpredict CO yields. They cannot be used, thus, to predict toxic fire hazard for ventilation controlled flashover fires, unless CO yields are calculated by analogy with full scale fire test results. Such tests do not underpredict yields of other toxicants, such as hydrogen chloride or hydrogen cyanide.
- CO yields in full scale flashover fires are approximately 0.2 g/g, which translates to a toxicity of 25 mg/L. If this is combined with a margin of error of a factor of 3, the consequence is that any toxic potency (LC_{50}) higher than 8 mg/L (i.e. any toxicity lower than 8 mg/L) will be subsumed within the toxicity of the atmosphere, and is of no consequence. Thus, values 8 or greater should be converted to 8 mg/L for reporting purposes.
- In order to correct small scale test data, the CO yield that should have been obtained can be calculated by making a CO correction.
- Toxic potency analyses show relatively small differences between materials, even in fires that have not reached flashover.
- The background for CO yield corrections are comprehensive studies of fire (and non fire) fatalities associated with CO [12-13]. By investigating almost 5,000 fatalities, they found:
    - Fire atmosphere toxicity is determined almost solely by CO levels, since victims of pure CO poisoning die at virtually identical levels, once other factors have been considered. No universal lethal CO threshold level exists (previously it was thought to be 50% carboxyhemoglobin, COHb). Lethal levels depend on the victim age and physical condition; any blood COHb value > 20 % can produce lethality on its own.

- Populations of victims of fire and non fire CO exposures are inherently very different: fire victims are both much older and much younger, and suffer from more preexisting disease. Thus fire victims are more sensitive to CO than those in non fire exposures.
- Fire fatality patterns before and after the plastics era are identical: the use of man-made materials to make household goods has made no difference to fire atmosphere toxicity.

YIELDS OF COMBUSTION PRODUCTS AND THEIR IMPLICATIONS

As stated above, the single critical yield of combustion products needed to assess the toxic hazard in flashover fires is that of carbon monoxide, which is 0.2 g/g. Other combustion product yields depend on the material burning and on the fire scenario; examples are shown in Table 1.

Table 1. Yields of Toxicants From Common Materials [8, 10, 14]

Material/Yield	CO (g/g)	HCl (g/g)	HCN	Irritants
Flashover	0.2	Decay	Decay	?
PVC	0.06-0.07	0.25-0.40	-	HCl + I
PVC (flash)	0.2	0.4	-	0.4
Polyolefins	0.08-0.10	-	-	(HCl + I) * 3
Douglas Fir	0.011-0.02	-	-	?
Douglas Fir (flash)	0.2	-	-	?
FR Rigid Polyurethane	0.06-0.08	-	0.002-0.005	?
FR Rigid Polyurethane (flash)	0.2	-	0.005-0.011	?
Polystyrene	0.1-0.5	-	-	?
Polyphen. Oxide	0.1-0.3	-	-	?
Flex. Polyurethane	0.01	-	0.001	?
Ethyl. Vinyl Acetate	0.1-0.3	-	-	?
GR Polyester	0.1	-	-	?

The table illustrates the fact that quite a lot is known about the yields of carbon monoxide, from many materials and often under more than one circumstance. However, little if anything is known about yields of most other toxicants; particularly those of irritants. This is due, in part, to experimental difficulties involved in measuring minor combustion products (which require the use of new, complex and expensive, Fourier Transform InfraRed spectral techniques), and, in part, to the fact that not all combustion products have been, as yet, fully identified.

Also of interest is the fact that an analysis of irritancy showed that the common irritants contained in fire atmospheres are not the most potent irritants found in fire atmospheres [14]. Thus, for example, halogen-free polyolefins, which do not release significant amounts of any of the materials considered typical irritant combustion products, were found to be 3-5 times more irritating than poly(vinyl chloride) materials intended for the same use (in this case wire and cable). In the work, a variety of combustion products were analyzed, with their known irritant effect, and yet the irritancy of the polyolefins could not be attributed to that of the compounds found. Thus, an analysis based on the well-known irritants, or even many of the measurable irritants, would lead users to ignore the actual major irritants present.

Carbon monoxide is an asphyxiant toxicant, and the most common other asphyxiant toxicant is hydrogen cyanide. They act by inhibiting the normal distribution of oxygen to body tissues (especially the cardiovascular system and the brain), thereby causing hypoxia, and, if severe, eventual death by asphyxiation. The fatality occurs immediately following the exposure, if a sufficiently high dose is involved. On the other hand, irritant combustion products can have two principal effects. First, they can cause the more immediately noticeable sensory irritation, which results in an immediate painful sensory stimulation of the eyes, nose, throat and lungs, accompanied by upper respiratory tract damage, breathing difficulties and hypoxia. Second, they can cause deep lung inflammation and oedema, and perhaps eventual death due to impairment of respiration, usually several hours after exposure [15].

Inhalation toxicological exposure is always related to exposure dose, i.e. a certain exposure maintained over a sufficiently long period to cause an undesirable effect. Thus, thresholds must be based on the concept of dose, in other words the product of the concentration of a toxicant times the exposure time. Equation (1) is the traditional N-gas model prediction of smoke toxicity [10], where smoke is lethal if FED (fractional effective dose) is near unity:

$$FED = \frac{m[CO]}{[CO_2]-b} + \frac{[HCN]}{LC_{50}HCN} + \frac{[HCl]}{LC_{50}HCl} + \frac{[HBr]}{LC_{50}HBr} + \frac{21-[O_2]}{21-LC_{50}O_2} \qquad (1)$$

The constants for use in Equation (1) (which refers to 30 min exposure) are:

m:	-18	Units: 1/ppm
b:	122,000	Units: ppm
LC_{50} HCN:	200	Units: ppm
LC_{50} HCl:	3,700	Units: ppm
LC_{50} HBr:	3,000	Units: ppm
LC_{50} O_2:	5.4	Units: %

Work in different organizations has shown that the individual effects of asphyxiants and of toxicants can be added in the N-gas model as shown in Equation (1) [10, 16, 17].

With regard to one specific irritant (the work addressed hydrogen chloride, but the finding is probably more general), "the data generated ... suggest that 820 ppm of HCl is lower than the threshold lethal concentration and concentrations of this level or less do not provide any additive toxicity in combination with other gases" [10]. This concentration value may not be exact, as combined effects of CO and HCl were found in another study [17], but is indicative of the existence of a minimum threshold before irritant gases start causing severe health effects. These low level effects of irritants, particularly on humans (generally the researchers themselves), were studied exhaustively around the end of the 19th century at European universities [18-22].

INCAPACITATION

Recent work, within the international standards community (namely a group of ISO TC92, Subcommittee 3 on Toxicity) has focussed on a different concept than lethality: incapacitation due to smoke. Unfortunately, this would create serious problems, that will be analyzed here.

Normally, codes addressing fire safety, intend to protect building occupants so they do not die in fires (except people either responsible for the fire or in close vicinity to its initiation). For example, NFPA 101, Life Safety Code, states: "As related to fire safety, the objective of this Code is to protect the occupants not intimate with the initial fire development from loss of life and to improve the survivability of those who are intimate with the fire development." This is a very logical, and achievable, objective. On the other hand, the draft document ([23], ISO DIS 13571) prepared by ISO TC92SC3WG5, states: "The ... protection, if occupant exposure should occur, is to ensure that the consequences of such exposure are not serious and that safe escape or refuge can be accomplished" and recommends " ... establishing levels of exposure that would not be expected to seriously impede escape nor impair health". Thus ISO DIS 13571 suggests a much higher level of fire protection to occupants than has ever been considered reasonable.

The problem with such unreasonable protection, as will be shown here, is that it leads to imposing excessive (and unwarranted) limitations in the amount of material that can be used in an interior application for the type of life style that is now prevalent in developed countries.

When incapacitation concepts are being used by the ISO working group, the draft document states: "The basic principle for assessing the irritant gas component of toxic hazard analysis involves only the *concentration* of each irritant. Fractional Effective Concentrations (FECs) are determined for each irritant at each discrete increment of time. Their sum at each time increment is then compared with a predetermined total FEC threshold value. If the total FEC value is greater than the threshold FEC, the incidence and severity of irritation effects for those exposed are considered to represent a significant potential for adversely affecting occupants' safe escape." See Equation (2) for the use of the FEC concept (exclusively looking at irritancy).

The constants proposed by ISO DIS 13571 for Equation (2) (which has no time component) are can be compared with literature data for lethal toxic potency (over a 30 min exposure).

$$FEC = \frac{[HCl]}{IC_{HCl}} + \frac{[HBr]}{IC_{HBr}} + \frac{[HF]}{IC_{HF}} + \frac{[SO_2]}{IC_{SO_2}} + \frac{[NO_2]}{IC_{NO_2}} + \frac{[acrolein]}{IC_{acrolein}} + \frac{[formaldehyde]}{IC_{formaldehyde}} + \sum \frac{[irritant]_i}{IC_i} \quad \textbf{(2)}$$

IC HCl	100 ppm	LC_{50} (30 min)	3700 ppm [10]
IC HBr	100 ppm	LC_{50} (30 min)	3700 ppm [10]
IC HF	50 ppm	LC_{50} (30 min)	900-3600 ppm [24]
IC SO_2	15 ppm	LC_{50} (30 min)	300-500 ppm [24]
IC NO_2	25 ppm	LC_{50} (30 min)	60-250 ppm [24]
IC acrolein	3 ppm	LC_{50} (30 min)	140-170 ppm [24]
IC formaldehyde	25 ppm	LC_{50} (30 min)	700-800 ppm [24]

There is, however, no toxicological evidence that incapacitation of exposed victims ever occurs as a function of a certain concentration of any toxicant. In consequence, the concept of "FEC" has no technical validity and has not been proven with experimental studies.

Moreover, this concept of incapacitation levels being lower than lethality levels, although logical on paper, is flawed in reality, when applied to irritants. It has been shown that irritants (such as hydrogen chloride or acrolein) do not cause incapacitation at dose levels so high that the victim eventually dies of inhalation toxicity after the exposure. This is a complex concept, but is critical: when primates have been exposed to doses of irritants at levels where they died a few days after exposure, they were still capable of performing the necessary avoidance responses to escape the exposure, thus not being incapacitated [25]. Interestingly, the concept of incapacitation is only applied to irritants; see Equation (2). Interestingly, it has also been found that incapacitation from asphyxiants occurs at levels very similar to those leading to lethality, and not at levels an order of magnitude lower [26].

The issue of decay of concentration of reactive combustion products (particularly hydrogen halides and other acids, most of which are included among typical irritants) has been studied in depth (e.g. [27-34]). This has shown that the concentration, of hydrogen chloride, for example, can be much lower than the initial emitted levels after it has travelled some distance from the fire source (in some cases becoming undetectable). This issue must be considered when dealing with toxicity of combustion products, especially regarding incapacitation by irritants.

The ISO DIS 13571 draft raises a different, very interesting, and valuable, issue: people in a fire environment are affected by convected heat and by being unable to see due to smoke obscuration, as well as being affected by the toxicity of the atmosphere.

PRACTICAL IMPLICATIONS OF INCAPACITATION THRESHOLDS

Under the assumption that a typical 50 kW fire requires 2 ft^2 (0.19 m^2) of burning surface [35], it is possible to calculate the amount of the critical toxicant that would be emitted from such a surface burning for four different materials. The estimates were made based on the yields of combustion products found in the literature [10, 14] and on fire test data [10, 36].

Table 2. Results of Burning 2 Square Feet of Four Different Materials

Estimates	PVC	Non FR Polyurethane Foam	FR Douglas Fir	XL Polyolefin
RHR (kW)	20	350	60	30
Density (kg/m^3)	1490	100	550	1500
Thickness (mm)	2	20	2	2
Mass Material (kg)	0.6	0.4	0.2	0.6
Ht Combustion (MJ/kg)	12	25	15	20
Toxicant yield (g/g)	0.4 (HCl)	0.005 (HCN)	0.1 (CO)	> 1 * (irritant)
Burning rate (g/s)	1.5	14.9	3.7	1.4
Toxicant Emission (g/s)	0.6	0.07	0.4	1.7 *
Air Entrainment (L/s)	490	490	490	490
Toxicant Level (ppm)	900	100	500	2400 *
Lethality FED Toxicant	0.24	0.50	ca. 0.12	?
Exceeds ISO 13571 FEC?	Yes	No	No	No
Ht Hazard (Low is Best)	1	4	3	2

*: Based on the finding that the irritancy of the combustion products of such materials exceeds that of PVC combustion products by a factor of 3-5 [14].

The results indicate the following:

1. A small amount of PVC (corresponding, for example, to a floor cove trim 6 ft long and 4 inches wide) weighing 0.6 kg could not be used in a room, because it would drastically exceed the recommended level for IC HCl (100 ppm). However, when the material burns, its heat release rate is only ca. 20 kW, a level smaller than a burning waste basket. Such small fires are usually not reported to the fire departments, but controlled in house.

2. A similar amount of a halogen-free cross-linked polyolefin material (perhaps intended for a similar application) releases ca. 2.5 times the level of irritants. However, in spite of generating a much higher incapacitating level, the irritants it generates are of unknown composition, and thus not usually assessed by Equation (2), although they should actually be included in the term that has the summation of irritant concentrations (if the IC levels were known). From the point of view of a realistic fire hazard (namely heat release) such a material releases only 30 kW, still less than a burning waste basket.

3. A similar surface and thickness of fire retarded wood (with smaller mass, because of its lower density, which could also be used as interior trim) releases carbon monoxide and virtually no irritants, and is thus unaffected by the assessment in Equation (2). From the point of view of a realistic fire hazard (namely heat release) this material releases 60 kW, making it a slightly more severe problem than the two earlier materials (and one that is likely to be reported), but still a small fire.

4. A similar surface (but at 10 times the thickness, to account for logical use as foam) also releases only ashpyxiants as measurable combustion products, and thus is unaffected by Equation (2) (unless measurements of other gases are made). If a quarter of the HCN released had been converted to NO_2, this material would have exceeded the corresponding Equation (1). However, this material has very large heat release rate, so that now it is likely that a large fire has occurred, and not only has the fire department been notified, but severe destruction may have followed, via burning of adjacent materials/products.

This analysis indicates that a small amount of any material releasing notorious irritants (such as halogen acids, sulphur dioxide, nitrogen oxides, formaldehyde or acrolein) even if it causes a fire that is probably not even reported, would trigger the threshold for incapacitation of Equation (2). This would then indicate to a designer, architect, or specifier, that 1 kg of that material cannot be used in any compartment!

The preceding analysis has ignored the fact that draft ISO DIS 13571, at the same time it contains illogically small threshold values for irritants, also contains equally illogical threshold values for asphyxiants. Thus, the problems discussed here can be extended to other materials.

Dr. Fredric Clarke has been the intellectual author of the analysis in the following paragraph, consequent to the fact that fires with small amounts of PVC cause incapacitation.

> NFPA data shows that between 1989-1993 there have been 54,000 residential fires, reported to the fire departments, where the material first ignited is wire and cable insulation or a wall covering, many (if not most) of which are made of PVC. Some 14,000 of these fires were big enough to spread beyond the room of fire origin (and thus reach flashover). Flashover fires where upholstered furniture was the item first ignited kill at least 10 people for each 100 fires, and it is logical to suppose that other residential flashover fires cause similar fatalities, and expose at least 10 times as many people. As less than 1 kg of burning PVC is sufficient to cause incapacitation, it is logical to assume that virtually all exposed people in a flashover fire became incapacitated, and most died. However, the actual number of fatalities in these fires was not 14,000, as results from this analysis, but a *miraculously low* 343 fatalities, more than 40 times less.

The thresholds in draft ISO DIS 13571 will not result in credit to a material that has been adequately fire retarded since they do not address fire performance properties of a material or product, including ignition resistance, lower heat release rate, lower burning rate or lower flame spread. In consequence, it appears clear that the implications of using those threshold levels would be that products made with combustible materials should be removed from inhabited areas, and replaced by ones made with non combustible ones (steel, concrete, ceramics). Thus would, of course, be very welcome by hermits desirous of an ascetic life in a cave, but not by those wishing the comforts of modern life.

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CONCLUSIONS

- Fire hazard (or the potential for harm associated with a fire) is associated with the critical fire properties of the materials and products contained in the fire scenario and that can prevent or inhibit the escape of exposed people. These are, primarily, heat release, burning rate, flame spread and smoke production tendency (of all materials or products) and ignitability (of materials or products adjacent to the material first ignited).

- A toxic fire hazard assessment needs to consider first those scenarios that cause the majority of fire fatalities, namely flashover fires. In such cases, material selection should be such that mass loss, heat and smoke release are minimized, as toxicity is a direct result of mass loss: carbon monoxide dominates post-flashover toxicity, and it is generated as 20% of the mass of the combustible materials burning.

- A toxic fire hazard assessment in pre-flashover fires must consider lethal levels of toxic products, as they have been assessed adequately, and can be combined by the N-gas model, irrespective of whether they are asphyxiants or irritants.

- The use of Fractional Effective Doses for assessment of lethal toxicity is a reasonable one, while that of Fractional Effective Concentrations (with threshold levels causing "severe effects" for incapacitation, and no time component) is not based on scientific data but on speculative assumptions, which have been proven to be inadequate.

- The levels of combustion products causing incapacitating levels are known in some cases: they are marginally smaller than those levels causing lethality (for some asphyxiants) and higher than those levels that will eventually cause post-exposure lethality (for many irritants). Assumptions that make them orders of magnitude smaller than lethal levels have no basis in scientific fact.

- The analysis of combustion product yields shows that the concept of critical irritant concentrations, and the associated recommended threshold values, would lead to bans in the use of combustible materials and products generating the comforts with which modern life has been associated in recent years.

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GBH Attachment 22

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THE TOXICITY OF HYDROGEN CHLORIDE AND OF THE SMOKE GENERATED BY POLY(VINYL CHLORIDE), INCLUDING EFFECTS ON VARIOUS ANIMAL SPECIES, AND THE IMPLICATIONS FOR FIRE SAFETY

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ABSTRACT

Toxicity of smoke is only one of many factors which determine the hazard or the risk resulting if a product were involved in a fire, in a specific scenario. Other factors include: amount of smoke (i.e. concentration of combustion products in the atmosphere), rate and quantity of heat release, mass loss rate and flame spread rate, as well as "environmental" factors, such as ignition source characteristics, fire detection and suppression devices, building occupancy and code enforcement. A factor almost specific to the smoke generated from the burning of poly(vinyl chloride) (PVC) is the decay of hydrogen chloride (HCl), by reaction with building surfaces. The values of smoke toxic potency measured will also be affected by a number of parameters, including combustion mode, exposure mode, toxicological end-point and statistical analysis of results.

A crucial factor, often overlooked, is the choice of an animal model appropriate as a surrogate for man, and its validation. Test animals are frequently chosen on the basis of convenience, cost or other characteristics (e.g. sensitivity) rather than because of their similarity to man. This is particularly important in combustion toxicology, where one test species may not be a good model for all the major combustion products generated. Thus, comparisons of materials producing different major combustion products must be approached with caution, in order to ensure that any apparent differences encountered in tests are not simply an artifact of test species.

Over recent years, increasing evidence has surfaced that some rodent species are poor models for the toxic response of man to irritant gases or to smoke containing irritants. Studies on HCl (as a pure gas) and on the smoke generated from the burning of PVC have indicated that mice are much more sensitive animals than rats. More importantly, they are much more sensitive animals than primates. It has also been established that rats are a good model for primates, in terms of the lethal effects of irritant products. Although primates have survived 15 min exposures to 10,000 ppm of HCl, 2,500 ppm is lethal to mice. Moreover, under the same exposure conditions, mice will die at PVC smoke levels 4-7 times lower, and HCl levels 7-10 times lower, than those at which rats will. In contrast, the lethal doses of asphyxiants, such as carbon monoxide (CO) are similar in rats and mice.

These results indicate that the response of the mouse significantly overestimates the toxic

potency of HCl and of PVC smoke to man.

PREFACE

This paper will deal with several aspects associated with fire safety. It is of interest, therefore, to present, right at the start, definitions of some of the terms to be used, in order to avoid confusion.

Fire hazard can be defined as the potential for harm associated with fire, addressing threats to people, property or operations, resulting from a particular fire scenario. Fire risk is a combination of (a) the fire hazard, (b) the probability of occurrence of a fire in that scenario and (c) the probability of the material or product being present in the fire scenario. Toxic potency (of smoke) is a quantitative expression relating concentration and exposure time to a certain adverse effect on exposure of a test animal, usually death. It should be stressed that the toxic potency of smoke is also heavily dependent on the conditions under which the smoke was generated. Finally, smoke is here used as the sum total of the gaseous, liquid and solid airborne products of combustion. Exposure dose represents an integration of the toxic insult, as calculated from the smoke concentration vs. time curve. If the insult results from an individual toxicant and its concentration is constant, the exposure dose is the product of concentration and time. Time of exposure and time to a toxic effect are very different: the action of many toxicants may take considerable time post-exposure.

Toxicity information is, unfortunately, expressed in a variety of common units. Toxic potency of smoke is usually expressed in mg/L (although the results of some tests, e.g. the UPITT test[3], tend to be reported in terms of the mass loaded, in g, based on a fixed size exposure chamber), while that of individual toxicants (commonly gases) is normally expressed in ppm. Exposure doses are thus presented in ppm min or (mg/L) min.

INTRODUCTION

During the 1970's and early 1980's a number of test methods were developed to measure the toxic potency of the smoke produced from burning materials (e.g. refs. 1-4). These methods differ in a variety of respects: in particular in the relative rankings they generate for the toxic potency of the different materials they test. A case in point was made in a study of the toxic potency of 14 materials by two methods[5]. It showed (Table 1) that the material deemed most toxic by one of the protocols appeared to be the least toxic by the other method! The test methods used in the latter paper[5] were different from the major ones in use today[1-4]. However, the work illustrates one of the dangers of relying on toxic potency test methods: different combustion atmospheres are generated in each toxic potency protocol, and these result in cross-overs in toxic potency results. This is due to the similarity in toxic potency of most materials in common use.

It has now become clear that the toxic potency of most materials is really very similar, with very few exceptions, a point clearly illustrated in Figure 1[6]. The Figure presents some results on toxic potency of smoke from a variety of common materials, as measured by the NBS cup furnace toxic potency test[1]. These toxic potency values are compared with the intrinsic toxic potency of other poisons and of toxic gases, as well as with textbook toxicity categories[7]. The reason for this similarity of toxic potencies is that the most important toxic product in any fire is carbon monoxide (CO), produced when all organic materials burn. Furthermore, there is wide agreement today that small-scale smoke toxicity tests only show broad toxicity categories and do not really distinguish among most materials.

This indicates that the toxicity of the smoke of most materials can be approximated by the product of a median toxic potency and the amount of smoke produced from the material per unit time, in other words the material's mass loss rate. The only materials that do not follow this rule are those very few ones with an exceptionally high toxic potency. PVC is not among these materials. That is why a low mass loss rate will generally mean a low toxic fire hazard, almost irrespective of the toxic potency of the smoke itself.

Most of the primary toxicants in a fire atmosphere can be classified in one of two categories, according to their mechanism of action: asphyxiants (e.g. CO, hydrogen cyanide (HCN), low oxygen) and irritants (e.g. hydrogen chloride (HCl), acrolein, hydrogen fluoride (HF), nitrogen oxides).

There has been, in recent years, a great deal of controversy regarding the smoke toxicity of poly(vinyl chloride) (PVC), much of it based on the lack of a proper understanding of the facts. The issue is of importance inasmuch as smoke toxicity is occasionally, albeit incorrectly, directly correlated with fire hazard or fire risk.

The majority of combustion products of PVC are the same as those given off by virtually all organic materials, both natural and synthetic: viz. carbon oxides, hydrocarbons and water [8, 9]. However, PVC releases an important combustion product not generated by natural materials: HCl.

This paper will present an update of available information regarding the toxicity of PVC smoke and that of HCl. It places special attention on the sensitivity of different animal species to them. This is important because animals are being used as models for humans in toxicity tests, and some are more appropriate than others. The paper will also, briefly, deal with HCl decay in a fire atmosphere. The toxicity of PVC smoke decreases rapidly, because of HCl decay. In contrast, the toxicity of the smoke of most other polymers remains the same, since the other main smoke toxicants do not decay.

It has already been stated that toxic fire hazard is associated mainly with the amount of combustion products being generated per unit time, viz. the mass loss rate. Combustion mass loss rate is, in turn, a consequence of fire properties, which are determined in small-scale tests, large-scale tests and can be predicted by fire models. The paper ends referring too to the low tendency of PVC polymer to burn and, thus, to generate toxic products at all.

BACKGROUND ON TOXICITY OF PVC SMOKE

A number of studies have evaluated the toxic potency of the smoke of groups of materials, based on a particular protocol. Almost invariably they show that the toxic potencies of most common smokes differ little, virtually irrespective of the protocol used. The comparative rankings of materials within a certain study can vary tremendously, however. Consequently, it has been suggested that if an exposure dose within the range of 300-3,000 (mg/L) min leads to animal lethality, this represents average smoke toxicity[10]. Figure 1 illustrates this point by putting smoke toxic potencies in an overall toxicological perspective.

Reviews by Hinderer[11], Huggett and Levin[12] and Doe[10] have discussed some of the most important studies of PVC smoke toxicity. Separately, Huggett[13] has analysed the reporting procedure, with respect to PVC smoke (and its major toxic gases: CO and HCl), of several protocols.

There is general agreement, both in the specific studies on PVC smoke and in many general toxicity studies such as those mentioned earlier, that the toxic potency of PVC is within the normal range of common materials.

However, considerable misinformation on the toxicity of PVC smoke still remains in the public domain, causing apparent controversies. These are based on articles studying particular incidents, such as the 1975 fire at the New York telephone exchange[14-16]. It would appear as if some such articles were written with disregard for a scientific interpretation of the facts. Although the claims made in each of the specific articles has been rebutted and their flaws highlighted[17-18], apparent confusion persists.

One of the best researched medical studies on human exposure to PVC smoke[19] showed that PVC decomposition products do indeed have short-term adverse effects on pulmonary function. These can be attributed to HCl, since they mirror the results of animal studies, which will be discussed later in this paper. The minor pulmonary function abnormalities seen after 3 months could not be separated from those due to smoking.

The first aspect to be discussed in this paper is the toxicity of the principal unique toxicant contained in PVC smoke: hydrogen chloride.

STUDIES ON HCl TOXICITY

VERY EARLY STUDIES

A number of very early studies were carried out on the inhalation toxicology of HCl, in the late 19th. century and early 20th. century, using a variety of animal species[20-24]. These studies used cats, guinea pigs, rabbits, hares, doves, frogs and humans. The exposure doses for the non-primate mammals ranged from a few thousand ppm min to over a million ppm min. The results indicated that HCl, as expected, was an irritant which could cause lethality at very high exposures.

Interestingly, there was, for each animal species, a threshold below which lethality was never observed (lowest lethal concentration). These investigators found considerable variation in the biological handling (absorption) and toxic response of the different species to HCl, but no evidence of synergistic effects. For example, a cat survived an exposure dose of >300,000 ppm min (3,400 ppm for 1.5 h). Rabbits were very variable: one survived an exposure dose of 560,000 ppm min (1,400 ppm for 6 h 40 min) but another one died at just over 100,000 ppm min; levels above 150,000 ppm min seemed often to be lethal in one study but levels of >300,000 ppm min were not lethal in another one. Lowest lethal exposure doses for guinea pigs were close to 200,000 ppm min, while rats survived exposure doses of almost 1,000,000 ppm min (2,400 to 4,500 ppm for almost 5 h). Multiple long-term exposures to low concentrations seemed to cause no serious effects in rabbits, guinea pigs or doves.

The studies on humans involved only fairly low concentrations and exposures (<5,000 ppm min) and were geared towards a search for safe work place concentrations. All of the effects experienced by the subjects were minor and disappeared soon after exposure.

An Appendix contains an edited translation of the major aspects of these early studies.

MORE RECENT STUDIES

Recent studies of lethality concentrated primarily on 3 animal species: baboons, rats and mice[25-38]. A comparative study of the effects of HCl exposure on a rodent (rat) and a non-human primate (baboon)[28] investigated the ability of these animals to escape from a hazardous fire environment. Some earlier investigators had speculated how HCl would reduce escape ability based on investigations of mouse sensory irritation. This study provided the first indication of how primates and rodents respond to similar levels of HCl exposure. The baboons were able to accomplish a complicated escape paradigm after 5 min exposure to very high HCl levels, without being incapacitated. The rats did not suffer incapacitation due to HCl either.

The studies by Kaplan et al.[28, 30, 31] also indicated that primates are much more tolerant of HCl than was previously believed. All the baboons exposed to doses of up to 150,000 ppm min survived the normal 14 day post-exposure period used for testing inhalation toxicity.

However, two of these animals later developed pulmonary infections and were not adequately treated. They died post-exposure, at 18 days (after 16,570 ppm HCl for 5 min) and at 76 days (after 17,290 ppm HCl for 5 min). Since these 2 baboons developed pulmonary infections it is not possible to determine whether they would have survived in the absence of infection or if they had received the same level of treatment that would have been provided to a human being. It has been suggested that the exposure of the baboons to HCl might have increased their susceptibility to pulmonary infection. This is a reasonable hypothesis, which cannot easily be confirmed either way. However, infection-free baboons have survived exposures of 150,000 ppm min (30,000 ppm for 5 min, 15,000 ppm for 10 min or 10,000 ppm for 15 min). Furthermore, 3 baboons have later been exposed to levels of 10,000 ppm for 15 min (i.e. 150,000 ppm min) without observing any mortality. Exposures of baboons to doses of over 150,000 ppm min were not carried out and this level is therefore, conservatively, estimated to be close to a lethality threshold.

The lethality response to HCl of the rat and the primate thus appears to be very similar. The lowest lethal dose for a 5 min exposure (including post-exposure) is virtually identical for rats and baboons. At longer exposures the primate appears to be somewhat less sensitive than the rat, for a 30 min HCl exposure [28, 30, 31].

It is of interest, for comparison purposes, to mention the long-term exposure of rats and primates to another irritant, chlorine[39, 40]: it gave similar results. Chlorine produces both upper and lower respiratory tract effects in rats, but only upper respiratory tract irritation in primates.

It was suggested[41] that rodents are less sensitive to HCl because rodents differ from primates by breathing through their noses only. Thus, it was further speculated, rodent nose ciliae will "scrub" out the water soluble gases. In an effort to demonstrate this effect[42], mice were cannulated to bypass their noses and exposed to HCl: HCl LC_{50} was reported to decrease considerably. The author speculated that results with mice needed "correc- tion" by this same factor to be an appropriate model for humans. However, tracheal cannulation bypasses the pharynx, the larynx and a portion of the trachea, all of which are of major importance in scrubbing out water-soluble gases in man. For this reason, this approach exaggerates, unrealistically, the effects of HCl by sending it deep into the respiratory system. Such a procedure makes the mouse, an already sensitive animal, even more sensitive. An example of this excess sensitivity is the fact that mice often die of stress in the toxic potency test restrainers, prior to smoke exposure.

There is abundant evidence that, when exposed to HCl, mice are much more sensitive than rats or primates, and by implication humans. This excess mouse sensitivity ranges from 4 times, based on the LC_{50}[26], to 8-10 times, based on the lowest lethal dose for a 5 min exposure, both within exposure[38] and including post-exposure[27]. This suggests that, while the mouse is not a good model for humans in terms of lethality following HCl inhalation, the rat appears to approximate primate response well.

It has been suggested that this excess sensitivity of mice over rats may be due to the difference in body weight (rats being ca. 10 times heavier than mice). This is based on the assumption that the mouse is roughly 10 times more sensitive than the rat to all toxicants. However, studies with carbon monoxide suggest that both animal species have similar lethal sensitivities to asphyxiants: for a 30 min exposure the LC_{50} for rats is 4,600 ppm[43] and the one for mice is 3,000 ppm[44].

Exposure of rats and baboons to carbon monoxide has also suggested that both animal species are very similar in sensitivity to this asphyxiant gas, in terms of both incapacitation and lethality[28].

PULMONARY FUNCTION STUDIES: COMPARISON OF PRIMATES WITH RODENTS

It is critical to consider species differences when making qualitative and quantitative predictions of human response to pure gaseous HCl and to PVC smoke. Therefore, the Vinyl Institute sponsored a number of comparative studies of the response of primates and rodents. A fundamental objective of this investigation was to evaluate the validity of the various rodent species as models for man. The specific focus of the work was to gain information on HCl penetration damage into the respiratory tract. In particular, it was important to investigate whether the effects of HCl on pulmonary function reported by Burleigh-Flazer et al.[45] for the guinea pig also occur in other species, and, more importantly, in man. The primate chosen as surrogate for man was the baboon, because its respiratory response to irritants, its upper airways and its general physiology are all very similar to those of humans, in particular young children[46].

Experimental Details

Groups of three anesthesised baboons were exposed (head only) to air and to HCl at nominal concentrations of 500, 5,000 and 10,000 ppm for 15 min. One of two continuous HCl measurement methods[47, 48] was used to maintain constant concentration, by flow rate adjustments. Actual measurements were made with titration of soda lime tubes[49]. The average HCl concentrations measured during all the exposures were 562, 4,145 and 10,170 ppm. Room air was maintained at ca. 23 °C and 50% relative humidity. The exposure chamber was a ca. 200 l poly(methyl methacrylate) (PMMA) box (Figure 2).

Respiratory rate (f), tidal volume (V_T) and minute volume (MV) were measured continuously, with an inductive plethysmograph, starting prior to the test and ending 15 min after exposure. Pulmonary function was measured, before exposure and at 3 days and 3, 6 and 12 months, by 3 methods: 2 direct ones[50, 51] and an indirect one (CO_2 challenge: 5 min ramping up to 10% CO_2 and 5 min at this final value). Arterial blood samples were analyzed also for pH, and partial pressures of oxygen (PaO_2) and of carbon dioxide ($PaCO_2$) before, during and immediately after exposure, until the animal's appearance was normal. Anteroposterior and lateral chest X-rays were taken, within 1 h after all exposures to the highest HCl concentration (10,000 ppm).

Further details of these experiments have been published elsewhere[36].

Results

The response of the baboons exposed to the lower HCl concentration (500 ppm) was not statistically distinguishable from that of those exposed to air, for all parameters measured.

For the baboons exposed to 5,000 and 10,000 ppm HCl, their respiratory frequency increased during exposure, after they had held their breaths for 10-20 s. This is consistent with previous findings[52, 53] of responses of human and non-human primates to irritants. On the other hand, rodents respond to irritants by decreasing their respiratory frequency. The tidal volume of all baboons remained unchanged. In other words, the baboons exposed to high HCl concentrations breathed more frequently, but took in the same amount of air in each breath. However, their arterial oxygen pressure decreased rapidly, throughout exposure and up to 10 min post-exposure. These decreased PaO_2 values reverted to normal within 10 min and remained normal throughout at least 3 months post-exposure.

The arterial blood pH and CO_2 pressure did not change for the baboons at any dose level. This contrasts with reports on rodent (rabbit) exposures to PVC combustion products (including HCl) wherein decreased blood pH was measured[54]. This may be due to baboons being better able than rabbits to compensate for pH changes or to a lack of proper statistical analysis of the rodent data. It is also possible, albeit unlikely, that a species other than HCl is responsible for the increased blood acidity.

The non-invasive pulmonary function tests showed no significant differences between the control and the exposed groups throughout at least 3 months post-exposure.

The carbon dioxide challenge tests showed considerable variability among the animals in each group, making the results difficult to interpret. The tidal volume response was not changed. The respiratory frequency of the baboons appeared to increase at 3 months (although not at 6 months) for the baboons at the highest exposure levels. This is likely to be a measurement artifact, since an impairment in lung function due to HCl producing any obstructive lung disease would result in a decrease in ventilatory response.

Guinea pigs have been shown to develop decreased respiratory response to CO_2 challenge up to 10 days after exposure to HCl levels as low as 1,040 ppm for 30 min (31,200 ppm min)[45]. For the primates tested in this study no evidence of changes in pulmonary function were observed after exposures to levels of HCl as high as 10,000 ppm for 15 min (i.e. 150,000 ppm min) following 3 months of post-exposure observations.

The X-rays and the clinical observations show that these baboons, exposed to high levels of HCl (75,000 - 150,000 ppm min), suffered no pulmonary edema, but only some hypoxia via small airway constriction. This is in contrast to reports of pulmonary edema in guinea pigs, although those rodents were exposed to much lower HCl doses[45]. It is interesting that in a recent study on guinea pigs these animals were shown to be both much more sensitive to HCl than rats (guinea pig HCl LC_{50} values of 1,350 ppm for 15 min and 2,900 ppm for 30 min[55]), and much less sensitive to CO.

Primates can tolerate 150,000 ppm min HCl without lethality occurring, while death was observed at exposures as low as 16,000 ppm min for mice[28] and 30,000 ppm min for guinea pigs[45].

HCl is an irritant, the effect of which often occurs long after exposure. It has now been established that HCl will not cause lethality until exposures to very high concentrations are maintained for long periods. The combination of HCl with other toxicants, in particular the asphyxiants CO and HCN, appears to cause additive, but not synergistic, toxic effects[37, 55]. This is similar to the combined effects of CO and HCN[43], even though the mechanisms of action of the various toxicants are very different.

However, HCl has a very disagreeable odor, noticeable at an extremely low concentration: less than 1 ppm[56]. Moreover, low concentrations of HCl can cause unpleasant irritating effects which make its presence noticeable very early on in a fire. The appearance of such an odor at a concentration much lower than one which will cause health effects may serve, of course, as a warning of the need to leave the room or building, although it produces the erroneous impression that HCl is causing severe harm.

Overall: HCl toxicity on animal species can be summarized as follows:

Baboons:

(1) Incapacitation: baboons will not be incapacitated by exposure to up to 30,000 ppm HCl in 5 min, or to other exposure doses of 150,000 ppm min.

(2) Lethality: baboons have survived, without adverse long-term effects, exposures of up to 30,000 ppm HCl for 5 min (although one baboon died 18 days after an exposure to 16,570 ppm) and other exposures to ca. 150,000 ppm min. The lethal exposure dose threshold is, however, unlikely to be much higher than 150,000 ppm min.

(3) Pulmonary function: baboons have not developed long-term physiological or pulmonary function effects after exposures to nominal concentrations of 5,000 or 10,000 ppm HCl for 15 min.

(4) Model for humans: baboons have an anatomical and physiological system very similar to that of a young child.

Rats:

(1) Incapacitation: rats will not be incapacitated by up to 76,730 ppm HCl in 5 min, although they will die post-exposure at concentrations higher than 20,000 ppm.

(2) Lethality: rats do not die from exposures of 5,000 ppm for 15 min.

(3) Lethality: rats have a lowest lethal concentration at 5 min within exposure of 87,660 ppm, and at 7 days' post-exposure of 32,255 ppm.

(4) Lethality: rats have a lethal exposure dose ranging between 112,000 and 169,000 ppm min, depending on time of exposure.

(5) Model for humans: while rats are not similar to primates either in lung anatomy or in respiratory response (i.e. they are obligate nose breathers and respond by respiratory depression), their lethality response to HCl appears to model that of baboons very well.

Mice:

(1) Incapacitation: mice will be incapacitated and die at an exposure of 2,550 ppm for 15 min.

(2) Lethality: mice have a lowest lethal concentration of 11,482 ppm at 5 min within exposure, and of 3,200 ppm after 7 days' post-exposure, i.e. 1/8 to 1/10 of rat levels.

(3) Lethality: the LC_{50} for mice is 3-8 times lower than the one for rats, when exposed to smoke containing irritants, in similar scenarios.

(4) Lethality: mice and rats are of similar sensitivity towards asphyxiants.

(5) Model for humans: mice have a much higher sensitivity to HCl, in particular, and to irritants in general than rats or primates.

STUDIES ON PVC SMOKE TOXICITY

Influence of Toxicity Protocol and Animal Species

A number of screening tests are being used to evaluate the toxicity of smoke from burning materials. Some of them even form the basis of regulation or specifications. Three test methods were, therefore, chosen in order to investigate how they would affect a number of flexible PVC compounds[38]. The test methods chosen were the NBS protocol, in the flaming and non-flaming modes[1], the radiant furnace test (in the flaming mode, at $5W/cm^2$)[4] and the UPITT test[3]. The PVC compounds chosen were two standard commercial compounds (a standard jacket (SJ) and a standard insulation (SI)) as well as two experimental wire coating materials. Results on a nylon compound and on wood (Douglas fir) were also used for some comparisons.

The concentrations of the major toxicants in PVC smoke, viz. HCl (by a combination of a continuous method[48] and soda lime tubes[49]) and CO, as well as carbon dioxide and oxygen, were measured for all protocols and materials. The mechanisms by which lethality occurs in each case were inferred from toxicological interpretation of the analytical results.

The experimental compounds were developed in order to decrease HCl emission. According to a laboratory procedure[57] they generate only 38.1% (EXP B) and 19.3% (EXP C) of their available chlorine as HCl. This is much less than the percentage of available chlorine generated by most standard commercial compounds; the ones investigated here released 87.7% (SI) and 95.3% (SJ) of available chlorine. Interestingly, the experimental compounds also generate much less HCl, per unit mass burnt, than the standard materials in all the test protocols (Table 2 shows results based on total gas measurements). Furthermore, the experimental compounds also generate much less CO than the standard materials (Table 2). It is not surprising, therefore, that their associated toxic potencies, as measured by the LC_{50} according to the published protocols (Table 3), are also much lower.

This is an important result in itself, because it indicates that the toxic potency of a PVC compound is not a fixed value. Comparisons between the various test protocols give some further insight into the extent of the protocols' utilities. Table 3 also shows the extent to which results can be differentiated, by changing the letters for those results which are significantly different at $p=0.05$ level (i.e. with statistical validity).

In the NBS protocol, non-flaming mode, the LC_{50}'s of the 4 compounds can be statistically differentiated into two groups: standard compounds and experimental compounds. Moving on to NBS, flaming, differentiation becomes even clearer: while the LC_{50}'s of the standard compounds are similar, the LC_{50} of EXP B is statistically different and higher and the LC_{50} of EXP C even higher. In the radiant furnace protocol, the LC_{50}'s of all four compounds are statistically differentiable. In fact, in the NBS flaming and in the radiant heater protocols, there is a 5-fold difference between the LC_{50} of standard insulation and that of EXP C! However, in the UPITT protocol, only the LC_{50} of EXP C can be statistically differentiated from that of the other compounds.

This suggests that there may be some specific problems with the UPITT test protocol. A deeper study of this protocol identified some of the problems[58]. The analytical data showed that the experimental materials generated atmospheres of very low lethal potential. Furthermore, the analytical ranking of toxic potential was the following, similar to that of the NBS and radiant furnace protocols:

$$SJ > SI \gg EXP\ B > EXP\ C$$

There are two main reasons for the discrepancies: (1) the extreme sensitivity of the mouse as an animal model for inhalation of irritants, and of HCl in particular (which has already been discussed), and (2) the short burst of extremely high toxic gas concentrations during the test.

The mouse is much more sensitive than the rat (or, for that matter, the primate) to HCl. Moreover, while HCl decreases the sensitivity of rats to CO[38], it increases the sensitivity of mice to CO.

The LC_{50}'s of four materials were also tested, using identical tests but varying the animals. Table 4 shows that mice are 2.14 to 7.5 times more sensitive than rats to smoke containing irritants[38], a result similar to that found for pure gases.

The UPITT method generates the toxic gases over a very short period: for many materials the entire mass loss process takes place over a 3-7 min period. This type of exposure is generally much more toxicologically severe than exposure to the same dose, but involving lower concentrations and a longer exposure period.

The type of exposure simulated in this test would correspond to a very intense fire, in the proximity of the victim. Fire exposures in the room of origin are only of real-life relevance if they are limited to pre-flashover conditions. After flashover the smoke and toxic gases will be transported to other rooms, and the exposures will no longer be so short and intense.

Other serious technical problems have been identified for the UPITT test protocol: design features leading to leakages[59] and safety concerns and unrealistic representations of any stage of a real fire[60], as well as a poor statistical method of calculation of results[61]. Recent results suggest that multiple LC_{50} values can also be obtained for a single material[62].

The specific problems with the UPITT protocol should not overshadow the fact that the measurement of LC_{50}'s is a very poor means of quantifying toxic hazard. Several better ways have been identified recently. Two intermediate procedures are a test for potential toxic hazard, being developed by the National Institute for Building Sciences (NIBS) for application to end-use products and a quick measure of toxic hazard, based on the combination of toxic potency, mass loss rate and time to ignition.[6] Both of these methods recognise that the comparison of product toxicity should take into account their propensities to resist burning. Ultimately, toxic hazard is but one element in an overall fire hazard assessment.

Overall results of recent studies on PVC smoke toxicity can be summarized as follows:

(1) the toxic potency of PVC smoke is within the normal range found for those of all common products;
(2) different PVC products can have a very wide range of toxic potencies, within that overall range;
(3) lower toxic potency is, as stated before, only a minor aspect of fire safety;
(4) toxic potency test protocols, measuring LC_{50}'s, are a poor way of measuring potential toxic hazard;
(5) the UPITT test is the least satisfactory protocol in U.S. use.

DECAY OF HCl

A series of studies was also done to investigate the lifetime of HCl in a fire atmosphere[49, 63-64]. These studies showed that HCl reacts very rapidly with most common construction surfaces (cement block, ceiling tile, gypsum board, etc.). Therefore, the peak HCl concentration found in a fire is much lower than would have been predicted from the chlorine content of the burning material. Moreover, this peak concentration soon decreases and HCl disappears completely from the air. The peak HCl concentration found in a full-scale plenum was only up to 35% of the theoretical concentration[50]. In a simulated smaller-scale plenum this decreased even further: 10% of theory[63]. These, and other, studies were used as the basis for developing a mathematical model for HCl generation, transport and decay[64]. This model was also applied, successfully, to PVC burning and HCl emission in experiments involving a full-scale room-corridor-room design[65].

One of the consequences of these studies is that toxicity tests carried out in glass or plastic exposure chambers may exaggerate PVC smoke toxicity. On such surfaces HCl does not decay as fast as on realistic surfaces, so that toxic gases remain present longer than in real fires.

Carbon monoxide gas phase concentration does not decay in a fire atmosphere[49]. Carbon monoxide causes physiological harm by reacting with hemoglobin in blood and forming carboxyhemoglobin (COHb). Interestingly, high blood COHb levels have been found to correlate well with fire fatalities[6]. Furthermore, actual HCl concentrations found in real fires are much lower than those of CO[6]. This means that the toxic hazard associated with HCl in a fire is likely to be relatively small, as compared with that of the main fire toxicant: CO.

FIRE PROPERTIES OF PVC

There are a great variety of PVC products, with tremendous differences in fire performance. However, there is one common thread: PVC contains chlorine in its structure. This decreases the tendency to ignite or burn, because it is one of the very few chemical elements conferring fire retardancy, when introduced at the appropriate level and form[9].

In general, unplasticised (rigid) PVC products will not sustain combustion or spread flame in the absence of a continuous applied heat source. Most small-scale test results show PVC products (particularly rigids) to be among those with better fire properties. Such results are further confirmed by large-scale tests[66] and by model calculations[67].

CONCLUSIONS

(1) There is no single toxicity for the products in PVC smoke: it can vary widely.

(2) The toxic potency of the smoke from most PVC products is similar to that of most ordinary products in use in society.

(3) PVC is unusual because it liberates HCl when it burns.

(4) HCl is of similar toxicity to the principal fire toxicant: CO.

(5) HCl decays rapidly in a fire atmosphere while CO does not.

(6) Rats are reasonable models of lethality for humans but mice are excessively sensitive.

(7) Toxicity tests based solely on LC_{50}'s cannot predict toxic hazard, and the UPITT test is less satisfactory than other tests.

(8) Better predictions can be made from measurements combining toxicity, mass loss rate and ignition resistance, leading ultimately to fire hazard assessment.

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Table 1
Comparative Mortality Data of Combustion Products of Polymers

LC_{50} g	STATIC CHAMBER Sample	Toxicity Ranking (Toxicity Increases Upwards)	DYNAMIC CHAMBER Sample	LC_{50} g
9	Red Oak	1	Wool	0.4
10	Cotton	2	Polypropylene	0.9
21	ABS (FR)	3	Polypropylene (FR)	1.2
23	SAN	4	Polyurethane foam (FR)	1.3
25	Polypropylene (FR)	5	Poly(vinyl Chloride)	1.4
28	Polypropylene	6	Polyurethane foam	1.7
31	Polystyrene	7	SAN	2.0
33	ABS	8	ABS	2.2
37	Nylon 6,6	9	ABS (FR)	2.3
37	Nylon 6,6 (FR)	10	Nylon 6,6	2.7
47	Polyurethane foam (FR)	11	Cotton	2.7
50	Polyurethane foam	12	Nylon 6,6 (FR)	3.2
50	Poly(vinyl Chloride)	13	Red Oak	3.6
60	Wool	14	Polystyrene	6.0

Table 2
Relative Generation of Major Toxicants in Test Protocol Atmospheres

	NBS NF	NBS F	RF	UPITT
		HCl		
SI	100	100	100	100
SJ	62	91	66	197
EX B	21	11	8	45
EX C	4	0.2	0	17
		CO		
SI	100	100	100	100
SJ	66	82	63	125
EX B	30	48	38	63
EX C	25	23	23	36

Table 3

Lethal Potencies (LC_{50} Values) of PVC Compounds Determined by Three Test Methods[a,b,]

NBS Non flaming (mg/L)		NBS Flaming (mg/L)			
A	Sl	25.0 (20.0-32.4)	A	SJ	29.6 (22.7-37.4)
A	SJ	31.6 (27.8-36.1)	A	Sl	35.0 (31.3-39.2)
B	EXB	55.7 (44.5-66.0	B	EXB	60.8 (53.0-70.0)
B	EXC	59.9 (52.5-64.9)	C	EXC	159.0 127.0-199.0)

RADIANT HEATER (mg/L)		UPITT		(g)	
A	Sl	33.4 (29.5-56.1)[c]	A	SJ	5.5 (4.2-7.1)
B	SJ	53.1 (49.6-55.9)	A	Sl	5.6 (3.9-8.2)
C	EX B	86.2 (79.0-93.5)	BA	EX B	10.0 (5.1-19.4)
D	EX C	149.0 (122.0-184.0)	B	EX C	21.6 (11.1-42.0)

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[a] Values are LC_{50} values and 95% confidence limits, calculated from initial sample weights. UPITT values were determined using a standard 2.3 L exposure chamber.

[b] Values with a different letter are significantly different at $p = 0.05$ level. For NBS and Radiant Heater Materials, comparisons were done by potency ratio analysis. UPitt statistical comparisons by S. Debanne of Case Western Reserve University.

[c] Calculated from three experiments: 25 mg/L: O/6; 30 mg/L: 1/6; and 35 mg/L: 4/6.

Table 4
Lethal Potencies (LC_{50} Values) of SJ, EX C, NR and Douglas Fir Determined by NBS Test Method with Rats and Mice

	NBS-NF[a] RATS	NBS-NF[a] MICE	NBS-F[b] RATS	NBS-F[b] MICE
SJ	31.6 (27.8-36.1)	4.2 (2.5-6.7)		
EX C	59.9 (52.5-64.9)	13.9 (7.7-20.8)		
			49.0 (42.2-57.0)	20.2 (14.3-30.4)
DF[c]	32.8 (29.3-36.7)	8.9 (6.5-11.8)	37.6 (33.2-44.6)	

* Values are sample charges in mg/L units.

a. NBS nonflaming mode.

b. NBS flaming mode.

c. DF = Douglas fir.

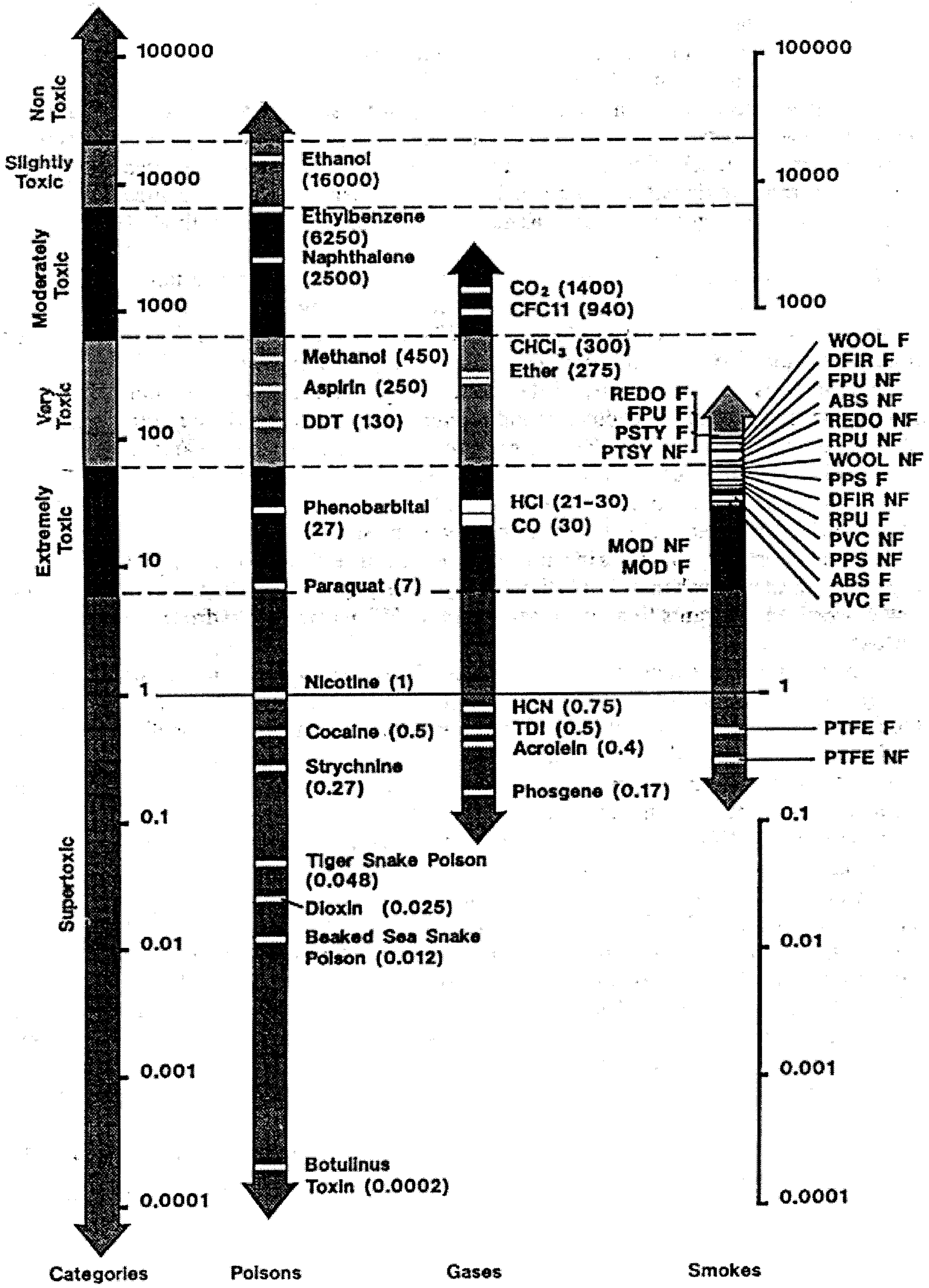

FIG. 1—*Toxic potency (expressed as the lethal dose required to kill half the exposed animals, LD_{50}, in mg/kg) of substances and of smoke. The smoke toxic potency was measured using the cup furnace (NBS) protocol. The animal models used were rats or primates.*

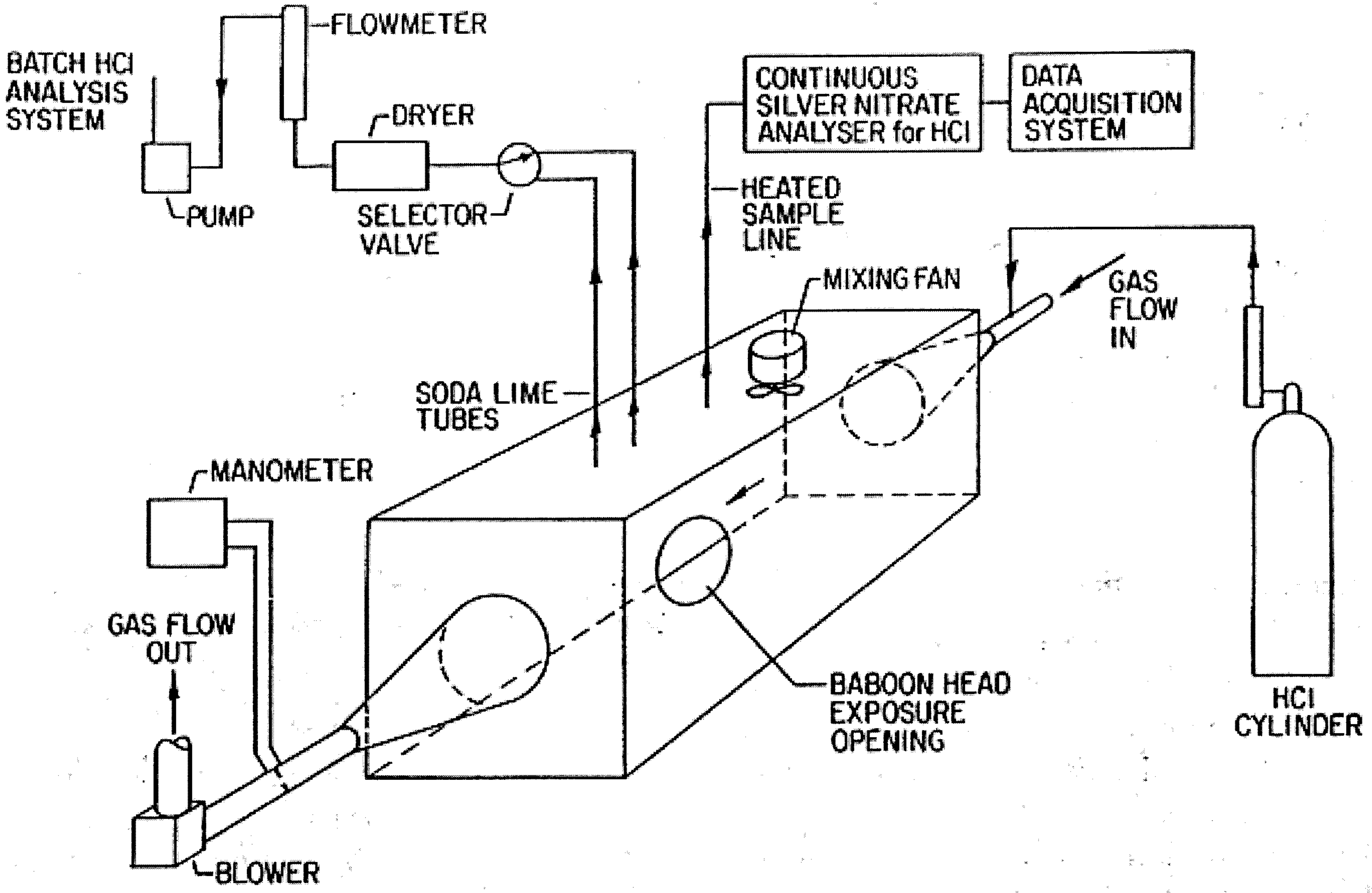

FIG. 2—*Baboon exposure system.*

Robert K. Hinderer[1] *and Marcelo M. Hirschler*[2]

The Toxicity of Hydrogen Chloride and of the Smoke Generated by Poly (Vinyl Chloride), Including Effects on Various Animal Species, and the Implications for Fire Safety

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REFERENCE: Hinderer, R. K. and Hirschler, M. M., **"The Toxicity of Hydrogen Chloride and of the Smoke Generated by Poly (Vinyl Chloride), Including Effects on Various Animal Species, and the Implications for Fire Safety,"** *Characterization and Toxicity of Smoke, ASTM STP 1082,* H. K. Hasegawa, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 1–22.

GBH Attachment 23

AB59-COMM-7-23

REGULATORY DEVELOPMENTS IN NORTH AMERICA THAT WILL AFFECT THE USE OF FLAME RETARDANTS

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ABSTRACT

Requirements associated with fire safety in North America, and especially in the US, are based on a combination of federal government (and local government) regulation and codes and standards issued by private organizations. Some of the recent regulatory developments of interest address several products and occupancies and will affect the use of flame retardants, both in a positive and in a negative fashion. In both the US and Canada there has been activity regarding: plenum cables, trains and underground passenger vehicles and cigarettes. In the US alone there has been activity regarding mattresses, upholstered furniture, filled bed products, children's playgrounds and siding. The developments and their implications are discussed in the paper.

INTRODUCTION

North American fire safety requirements are not, and probably never will be, uniform!

Canada has a system that is intermediate between the European Union regulatory system (which is intended to be, at least ultimately, based on directives and/or regulations from the European Commission) and the US system (where codes and standards are both developed by private companies and can be adopted, or not, by the various state and local governments). The National Building Code of Canada can be different from provincial building codes and standards are issued by private companies.

In the US, there are two primary code developing companies: ICC (International Code Council) and NFPA (National Fire Protection Association). The former develops a full family of codes, including the following: International Building Code (IBC), International Fire Code (IFC), International Mechanical Code (IMC), International Wildland Urban Interface Code (IWUIC) and International Existing Building Code (IEBC), which have been adopted widely throughout the country. NFPA also develops a full family of codes, but two of them (National Electrical Code, or NEC or NFPA 70[1], and Life Safety Code, or NFPA 101[2]) are unique and have no ICC equivalent. NFPA is also one of the premier developers of fire safety standards, including a few key ones: NFPA 90A[3] (air conditioning standard), NFPA 13[4] (sprinkler standard) and NFPA 130[5] (rail standard). Fire tests are developed primarily by ASTM International and by NFPA, although FM Global (formerly Factory Mutual) and Underwriters Laboratories have also developed some widely used tests.

The US Federal Government, as represented primarily by the Consumer Product Safety Commission (CPSC) is entitled to regulate consumer products (except for cigarettes), with an emphasis on those that contain "flammable fabrics". In that connection, there has long been CPSC regulation of the flammability of wearing apparel (via a very mild gas burner test), of carpets and rugs (via the methenamine pill test) and of the smoldering performance of mattresses. CPSC has also long had a test for assessing what is a "flammable solid", although this has not formed the basis of any federal regulation.

The individual US states have always been entitled to issue their own regulation, as long as they are not contradictory with federal legislation, normally non-existent. Thus, California has long had regulation for the fire performance of upholstered furniture and mattresses, based on requirements developed at the

California Bureau of Home Furnishings and Thermal Insulation (CBHF) and this has, on occasion, been emulated by some other states.

PLENUM CABLES

The National Electrical Code (and the Canadian Electrical in Canada Code) regulates the requirements for fire safety in electrical installations. An application that is rare outside of North America is the "plenum". A plenum is "A compartment or chamber to which one or more air ducts are connected and that forms part of the air distribution system." Virtually all public buildings in North America contain ceiling cavities (i.e. false ceilings) and/or raised floors in order to house these air ducts and the heating and air conditioning systems; those are the main types of plenums. With the growth in the need to transmit information (including voice and data) to ubiquitous computers and servers, virtually all office buildings used these ceiling cavity plenums, and raised floor plenums, to also house cables. It has always been understood that the fire performance of materials contained in plenums, and of plenum construction materials, needs to be particularly good, since fires starting in those areas could remain undetected for long periods.

A little-known decision by the NFPA Standards Council had assigned the responsibility for regulating all products and materials (including cables) in plenums to the technical committee on air conditioning, which was in charge of writing the NFPA 90A standard. For many years, electrical codes and NFPA 90A exhibited consistency in requirements, as did mechanical codes, which regulate ducts and plenum areas.

Since the 1970s the most severe requirement for fire safety of electrical cables has been the NFPA 262[6] fire test (initially known as the UL 910[7] fire test, and known in Canada as the CSA FT6 test[8]). The cables that meet requirements based on testing by NFPA 262 have thus, since the 1970s, been permitted to be used in plenums without being enclosed in metal raceways (such as metal conduits). The pass/fail criteria for this test were developed by comparing the flame spread and smoke generated by cables contained within a variety of metal raceways and ensuring that cables not in raceways would meet the same criteria. The use of plenum cables grew rapidly in the 1980s and 1990s, and this became a key market for flame retardants used in such cables.

In the 1990s an effort commenced to replace these requirements by new criteria based primarily on heat content by NFPA 259[9] (basically an oxygen bomb calorimeter test), so that cables would have to be made with "limited combustible" materials. The new requirements were intended to ensure that cables would have to be constructed with insulations and jackets (sheaths) made from fluoropolymers and not from PVC or polyolefins, as the latter materials would not meet the new requirements. Fluoropolymers do not require the use of flame retardants to meet the fire test criteria, while PVC and polyolefin materials do. Therefore, the new requirements would represent a severe loss of markets for flame retardants.

Details of the technical background for this commercial battle have been given elsewhere[10] and will not be repeated here: no evidence was ever presented, in terms of fire loss statistics or of fire hazard/fire risk to indicate that plenum cables made to the requirements of NFPA 262 (or UL 910 or CSA FT6) were unsafe.

The 2002 edition of NFPA 90A contained the requirement that cables in plenums had to be listed as "limited combustible" cables or as cables complying with the requirements of NFPA 90A. NFPA standards council stated that the term "limited combustible" should apply to building construction materials and not to contents, such as electrical or optical fiber cables. It then declared a freeze on revisions of the National Electrical Code, stating that the NEC could not be amended with regard to plenum cables, from the status quo in its 2002 edition, until the air conditioning committee "completed its revision of NFPA 90A".

The air conditioning committee went to work and developed a draft 2005 edition of NFPA 90A. It banned the use of flame-retarded plenum cables, except in plenums that are protected by sprinklers and are in buildings that are not protected by sprinklers. This would have amounted to almost a total ban, since plenums are virtually never sprinklered and most commercial buildings containing plenums require sprinkler protection. Once the implications of this ban became clear to the NFPA membership, they voted not to issue this edition of NFPA 90A. The technical committee responsible for NFPA 13, the standard on sprinkler installations, added a statement to the 2007 edition of its standard clarifying that the presence of cables in plenums would not trigger the requirement that sprinklers be installed in those plenums. As a result of the rejection of the 2005 edition of NFPA 90A, increased scrutiny was placed on the membership of the air conditioning committee, with several changes ensuing.

Now, the 2008 edition of the NEC has been issued this year and plenum cables can still be constructed of flame-retarded materials. More importantly, the 2008 edition of NFPA 90A will, in all likelihood, be issued in 2008. The plenum cable requirements in the draft NFPA 90A-2008 have returned to those in the 1999 edition; they recover the plenum cable market for flame retardants. The Canadian Electrical Code has been under the same pressure as the US NEC, and cables are still required to meet CSA FT6. This commercial battle between manufacturers of flame retardants (and of most polymeric materials) and manufacturers of fluoropolymers, now some 20 years old, is not over, as proposals for amending the NEC are due in 2008 and the freeze will be over. However, the tide has clearly turned in favor of the renewed use of flame retardants.

MATTRESSES

On March 28, 2000, attorney Whitney Davis, director of the Children's Coalition for Fire-Safe Mattresses submitted four petitions to CPSC concerning mattress flammability. The petitions proposed four options: (1) an open flame standard similar to the full-scale test set forth in California Technical Bulletin 129[11] (CA TB 129); (2) an open flame standard similar to the component test set forth in British Standard BS 5852[12]; (3) a warning label for mattresses warning of polyurethane foam fire hazards, and (4) a permanent, fire-proof mattress identification tag. Whitney Davis had previously been working with California Assemblyman John Dutra, as a result of which the California legislature passed a law, Assembly Bill AB 603, in 2001. AB 603 required that all mattresses manufactured or sold in California be "fire retardant", but did not go into specific details.

Before AB 603 was issued, the state of California required all foam used for mattresses to comply with California Technical Bulletin 117[13] (CA TB 117). CA TB 117 includes a vertical fire test for foam that could not be "passed" unless the polyurethane foam used contained some level of flame retardants. There is no consensus as to whether foam complying with CA TB 117 resulted in mattresses with highly increased fire safety. It is clear, however, that such foam would delay ignition of the mattress from small open flames and would even inhibit ignition from very small open flames. California also had in place a voluntary standard for high risk occupancies known as CA TB 129. The gas burner used as the ignition source in CA TB 129 is a T-shaped burner that applies propane gas for 180 seconds at a flow rate of 12 L/min. The test is severe enough that it can usually not be met unless the foam contained in the mattress is well flame-retarded. This also became a consensus standard as ASTM E 1590[14], which does not have its own pass/fail criteria.

AB 603 was initially expected to require that mattresses comply with CA TB 129. After a research project was conducted at the National Institute of Standards and Technology (NIST) on behalf of the mattress industry, a new test was developed, based on using a new dual burner[15][16]. This resulted in the issuance of California Technical Bulletin 603[17] (CA TB 603), which went into effect for all mattresses sold in the state of California from January 1, 2005. It is important to point out that CA TB 603 is a significantly less severe test than CA TB 129 and mattresses sold as complying with the test often use barriers without adding flame retardants into the foam. In fact, if the barrier is pierced or damaged (by the effect of vandalism and/or of children playing with sharp objects), experience indicates that mattresses can comply with CA TB 603 but release large amounts of heat. However, in the absence of vandalism, clearly mattresses complying with CA TB 603 offer a significant improvement in fire safety.

Eventually, the CPSC issued their rulemaking (law) and developed 16 CFR 1633[18], which is technically equivalent to CA TB 603, but has some added requirements, in terms of labeling and record keeping. 16 CFR 1633 went into effect throughout the US on July 1, 2007. 16 CFR 1633 requires that all mattresses, mattress/foundation sets and futons sold in the US meet the following pass/fail criteria: (a) the peak heat release rate does not exceed 200 kW during the 30 minute test, and (b) the total heat release does not exceed 25 MJ in the first 10 minutes of the test. The propane gas flames from the dual burner are applied for 70 seconds (top burner, at a flow rate of 12.9 L/min) and 50 seconds (side burner, at a flow rate of 6.6 L/min), giving a total applied heat release of 27 kW. The total observation period from the start of the test is 30 minutes.

The codes in the US have long interpreted this regulation to apply to residential mattresses only and that higher fire safety requirements should apply to high risk environments, such as jails or prisons, hospitals and university dormitories. NFPA 101 contains requirements that mattresses in health care occupancies and in detention and correctional occupancies that are not sprinklered must comply with a peak heat release rate of 250 kW and a total heat release no more than 40 MJ in the first 5 minutes of test when tested to ASTM E 1590 (or CA TB 129). The IFC[19] had the same requirements up to 2006, but revised the requirement in 2007 so that the peak heat release rate must be 100 kW and the total heat release cannot exceed 25 MJ in the first 10 minutes of test. It also revised the requirements for detention occupancies so they no longer have a sprinkler exception: the mattresses must comply with the requirements irrespective of the presence of sprinklers. The 2009 edition of NFPA 101 is likely to have the same requirements as those in the 2007 edition of the IFC. However, the IFC also requires, since 2007, that mattresses in college and university dormitories meet the same criteria as those in hospitals.

This dichotomy between residential and high risk environments is what offers both the opportunities for improved fire safety and new market uses for flame retardants.

FILLED BED PRODUCTS

As a result of the same petition that led to CA TB 603 and 16 CFR 1633, California AB 603 also mandated that filled bed products, such as comforters, pillows and bed spreads, would also have to exhibit improved fire performance. CBHF studied the flammability of filled bed products and found that these products significantly contribute to mattress fires. In collaboration with the federal government, industry, and commercial laboratories, CBHF is working on California Technical Bulletin 604 (CA TB 604) in order to address this hazard. CBHF intends CA TB 604 to be a performance-based standard that would not prescribe the use of any specific additives or flame retardants but would encourage the use of innovative methods and products to increase fire performance without affecting the environment. In effect, CA TB 604 will consist of three tests, all to be conducted in a small test chamber (or a small hood). They are: a flat filled/bed clothing products test, a pillow/cushion and loose fill materials test and a mattress pad test. The pass/fail criteria are based on weight loss (mass loss) for the first two tests and/or the generation of a hole for the flame to penetrate through (as seen by visual observation) in the third test. The ignition source is a propane gas burner tube (a 250-300 mm long stainless steel tube, 8 mm in outside diameter, 6.5 mm internal diameter. In the first test multiple layers of flat filling materials are inserted in a case made of standard sheeting fabric or of the product's actual cover fabric. The test specimen is placed on a horizontal cement board on a weighing device and ignited at one corner. In the second test the filling materials are encased in a case made of the standard sheeting fabric or of the ticking/fabric used in the actual bed product to encase the loose filling materials. The test specimen is placed on a horizontal cement board on a weighing device and ignited at one corner. In the last test, a specimen of the mattress pad or its filling material is sandwiched between layers of standard sheeting fabrics. The specimen is subjected to a small open flame applied to the center point of the top surface and observations of the burning behavior and burn patterns are used to assess fire performance.

The latest draft of CA TB 604 (second edition) was released to the public in October 2007 and developed further since then. Between the first and second editions there has been work on an interlaboratory round robin which was successful. The regulatory timeline has already started and it is expected that this standard will go into effect in California some time in 2008. This is a regulation that is likely to result in changes in requirements for all residential filled bed products and significantly increase fire safety. CPSC is, in theory, intending to have a similar regulatory development, but there is only a low expectation that that will happen in the near future.

UPHOLSTERED FURNITURE

In 1994, the National Association for State Fire Marshals (NASFM) submitted a petition to CPSC to enact mandatory regulation for the flammability of upholstered furniture. The recommendation by NASFM was that the requirements for upholstered furniture flammability used in California or those used in the United Kingdom be implemented. CPSC has been studying this issue since then: very long study!!!! In the meantime it has been estimated that over eight thousand people have died in the US in fires that started in upholstered furniture.

Initially, in 2001 CPSC recommended an ignition test for the upholstery fabrics similar to the small gas burner sources in BS 5852. This was widely derided as inappropriate, since it did not (and could not) address the issue of the heat release from the padding materials. A number of other obstacles were put in front of CPSC by upholstered furniture industry representatives and lobbyists and CPSC was forced to conduct studies of effectiveness of flame retardants, of toxicity of flame retardants and many others. In the meantime, CBHF developed a draft revision of CA TB 117 (often known as CA TB 117 plus), which was made public in February 2002. This revision addressed most of the concerns that had been expressed about CA TB 117, particularly regarding the fabric test and regarding the lack of substantive foam and composite tests. This draft standard was never implemented by CBHF because it was feared that it would contradict the eventual requirements from CPSC which were deemed to be imminent.

In 2005 CPSC staff proposed a complex fire test scheme of 14 options, including smoldering and open flame tests as well as individual component and composite tests; this was never approved. Part of the reason for the lack of progress in this area is that political pressures have gone into these delays. For example, CPSC is composed of technical staff and commissioners; the latter are political appointees and are the ones making the decisions based on the recommendations and the briefings from staff. In order for CPSC commissioners to be able to make decisions, there must be a minimum of three commissioners in office. In July of 2006 Harold Stratton, then Chairman of commissioners at CPSC, abruptly resigned leaving only 2 commissioners in office (one appointed by each of the main political parties: a Democrat and a Republican). One of his last acts was the issuance of the rulemaking for mattresses, resulting in 16 CFR 1633. By the end of 2007 Mr. Stratton had not been replaced and CPSC is not able to propose new rules. A series of resolutions have extended temporary permissions for the commissioners to make recommendations if they have unanimity.

The latest briefing by CPSC staff took place on December 6, 2007. At that time a series of four options were presented to the commissioners: (a) the adoption of CA TB 117 plus, (b) the adoption of the 2001 recommendation by CPSC staff, (c) the adoption of the 2005 recommendation by CPSC staff or (d) the adoption of a recommendation addressing only smoldering combustion. The commissioners always have two other options: either to do something else or to do nothing.

It needs to be pointed out that CPSC never implemented mandatory smoldering requirements for upholstered furniture fire safety but that there has been widespread voluntary use of smoldering tests for components (ASTM E 1353[20] or NFPA 260[21]) by the trade association for residential furniture manufacturers (Upholstered Furniture Action Council, UFAC) and for composites (ASTM E 1352[22] or NFPA 261[23]) by the trade association for contract furniture (Business and Institutional Furniture Manufacturers Association, BIFMA).

The presentation of this new proposal by CPSC staff brought the following response from the "consumer advocates" who are fighting to avoid using flame retardants: "Good news from the CPSC about a national furniture flammability standard that will not lead to chemical fire retardants". In essence, what CPSC staff has proposed is continued inaction, which is no different from what has been happening at CPSC since the petition was first made by NASFM back in 1994.

Requirements for upholstered furniture flammability exist in various states, including California, based on California Technical Bulletin 133[24] (CA TB 133), which was also made into a consensus standard by ASTM as ASTM E 1537[25]. The gas burner used as the ignition source in CA TB 133 is a square-shaped burner that applies propane gas for 80 seconds at a flow rate of 13 L/min. The test is severe enough that it can usually not be met unless the foam contained in the upholstered furniture item is well flame-retarded. The pass/fail criteria are a peak heat release rate of 80 kW and a total heat released that does not exceed 25 MJ over the first 10 minutes of test. In California, moreover, all foam contained within upholstered furniture must be flame-retarded to comply with CA TB 117. Moreover, the IFC and NFPA 101 both have the parallel requirements to those discussed above for mattresses. In other words, the 2006 editions of both codes contain requirements that upholstered furniture items in health care occupancies and in detention and correctional occupancies that are not sprinklered must comply with a peak heat release rate of 250 kW and a total heat release no more than 40 MJ in the first 5 minutes of test when tested to ASTM E 1537 (or CA TB 133). Also, the 2007 edition of the IFC and the 2009 edition of NFPA 101 will lower these values to 80 kW and to 25 MJ over 10 minutes. Finally, the IFC 2007 adds college and university dormitories to the list and eliminates the sprinkler exception for detention occupancies.

One more time, the dichotomy between residential and high risk environments is what offers both the opportunities for improved fire safety and new market uses for flame retardants.

An unusual added wrinkle is presented by the definition of what constitutes a flammable solid according to CPSC. A flammable solid is a material that exhibits a flame spread rate exceeding 2.5 mm per second when exposed to the flame in the 16 CFR 1500.44 test[26]. The amount of flammable solids that can be stored is very limited, unless the storage location has been constructed as a "hazardous location", which means that it is built to extreme safety. It has been found that non-flame-retarded polyurethane foam is a flammable solid. The consequence of this finding may be that upholstered furniture that is not flame-retarded cannot be stored (or kept) in showrooms or storage facilities that are not built as hazardous locations. This concept is still being developed, but it may lead to a voluntary requirement by major retailers of upholstered furniture that all furniture shipped to them must have flame-retarded foam.

CHILDREN'S PLAYGRONDS

Children's playgrounds abound in a variety of environments, such as shopping malls, fast food restaurants and transportation terminals (airports, train stations). These playgrounds are intended for young children, so that all exposed surfaces are soft and brightly colored. These structures can be fairly large and tend to contain large amounts of combustibles, including, typically, the following:

* Rigid plastics (usually non flame-retarded polyethylene)
* Foam padding, for structural use, usually covered by a textile
* Foam padding for tubes and pipes
* Foamed ball pool balls
* Various fabrics

A standard performance specification, ASTM F 1918[27], exists for these structures. Unfortunately there is no legal requirement that manufacturers comply with this performance specification. Moreover, until recently there were no code requirements since these playground structures are not considered to be kiosks, interior finish or decorations (all of which have to meet certain fire safety rules). There are two major concerns with the fire safety of these structures: (a) children can get trapped and will often need a relatively long period to exit or get rescued (due to potential entanglements) and (b) the large heat release rate that can be expected from the polyolefins foams (when they are not flame-retarded) often lead to severe damage not just to the playground but also to the associated restaurant or building.

This problem has now finally changed and both the 2007 edition of the IBC[28] and (probably) the 2009 edition of the Uniform Fire Code[29] contain requirements for children's playground structures. They must be constructed of noncombustible materials or of combustible materials that are one of the following:

- Fire-retardant-treated wood
- Light-transmitting plastics
- Foam plastics with peak heat-release rate ≤ 100 kW in accordance with UL 1975[30]
- Aluminum composite material (ACM) with peak heat release rate ≤ 800 kW, no flashover and low smoke in accordance with NFPA 286[31] (room corner test) or a flame spread index ≤ 25 and low smoke in accordance with ASTM E 84[32] (Steiner tunnel test)
- Textiles and films complying with the criteria of NFPA 701[33]
- Rigid plastics (such as tubes, windows, panels, junction boxes, pipes, slides and decks) with peak heat release rate ≤ 400 kW/m^2 in accordance with ASTM E 1354[34] (cone calorimeter)at an incident heat flux of 50 kW/m^2 in the horizontal orientation at a thickness of 6 mm
- Pool balls with peak heat release rate ≤ 100 kW in accordance with UL 1975
- Foam plastics must be covered by a fabric meeting the criteria of NFPA 701
- Floor covering under the structure must exhibit a critical radiant flux ≥ 0.45 W/cm^2 in accordance with NFPA 253[35] (flooring radiant panel).

These changes, which will slowly weave their way through the US regulatory system at the local level, will significantly affect the fire safety in malls and similar environments and create a new market for flame retardants.

POLYPROPYLENE SIDING

In the world of plastic siding, PVC (vinyl) is the dominant plastic siding material, principally due to its excellent fire performance. However it has some deficiencies: it can usually only be supplied in pastel colors (such as white, tan, light gray, light green or light blue) because of the high levels of titanium dioxide that must be added to it to achieve adequate weatherability (UV and temperature stability) and it cannot be used for long periods in climates with excessive heat and very low humidity. Polypropylene, especially filled, impact modified polypropylene that is UV stabilized with the appropriate organic stabilizers, can perform very well as a siding material in terms of its UV and weather stability. As it does not rely on high levels of titanium dioxide to achieve stability it can be pigmented with the full spectrum of colors, including dark and deep colors. However, it normally exhibits very poor fire performance. Therefore, polypropylene siding is not actually specifically permitted for use in the US today (and neither is it specifically prohibited). In fact, many of the major manufacturers of vinyl siding actually produce polypropylene siding, even if they are somewhat vague in the descriptions of their products. In at least one case a vinyl siding is described as being manufactured from polypropylene. The labeling of plastic siding is an important issue since vinyl siding is permitted for use by the codes based on compliance with a specification for vinyl siding, ASTM D 3679[36]. ASTM D 3679 states that vinyl siding needs to be manufactured from "of one or more layers of poly(vinyl chloride) (PVC) compound. Any layers of materials other than poly (vinyl chloride) (PVC) compound shall be kept to less than 20% by volume." The specification requires simply that the material needs to pass the very mild fire test in ASTM D 635[37], as it states: "The poly(vinyl chloride) siding material, when tested in accordance with Test Method D 635, shall not exceed an average extent of burn of 4 in. (100 mm), with an average time of burn not to exceed 10 s. A minimum sample thickness of 0.035 in. (0.9 mm) is required." ASTM D 635 is the horizontal version of the UL 94[38] fire test (UL 94 HB classification). The rationale for this fire test requirement is that there is an understanding that rigid PVC exhibits a fire performance that is good enough.

When tested in the cone calorimeter, ASTM E 1354, under the same conditions, it was found that non-flame-retarded polypropylene exhibits a peak heat release rate of 1509 kW/m^2, while a non-flame-retarded PVC material exhibits a peak heat release rate of 183 kW/m^2, and a Douglas fir material exhibits a peak heat release rate of 221 kW/m^2. Such very high heat release rate is unacceptable for a siding material.

The key new development that will affect the market for flame retardants is the issuance of a new specification for polypropylene siding (none existed before 2006), ASTM D 7254[39]. This specification requires the polypropylene material to exhibit a flame spread index ≤ 200 when tested in accordance with ASTM E 84 (Steiner tunnel test) and it adds that "The test specimen shall either be self-supporting by its own structural characteristics or held in place by added supports along the test specimen surface." It then defines self-supporting specimen as "a specimen that remains in place by its own structural characteristics both before and during the fire test." In order for polypropylene to achieve a 200 flame spread index in the Steiner tunnel while using "self-supporting specimens" the polypropylene material will have to be properly flame-retarded. An investigation was carried out to see whether this was feasible and the result was that flame-retarded polypropylene materials can be produced that can be made into "self-supporting specimens" at the thicknesses required to make siding and that achieve the required flame spread index. In the test conducted a flame-retarded polypropylene material 3.8 mm (0.15 inches) thick exhibited a flame spread index of 50 and a smoke developed index of 215, while remaining in place during the test.

The ASTM E 84 test does not have a standard mandatory mounting procedure for rigid plastics. The most common approach to testing rigid thermoplastics is to mount them on poultry netting and rods and to let the material melt and fall to the floor, while the required measurements are made in the section of the tunnel where the test specimen was originally placed, even though there is no longer any test specimen remaining there. Interestingly, an attempt to develop a standard mounting procedure for siding did not achieve consensus and is unlikely to be issued soon.

Traditional polypropylene siding was only very slightly flame-retarded because it simply needed to meet ASTM D 635. If it had to pass any ASTM E 84 requirements, it did so simply by melting away. It is to be expected that responsible manufacturers of new versions of polypropylene siding will comply with the letter and the spirit of ASTM D 7254 and compound the material in such a way that it is properly flame-retarded. Proposals have been made to the codes (IBC and IRC[40]) to request that the material used to make polypropylene siding exhibit not only the flame spread index requirements of ASTM D 7254 but also a peak heat release rate ≤ 400 kW/m^2 when tested in the cone calorimeter at an incident heat flux of 50 kW/m^2, just like rigid polyethylene needs to meet in children's playground equipment.

TRAINS AND UNDERGROUND PASSENGER VEHICLES

In 2007 the new edition of NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems, was issued. This standard contains requirements for passenger trains (underground and above ground), for the stations associated with the transportation system and for the associated trainways. This standard is not used for regulation per se in the US or Canada but the majority of the rail and underground service operators in both countries rely heavily on it and use it as their basic specification for ordering materials and components.

In 2007, the entire chapter on vehicles was completely rewritten. Many of the key requirements that were in place before have just been reworded, but requirements have now changed for electrical and optical fiber cables, especially those that are used for emergency systems. The standard also has an alternate approach, as a fire performance-based vehicle design requirement, which is much weaker than it was in the previous edition, but is still an option. This performance-based option uses as its model the approach of the Life Safety Code, NFPA 101, but with some specific vehicle amendments. The key fire tests for most materials continue to be traditional ones: the radiant panel test (ASTM E 162[41]) and the classic smoke chamber test (ASTM E 662[42]), as well as the flooring radiant panel for flooring materials, but heat release tests such as the cone calorimeter (ASTM E 1354) and the full scale furniture fire tests (ASTM E 1537 and ASTM E 1590) are also optionally used. The minimum requirement in terms of fire safety of cables is the vertical cable tray test (UL 1685[43]), which is a much more severe test than the minimal test for cables in buildings. Also, all cables must meet a smoke obscuration requirement.

The requirements for stations have also been substantially amended. First, wires and cables need to meet the same requirements as they would need to meet if this station was a stand-alone building and not associated with the rail system (i.e. like in the US National Electrical Code). However, again the UL 1685 test and some smoke obscuration requirements are deemed essential. Upholstered furniture in stations are now required to comply with the criteria of CA TB 133 (ASTM E 1537), as discussed above. Interior finish for walls and ceilings is now required to be tested in accordance with ASTM E 84 (and to exhibit a flame spread index ≤ 25 and a smoke developed index ≤ 450) or to be tested in the room corner test, NFPA 286, and exhibit no flashover, heat release ≤ 800 kW and low smoke release. Interior floor finish must exhibit a critical radiant flux of ≥ 0.8 W/cm^2. Finally, there is a "catch-all" statement that "Where combustible furnishings or contents not specifically addressed in this standard are installed in a station, a fire hazard analysis shall be conducted to determine that the level of occupant fire safety is not adversely affected by the furnishings and contents." This is clarified by the following: "The fire hazard analysis should determine that the fire does not propagate beyond the component of fire origin, and that a level of fire safety is provided within the station commensurate with this standard. Computer modeling, material fire testing, or full-scale fire testing should be conducted, as appropriate, to assess fire performance in potential fire scenarios."

Overall, there will be greater need for using flame retardants when designing trains and stations that comply with the new edition of NFPA 130, as compared to previous editions.

CIGARETTES

A key new development throughout North America is the requirements for cigarettes to comply with ASTM E 2187[44], so that they are less likely to cause ignition of upholstery fabrics. These cigarettes are often designated as "fire-safe cigarettes", an incorrect designation, since they are still capable of igniting cellulosic fabrics, in some 25% of the cases (since a cigarette complies with the regulation if it does not cause ignition > 25% of the time). However, this represents a dramatic decrease when compared to "normal" cigarettes, which tend to ignite almost all cellulosic fabrics. The cigarettes should more properly be designated as reduced ignition propensity cigarettes.

The key factor in determining smoldering combustion of cigarettes is their paper. The paper-modification approach most commonly used for manufacturing reduced ignition propensity cigarettes is the use of "banded" paper. This is roughly equivalent to increasing the weight of the paper or decreasing its porosity, but instead of changing these properties across the entire length of the cigarette, the paper is designed to have intermittent bands with altered properties. The intent is for the cigarette to self-extinguish when the ignited end hits a band and the cigarette is not being smoked, but to retain its normal smoking properties when it is not burning through a band.

On October 1, 2005 Canada became the first country to adopt the requirement for reduced ignition propensity cigarettes nationwide.

As of the beginning of late 2007, there were 22 states in the US with laws establishing a statewide standard for cigarette ignition propensity, covering well over 50% of the US population:

- New York (effective June 28, 2004),
- Vermont (effective May 1, 2006),
- California (effective Jan. 1, 2007),
- Oregon (effective July 1, 2007),
- New Hampshire (effective Oct. 1, 2007),
- Illinois (effective Jan. 1, 2008),
- Maine (effective Jan. 1, 2008),
- Massachusetts (effective Jan. 1, 2008),
- Kentucky (effective April 1, 2008),
- Utah (effective July 1, 2008),
- Montana (effective May 1, 2008),
- New Jersey (effective Jun. 1, 2008),
- Maryland (effective Jul. 1, 2008),

- Connecticut (effective Jul. 1, 2008),
- Alaska (effective Aug. 1, 2008),
- Rhode Island (effective Aug. 1, 2008),
- Iowa (effective Jan. 1, 2009),
- Minnesota (effective Jan. 1 2009),
- Texas (effective Jan. 1, 2009),
- Delaware (effective Jan. 1, 2009),
- Louisiana (effective Aug. 31, 2009) and
- North Carolina (effective Jan. 1, 2010)

Requirements for the sale of reduced ignition propensity cigarettes means that the probability of cigarette (smoldering) ignition of upholstery fabrics is decreased, even if the upholstery fabrics don't "pass" the smoldering ignition tests. Consequently, there is a growing volume of public opinion that says that the need for fire protection is lower.

This is the rationale (or the excuse) being used by CPSC staff for saying that there is no longer a critical need for improving the fire performance of upholstered furniture. This is a serious misrepresentation of the facts. When eventually an upholstery item catches fire (whether due to cigarette ignition, due to small open flame ignition or due to some non flaming electrical ignition source), the difference in heat release between a flame-retarded upholstery padding and an non-flame-retarded upholstery padding is enormous. For example, work on upholstered chairs showed differences between a peak heat release rate of 2 kW (for the well flame-retarded foam) and > 4 MW (for non-flame-retarded foam) (Hirschler 2004[45]) and similar type of results have been reported for mattresses (Hirschler 2005[46]).

The success of the campaign for "fire-safe" cigarettes has already started to lead to a discussion as to whether smoldering ignition (and even flaming ignition) tests should be eliminated. This would be a serious fire safety mistake. There are three reasons for still needing smoldering ignition tests in North America: (1) "fire-safe" cigarettes can still ignite fabrics, (2) traditional cigarettes are still commercially available (for example from the areas where there is no regulation, including the autonomous American Indian nations) and (3) the treatments used for improving the flaming performance of fabrics are usually ineffective in improving the smoldering ignition performance.

The requirement for cigarettes to be reduced ignition propensity is an excellent development in terms of fire safety. However this is one example of a case where there is no associated advantage in terms of marketing of flame retardants

CONCLUSIONS

This paper describes recent regulatory (and semi-regulatory) developments in North America, in the areas of fire safety that affect, or have the potential to affect, the use of flame retardants.

The lack of negative changes in the requirements for plenum cables in North America is the single development that probably will have the greatest effect in retaining an important market for flame retardants. This application was threatened by the potential to require a level of fire performance that cannot be achieved by the use of flame retardants.

Positive developments for both fire safety and flame retardants have occurred in the areas of rail transportation vehicles (underground and above ground) and children's playgrounds. Similarly, changes are occurring in the areas of regulated upholstered furniture and mattresses in high risk environments. Positive developments for fire safety but not necessarily for flame retardants have occurred in the area of residential mattresses. The potential exists for positive developments in the area of fire safety and in the use of flame retardants for polypropylene siding and for filled bed products. The prognosis for positive developments of any kind in the area of residential upholstered furniture looks very bleak. Finally, there is an area which is likely to lead to tremendous improvements in fire safety but will, at best, not affect the use of flame retardants: the requirements for cigarettes to have reduced ignition propensity.

In conclusion, the best way to effectively affect the use of flame retardants is to promote effective means of improving fire safety. It is essential, however, to recognize the legitimate concerns expressed by honest opponents of the use of flame retardants and to remain vigilant and ensure that changes in requirements are always associated with safe use of flame retardant materials.

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GBH Attachment 24

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FIRE TESTS AND INTERIOR FURNISHINGS

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ABSTRACT

Interior furnishings are consumer products found in various occupancies. They include furniture, bedding, curtains and drapes, surface finishes (wall, ceiling and floor coverings) and cabinetry. Among the features they have in common is the fact that they are rarely a single material, but that they generally involve various layers. This characteristic is important because it explains why testing of their individual components does not, usually, give adequate answers.

A survey of the development of such fire tests, and of the present status, is presented here. Special focus will be placed on upholstered furniture tests.

The flammability of upholstered furniture has been under a microscope since it was first discovered to be an important issue, in the late 1960's and early 1970's. However, relatively few tests have been developed and standardised, either in the USA or in other countries. The initial focus was on cigarette ignition and on component testing, resulting in tests such as the NBS mock-ups and the UFAC test (ASTM E1352 or NFPA 260 and ASTM E1353 or NFPA 261 respectively). This was followed by testing of entire chairs with cigarettes (CA TB 116). Eventually, composite component testing with small flames started, pioneered by British standard BS 5852. Parallel to this, material testing continued, using a variety of mostly small scale tests (the most frequently used tests being CS 191-53 and CA TB 117. In the mid 1980's, tests started to appear for the flaming behaviour of complete upholstered furniture items, CA TB 133 being among the most notable ones. The fire community has now understood that the most important fire property is the heat release rate, and this has been incorporated into contents and furnishings tests, as in ASTM E1537. The next step is the attempt to predict the results of such tests with bench scale heat release tests and fire models. This work is still in progress.

Fire tests for other interior furnishings have also undergone a complex history, which is reviewed. Tests for the different products are in various stages of development. It would appear that the fire testing of furnishings and contents in the future will entail mostly finished products and heat release equipment.

A flurry of activity is characterising the present emphasis on furnishings. Moreover, the majority of the new tests being developed generate results that can be used as input for models to carry out fire hazard or fire risk assessments.

1. BACKGROUND AND HISTORY

Interior furnishings and contents is a phrase used very often to describe products in use inside structures, residential or otherwise. However, interior furnishings and contents (or "furnishings", for short) are a very broad umbrella, which covers many products. An analysis of the National Fire Protection Association (NFPA) categories, as contained in NFPA standard 901, turns up more than 45 categories, among the 75 categories of products first ignited, which can be classified as "furnishings". In whichever form these products are categorised, they are under increasing scrutiny at the main American standards writing organisations: American Society for Testing and Materials (ASTM) and NFPA. Within the ASTM committee on fire standards, E-5, subcommittee E-5.15, addresses fire and "furnishings". NFPA has created two committees specialising in fire and "furnishings": the Life Safety Technical Committee on Furnishings and Contents and the Technical Committee on Contents and Furnishings, which have similar (and confusing) names but different responsibilities.

Fire statistics in the USA indicate that "furnishings" constitute a very large proportion of the fire problem. NFPA fire statistics for 1985-89 show that "furnishings" are the items first ignited in 40% of all structure fires, and in those fires that cause 40% of all structure fire fatalities [1]. The overwhelming majority of the fires and fire fatalities occur in residential environments, but the major headlines (and regulatory attention) address on non-residential construction.

In broad categories, major "furnishings" of importance in fires are: seating furniture (particularly if it is upholstered), bedding (particularly mattresses), surface finish (wall, ceiling and floor coverings), curtains and drapes, apparel and cabinetry. They will be dealt with, in that order, in subsequent sections.

A comparison between fire statistics in 1977-78 and in 1983-87 is more startling for similarities than for differences: rankings of the materials in the first few places are very similar (Table 1, [1-2]). In particular, the two items which dominate the fire fatality statistics in both sets of data are upholstered furniture and bedding: 70-80% of the data in the tables (although the statistics have different bases and cannot be compared directly). However, the importance of upholstered furniture and bedding seems to have decreased somewhat over time.

2. UPHOLSTERED FURNITURE

2.1 Background:

It is important to understand that, although upholstered furniture is the largest single product first ignited leading to fire fatalities, it is still only one of many causes. When the focus of fire statistics is restricted to upholstered furniture alone, it is the item first ignited in only 2.8% of all structure fires, in the 1985-89 time period, corresponding to 15.6% of all fire fatalities [1]. In residential environments, upholstered furniture is the item first ignited in 3.4% of all fires, corresponding to 16.3% of the fire fatalities. If all residential fires are excluded, upholstered furniture represents the item first ignited in only 1.4% of fires and 5.8% of the fire fatalities.

It should be noted that the majority of upholstered furniture fires result from ignition by smoking materials, with a strong emphasis on cigarettes. The relative contribution of cigarettes varies according to the source of information. They may contribute ca. 65% of the total [3] or 77% of the total, in the 1980-84 period [4]. Fires initiated by cigarettes are smouldering fires, but they can easily (after varying times) transition into flaming fires.

In 1982, cigarette initiated fires caused ca. 30% of all fire deaths in the USA [5], of which over 80% are residential. However they were responsible for only 10% of all residential fires. This indicates that the mortality rate of such fires is very high. The overwhelming majority (70-80%) of all cigarette initiated fires start in upholstered furniture or bedding. In 1982, 20.1% of all civilian fire fatalities in the USA started with the ignition of upholstered furniture [6-7]. Smoking materials igniting upholstered furniture in residences were responsible for starting the fires resulting in 16.5% of all civilian fire fatalities during that year [5].

In the intervening years, cigarette initiated upholstered furniture fires and fire fatalities have decreased. Table 2 contains information, gathered by the Upholstered Furniture Action Council (UFAC), on fires and fire fatalities, with particular emphasis on upholstered furniture in residences, in the years 1978 and 1989 [8]. The decreases in all categories can be attributed, at least partially, to two causes: more extensive scrutiny of products by manufacturers before being offered for sale and a higher penetration of smoke detectors. However, recent statistics still find that, in the 1984-88 period, 27.9% of all fire fatalities result from fires started by smoking materials [9-10].

The flammability of upholstered furniture has been a major concern in the USA since the late 1960's, and became a federal issue with the 1967 amendments to the Flammable Fabrics Act of 1953 (see section 7).

2.2 Ignition by Smoking Materials:

On November 29, 1972 the Federal Register stated, on behalf of the Department of Commerce, that a flammability standard or other regulation might be needed for upholstered furniture. The emphasis was to be placed on ignition of furniture by smoking materials, particularly cigarettes. The technical work was started at the National Bureau of Standards (NBS, today National Institute of Standards and Technology, NIST). When the Consumer Product Safety Commission (CPSC) was established in May 1973, it was given the authority to deal with the issue. A private organisation, UFAC, was created in 1974, as a voluntary industry association to focus on the problem of the flammability of upholstered furniture. Its funds come from the majority of the large furniture manufacturers producing upholstered furniture for the residential market, many of whom belong to the American Furniture Manufacturers' Association (a trade association). Thus, during the mid to late 1970's, parallel work was being carried out in the public and in the private sector, to develop tests to prevent ignition by cigarettes, i.e. smouldering ignition. The public sector work was being done at NBS and the private sector work at Guilford Laboratories (Greensboro, NC), on behalf of UFAC.

Both efforts culminated in test methods. NBS developed a test for cigarette ignition of upholstered furniture mock-ups in 1976. This test was eventually standardised both by NFPA (NFPA 261, 1983) and ASTM (ASTM E1352, 1989). UFAC developed their series of 6 test methods for cigarette ignition of upholstered furniture components and constructions somewhat later, but the voluntary program went in effect in 1978. CPSC decided, in 1979, to defer implementation of mandatory federal regulation while it monitored UFAC activities, a position still in effect today. These test methods were also standardised at ASTM (ASTM E1353, 1989) and NFPA (NFPA 260, 1983). Precision and bias statements for ASTM E1352 and E1353 were developed in 1993, following a round robin for both tests, carried out through joint work between ASTM E-5.15 and ASTM D-13.52.

The State of California, at the California Bureau of Home Furnishings (CBHF), passed Technical Bulletins 116 [11] and 117 [12], which required compliance, respectively, with cigarette ignition of full items of upholstered furniture and with cigarette and flaming ignition of furniture components by October 1977. Today they are applicable to all upholstered furniture items offered for sale in the state of California: TB 116 on a voluntary, basis while TB 117 is a requirement. Manufacturers of contract furniture (i.e. non residential) are mostly associated within the Business and Institutional Furniture Manufacturers' Association (BIFMA). They have adopted the NBS mock-up test as a voluntary standard (BIFMA X5.7, pt. 5), as well as a small flame test: the 45°

angle test for apparel (incorporated into BIFMA X5.7, pt. 4, into CA TB 117, for fabrics and other components, and CS 191-53, see section 7, for fabrics only).

The development of furniture resistant to cigarette ignition has meant that the materials used, particularly for fabrics, have changed. The trend was to move away from materials which smoulder easily to materials which do not smoulder. Thus, lightweight cellulosic materials (like cotton, linen or rayon), have been mostly replaced by synthetic materials, unless they have been treated with fire retardants. These synthetic materials (thermoplastics) tend to shrink away from the flame, and are, thus, much more likely to resist ignition by cigarettes. However, the same thermoplastic materials which do not smoulder, may be easily ignited by small flames.

The introduction of the cigarette ignition tests have resulted in a very large decrease in the preponderance of some extremely flammable fillings, such as sisal, kapok, jute or untreated cotton, from furniture offered for sale commercially. Some of the more flammable polyurethane foams are also no longer used in commercial furniture. However, the UFAC test requires that the foam filling be tested under a fabric which passes the cigarette ignition test. Thus, it is possible for foams to have relatively poor fire performance, and yet pass the test because they are covered with a fabric that resists smouldering.

2.3 Flaming Ignition Sources:

The first serious attempt at developing a flaming ignition standard for upholstered furniture systems was a British Standard (BS 5852, pt. 2, [13]), developed as a consequence of a famous 1979 furniture store fire in Manchester (UK). This test uses a variety of wood cribs, and it tests a combination of fabric and filling, made up into two standard cushions: bottom and back. The wood cribs range from # 4, weighing only 8.5 g, to # 7, weighing 126 g. A recent study showed that the "rankings" resulting from testing fabric/foam combinations in this test correlated well with those that could be obtained from using the cone calorimeter at 25 kW/m^2 [14]. Over the last few years, the standard has been modified somewhat, so that testing for qualification is now done effectively on separate items. Fillings are qualified when tested under a "standard" flame retarded polyester fabric and fabrics are qualified when tested over a filling deemed acceptable. Thus, it is not required to test the system actually proposed for use, which is likely to be less satisfactory than testing finished systems.

In the USA, in order to address the issue of flaming ignition, independently, CBHF and the Boston Fire Department (BFD), started developing fire tests for flaming ignition of seating furniture: California Technical Bulletin 133 [15] and the Boston chair test. These tests were designed for very high risk furniture. In fact, the test under the jurisdiction of CBHF became applicable, in 1992, to seating furniture in institutions, hospitals, mental health facilities, health care facilities, nursing homes, board and care facilities, convalescent homes, child day care centers, public auditoriums, stadiums and public assembly areas of hotels, motels or lodging houses containing 10 or more articles of seating furniture, with an exception allowed if they are fully sprinklered. The BFD test had somewhat similar applicability, except that Boston does not generally give the same exceptions for sprinklers.

In May 1984 CBHF issued the first version of TB 133. This test involved burning a full item of seating furniture, inside a room of specified dimensions (12 by 10 by 8 ft high (3.7 by 3.1 by 2.4 m high)), using as flaming ignition source a wire cage, containing 5 crumpled double sheets of newspaper. In order to pass the test, the item could not exceed a series of 6 criteria, involving temperature increase, smoke obscuration, carbon monoxide generation and weight loss (Table 3). A survey of the number of failures indicated that the vast majority of failures involved one or both of the temperature increase criteria [16]. This is illustrated in Figure 1. The test has, in the meantime, been modified several times, but the basic concept remains the same. The crucial change resulted from cooperative work between CBHF and NIST [17-19]. It has been shown recently that the most important fire property is the rate of heat release [20]. This ties in well with the concept that the main failure criteria are based on energy increase. Thus, the NIST/CBHF work focussed on three aspects: (a) find a heat release rate corresponding to the temperature increase in the upper layer of the room, (b) find a more reproducible ignition source than the newspaper and (c) understanding whether there is a difference between tests carried out in different rooms. The results were: the 200 °F (111 °C) increase in temperature can be modelled by a 80 kW heat release rate and the newspaper ignition source can be modelled by a square propane gas burner, with a gas flow of 13 L/min for 80 s. The research also showed that the heat release rate is not affected by the size and shape of the room, within certain limits, if the heat release rate does not exceed 600 kW [18].

The state of California adopted a new version of TB 133 in January 1991, which requires the use of the square gas burner. It allows the measurement of temperature increase or of heat release rate as pass fail criteria. In order to pass the test a furniture item has to avoid exceeding any of the following 4 criteria: heat release rate of ≤ 80 kW, total heat release of ≤ 25 MJ in the first 10 min (both in the exhaust duct), ≤ 75% smoke opacity at a smoke obscuration monitor located at 4 ft (1.2 m) from the floor and emit ≤ 1,000 ppm carbon monoxide for a 5 min period, at a room monitoring location (Table 3). TB 133 also allows testing in a "furniture calorimeter", i.e. under a hood, rather than inside a room, where the first two requirements only can be met. If heat release is not measured, the test criteria needed to pass TB 133 include temperature increases of ≤ 200 °F (111 °C) at a ceiling thermocouple, ≤ 50 °F (28 °C) at a 4 ft (1.2 m) thermocouple and weight loss of ≤ 3 pounds (1.36 kg) in the first 10 min. TB 133 has now relegated the newspaper source to the status of a screening test only. It has also been announced that room measurements will no longer be acceptable beyond the fall of 1993.

It is worth mentioning an interesting study that compared the performance of 5 upholstered furniture systems in three tests: CA TB 133 (without heat release), BFD and BS 5852 (crib 7), and showed similarities and differences [21].

ASTM has now developed a version of California TB 133: ASTM E1537, with three main differences. First, ASTM E1537 offers three equal alternatives: the "ASTM room" (2.4 by 3.7 by 2.4 m high), the California room (3.7 by 3.1 by 2.4 m high) and a furniture calorimeter); TB 133 recommends the use of the California room, while allowing the other alternatives. Second, ASTM E1537 requires smoke obscuration and gas (carbon monoxide and carbon dioxide) measurements in the exhaust duct, whereas TB 133 requires measurements in the room for them, but only if the heat release measurements are made in the room. Third, ASTM E1537 has no pass/fail criteria, while TB 133 does (Table 3). ASTM E1537 is also much more detailed in equipment description, calibration, use, the theory behind it, and limitations, than TB 133.

CBHF managed a preliminary round robin of the test, in mid 1992. Unfortunately, the laboratories had dissimilar facilities: in fact only some of them were capable of measuring heat release, and the round robin results were inconclusive and disappointing. The publication, in the meantime, of a "Code of Practice", by CBHF, as well as of ASTM E1537, will aid in ensuring that laboratories will have detailed procedures to follow. Thus, a new round robin should have a more satisfactory outcome and may also be useful for the development of precision and bias statements for ASTM E1537.

Another full scale test for flaming ignition of upholstered furniture exists: the furniture calorimeter. This name is given to a test where the item of furniture is placed on a load cell, underneath a hood. Heat, smoke (and potentially toxic gas) release is measured in the exhaust duct, while mass loss can also be measured. There is no compartment in which the item to be tested is placed. Thus, the compartment is considered of infinite size, so that the walls cause no radiation effects. Consequently test results are due entirely to the item tested. Measurements of temperature, smoke obscuration or toxic gases in a room cannot be made when using a furniture calorimeter. This is, normally, of no consequence, since room measurements are of little or no value for fire hazard assessment, since small differences in measurement location can result in large differences in output. A furniture calorimeter is more satisfactory to measure heat release rates of furniture burning intensely, at heat release rates well over 600 kW, but room size and shape do not affect the results at lower heat release rates. Work by NIST/CBHF showed that differences between furniture calorimeter and room heat release results start to differ only at heat release rates above 600 kW (if the item is burning in a corner, or even higher if the item is burning in the center) [18]. Thus, the added expense of building a very large room in order to house a furniture calorimeter yields no significant advantage. The only USA standard for fire tests on upholstered furniture to date is UL 1056, the first edition of which was issued in 1989, using a 3/4 lb (340 g) wood crib as ignition source. It is likely to be amended to replace the wood crib by a gas burner.

2.4 Furniture requirements in codes

There has never been a mandatory national standard for fire testing in the upholstered furniture area, partially because of the preponderance of residential furniture compared to furniture used in public occupancies. However, some state and local authorities have implemented mandatory flammability requirements, the most comprehensive one being that adopted by California (see section 2.2). At present, too, the NFPA Safety to Life Code (NFPA 101, 1991 edition [22]) contains provisions (31.1.4.2) for testing upholstered furniture to determine their resistance to cigarette ignition, as tested according to NFPA 260 and NFPA 261 (Class I components in NFPA 260 and char length less than 1.5 in (38 mm) in NFPA 261), which is deemed unnecessary by the code if an approved automatic sprinkler system has been installed. This does not apply to residential occupancies, assembly occupancies, educational occupancies (which include day care centers), mercantile occupancies or business occupancies. The use of NFPA 261 applies to health care occupancies (31.4.5.2), detention and correctional facilities (31.5.4.2), and board and care homes (31.7.5.2) and is recommended for corridors or similar areas in non sprinklered hotels, dormitories or apartment buildings (A31.6.6).

NFPA 101 also made a very significant change in its 1991 version: it introduced heat release requirements for upholstered furniture (and mattresses). The requirements in the code are not very stringent. However, it is the first time that a heat release rate requirement has been adopted by an NFPA code. Section 31.1.4.3 specifies a peak heat release rate for a single item of upholstered furniture of no more than 250 kW (unless the facility has either smoke detectors or automatic sprinklers) or 500 kW (unless the facility is sprinklered). It further requires total heat release not to exceed 75 MJ in the first 5 min of the test (unless the facility is fully sprinklered). In the 1994 version of NFPA 101, the requirements will be tightened: the exemption for smoke detectors is eliminated and limits will be set at 250 kW and 40 MJ. This applies only to detention and correctional occupancies (31.5.4.2) and is recommended for health care occupancies (A31.4.5.2) and board and care homes (A31.7.5.2). The original requirements were put in based on the basis of maintaining a tenable environment in the room of origin (250 kW) or avoiding flashover in it (500 kW) with a single item of furniture burning. Many states adopt NFPA 101, but it often takes several years before the most recent version is actually in use.

Two of three model building codes have no flammability requirements for furniture: those developed by the Building Code and Administrators International (BOCA, the Basic/National Building Code, used mainly in the Northeast) and by the International Conference of Building Officials (ICBO, the Uniform Building Code, effective in the Western states). However, the third one, viz. the Southern Building Code Congress International (SBCCI, the Standard Building Code, valid mostly throughout the South) adopted a requirement of a peak heat release rate of 500 kW for hospitals and nursing homes without automatic sprinklers, as well as the NFPA 260 cigarette test. The code also contains, in appendices, requirements based on NFPA 260 and 261 and on CS 191-53 (see section 7). These requirements, however, are for guidance of local ordinances only.

2.5 Prediction of full scale fire test results

It is always desirable to have a small scale test which can predict the results of the full scale one. If the small scale test does not do that, it serves little useful purpose. It has been shown that results from the cone calorimeter can be used to predict results of full scale chair burns, because the cone calorimeter measures heat release, smoke release, ignitability, and weight loss [3, 18]. Both the cone and the OSU rate of heat release calorimeters are suitable for testing fabric/foam combinations for heat release [14, 23-24]. Moreover, the results of both rate of heat release instruments correlate with one another [23, 25-26]. Therefore, both ASTM and NFPA have developed standards to use the cone calorimeter for testing upholstered furniture components, destined for high risk applications: ASTM E1474 and NFPA 264A. In both cases the incident heat flux is 35 kW/m^2. If the 3 min average heat release rate is less than 100 kW/m^2, the furniture item is unlikely to cause a self propagating fire and, thus, to fail the full scale test [18]. However, the cone calorimeter tests could potentially be modified (by using a less intense heat source) so as to make them more relevant to residential furniture, where a 25 kW/m^2 heat flux has been shown in two studies to be satisfactory [14, 23].

2.6 Stacking chairs

Stacked stacking chairs are also under investigation at ASTM. A task group of ASTM Subcommittee E-5.15 is working closely with CBHF, a fire testing laboratory and some furniture manufacturers to develop a flaming source test, based mainly on heat release requirements. The investigation addressed the type of gas burner, the flame intensity (gas flow rate), the duration of the ignition source (40-100 s) and the number of chairs in the stack (3 to 7). After the preliminary investigation, it was decided to use a T-shaped burner (the same one used for mattress testing, see section 3) and a flame gas flow rate of 12 L/min. The recommendations by both testing organisations were that a gas flame duration of 80 s and a stack of 5 chairs would serve the purpose of identifying the undesirable products. Adoption of an ASTM standard is still likely to be some time away.

3. BEDDING

The flammability requirements for bedding (which for most practical purposes means mattresses) closely follows that for upholstered furniture. Having stated this, it should be mentioned that the addition of other bedding products (sheets, blankets, pillows) may make a substantial difference to the overall heat release. There are federal requirements, which involve the cigarette ignition of mattresses, mattress tickings and mattress pads (Department of Commerce (DOC) FF 4-72, or Code of Federal Regulation (CFR) 1632 [27]). This test, as amended, went into effect in 1985.

CBHF developed TB 121, which has newspaper under the mattress as the ignition source in 1980 [28] and the first draft version of TB 129 (with a gas burner as the ignition source), equivalent to the new version of TB 133, in 1992 [29]. In TB 121, a set of 10 double sheets of newspaper (185 g) is placed in a galvanised metal container at the geometric enter and beneath the bottom mattress surface. The failure criteria are: > 10% weight loss in the first 10 min of the test, a temperature of 500 °F (260 °C) at a thermocouple beneath the ceiling and above the mattress and a carbon monoxide concentration of 1000 ppm at any point in the test room. The failure criteria for TB 129 are similar to those for TB 133 (see Table 3), but the peak heat release rate allowed is 100 kW. It appears that TB 121 is more stringent than TB 129, which is why it is still applicable to very high risk occupancies, such as correctional institutions. Both ASTM and NFPA are developing versions of TB 129. The gas burner used is a T-shaped burner rather than a square burner, and the gas flow is 12 L//min, for a period of 180 s. A furniture calorimeter standard also exists for mattresses: UL 1895. NFPA 101 requirements for mattresses are identical ~~than~~ to those for upholstered furniture.

It has been shown that the cone calorimeter can also be used as the small scale predictive test for this application [30].

4. WALL COVERINGS

The flammability of wall coverings has been regulated in many countries for years. This has caused considerable discomfort to the fire science community, since there is no correlation at all between the results of those old fashioned tests. In 1973 Howard Emmons [31] published a comparison between the rankings of 24 wall coverings according to the methods used in 6 European countries. The results are shown in Figure 2: a scatter-gun would have given equally good predictability.

The traditional means by which wall coverings are tested in the USA is the long familiar "Steiner tunnel" test, ASTM E84. The test requires burning a 24 ft x 20 in (7.3 m x 51 mm) sample (although pieces can be lined up in series) lining the roof of a tunnel, and exposed to a 300,000 BTU/h (ca. 90 kW) methane gas flame for 10 min. The results are expressed in terms of an index, based on the arbitrary decision that 23/32 in (18.3 mm) select grade red oak flooring sheets have an index of 100 and that 0.25 in (6.4 mm) inorganic reinforced cement boards have an index of 0.

However, wall coverings frequently have very low thickness, and low mass. Anomalies are common where wall coverings achieve excellent results in the Steiner tunnel test, without offering an adequate degree of fire protection. In fact, it was found that many textile wall coverings meet Class A (flame spread index ≤ 25) requirements in the Steiner tunnel test but cause flashover when tested in a room corner scenario [32-33], in a study for the American Textile Manufacturers' Institute (ATMI) (Table 4). The scenario used was the Williamson screening test [34]. In some cases a fully lined room was used, which is in fact a standard test, Uniform Building Code UBC 42-2 test [35], now also adopted by NFPA, as NFPA 265 (Standard Fire Test for Evaluating Room Fire Growth Contribution of Textile Wall Coverings).

The tunnel test is very severe, but it is, unfortunately, also known to have poor reproducibility. Furthermore, false positives are very common, i.e. it is possible to manufacture products in such a way as to appear not to spread flame in this test, without actually improving their fire performance in a real fire. The test is unsuitable for materials which melt or drip, because they may not burn simply because they are no longer exposed to the flame. They would then appear not to spread flame nor release smoke, giving the false impression of being safe. The test is also unsuitable for very thin materials. The test can also give false negatives, particularly in terms of smoke emission, because of its unrealistic fire model. Attempts to correlate the flame spread results from the tunnel with those of full scale room fires have usually failed, although the test does seems reasonably well suited for wood products. Thus its results cannot really be used for fire hazard assessment or for good fire safety choices.

The Uniform Building Code refers to two full scale room corner tests (UBC 17-5 [36] and UBC 42-2 [35]) applicable to wall lining materials. The former test was really designed for foam plastic insulation, but can also be used for wall linings. Two other tests have been developed for full room testing of wall linings: one has been under consideration at ASTM for several years and one is an international standard (ISO 9705 [37]). The former has undergone a 1992 round robin, for precision and bias development. Table 5 compares these various tests and the Williamson screening test.

In view of the known deficiencies of the Steiner tunnel test (ASTM E84) several efforts have been made to investigate whether other small scale tests can be used to predict full scale fire test results. It is worth mentioning in particular a study where many of the ATMI wall coverings were tested in the cone calorimeter (ASTM E1354) and in the lateral ignition and flame spread test (LIFT, ASTM E1321, [38]). Unfortunately, the results of both tests (Tables 6 and 7) could not immediately give the same "ranking" of materials, and further work is needed to understand fully the degree of correlation with the full scale tests.

An international effort (EUREFIC) culminated in 1991, whereby the predictability of various tests was considered, with regard to the international room corner standard (ISO 9705) [39]. The tests under consideration were traditional reaction to fire tests in 3 of the major European countries: France (Epiradiateur, NF P792-501 [40]), Germany (Brandschacht, DIN 4102 Pt 1 [41]) and Great Britain (surface spread of flame apparatus, BS 476, Pt 7 [42]). The correlation of the rankings between the small scale and full scale tests were: 48% for the French test, 37% for the British test and 61% for the German test. In contrast cone calorimeter rankings showed 94% correlation with full scale ones (Figures 3-6). EUREFIC, furthermore, also developed a computer model to predict the time-temperature curve and time to flashover in the full scale test from cone calorimeter input. These are not simple manual computations.

ASTM E-5.15 is working on the development of a standard for the application of the cone calorimeter to wall coverings. In that connection, it is important to consider the fact that the cone calorimeter is recommended for horizontal testing and not vertical testing [43], while wall coverings are normally, of course, used in a vertical orientation. In view of the work done to date, however, it would appear that cone calorimeter testing is a viable option.

5. FLOOR COVERINGS

The flammability of floor coverings became an issue in the late 1960's, after some serious fires where flames were reported as spreading slowly along carpeted corridors, during the development stages of the fire. The result was the promulgation of Federal Flammability standards DOC FF 1-70 and DOC FF 2-70 (CFR 1630 and 1631 [44-45]), addressing flammability of carpets and rugs (and small carpets and rugs). The test, commonly known as "pill" test or "methenamine pill" test, uses a lighted flat methenamine tablet as the source of energy applied to the carpet. CFR 1630 is a mandatory requirement for all carpets sold in the USA; small carpets and rugs need not pass the test, but must carry a large "Flammable" label if they do not. DOC FF 1-70 is mandatory since April 1, 1971. ASTM standardised a similar test (ASTM D2859) at about the same time (1970). The test is, probably, an adequate measure of ease of ignition when no radiant energy is applied to the carpet.

In January 1970 a serious fire spread along a corridor in a Marietta, OH, nursing home, resulting in 31 fire fatalities [46]. This, and a few other fires [47-48], suggested the need to develop a test for the fire performance of carpets when subjected to a certain incident flux. The first approach was to use the Steiner tunnel test (ASTM E84), since no other test existed. However, it was soon decided the test was inadequate [49] and that a specific flame spread test for floor coverings had to be devised. A few years later, as a result of extensive work at NBS, involving both small and large scale fire tests [50-51] and a flame spread hazard study [52], the concept of critical radiant flux was developed, as a potential measure of the danger associated with carpet flame spread [53]. This led to the flooring radiant panel test, which measures the critical radiant flux required to cause a carpet to spread flame along the entire sample distance [54-55]: ASTM E648 (first standardised in 1978). A similar test was also standardised by NFPA (NFPA 253). The test has received some criticism as to its correlation with real scale fires, since its results do not appear to be adequate to "rank" carpets for their fire performance.

The flooring radiant panel test has undergone considerable scrutiny in recent times. In particular, ASTM has recently developed a modified pilot burner to get more consistent results

(ASTM E648-91, changes not introduced into NFPA 253). However, the modification has been criticised because it makes the test more severe. The test is extensively used for specifications by various agencies, and the NFPA version is quoted in NFPA 101, but it is not a federal flammability standard.

In the international front, ISO and CEN are considering the adoption of the critical radiant flux test for both flame spread and smoke release. In fact, this has already happened in Germany (DIN 4102, Pt. 14 [56]), where a smoke obscuration monitor has also been added, into the exhaust duct. The test has been allocated a work project by CEN [57] and a number by ISO: ISO 9239.

In the period since the original development of the flooring radiant panel, several investigations have addressed aspects of fire hazard associated with carpets, after the initial flame spread study [53]. The Carpet & Rug Institute financed an extensive study, which shows that the potential toxic fire hazard of carpets and rugs is of no greater consequence than that of any other product burning in a fire [58]. More recently, a study for the National Fire Protection Research Foundation Fire Risk Assessment Research Project concluded that carpets, in offices, played no significant role in fire fatalities [4]. This is a consequence of two major issues: (1) heat and fire travel upward, and thus away from floor coverings and (2) most carpets in use comply with the federal flammability standards, and are, therefore, relatively difficult to ignite. Thus, existing standards have successfully eliminated most of the "worst actors" formerly present.

However, NFPA fire statistics show floor coverings as the furnishing item first ignited associated with the fourth largest number of fire fatalities (after upholstered furniture, bedding and clothing) [59]. It must be pointed out that materials classified under the category of floor covering include accelerants and other items lying on the floor. When the data are analysed in greater detail, thus, it is found that carpets and rugs are associated with less than one third of the fire fatalities ascribed to those items first ignited described as floor coverings.

In spite of the relatively low importance of floor coverings to fire hazard, their fire performance is often specified. This may involve the development of ranking classifications using the "pill" test or the flooring radiant panel test. It also may mean using pass/fail criteria based on smoke obscuration, usually via the NBS smoke density chamber (ASTM E662), or smoke toxicity (as is the case in New York city). ASTM E-5 has been in the process of developing a fire hazard assessment standard for floor coverings (especially carpets) for some time, but no consensus exists.

The cone calorimeter has been shown to be an excellent tool for testing the fire performance of floor coverings [60-64]. The incident fluxes used tend to be in the range of 25-30 kW/m^2. The references cited have found good correlation between the results of cone calorimeter tests and full scale tests but that the flooring radiant panel test can give misleading results. Smoke results from NBS smoke chamber were also found inadequate. In this connection, it is worth recalling that the cone calorimeter has been shown to be an excellent instrument for measuring smoke obscuration [65-66].

6. CURTAINS AND DRAPES

In 1967, the Flammable Fabrics Act of 1953 was extended to include interior furnishings and other products which might constitute an unreasonable flammability risk. The Flammable Fabrics Act defined interior furnishings as: "any type of furnishings made in whole or in part of fabric and related materials and intended for use, or which may reasonably be expected to be used, in homes, offices, or other places of assembly or accommodation."

The flammability of curtains and drapes was first addressed by the promulgation of the NFPA 701 test, in 1969. This standard contains two tests: a small scale and a large scale one, both addressing vertical flame spread. The traditional small scale version for curtains uses a 38 mm methane flame (from a laboratory burner and in a cabinet similar to that in CS 191-53) exposing a 90 x 255 mm sample for 12 s. The large scale one uses a 280 mm flame exposing a 2.1 m high x 0.6 m wide sample for 2 min. The pass/fail requirements are based on char length and afterglow; no flaming drips are allowed to continue burning.

However, the test, in its original version, did not address multiple layers of curtains. A number of full scale experiments indicated that full length burning of the curtain, or even flashover, can be reached in a room when combining multiple layers of curtain materials, each one of which will comply with the NFPA 701 test [67-68]. In order to avoid the need for full scale room testing, a new small scale test was developed, commonly known as the "phone booth" test. In this test, a 150 mm x 400 mm sample (which may contain multiple layers) is exposed to a 100 mm methane flame for 45 s. The pass/fail criterion for this test is based on sample mass loss, with 40% the limit. This test was first proposed for standardisation at NFPA, within the umbrella of NFPA 701, in 1992. Some work has been done with the test, including a round robin with 9 laboratories, but both its degree of predictability of full scale fire performance and its reproducibility are still unclear. All three tests are now under consideration at ASTM.

7. APPAREL

7.1 Early attention

The result of the first serious public scrutiny of the flammability of textile "furnishings" was the standardisation of ASTM D1230, in 1952. Soon afterwards followed the promulgation of the Flammable Fabrics Act in 1953, amended in 1954. The major emphasis at the time was placed on apparel, with the objective of banning "torch sweaters" and highly flammable children's "cowboy chaps". A 45 ° angle flammability test was thus developed, for apparel fabrics (CS 191-53), which became effective in 1954, and is still valid, as CFR 1610 [69]. The two tests, ASTM D1230 and CFR 1610 are similar, but not identical. The test was not designed to raise the general level of fabric flammability performance. However,in view of the lack of other tests, the federal test has received extensive criticism, because it is mildness, and limitations. A list of limitations of the test has been published [70]. These limitations can be summed up in two major ones: (a) it does not mirror actual fire conditions and (b) virtually every fabric in existence in the 1990's will comply with it. Several authors have suggested that the test can be modified to update it [70-71]. It is not clear whether a more stringent test is required, or whether this would simply eliminate many fabrics from sale, without added safety benefit. An NFPA study of statistics on products first ignited in residential fires in the 1983-87 period shows that clothing (on a person) is the fifth leading known cause of ignition leading to fire fatalities [59], representing 130 deaths/year. In fact, if all clothing is counted together, it moves up to the fourth leading cause, with 237 fatalities/year. Thus, fire fatalities from this cause have not changed ranking since 1977-78, when a previous such study was made [2]. In fact, the fire death rate per fire for fires initiated in worn clothing has gone up from 1 in 10 (1977-78) to 1 in 7 (1983-87).

When considering apparel, it must be borne in mind that textile fabrics can be, broadly, classified into: charring and melting. The former are mostly cellulosics, like cotton, or materials like wool, and they tend to propagate flame upwards. The latter are mostly thermoplastics (e.g. nylon, polypropylene, polyester), which shrink away from the flame and may <u>not</u> propagate the flame upwards. Thermoplastic fibres are, thus, less prone to cause extensive fire damage, if they are not held tightly in position. Moreover, thermoplastic fibres are also usually resistant to smouldering ignition. However, they are often less resistant to small flaming ignition sources when held in position and prevented from shrinking, unless adequately flame retarded. One exception to this trend are vinyl fabrics, which, although thermoplastic, tend to resist both smouldering and small flaming ignition sources. This issue has been investigated in detail in 1982 by John Krasny [72].

It is important to note, too, that combinations of fabrics will, often, perform like the poorer component in the system. Thus, when a thermoplastic is attached to a char former, this will often result in more intense burning than the additive effect of two combustibles of similar characteristics. This is important in lined clothing, and can even be noticed depending on the type of thread used to sew the items. Curiously, however, such combinations can cause more intense fires, but with lower upward flame spread rates.

7.2 Children's sleepwear

Following extensive press coverage of several fire fatalities involving ignition of children's sleepwear in the late 1960's and early 1970's, a test was devised, which would protect small children from the danger inherent in using the then prevalent long loose nightgowns made of non fire retarded cotton. Two federal flammability standards address this issue: DOC FF 3-71 (CFR 1615, for children up to 6 years' old [73]) and DOC FF 5-74 (CFR 1616, for children 7 through 14 years' old [74]). Both tests are virtually identical. They involve applying a 3.8 cm methane flame, at a 25° angle on a vertical sample for 3 s. In order to pass the test, char length may not exceed 17.8 cm average, or 25.4 cm (under load) for any burn (out of 10). Sleepwear which does not pass the test must be labelled Flammable and displayed separately from the ones that pass the test. This test has virtually eliminated the earlier materials used for children's nightwear. However, in recent years, products are being sold in the USA which look very similar to acceptable nightwear, but are not labelled as children's nightwear (and do not pass the test). These products need to meet only CFR 1610. This is one of the most compelling arguments for updating CFR 1610. However, the Consumer Product Safety Commission (CPSC) has proposed, in early 1993, to decrease enforcement of children's sleepwear requirements, in view of the scarcity of serious incidents and the enforcement difficulties.

7.3 Protective clothing

For a long time, thermoplastic fibers were proposed as protective clothing for structural fire fighters. It has now become clear that they are, usually inadequate. They have, mostly been replaced by aromatic polyamides and polyimides. Standards addressing requirements for the apparel worn by fire fighters have been issued by NFPA: they are NFPA 1971 (protective apparel for structural fire fighting), NFPA 1973 (gloves for structural fire fighters) and NFPA 1975 (station/work uniforms for fire fighters). The materials for the coats are required to be tested by Federal Test Method Standard 191A, Method 5903.1. This is a vertical exposure to a 38 mm methane flame for 12 s. The pass requirements are an afterflame of less than 2 s and a char length of less than 102 m, with no melting or dripping. Station trousers, exposed to the same test, are allowed a char length of less than 152 mm. Finally, gloves are allowed some after glow (4 s) but a char length of only 25 mm.

8. CABINETRY

The fire standard that applies to office furnishings is contained in section 18 of UL 1286 (Standard for Office Furnishings) [75]. The second edition was issued in 1988, with some revisions issued in July 1990, none of which address fire.

The standard states (section 18.1) that "components of a major part of an office furnishing system or individual unit, and that have an individual or a mechanically contiguous surface of 10 ft^2 (0.93 m^2) or more shall have a flame spread index of 200 or less, and smoke developed index of 200 or less, when tested in accordance with" UL 723 (ASTM E84 or NFPA 255, the Steiner tunnel test). However, there is an exception: no smoke development number is required, provided the result is marked appropriately, in a way visible after installation (see Marking, section 34.4).

Decorative moldings, base raceway covers, shelves and similar items, when made of combustible material (the standard calls it polymeric) "and is mechanically contiguous across and runs at least the full width of one unit" have to meet simply the V-0 or 5-V requirements of the UL 94 small scale test. In this test, vertical specimens are exposed to a small laboratory flame. To achieve a V-0 rating, five, 5 in (127 mm) long, use thickness, specimens are exposed from underneath to a 3/4 in (19 mm) flame. They achieve a V-0 rating if they do not burn for over 50 s, are completely destroyed, and do not drip so as to ignite cotton placed underneath. For a 5-V rating both bars (5 in (127 mm) long) and plaques (6 by 6 in (152 by 152 mm)) are exposed to a 5 in (127 mm) flame. The bars may not burn for 60 s or drip so as to ignite the cotton. If the plaques have a hole after the burn, the sample is classified as 5-VB, and if not it is a 5-VA.

Both of these tests, UL 723 and UL 94, are well established and ingrained into many codes and regulations. Consequently, the tunnel test is unlikely to be replaced any time soon. The UL 94 test is also required in many specifications of plastic materials (all materials going into small appliances and other electrical equipment parts, for example). It is not particularly indicative of good fire performance, particularly because of the low intensity fire source, and materials with poor fire performance may yield falsely satisfactory results.

A more modern flame spread test was designed at NIST: the LIFT (lateral ignition and flame spread test, ASTM E1321, mentioned earlier). It gives data acceptable for fire hazard assessment through modelling. Unfortunately, it has had very limited popularity so far, with only a handful of apparatuses in existence, either in the USA or internationally. It cannot test materials that melt and drip, because the sample is vertical. A modification already exists (HIFT: horizontal ignition and flame spread test) which turns the apparatus 90° and solves that problem. There is, however, even less experience with it.

Another alternative for replacing the tunnel is the use of room corner tests, such as UBC 42-2 (NFPA 265), or others (Table 5). This approach is likely to lead to fruition, because it is based on the idea that the results of such room tests, which measure heat release rate, will soon be predictable from cone calorimeter results. Unfortunately, in the short run there is still no established test for flame spread adequate for fire hazard assessment. The most famous new test instrument, the cone calorimeter <u>does not measure flame spread</u>, although it appears that flame spread can be calculated from some of its results (particularly the inverse of the time to ignition).

9. ASTM E-5 ACTIVITIES

The subcommittee of ASTM E-5 dealing specifically with fire and "furnishings" is E-5.15. The ultimate focus of the activities of this subcommittee is the development of fire hazard and fire risk assessment standards. However, since the technology for writing fire hazard assessment standards is still in its infancy, the subcommittee also deals with fire-test-response standards.

It is interesting that this subcommittee developed a standard in 1985 called "Standard Practice for Assessment of Fire Risk by Occupancy Classification", which was published under the number ASTM E931-85. A detailed history of this standard can be found in "Concepts Behind ASTM E931", in this volume [76].

The subcommittee also has task groups working on fire hazard assessment of individual "furnishings": upholstered furniture, floor coverings and wall coverings. It is likely that the work will be long term, based on the standard guide for development of fire hazard assessment standards, ASTM E1546. The most advanced of these potential fire hazard assessment standards addresses carpets, and had an unsuccessful subcommittee ballot in early 1992. This ballot was held through subcommittee E-5.35, before the activity was returned to E-5.15 for further study. A joint task group was then formed, between E-5.15 and E-5.35 to complete the project.

ASTM E-5.15 has responsibility for four standards, as well as E931: E1352 and E1353, for smouldering ignition of upholstered furniture components, by the action of cigarettes, E1474, for radiant ignition of upholstered furniture or mattress composites in the cone calorimeter and E1537, for flaming ignition of full scale upholstered furniture items.

Work is underway to generate fire-test-response standards involving stacked stacking chairs, mattresses, wall coverings and curtains and drapes. The subcommittee is also considering the development of a test for vandalised mattresses in correctional institutions. Table 8 is a list of the active task groups in the subcommittee and the "furnishings" issues they are working on.

CONCLUSIONS

The area of furnishings and contents often remains unaddressed by codes or regulations. The reason for this is very clear: many of these products are bought by the consumers and installed in buildings after they have been approved by the code officials.

A relatively large number of standards and tests exist which are used for furnishings and contents. Progress in all areas is not of the same caliber, however: some tests are of a much more advanced nature than others. It is, however, very noticeable that the emphasis being placed on the fire performance of furnishings and contents has increased considerably in recent years. New tests also often emphasise heat release measurements.

Recent progress has involved changing from testing individual materials to testing finished systems or products. The next step, already underway, is to test full scale systems by determining heat release rate. This must be followed by the use of small scale tests which can be truly predictive of the fire performance of the full scale tests. Predictions will, in all likelihood, result from the added use of mathematical fire models. The final step should be the utilization of small scale test results and mathematical models to predict fire hazard or fire risk in real occupancies.

It is encouraging that the thrust of the majority of new tests being developed and being considered for standardisation is that they should be useful to generate results that can be used in fire hazard or fire risk assessment.

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Figure Legends and Keywords

Figure 1: Failures in California Technical Bulletin 133: Number of failures out of 93 chairs tested up to 1990 (they may fail more than one criterion)

Figure 2: Flammability of wall coverings: individual laboratory rating and average rating, according to the standard test used in 6 countries.

Figure 3: Correlation of wall linings between rankings in the full scale ISO 9705 test and in the French national standard NFP 92-501 (Epiradiateur).

Figure 4: Correlation of wall linings between rankings in the full scale ISO 9705 test and in the German national standard DIN 4102 Pt 1 (Brandschacht).

Figure 5: Correlation of wall linings between rankings in the full scale ISO 9705 test and in the British national standard BS 476 pt. 7 (spread of flame test).

Figure 6: Correlation of wall linings between rankings in the full scale ISO 9705 test and in the cone calorimeter (ISO 5660 and ASTM E1354).

Keywords

Fire, fire hazard, fire test, flame spread, furnishings, floor coverings, heat release, mattresses, rate of heat release, smoke obscuration, upholstered furniture, wall coverings.

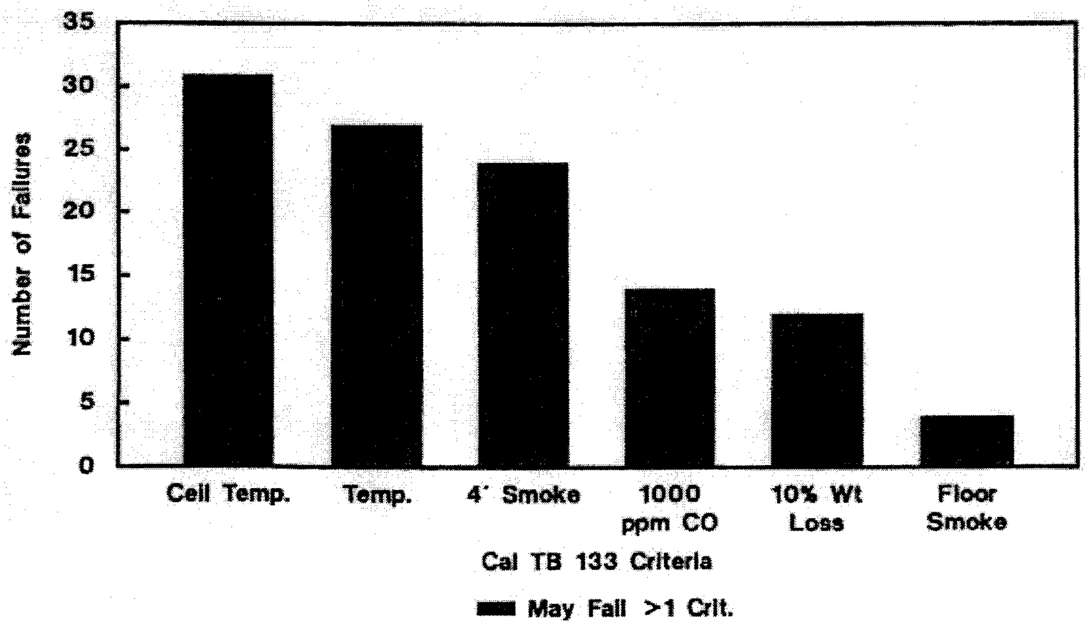

FIG. 1—*Failures in California Technical Bulletin 133: Number of failures out of 93 chairs tested up to 1990 (they may fail more than one criterion).*

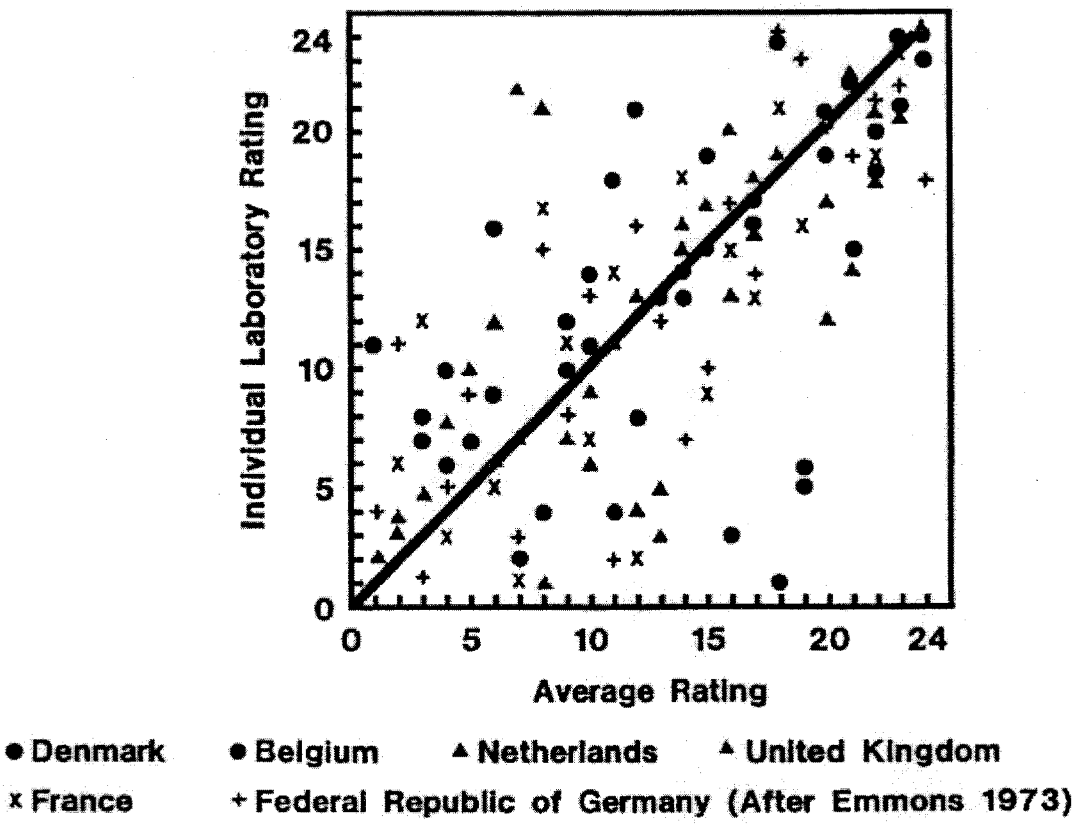

FIG. 2—*Flammability of wall coverings: individual laboratory rating and average rating, according to the standard test used in 6 countries.*

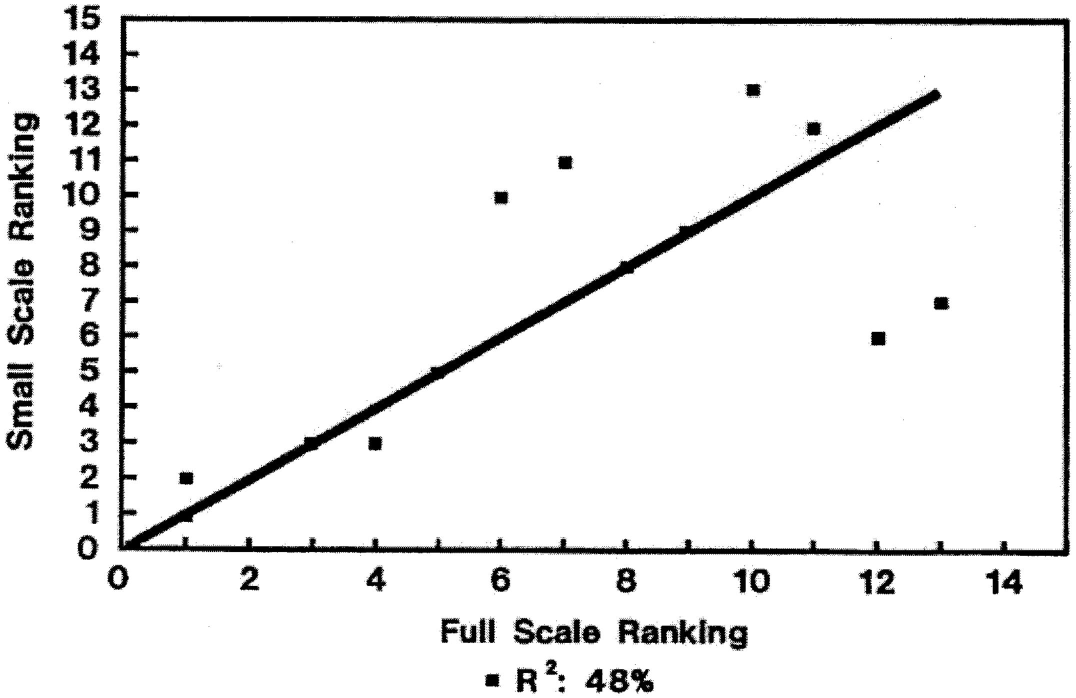

FIG. 3—*Correlation of wall linings between rankings in the full-scale ISO 9705 test and in the French national standard NFP 92-501 (Epiradiateur).*

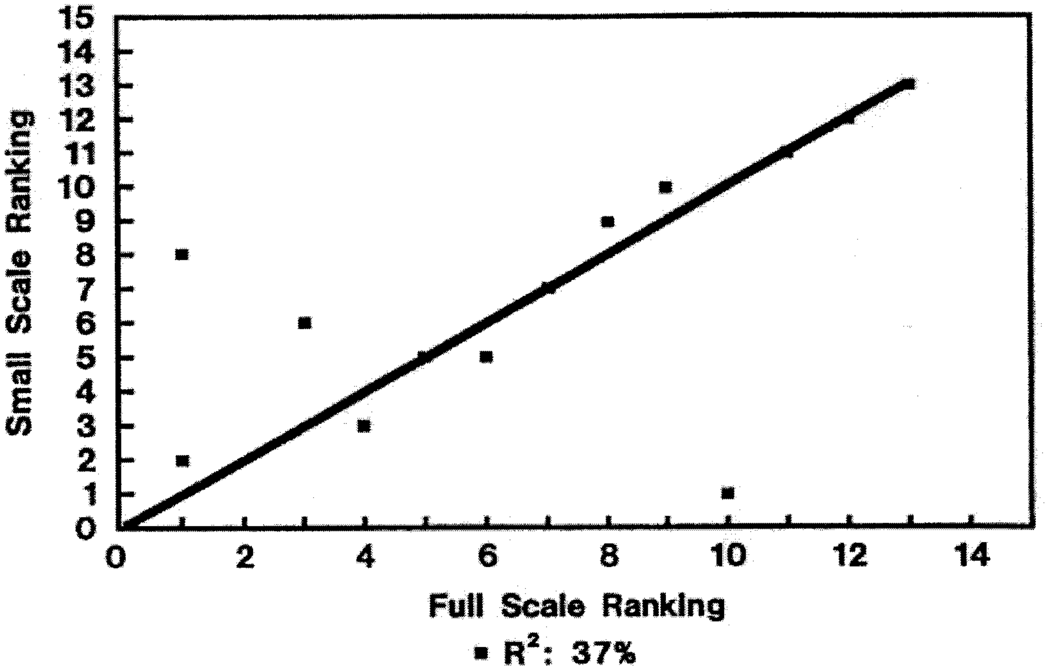

FIG. 4—*Correlation of wall linings between rankings in the full-scale ISO 9705 test and in the German national standard DIN 4102 Pt 1 (Brandschacht).*

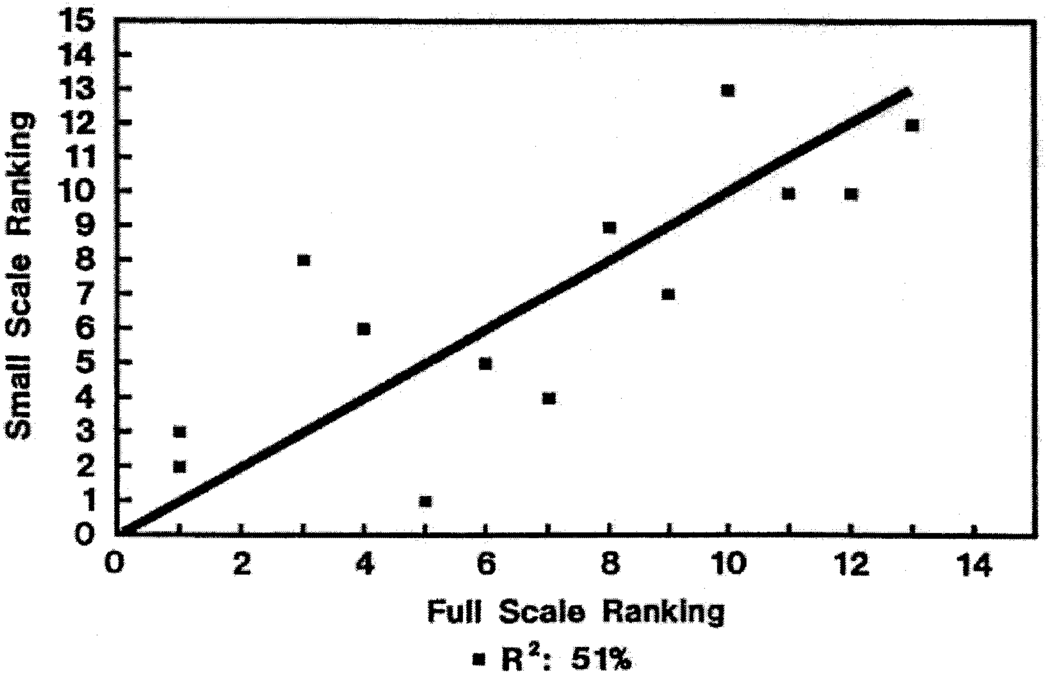

FIG. 5—*Correlation of wall linings between rankings in the full-scale ISO 9705 test and in the British national standard BS 476 Pt 7 (spread of flame test).*

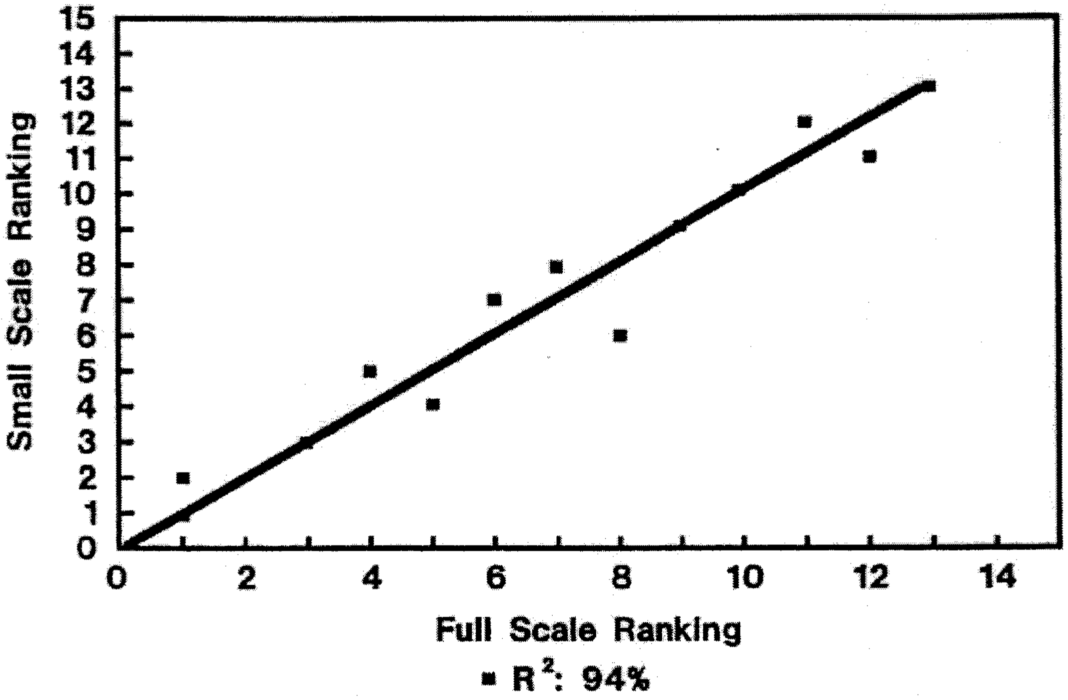

FIG. 6—*Correlation of wall linings between rankings in the full-scale ISO 9705 test and in the cone calorimeter (ISO 5660 and ASTM E 1354).*

Table 1
Fire Statistics in the 1970's and 1980's

Residential Fire Fatalities by Item First Ignited (% of total)

	1977-78	1983-87
Upholstered Furniture	43.5	22.9
Bedding	33.0	16.1
Interior wall covering	?	7.1
Floor covering	4.3	3.9
Clothing (worn)	6.0	2.9
Clothing (not worn)	4.7	2.3
Curtains and drapes	2.9	0.9

Residential Fires by Item First Ignited (% of total)

	1977-78	1983-87
Upholstered Furniture	18.5	3.9
Bedding	39.6	7.8
Interior wall covering	?	4.3
Floor covering	3.7	2.3
Clothing (worn)	0.8	0.2
Clothing (not worn)	13.2	2.7
Curtains and drapes	5.1	1.2

Note: 1977-78 statistics address textile products in structure fires (Tovey and Katz 1981) while 1983-87 statistics address all materials in residential fires (Miller 1991). The latter statistics contain a total of 31 categories, as well as unknown (or "others"). The major items first ignited in 1983-87 residential fires not in the table are: rubbish (15.7%), cooking materials (14.0%), structural members (7.8%), wire and cable (6.8%), as well as "others" (14.1%). The major items first ignited in 1983-87 residential fire fatalities not in the table are: structural members (7.6%), flammable liquids (6.6%) as well as "others" (8.9%).

Table 2

Fires and Fire Fatalities Related to Upholstered Furniture

	1978	1989
Fires		
Total Residential Fires	757,500	513,500
Total Upholstered Furniture Fires	43,000	18,600
Smoking materials	28,000	9,700
Open flames	7,900	4,200
Others	7,100	4,700
Fire Fatalities		
Total Residential Fires	6,840	4,440
Total Upholstered Furniture Fires	1,600	890
Smoking materials	1,300	670
Open flames	200	130
Others	100	90

Table 3
Failure Criteria for CA TB 133; January 1991

Criteria A (No Heat Release)

#	Measurement	Value	Location
1.	Temperature increase	≤ 200 deg F	Ceiling thermocouple
2.	Temperature increase	≤ 40 deg F	4 foot thermocouple
3.	Smoke opacity	≤ 75 %	4 foot monitor
4.	Carbon monoxide	≤ 1,000 ppm; 5 min	Top corner monitor
5.	Weight loss	≤ 3 lbs; 10 min	

Criteria B (Heat Release)

#	Measurement	Value	Location
1.	Pk Heat Release Rate	≤ 80 kW	Duct measurement
2.	Total Heat Release	≤ 25 MJ; 10 min	Duct measurement
3.	Smoke opacity	≤ 75 %	4 foot monitor
4.	Carbon monoxide	≤ 1,000 ppm; 5 min	Top corner monitor

Note:

The original criteria included a smoke opacity criterion of ≤ 50% smoke opacity at a floor monitor, and stated that carbon monoxide concentration was not to exceed 1,000 ppm continuously for 1 min.

Table 4. Results of Corner Room Tests run by ATMI

Test#	Material	Pk RHR kW	THR MJ	Ceil T deg C	Floor Flux kW/m^2	E84 FSR	Time Pk s
6	G	83	10.1	272	2.2	25	510
7	AA	684	30.6	672	17.7	15	510
8	Q	207	8.3	365	6.5	15	520
9	Qfr	310	9.0	388	7.5		520
10	BB	93	9.5	269	2.5		510
11	C	62	2.2	237	2.1		510
12	B	207	5.8	342	5.3		525
13	Zfr	142	3.3	293	3.6		510
19	Lfr	182	13.0	448	6.6	15	510
20	R	587	51.1	582	19.3	15	550
21	H	46	5.4	297	2.3		510
22	L	227	20.2	404	7.1		510
23	Q*	297	21.2	369	4.4	15	510
24	PWfr	366	23.0	672	10.6		1090
26	R*	5771	228.1	929	150	15	580
28	Q #	497		553	8.1	15	520
29	Q #	474		642	9.3	15	520
30	Q #	928		763	24.5	15	520
31	R #	590		590	13.4	15	550
32	R' #	331		542	4.9	15	520
33	H #	160		405	2.3		520
34	C #	119		326	1.8		540
35	B #	298		477	5.3		540
36	PP-95 #	337		567	5.3		520
37	PP-PF #	1166		785	26.6		530
38	DD #	249		477	4.7		580
39	113-9 #	309		578	7.3		520
40	113-9 #	728		765	20.9		600

* Fully lined room (FLR); UBC 42-2.
# 2 ft wide samples.

Explanation: Pk RHR: peak rate of heat release (in kW), THR: total heat released (in MJ), Ceil T: Ceiling temperature (in degrees centigrade), Floor Flux: radiant flux to the floor (in kW/m^2), E84 FSR: flame spread rating in the Steiner tunnel test (ASTM E84), Time pk: Time to reach peak rate of heat release, in s.

Table 5. Comparison of Full Scale Room Corner Tests

	ASTM Proposed	UBC 42-2	ISO 9705	UBC 17-5	Williamson
Room Size	8x12x8'	8x12x8'	2.5x3.7x2.5m	8x12x8'	8x12x8'
Doorway	Symmetrical, opposite central test wall				
Igniter	Gas Burner	Gas Burner	Gas Burner	Wood Crib	Gas Burner
Location	Against wall	2" off wall	Against wall	1" off wall	2" off wall
Sample	3 walls	3 walls	3 walls + Ceiling	3 walls + Ceiling	Wall section 1'or 2' wide
Amount	ft^2 256	ft^2 256	m^2 36.5	ft^2 352	ft^2 46 (*)
Testing					
Duration	15 min	15 min	20 min	15 min	15 min
Intensity					
Initial	40 kW	40 kW	100 kW	30 lb wood	40 kW
Duration	5 min	5 min	10 min	15 min	5 min
Final	160 kW	150 kW	300 kW	None	150 kW
Duration	10 min	10 min	10 min	-	10 min
Measurements					
RHR	Yes	Yes	Yes	No	Yes
Floor Flux	Yes	Yes	Yes	No	Yes
Ceiling T	Yes	Yes	Yes	No	Yes
Smoke Obsc.	Yes	No	Yes	Yes	No
CO	Yes	Yes	Yes	No	No
CO2	Yes	Yes	Yes	No	No
Visual	Yes	Yes	Yes	Yes	Yes

Comments:

UBC 17-5 requires that "inside of room" is that dimension.
Other tests use a standard room, and line walls (and ceiling if needed).
ISO 9705 test has other alternatives, but this is the preferred one.
*: For 1 foot wide strips; for the 2' wide strips the area is 64 ft^2.

Table 6. Test results for ATMI samples in the cone calorimeter

Material	Cone 30 Pk RHR	Cone 50 Pk RHR	Cone 30 THR	Cone 50 THR	Cone 30 TTI	Cone 50 TTI	Cone 30 TTI/RHR	Cone 50 TTI/RHR
G	70	73	2	2	240	50	3.4	0.7
AA	233	252	21	25	105	40	0.5	0.2
Q	140	225	3	7	205	60	1.5	0.3
Qfr	169	213	3	8	220	75	1.3	0.4
C	108	124	4	5	100	50	0.9	0.4
B	137	247	2	6	205	60	1.5	0.2
R	43	288	3	9	370	60	8.6	0.2
H		105		4	60		0.6	
PP-PF	209	262	8	17	110	70	0.5	0.3

	Cone 30 Pk MLR	Cone 50 Pk MLR	Cone 30 Burn time	Cone 50 Burn time
G	9	7	15	22
AA	12	8	152	132
Q	8	16	28	35
Qfr	10	12	25	42
C	10	11	20	23
B	9	8	23	27
R	4	12	43	52
H		6		30
PP-PF	9	8	113	78

Table 7. Test results for ATMI samples in the LIFT apparatus

Material	LIFT Q" ig	LIFT T ig	LIFT krhoc	LIFT Q" s	LIFT T s	LIFT Phi	LIFT b	LIFT Q"e 50
G	20	434	1.04				0.054	30
AA	18.1	386	0.85	7.2	248	27.9	0.053	30
Q	24	473	0.84	6.6	235	25.3	0.065	38
Qfr	24	473	0.86	10.7	305	35	0.064	35
C	20.5	440	0.68	9.9	300	20.6	0.072	35
B	26	491	0.82	12.5	340	33.5	0.068	34
R	24	473	0.87	6.8	240	15.7	0.064	39
H	24.7	480	0.47	16.7	397	15.3	0.089	50
PP-PF	16	386	0.85	7.2	248	27.9	0.053	29

Explanations: Cone 30 and cone 50: cone tests at 30 and 50 kW/m^2 incident flux, Pk RHR: peak rate of heat release, in kW/m^2, THR: total heat release, in MJ/m^2, TTI: time to ignition, in s, TTI/RHR: ratio of time to ignition to peak rate of heat release, in s m^2/kW, Pk MLR: in g/s m^2, Burn time: average time of main burn, in s. LIFT: Q" ig: critical flux for ignition, in kW/m^2, T ig: ignition temperature, in degrees centigrade, krhoc: thermal inertia, in $(kW/m^2\ K)^2$ s, Q" s: critical flux for spread, in kW/m^2, T s: flame temperature, in degrees centigrade, Phi: flame heating parameter, in kW^2/m^3, b: ignition parameter, in $s^{-1/2}$, Q"e 50: surface flux at 50 mm, in kW/m^2.

Table 8
Active Task Groups in ASTM E-5.15 in 1993

#	Rough Title	Chair	Main Subjects
		Subcommittee Chairman: Marcelo Hirschler	
2	Curtains & drapes	John Michener	Phone booth test; fire hazard assessment
3	Floor coverings	Andrew Fowell	Fire hazard assessment
4	Stacking chairs	Gordon Damant	Full scale heat release test of full scale stacked chairs
5	Upholst. furn.	John Michener	Cigarette ignition stds: precision and bias, fire hazard assessment
6	Wall coverings	John Michener	Fire hazard assessment
7	E931 Review	Hugh Talley	Review of occupancy classification practice
8	Full scale furn.	Marcelo Hirschler	Full scale heat, smoke and toxic gas release test for upholstered furniture
10	Mattresses	Vytenis Babrauskas	Full scale heat, smoke and toxic gas release test for mattresses; small scale test for mattress composites
11	Cone applications	Thomas Fritz	Small scale cone calorimeter application to wall coverings
12	Vandalised mattr. in prisons	Marcelo Hirschler	Search for tests for vandalized mattresses in correctional institutions

GBH Attachment 25

AB59-COMM-7-25

Developments in Codes, Standards and Regulations Associated with Upholstery in the United States

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ABSTRACT

There have been requirements associated with the fire performance of upholstered furniture and mattresses for many years in the United States. However, recent years have seen an increase in public activity in the area. This work will discuss present regulations, codes, standards, guides and potential upcoming changes which are being considered.

INTRODUCTION and BACKGROUND

It has long been known that the fire performance of an individual furnishing item can be crucial on whether a room becoming untenable in a fire, thus resulting in fire fatalities. The first type of product identified as a potentially serious concern is upholstered furniture: a single item can yield a fire severe enough to engulf a whole room and take it to flashover [1-2]. On November 29, 1972 the Federal Register stated, on behalf of the Department of Commerce, that a flammability standard or other regulation might be needed for upholstered furniture. The emphasis was to be placed on ignition of furniture by smoking materials, particularly cigarettes. The technical work was started at the National Bureau of Standards (NBS, today National Institute of Standards and Technology, NIST). When the Consumer Product Safety Commission (CPSC) was established in May 1973, it was given the authority to deal with the issue. A private organization, Upholstered Furniture Action Council (UFAC), was created in 1974, as a voluntary industry association to focus on the problem of the flammability of upholstered furniture. Its funds come from the majority of the large furniture manufacturers producing upholstered furniture for the residential market, many of whom belong to the American Furniture Manufacturers' Association (a trade association). Thus, during the mid to late 1970's, parallel work was being carried out in the public and in the private sector, to develop tests to prevent ignition by cigarettes, i.e. smouldering ignition. The public sector work was being done at the National Bureau of Standards (NBS) and the private sector work at Guilford Laboratories (Greensboro, NC), on behalf of UFAC. Both efforts culminated in test methods. NBS developed a test for cigarette ignition of upholstered furniture mock-ups in 1976. This test was eventually standardized both by the National Fire Protection Association (NFPA) (NFPA 261, 1983 [3]) and the American Society for Testing and Materials (ASTM) (ASTM E 1352, 1989 [4]). UFAC developed their series of 6 test methods for cigarette ignition of upholstered furniture components and constructions somewhat later, but the voluntary program went in effect in 1978. CPSC decided, in 1979, to defer implementation of mandatory federal regulation while it monitored UFAC activities, a position still in effect today. These test methods were also standardized at ASTM (ASTM E 1353, 1989 [5]) and NFPA (NFPA 260, 1983 [6]). The State of California, at the California Bureau of Home Furnishings (CBHF), passed Technical Bulletins 116 [7] and 117 [8], which required compliance, respectively, with cigarette ignition of full items of upholstered furniture and with cigarette and flaming ignition of furniture components by October 1977. They are applicable to all upholstered furniture items offered for sale in the state of California: TB 116 on a voluntary, basis while TB 117 is a requirement. Manufacturers of contract furniture (i.e. non residential) are mostly associated within the Business and Institutional Furniture Manufacturers' Association (BIFMA). They have adopted the NBS mock-up test as a voluntary standard (BIFMA X5.7, pt. 5), as well as a small flame test: the 45° angle test for apparel from CFR 1610 (incorporated into BIFMA X5.7, pt. 4, into CA TB 117, for fabrics and other components, and CS 191-53 [9], in section 7, for fabrics only). The development of furniture resistant to cigarette ignition has meant that the materials used have changed. The trend was to move away from materials which smoulder easily to materials which do not smoulder. Thus, lightweight cellulosic materials (like cotton, linen or rayon), have been mostly replaced by synthetic materials, unless they have been treated with fire retardants. These synthetic materials (thermoplastics) tend to shrink away from the flame, and are, thus, much more likely to resist ignition by cigarettes. However, some thermoplastic materials which do not smoulder may be easily ignited by small flames. The introduction of the cigarette ignition tests resulted in a large decrease in the preponderance of some extremely flammable fillings, such as sisal, kapok, jute or untreated cotton, from furniture offered for sale commercially. However, the UFAC test requires that the foam filling simply be tested under a fabric which passes the cigarette ignition test and not tested for flaming ignition. Thus, it is possible for foams to have relatively poor fire performance, and yet pass the test because they are covered with a fabric that resists smouldering.

At the same time that the Department of Commerce identified the problem of smoldering ignition of upholstery items, it also identified the problem of flaming ignition. However, it did not develop a federally mandated solution, but gave the responsibility to the manufacturers of upholstered products. The first serious attempt at developing a flaming ignition standard for upholstered furniture systems was a British Standard (BS 5852), developed as a consequence of a famous 1979 furniture store fire in Manchester (UK) [10]. This test uses a variety of wood cribs, and it tests a combination of fabric and filling, made up into two standard cushions: bottom and back. The wood cribs range from # 4, weighing only 8.5 g, through # 5 (weighing 17 g) to # 7, weighing 126 g. Less severe ignition sources address smokers' materials: cigarettes and butane gas burner flames simulating matches (ignition sources 0 through 3). One study [11] showed that the "rankings" resulting from testing fabric/foam combinations in this test, with wood cribs, correlated well with those that could be obtained from using the cone calorimeter (ASTM E 1354 [12], a modern fire test used on small specimens of materials, and suitable for fire hazard calculations) at 25 kW/m^2. The cone calorimeter has been shown to be an effective predictor of whether a product will cause flashover on its own [2], and it is particularly effective when used for upholstery (furniture or mattress) composites, with the ASTM E 1474 test protocol [13]. In 1990, following the issuance of the 1988 UK Furniture and Furnishings (Fire) (Safety) Regulations [14], the BS 5852 British standard [10] was modified somewhat, so that testing for qualification for residential items is now permitted to be done effectively on separate items. Foam fillings are qualified when tested under a "standard" flame retarded polyester fabric and fabrics are qualified when tested over a filling deemed acceptable. Other (non foam fillings) are tested to ignition source # 2, which is a 145 mm long butane gas burner flame applied for 40 s. Thus, different fillings have different requirements, with foam fillings being those required to meet the most severe test, namely the # 5 crib. Thus, the British system does not require (for residential use) testing of the system actually proposed for use. This is, of course, likely to be less satisfactory than testing finished systems, but it also means that testing costs are kept very low and are made easy for component manufacturers. All furniture (residential and commercial) must also pass cigarette smoldering ignition fire tests.

In the USA, in order to address the issue of flaming ignition, independently, CBHF and the Boston Fire Department (BFD), started developing fire tests for flaming ignition of seating furniture: California Technical Bulletin 133 [15] and the Boston chair test. These tests were designed for very high risk furniture. In fact, the test under the jurisdiction of CBHF became applicable, in 1992, to seating furniture in institutions, hospitals, mental health facilities, health care facilities, nursing homes, board and care facilities, convalescent homes, child day care centers, public auditoriums, stadiums and public assembly areas of hotels, motels or lodging houses containing 10 or more articles of seating furniture, with an exception allowed if they are fully sprinklered. This test was never used to regulate residential upholstered furniture, where the responsibility was still retained by the manufacturers. In May 1984 CBHF issued the first version of TB 133. This test involved burning a full item of seating furniture, inside a room of specified dimensions (12 by 10 by 8 ft high (3.7 by 3.1 by 2.4 m high)), using as flaming ignition source a wire cage, containing 5 crumpled double sheets of newspaper. In order to pass the test, the item could not exceed a series of 6 criteria, involving temperature increase, smoke obscuration, carbon monoxide generation and weight loss. The test was thus initially intended to be a "low-tech" tool for qualitative use by manufacturers. In other words, the simple application of the ignition source, with little instrumentation would permit a test user to assess whether the chair would burn vigorously or not. Unfortunately, the output was not usable for more comprehensive assessments of fire safety. A survey of the number of failures indicated that the vast majority of failures involved one or both of the temperature increase criteria. For those reasons, the test has, in the meantime, been modified to add heat release requirements, but the basic concept remains the same. The crucial change resulted from cooperative work between CBHF and NIST, after it ha been shown that the most important fire property is the rate of heat release [16]. This ties in with the concept that the main failure criteria are based on energy increase. Thus, the NIST/CBHF work focused on three aspects: (a) find a heat release rate corresponding to the temperature increase in the upper layer of the room, (b) find a more reproducible ignition source than the newspaper and (c) understanding whether there is a difference between tests carried out in different rooms. The results were: the 200 °F (111 °C) increase in temperature can be modeled by a 80 kW heat release rate and the newspaper ignition source can be modeled by a square propane gas burner, with a gas flow of 13 L/min for 80 s [17-18]. The research also showed that the heat release rate is not affected by the size and shape of the room, within certain limits, if the heat release rate does not exceed 600 kW. The state of California adopted a new version of TB 133 in January 1991, which requires the use of the square gas burner. It allows the measurement of temperature increase or of heat release rate as pass fail criteria. In order to pass the test a furniture item has to avoid exceeding any of the following 4 criteria: heat release rate of $\leq$ 80 kW, total heat release of $\leq$ 25 MJ in the first 10 min (both in the exhaust duct), $\leq$ 75% smoke opacity at a smoke obscuration monitor located at 4 ft (1.2 m) from the floor and emit $\leq$ 1,000 ppm carbon monoxide for a 5 min period, at a room monitoring location. TB 133 also allows testing in a "furniture calorimeter", i.e. under a hood, rather than inside a room, where the first two requirements only can be met. If heat release is not measured, the test criteria needed to pass TB 133 include temperature increases of $\leq$ 200 °F (111 °C) at a ceiling thermocouple, $\leq$ 50 °F (28 °C) at a 4 ft (1.2 m) thermocouple and weight loss of $\leq$ 3 pounds (1.36 kg) in the first 10 min. TB 133 has now relegated the newspaper source to the status of a screening test only. Both ASTM and NFPA developed consensus standard versions of this test, as ASTM E 1537 [19] and NFPA 266, which has since been withdrawn [20]. CA TB 133 has been used for regulation in several USA states (including California), in codes and in various specifications, since the early 1990s, but mostly for contract furniture. NFPA 101, Life Safety Code [21], NFPA 301, Life Safety Code for Ships [22], and the International Fire Code, IFC, [23] all have requirements for upholstered furniture in some occupancies (health care and detention) using ASTM E 1537, as do, by reference, the NFPA Fire Prevention Code (NFPA 1) and the new NFPA Building Code (NFPA 5000). However, the codes tend to have milder failure criteria: 250 kW and 40 MJ.

The UK Department of Trade and Industry commissioned a study to investigate the effectiveness of the regulation on upholstery [24, 25]. The research showed that dramatic improvements occurred between 1988 and 1997 (the years where the UK regulation on upholstery was issued and the last year for which statistical information was available at the time of the study). Table 1 contains some key benefits of the 1988 UK legislation, in terms of lives saved, decreased number of injuries and economic impact [25], based on the official UK government publication, for upholstered furniture only. A follow-up study, from the same academic team of British researchers, showed that neither the incidence of smoke detectors nor the changes in smoking patterns can explain the improvement in fire losses [26]. The study indicates that 710 lives (and over £5 billion[1]) were saved over a 10 year period, in spite of the relatively low smoke detector penetration into the UK.

Table 1 - Benefits Resulting From UK Upholstery Regulations

Benefit measure	Annual benefit 1992	Annual benefit 1997	Cumulative benefit 1988-1997
Number of dwelling fires	3,715	8,769	42,754
Total lives saved	169	362	1,856
Lives saved for upholstery as item first ignited	65	138	7,100
Total non-fatal injuries saved	1,548	3,315	17,000
Injuries saved for upholstery as item first ignited	526	1,126	5,774
Loss adjusted cost saving £m/yr	23	53	249
Final cost saving £m/yr	507	10,835	5,567
Total cost saving £m/yr	530	1,138	5,615

In conclusion, while there is effective legislation at point of sale in the UK for both smoldering and flaming ignition of upholstered furniture, there is no mandatory federal legislation for any flammability requirements for residential upholstered furniture in the USA. The voluntary requirements managed by UFAC have been quite effective in decreasing the incidence of fires initiated by smoldering cigarettes.

With regard to mattresses, CPSC has established a mandatory requirement for smoldering ignition by cigarettes [27], but no test for flaming ignition. CBHF also developed a test for mattresses, which is analogous (but not identical) to CA TB 133: CA TB 129 [28].

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[1] The exchange rate between the UK and the USA can be estimated at £1=$1.5.

However, this test was never used for regulations by either the state of California, or any other USA state. However, the test method is also included as a requirement for certain occupancies in NFPA 101 [21], NFPA 301 [22] and the IFC [23], as ASTM E 1590 [29] (or as NFPA 267 [30], now in the process of being withdrawn). Both ASTM E 1590 and NFPA 267 are functionally identical to the original CA TB 129, and involve exposure of mattresses for 3 min to an 18 kW propane gas flame from a T-shaped burner (12 L/min). Again, just as with CA TB 133, the original failure criteria (100 kW and 25 MJ) were more severe than those used in codes: 250 kW and 40 MJ. However, while there has never been any federal requirement in the United States for protection of residential mattresses or mattress pads from flaming ignition sources, foam fillings of UK mattresses have been covered for many years by the UK fire safety legislation. In fact, foam fillings of residential mattresses are required to meet the same fire tests than those of domestic upholstered furniture, namely a crib # 5, under the standard fabric [31].

Data presented in Figure 1 shows that the fire fatalities in the UK are much lower than those in the USA for fires starting with bedding (which includes mattresses) or upholstery. Furthermore, as shown in Figure 2, the differences cannot be explained based on the larger USA population. The data in Figure 1 shows that fatalities in UK fires where a mattress or bedding product was the item first ignited decreased by 58.2%, while, if the first product ignited was an upholstered furniture item, fatalities decreased by 53.4% in the same period. Corresponding USA decreases were much less impressive: 39.4% for mattress and bedding fires and 38.7% for upholstered furniture fires. The widespread, and growing use, of smoke detectors is probably one of the main reasons of the USA improvements, as there have been no requirement for changes in the composition of upholstery or mattress materials in recent years. Thus, Table 1 and Figures 1 and 2 indicate that significant savings should also be expected from mattress and bedding fires. In both cases, the number of corresponding UK fire fatalities has been decreasing, and much more than in the USA. A particularly important aspect of the UK study has been the economic analysis, included the cost to industry (which, by and large, was not passed on to the consumer) of developing and selling products with greatly improved fire performance.

In conclusion, while regulations exist in the United Kingdom to protect people at point of sale from the dangers of burning residential mattresses, both those that start with smoldering cigarettes and those that start with small flaming ignition sources, the USA has no federal requirements for residential mattresses that address flaming ignition. All mattresses sold in the USA must meet the cigarette smoldering test in CFR 1632 [27].

STANDARDS, CODES and REGULATIONS

It is important to start by clarifying the terminology used:

- Regulations are documents with the force of law which list general objectives and act as a framework for more detailed requirements. They may also address certain requirements for point of sale of products.
- Codes are documents connected with regulations, but which comprise more specific requirements and are valid for particular cases such as hospitals or schools. If they also offer practical solutions, they may be called codes of practice.
- Standards are documents referred to either in regulations or in codes and which put forward special techniques to quantify results. Typical examples of standards are test methods for various properties.
- Guides are documents that explain the concepts associated with particular issues, such as test methods or properties.

Organizations Issuing Codes in the USA:

Traditional Building Codes: *None of them issue codes any longer*

- Intern. Conf. Building Officials (ICBO):
  Uniform Building Code - UBC (West of Mississippi) - Last edition: 1997
- Building Officials & Code Administrators Intern. (BOCA):
  National Building Code - NBC (Northeast and Midwest) - Last edition: 1999
- Southern Bldg Code Congress Intern. (SBCCI):
  Standard Building Code - SBC (Southeast) - Last edition: 1999

New Building Codes:

- International Code Council (ICC; Members: ICBO, BOCA, SBCCI)
  International Building Code: IBC (Countrywide)
- National Fire Protection Association (NFPA)
  NFPA 5000 (Countrywide)

Fire Codes:

- Uniform Fire Code (UFC: issued by Western Fire Chiefs)
  (now combined with NFPA 1)
- International Fire Code (IFC: issued by ICC)
- NFPA 1: Fire Prevention Code (issued by NFPA)

Other National Fire Protection Association codes relevant to upholstery:

- NFPA 101 (Life Safety Code: Code for Safety to Life from Fire in Buildings and Structures)
- NFPA 130 (Standard for Fixed Guideway Transit and Passenger Rail Systems)
- NFPA 301 (Ships: Code for Safety to Life from Fire on Merchant Vessels)
- NFPA 501 (Standard on Manufactured Housing)

Other Code relevant to upholstery:

- International Residential Code (IRC): issued by ICC

Organizations Issuing Fire Standards Relevant to Upholstery:

ASTM: American Society for Testing and Materials

- Committee E05 on Fire Standards
- Committee D13 on Textiles
- Committee D20 on Plastics
- Committee F15 on Consumer Products
- Committee F25 on Ships
- Committee F33 on Detention Occupancies

CBHF: Bureau of Home Furnishings and Thermal Insulation of California
CPSC: Consumer Product Safety Commission
FAA: Federal Aviation Administration
FM: Factory Mutual (now FM Global)
IMO: International Maritime Organization
ISO: International Organization for Standardization
NFPA: National Fire Protection Association: Technical Committee on Fire Tests
UL: Underwriters Laboratories
ULC: Underwriters Laboratories of Canada

Building codes do not contain requirements for building contents, such as upholstered furniture or mattresses, but they do reference the companion documents, such as the fire code (or fire prevention code) and the life safety code.

International Fire Code (IFC):

* Requires newly introduced upholstered furniture and mattresses into unsprinklered health care facilities, nursing homes and detention occupancies to meet ASTM E 1537 (or ASTM E 1590 for mattresses) with a peak heat release rate of 250 kW and a maximum heat released of 40 MJ.

Life Safety Code (NFPA 101):

* Requires newly introduced upholstered furniture and mattresses into unsprinklered health care facilities and detention occupancies to meet ASTM E 1537 (or ASTM E 1590 for mattresses) with a peak heat release rate of 250 kW and a maximum heat released of 40 MJ.

Fire Prevention Code (NFPA 1):

* Requires all furnishings and contents to comply with the Life Safety Code.

Life Safety Code for Merchant Vessels (NFPA 301):

* Requires all upholstered furniture and mattresses in ships to meet ASTM E 1537 (or ASTM E 1590, for mattresses) with a peak heat release rate of 80 kW (or 100 kW for mattresses) and a maximum heat released of 25 MJ.

DEVELOPMENTS IN THE USA BETWEEN 1994 and 2002

Upholstered Furniture

Following a 1993 petition by the US National Association of State Fire Marshals (NASFM), on May 12, 1994, the U.S. Consumer Product Safety Commission (CPSC) voted (2-1) to direct staff to prepare an Advance Notice of Proposed Rulemaking (ANPR) dealing with upholstered furniture fires caused by small open flames from sources such as matches and cigarette lighters. An ANPR is the first step in agency rulemaking. Chairman Ann Brown and commissioner Thomas Moore voted in favor and commissioner Sheila Gall voted against. The ANPR was published on June 15, 1994, and a team was assigned to manage the project. This involved a number of steps, including: (a) a fire hazard assessment, (b) an economic analysis and (c) the development of a small open flame test method. Along the way, the CPSC team encountered several obstacles, including a variety of public comments, and the requirement imposed upon it to conduct a National Academy of Sciences (NAS) chemical risk study (on the fire retardants to be used for the fabrics), an Environmental Protection Agency (EPA) evaluation under the Toxic Substances Control Act (TSCA, including Significant New Use Rules, SNUR, and Significant New Use Notification, SNUN) and a National Institute for Occupational Safety and Health (NIOSH) worker health study). It also investigated what test methods were available and conducted a number of fire tests and correlations. Eventually, CPSC issued a briefing package on October 30, 2001, just after the NASFM felt the approach was both flawed and too slow, and withdrew their petition.

Technical considerations: There is agreement, fairly generally, that there is a severe fire hazard problem. CPSC states that there were, for example, 420 deaths, 1080 injuries and $120 million in property damage in the USA in 1998, and that many of the losses (including a third of the deaths) involve children. There is also general agreement that the most commonly used fire test for fabrics, that corresponding to apparel [9], which is also the fabric test in CA TB 117, is unsuitable. Thus, a fabric test would most likely be based on either: (a) some variation of the NFPA 701 test [32], perhaps even the abandoned small scale test from the 1989 edition [33], or (b) a variation of the BS 5852 test [10]. There is no general agreement, however, on what needs to be done for protection. For example, CPSC chose to develop a test for fabric ignition, and assume that preventing ignition would ensure a decrease in fire losses, without considering the effect of the padding on fire hazard. Other approaches consider that heat release is more critical, and, therefore, that the padding would have a critical role to play. Similarly, there is no general agreement on whether regulatory tests should be done on a true composite, on components in a composite format or simply on separate components.

CPSC chose to develop an automatized variation of BS 5852, where the seating area fabric is tested with a standard (non fire retarded) polyurethane foam. The test on the seating area fabric involves a BS 5852-Source 1 Gas Flame (35 mm butane flame, for 20 s) applied to the crevice, mounted on a BS 5852-type rig. The dust cover (Fabric) is tested on its own, when placed horizontally above a similar gas flame source. There is also a test on a barrier fabric, which is tested on the BS 5852-type rig, with the non FR foam, using a BS 5852 ignition source crib # 5. The fabric fails if the test specimen burns for more than 2 min, if it burns up completely or if it shows evidence of progressive flaming or smoldering. This means that the fire performance of the foam (or other padding) is not taken into account, and systems (fabrics, including backcoated fabrics or fabrics with barriers) that are known to perform well with the CA TB 133 system have been shown to fail the test.

CPSC conducted an interlaboratory evaluation of the test procedure, using nine labs, between 1999 and 2000. The study involved 5 fabrics, some of which were expected to perform well and some that were expected to perform poorly, including 2 fire retarded fabrics. The statistical analysis of the results, including an analysis of consistency, showed reasonable consistency both within laboratory and between laboratories, and the CPSC staff considered the interlaboratory test data sufficient to support the use of their test in a standard (an opinion not universally shared). The precision was assessed both in terms of continuous numerical results and in terms of the practical application of the test, as a pass/fail method. It is possible to calculate relative standard deviations (coefficients of variation) based on the data presented, and the information is shown in Table 2. The repeatability was calculated to be 44.9 (range 0-84, as continuous data) and 0.22 (range 0-0.41, as pass/fail data).

Table 2. Statistical Analysis of CPSC Fabric Ignition Test Data

Data as Continuous Numbers	**Avg**	S_r	S_R	**r**	**R**	**RSD r**	**RSD R**	**R/r**
B	9.46	13.06	13.06	36.6	36.6	138.05	138.05	1.00
E	17.59	8.02	8.82	22.5	24.7	45.59	50.14	1.10
D	48.72	29.16	34.86	81.6	97.6	59.85	71.55	1.20
I	85.94	30.01	35.69	84.0	99.9	34.92	41.53	1.19
F	120	0	0	0.0	0.0	0.00	0.00	-
Avg	56.3	16.1	18.5	44.9	51.8	55.7	60.3	1.1
Data as Pass/Fail	**Avg**	S_r	S_R	**r**	**R**	**RSD r**	**RSD R**	**R/r**
B	0.09	0.09	0.09	0.3	0.3	100.00	100.00	1.00
E	0.04	0.07	0.07	0.2	0.2	175.00	175.00	1.00
D	0.68	0.15	0.24	0.4	0.7	22.06	35.29	1.60
I	0.9	0.09	0.12	0.3	0.3	10.00	13.33	1.33
F	1	0	0	0.0	0.0	0.00	0.00	-
Avg	0.5	0.1	0.1	0.2	0.3	61.4	64.7	1.2

Once a test was developed, political issues came back to the surface. CPSC is permitted to defer to consensus standards organizations, if they issue a voluntary standard which is likely to be widely adopted and used. Thus, the CPSC test method had been presented to two standards developing organizations, but neither one rushed to embrace the method and to develop it as their own consensus standard: ASTM E05 Committee on Fire Standards (and its subcommittee E05.15, on furnishings and contents) and NFPA Technical Committee on Fire Tests. This left CPSC with the decision to either proceed with mandatory rulemaking (which would address the introduction of requirements at point of sale) or abandon the project. In January 2001, the USA presidency changed; a new person and a new party came to power. This resulted in the eventual resignation of the chair of the CPSC, Ann Brown in late 2001, and she was not replaced until Chairman Hal Stratton (Republican) was appointed in July 2002, to join Mary Sheila Gall (Republican, appointed November 1991) and Thomas Moore (Democrat, appointed October 1996). CPSC is not permitted to make decisions unless there are 3 commissioners (other than for an interim period of 6 months). However, CPSC conducted a public meeting June 18-19, 2002 to discuss options for addressing upholstered furniture flammability. The meeting was not a Commission hearing (since there were only 2 commissioners available). The focus of the discussions was the supporting information and draft upholstered furniture flammability standard developed by CPSC staff included in the October 30, 2001 briefing package entitled ``Upholstered Furniture Flammability: Regulatory Options," the progress of outside groups in addressing the same problem, and recent developments in related flammability issues. In particular, developments in California, by the California Bureau of Home Furnishings and Thermal Insulation (CBHF), were high on everyone's mind.

CBHF had issued CA TB 117 in California in 1977 [8], but it contained an unsuitable fire test for fabrics (the same test that all apparel fabrics in the USA have to meet [9]). Moreover, there was a growing belief that even the flaming ignition test for foams was no longer adequate. Thus, the realization grew at CBHF that the CA TB 117 standard needed to be updated, so that it would remain a viable alternative to the CPSC approach, whatever that approach would eventually be. The development of a new complete revision of CA TB 117 was publicly announced in October 1999. The technical concerns were similar to those being considered by CPSC with regard to the fabric test (whether regulatory tests should be done on a true composite, on components in a composite format or simply on separate components). However, there was always a certainty that tests would involve assessing both the fabric and the padding (as well as any interliners or barriers). CBHF announced that its goal was to enhance CA TB 117 so it reflects advances in science and product technology, and to use performance-based flammability specifications intended to protect consumers and to encourage effective, efficient and innovative compliance strategies. Again, politics interfered, as the change in state governor (also involving a party change) in early 1999 resulted in a new person eventually being appointed to head CBHF. However, this simply slowed the process down slightly, but did not derail it. In February 2002, a draft new edition of CA TB 117 was widely distributed, and comments were sought by July 1, 2002.

The new draft CA TB 117 included:

- An improved fire test for upholstery fabrics (tested over standard polyurethane foam)
- A new dust cover flame test
- A new horizontal small flame test for natural, synthetic and blended fibers, which requires no melting and dripping
- A new test for loose fillings.
- An improved foam fire test with a small seat mock-up, that replaces the vertical fire test from the traditional CA TB 117
- A more severe vertical foam test
- A composite seat and back mock-up test to confirm the performance of non-complying upholstery fabrics, combined with fillings previously qualified in component tests

In the new draft CA TB 117 standard, all upholstery fabrics are to be tested in the open-flame mock-up test over standard fire retarded polyurethane foam. If the upholstery fabric **fails** the open-flame test on standard fire-retarded polyurethane foam, the manufacturer must qualify the fabric by showing that it **passes** in a composite test over a CA TB117-complying filling component to be used in actual furniture. Thus, fabric manufacturers can use any fabric, provided they choose a system that has a barrier/interliner and a padding that are suitable to prevent a hazardous situation, even with a poorly performing fabric.

The seating area fabric is tested with a standard fire retarded polyurethane foam. The test on the seating area fabric involves a BS 5852-Source 1 Gas Flame (35 mm butane flame, for 20 s) applied to the crevice, mounted on a BS 5852-type rig. The pass/fail criterion is that the test specimen loses less than 4% of the weight of the combined fabric-foam system weight in the first 10 min of test, and with no progressive burning. The foam is tested in the same way (without fabric) and with the same pass/fail criterion. Similarly, composite systems are also tested the same way, also with the same criteria. Alternatively, the foam can still be tested in a vertical orientation, but with tougher criteria. The maximum char length is down from 8 in. to 4 in. (203 to 102 mm), the average char length is down from 6 in. To 3 in. (152 to 76 mm) and the maximum after-flame time is down from 10 to 8 s, with the average after-flame time down from 5 to 4 s. There is a separate test for a dust cover (fairly similar to that in the proposed CPSC test) and a horizontal test for all fiber fillings (battings and pads). The specimen is tested over a cotton sheet, horizontally, with a 35 mm butane gas flame applied on the lower surface for 20 s, where melt through of the fiber sample is a failure, and the sample must essentially "char in place". The concern with these materials is the melting away from the flame allowing direct ignition of the underlying substrate, which results in melt/wick into fabrics and foams, which then continue burning (a negative interaction). Loose fillings must be enclosed (as a cushion) in the actual fabric to be used, which must withstand the flame without penetration, and also lose less than 5% of the weight of the system.

A comparison between the proposed CPSC and CBHF/CA TB 117 standards:

- CPSC retains only heavily fire retarded fabrics, while the old CA TB 117 retains virtually all fabrics and the new draft CA TB 117 eliminates the poorest fire-performing fabrics only, while it retains mediocre fabrics, when used as part of a good fire performing system

- CA TB 117 eliminates bad and mediocre foams, while CPSC retains all foams, including very poor performers.

Alternative suggestions have been made by various sectors in the affected industries, which involve fabrics, fillings and furniture. It is worth looking at this from a slightly detached view, and it appears that gradually some consensus is being reached, and all the various proposals are growing closer together.

Mattresses

On June 12, 2000 CPSC announced that it had received correspondence from Whitney A. Davis, director of the Children's Coalition for Fire-Safe Mattresses, requesting that the Commission take various actions concerning mattress flammability. The Commission docketed as petitions requests for rules requiring: (1) An open flame standard similar to the full-scale test set forth in California Technical Bulletin 129; (2) an open flame standard similar to the component test set forth in British Standard 5852; (3) a warning label for flammable mattresses; and (4) a permanent mattress identification tag attached to the inner spring of the mattress. The petitioner focused primarily on the role polyurethane foam plays in mattress fires. He noted that the Commission's existing mattress flammability standard only addresses cigarette ignition; yet child play with open-flame sources causes nearly two-thirds of mattress fires. He argued that with polyurethane foam mattresses, fires have become increasingly more deadly than with cotton batting mattresses due to increased smoke generation, heat production and flame spread. With regard to labels, he noted that polyurethane foam manufacturers provide warnings to mattress manufacturers, but these warnings are not passed on to the consumer. With regard to an identification tag, the petitioner argued that such a tag would help to identify mattresses involved in fires because often only the inner spring unit remains after a mattress fire. The focus that was brought forward in the petitions was the issue that mattress fires are often deadly (600 deaths and 3,000 injuries a year in the USA from mattress fires), and that children are disproportionately represented among the fatalities. The recommendation focused on the need for a flaming ignition test for mattresses or, at least, mattress components.

At about the same time, the National Institute of Standards and Technology (NIST) issued NISTIR 6497 [34], as a result of a collaborative study between its Building and Fire Research Laboratory and the mattress industry (International Sleep Products Association, ISPA). A critical issue that was brought forward by the mattress industry, and studied in NISTIR 6497 was the importance of bed clothing (i.e. sheets, blankets, comforters, pillows, and so on) on the fire performance of mattresses and bedding. NISTIR 6497 tested 12 bed clothes combinations on an inert mattress, and in duplicate, and found that they ranged in peak rate of heat release between less than 40 kW to almost 200 kW. In fact, the average peak rate of heat release of the 12 combinations of bed clothing ranged between less than 60 kW to less than 170 kW. The most severe combination of bed clothing tested involved: two sheets, a mattress pad, a pillow, a blanket and a comforter. Another combination with the same numbers and type of bed clothing (but somewhat different composition) gave an average peak rate of heat release of less than 80 kW. NISTIR 6497 included a proposed standard test method, with a dual burner (or 2

T-shaped burners): one from the top and one from the side of the mattress. The test was placed on hold because the industry felt the need to develop a smaller scale test based on "mini-mats", for screening purposes, before issuing the full scale test. Until September 2002, no further test information has been issued by either NIST or ISPA.

On August 12, 2001, the Legislature in the State of California issued the Dutra bill (CA Assembly bill 603), named after the proponent, Assembly Member John Dutra. The bill requires all mattresses sold in the state to be fire retarded, and commissions CBHF to develop requirements by January 1, 2004. The requirements must be based either on ASTM E 1590 [29] (which is of course based on CA TB 129) or on another test developed by CBHF, with the clear understanding that it should not offer less protection (see entire bill as appendix 1). As a consequence, CBHF is now working on the development of a test method and requirements. New developments are to be expected soon.

In other environments there are also requirements for fire safety of mattresses. In detention occupancies, in general requirements are based on ASTM E 1590 and on a smoke chamber test (ASTM E 662 [35]) although many individual facilities require the use of the so-called "Michigan-Roll" test [36], which is very severe and was developed in the late 1970s. ASTM has issued a short description of it in a guide for test methods of interest to detention occupancies (ASTM F 1870 [37]). The US Navy requires a 100 kW rate of heat release test using a gas burner similar to that used in room-corner tests. The merchant navy (US Ships) uses NFPA 301, which contains ASTM E 1590, but with the CA TB 129 pass/fail criteria. In trains, the requirements are for separate tests for foam and for fabric: flame spread is assessed by ASTM D 3675 ([38], for foams) and by ASTM E 162 ([39], for fabrics) and smoke is assessed by ASTM E 662.

CONCLUSIONS

In conclusion, there has been a lot of potential regulatory activity on upholstery (both upholstered furniture and mattresses) in the 1990s, which should reach a conclusion in the early part of the first decade of the new millennium. As has been the case often in the past, activity at the federal level (Consumer Product Safety Commission) and at the state level in California (California Bureau of Home Furnishings and Thermal Insulation) is taking place side by side, while industry is participating actively in the debate.

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Appendix - AB 603, Dutra Bill (2001)

Home furnishings.

(1) The Home Furnishings and Thermal Insulation Act, which establishes the Bureau of Home Furnishings and Thermal Insulation, requires, among other matters, that all mattresses manufactured for sale in this state as well as specified furniture sold or offered for sale for use in a place of public accommodation in this state and specified reupholstered furniture be fire retardant. Under the act, the failure to comply with these provisions is a crime. This bill would require, on and after January 1, 2004, that all mattresses and box springs manufactured for sale in this state, except in specified establishments with automatic fire extinguishing systems, be resistant to an open flame under a standard specified by the bureau. The bill would require that this requirement be made applicable to other bedding if the bureau concludes that they contribute to mattress fires. The bill would make these regulations inoperative if a flame resistance standard for these products is adopted under federal law and would require the bureau to report to the Legislature summarizing its regulatory findings.

(2) Existing provisions of the act authorize the chief of the bureau to set license fees not exceeding specified amounts for licenses under the act. This bill would increase the maximum fees that could be set for an importer's license and a furniture and bedding manufacturer's license under the act.

(3) Because a violation of the bill's expanded fire protection standard applicable to mattresses would be a crime, this bill would impose a state-mandated local program by expanding the scope of an existing crime.

(4) The California Constitution requires the state to reimburse local agencies and school districts for certain costs mandated by the state. Statutory provisions establish procedures for making that reimbursement. This bill would provide that no reimbursement is required by this act for a specified reason."

"THE PEOPLE OF THE STATE OF CALIFORNIA DO ENACT AS FOLLOWS:

SECTION 1. The Legislature finds and declares all of the following:

(a) Mattresses are currently subject to federal and state flammability requirements. In the early 1970's, the United States Consumer Product Safety Commission (the CPSC) established the Federal Mattress Flammability Standard, which requires that mattresses resist ignition by smoldering cigarettes. In addition, the bureau and the mattress industry developed California Technical Bulletin 129 (TB-129), which establishes an open-flame standard for mattresses used in high-occupancy institutional settings such as prisons, dormitories, and hospitals. TB-129, in turn, provided the impetus for ASTM E 1590, a consensus standard promulgated by the American Society for Testing and Materials to establish product performance test methods for mattresses used in institutional settings.

(b) Beginning in the 1990's, national fire statistics indicated that the Federal Mattress Flammability Standard did not materially affect the incidence of residential mattress fires ignited by small open flames. More recent research conducted by the CPSC, the fire safety community, and private industry also shows that in many mattress fires involving open-flame ignitions, the bedding, which includes the pillow, comforter, and bedspread, is the first product to ignite, as opposed to the mattress itself.

(c) As a result, the mattress industry commissioned the National Institute of Standards and Technology (NIST) to conduct scientific research into the interaction between ignited bedding and a mattress. In 2000, NIST published the results of its initial research, which indicate that bedding and box springs, also known as the mattress foundation, have a material impact on the rate at which a mattress ignites and the resulting fire spreads, as well as the fire's intensity and the risk that it will spread beyond the bedroom. NIST's continuing research will use computer models to estimate the number of fire-related casualties that can be avoided if the fire size and spread rate for bedding and mattress-related fires are reduced to specified levels.

(d) Although Section 19161 of the Business and Professions Code, within the Home Furnishings and Thermal Insulation Act (Chapter 3 (commencing with Section 19000) of Division 8 of the Business and Professions Code), requires that all mattresses sold in this state be fire retardant, it does not authorize the bureau to set flammability standards for bedding or box springs. This act would authorize the bureau to better protect the public from open-flame ignited mattress fires by establishing flammability standards for not only mattresses, but also for box springs and bedding, as the bureau considers appropriate."

"SEC. 2. Section 19089.5 of the Business and Professions Code is amended to read:
19089.5. Any upholstered furniture or mattress that is made from or contains nonflame retardant cellular foam shall be labeled in a manner approved by the chief. On and after January 1, 2004, all bedding that is made from or contains nonflame retardant cellular foam shall also be labeled in a manner approved by the chief. Notwithstanding the provisions of this section, no label is required for a product that complies with the regulations required by Section 19161 or with applicable federal flammability regulations."

"SEC. 3. Section 19161 of the Business and Professions Code is amended to read:
19161. (a) All mattresses and box springs manufactured for sale in this state [CA] shall be fire retardant. The bureau shall adopt regulations no later than January 1, 2004, requiring that fire retardant mattresses and box springs meet a resistance to open-flame test that uses a pass or fail performance criteria based on a test method developed by the bureau [CBHF] or that is based on ASTM E 1590. If the bureau [CBHF] concludes that other bedding contributes to mattress fires, the regulations shall require the other bedding to be flame retardant under the resistance to open-flame test. If feasible, the bureau's regulations shall permit a manufacturer to comply with the resistance to open-flame test by testing a small scale version of its product. In developing these regulations, the bureau may contract, cooperate, or otherwise share resources with other

government agencies, private organizations, or independent contractors that it considers appropriate for purposes of reviewing test criteria and methods, equipment specifications, and other relevant subjects. These regulations shall become inoperative upon the effective date of any federal law or regulation establishing an open-flame resistance standard for these products. The bureau shall submit a report to the Legislature on or before January 1, 2004, summarizing its regulatory findings.

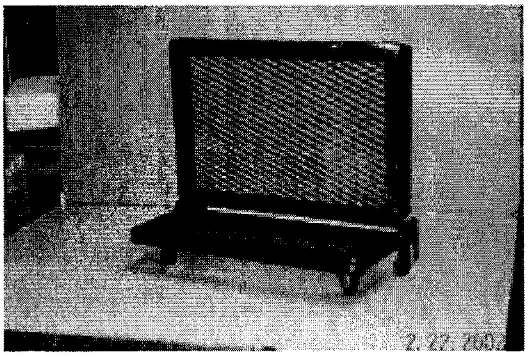
(b) Requirements for flame resistant mattresses, box springs, or other bedding products shall not apply to any hotel, motel, bed and breakfast, inn, or similar transient lodging establishment that has an automatic fire extinguishing system that conforms to the specifications established in Section 904.1 of Title 24 of the California Code of Regulations.

(c) All seating furniture sold or offered for sale by an importer, manufacturer, or wholesaler for use in this state, including any seating furniture sold to or offered for sale for use in a hotel, motel, or other place of public accommodation in this state, and reupholstered furniture to which filling materials are added, shall be fire retardant and shall be labeled in a manner specified by the bureau.

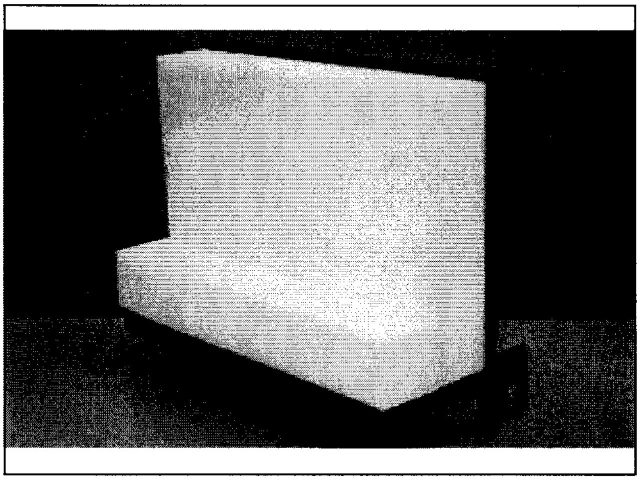
(d) "Fire retardant," as used in this section, means a product that meets the regulations adopted by the bureau. This does not include furniture used exclusively for the purpose of physical fitness and exercise.

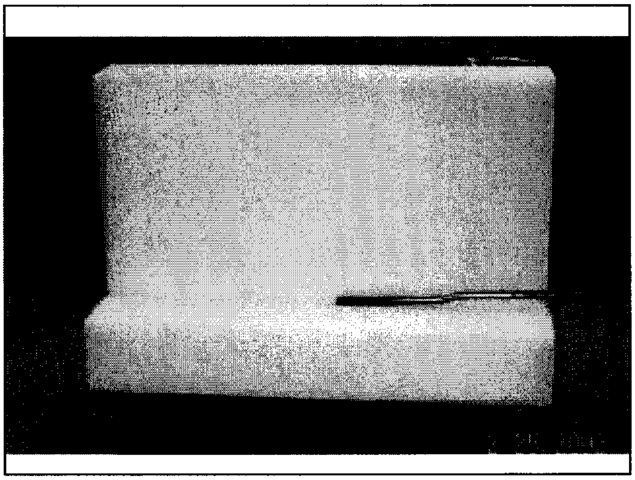
Draft CA TB 117

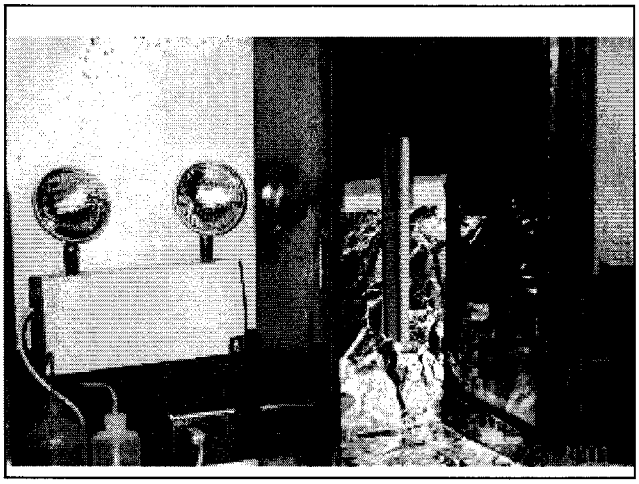
- Frame for Composite Test (2)
- Frame and Foam (with Igniter, 3-4)
- Alternate Test for Foam (5-7)
- Composite Test, Twice (8-9, 10-13)
- Fiber Test, Twice (14-16, 17-18)
- Loose Materials Test (19)

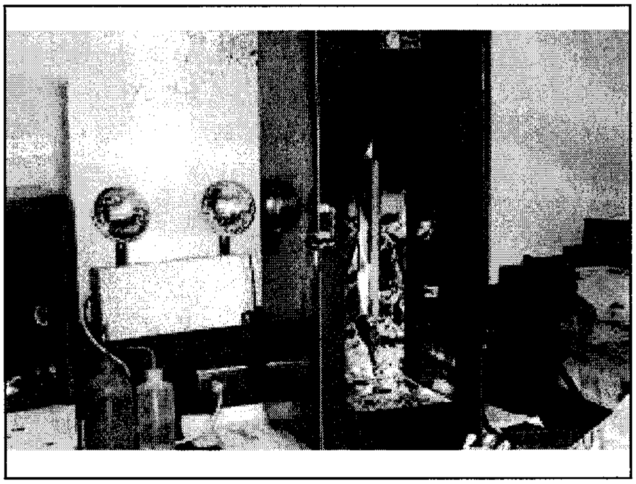


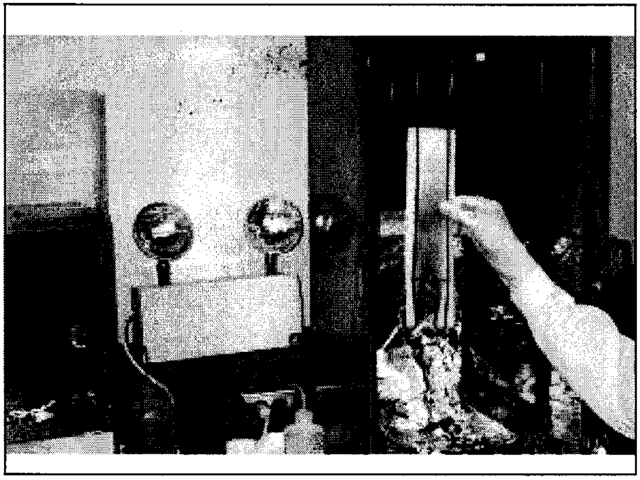
Frame for Proposed CA TB 117 Tests

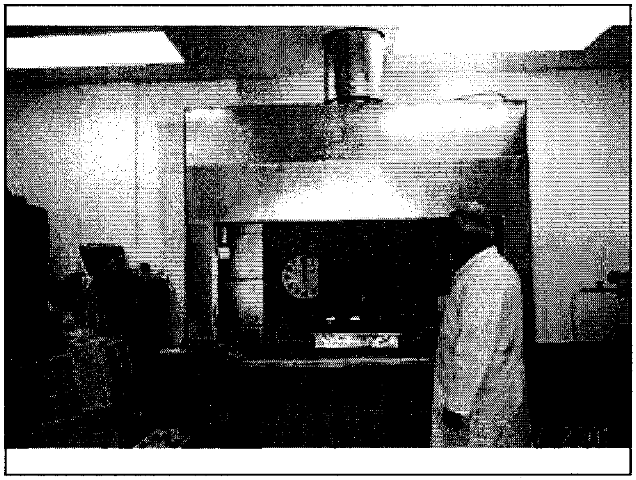


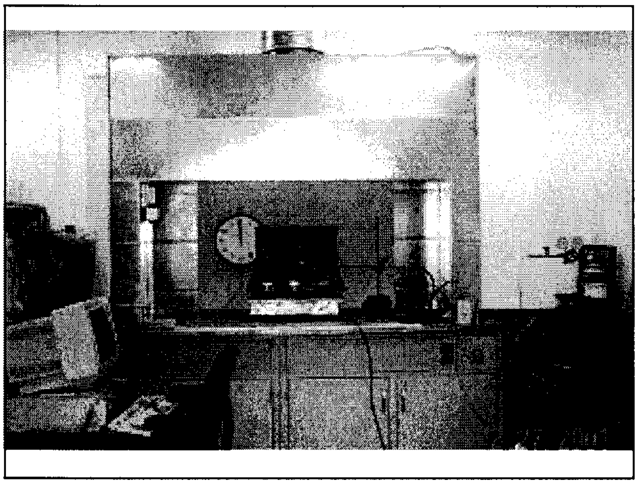


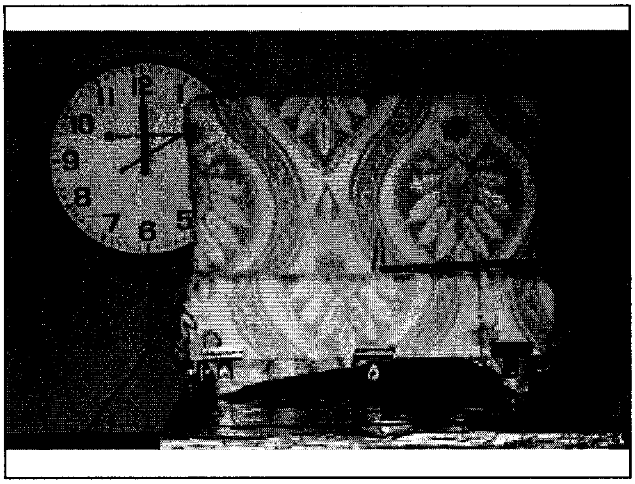


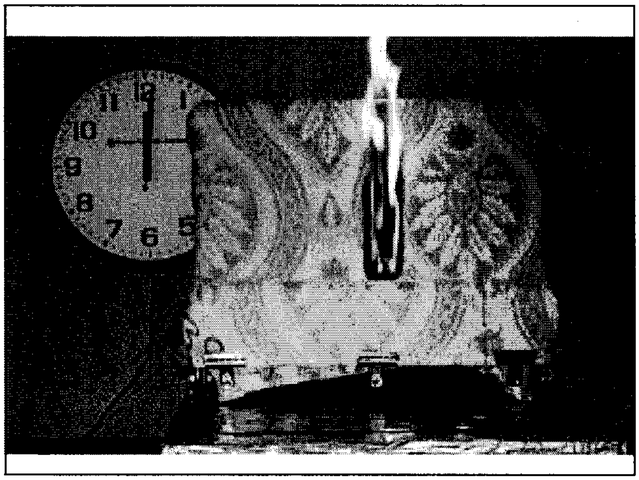


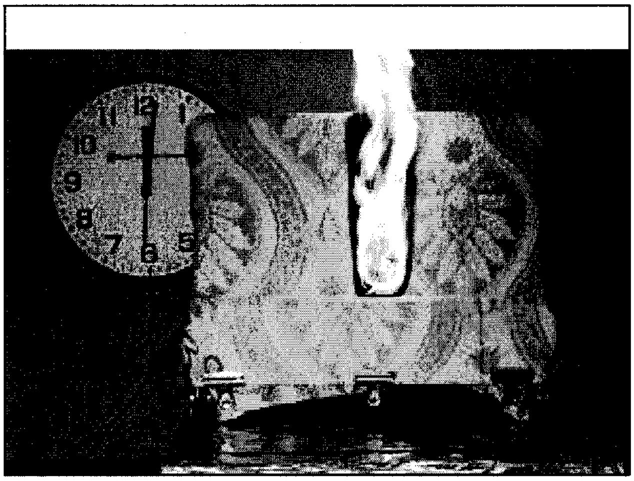


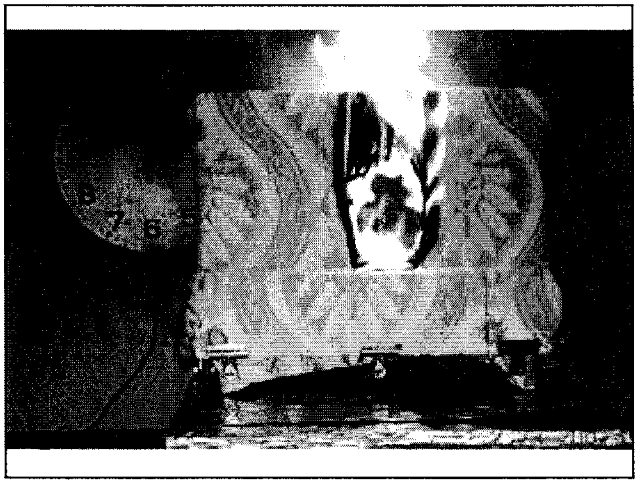


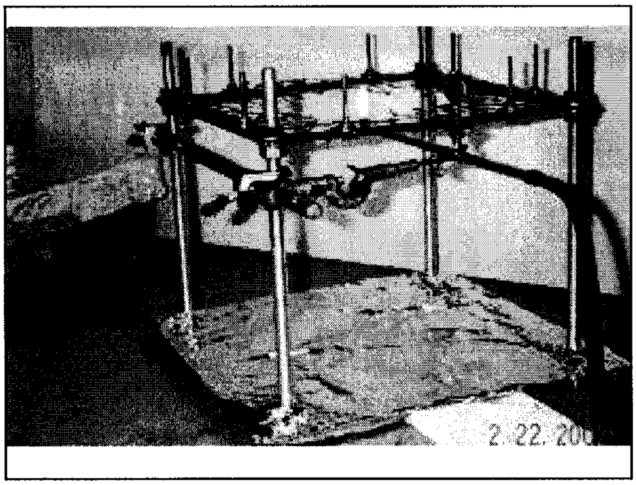








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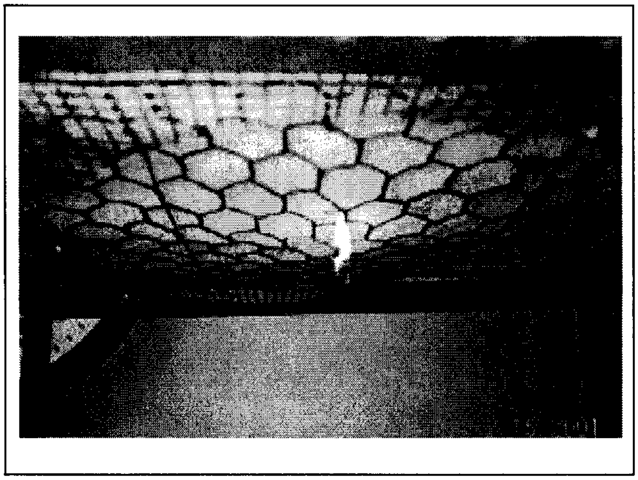

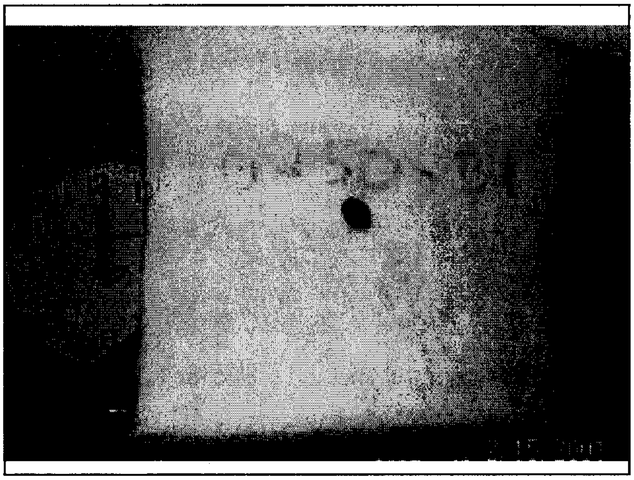

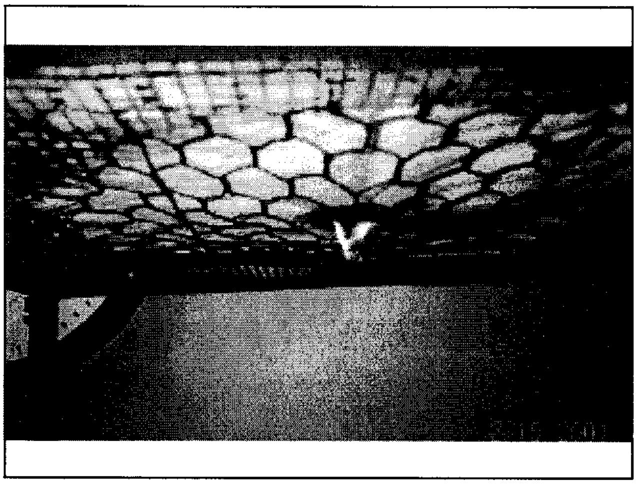

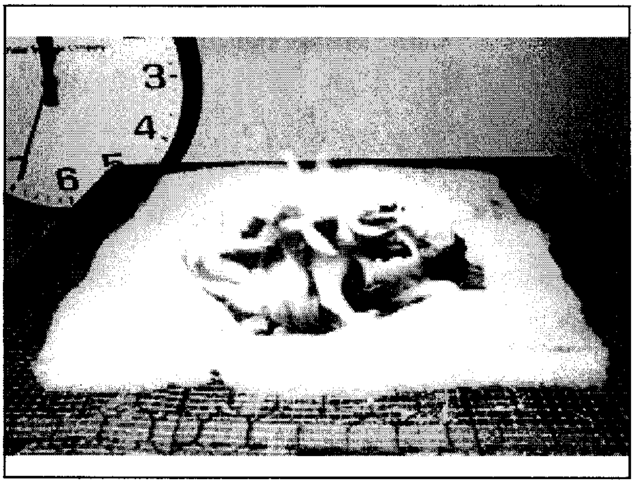

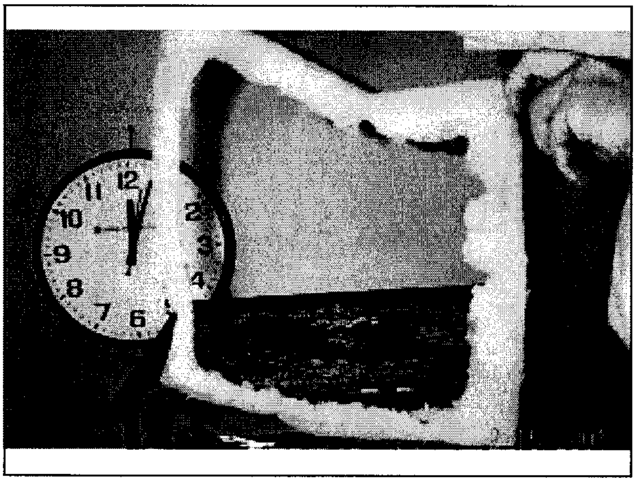

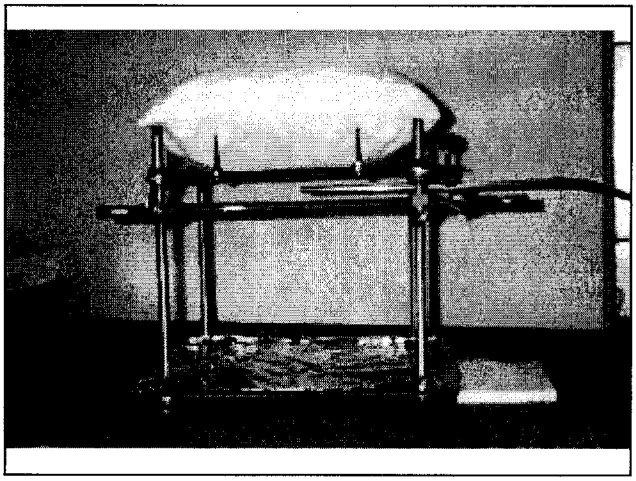

GBH Attachment 26

AB59-COMM-7-26

SURFACE PARAMETERS FROM SMALL SCALE EXPERIMENTS USED FOR MEASURING HCl TRANSPORT AND DECAY IN FIRE ATMOSPHERES*

F.M. Galloway**, M.M. Hirschler**,*** and G.F. Smith**
The Vinyl Institute
A Division of the Society of the Plastics Industry, Inc.

"Surface parameters from small scale experiments used for measuring HCl transport and decay in fire atmospheres", F.M. Galloway, M.M. Hirschler and G.F. Smith, Fire and Materials, 15, 181-89 (1992).

ABSTRACT

The decay of HCl was investigated in two small scale scenarios: pure HCl injection into a 3 L chamber and combustion of plasticised PVC in a 200 L chamber. The effects investigated included: (a) humidity, (b) temperature, (c) concentration of HCl and (d) wall material. Surface materials investigated were: PMMA, ceiling tile (front and back), Marinite , painted PMMA, unpainted gypsum board and cement. In view of the very rapid HCl decay in most of those surfaces, the effects were often studied with small "chips" of materials in a PMMA chamber, with fresh walls for each experiment. Experiments were also done to investigate the effect of surface ageing, with painted gypsum board, painted PMMA and unpainted gypsum board walls.

HCl decay is very fast in cement or unpainted gypsum board surfaces (almost impossible to saturate with HCl) and almost as fast on ceiling tile and Marinite . Saturation of HCl can be reached on painted gypsum board and painted PMMA surfaces, albeit at different rates.

An earlier empirical model, from mathematical fitting had been followed by a new HCl generation, transport and decay model, with a sound physical basis. This model allowed calculations of parameters for all the surfaces used.

Much work has already been done in devising and writing a zone model for use together with fire hazard models (in particular the NIST model FAST) to calculate correct HCl concentrations in various fire scenarios. This work, which concludes the investigation of these two static fire scenarios for the surfaces analysed, represents one more step in the pursuit of that goal.

[*] A version of this paper was presented at the Interflam' 90 conference, in Canterbury, UK, September 3-6, 1990.

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INTRODUCTION

Much work has now shown that hydrogen chloride (HCl) does not remain for long in a fire atmosphere [1-16]. The reactivity of HCl is such that it "decays". In other words, the atmospheric concentration of HCl decreases, at a rate dependent on external conditions. The decay of HCl takes place at most gas-solid interfaces, by adsorption onto the solid material followed by a mixture of reaction and diffusion. This work did not result in models to predict HCl concentrations for transport and decay processes, however.

The process of HCl decay is important for fire safety because HCl is a major product resulting from the combustion of a widely used synthetic material, poly(vinyl chloride) (PVC) [17-18] which is often present in fires because of its wide range of applications. In fact, the results of two studies, in which fire fighters entered buildings on fire equipped with gas sampling probes, found HCl in one third of the incidents [19-20]. Interestingly, the highest HCl concentration measured was only 280 ppm [19-21]. Therefore, studies of fire hazard need to take into account HCl decay in order to avoid overestimating the fire hazard of materials containing PVC.

A program has been in progress recently which has involved many experimental series of studies, to investigate the lifetime of HCl in a fire atmosphere, accompanied by appropriate modelling work [22-30]. These studies have shown that HCl reacts very rapidly with most common construction surfaces (e.g. cement block, ceiling tile, gypsum board). Peak atmospheric HCl concentrations found in fires are always much lower than would have been predicted from the chlorine content of the burning material. Furthermore, the peak concentration soon decreases and HCl disappears completely from the atmosphere. The model developed, which accounts for the generation, transport and decay of HCl in a fire [25,31], has been validated with a series of large- and small-scale experiments using HCl and different kinds of PVC [26-30].

The present work extends the model by discussing two small scale static scenarios and completes their investigation by analysing the effect of repeated exposures of the same surface.

EXPERIMENTAL

Experiments in 3 L chamber

In all the experiments a box was built, with a total internal volume of 3 L, the walls of which were made of various construction materials, viz. painted and unpainted gypsum board (PGB, UPGB), painted and unpainted poly(methyl methacrylate) (PPMMA, PMMA), ceiling tile (CT), cement block (CB) and Marinite^R (MAR). The paint used was a Satin Latex Wall Paint matte flat, and two thick layers were applied.

The box was held together snugly within a stainless steel frame, and surrounded by heating tape to achieve the desired temperature (ranging from 396-495 K). Three holes were made on the top, for the insertion of a mechanical stirrer and for the inlet and outlet of purge gas (dry air). This stirrer ensured reasonable uniformity of HCl gas concentration in the box. After the purge was completed (at least several hours purge), the two apertures were closed off and HCl was injected (ranging from 1-10 cm^3) with a syringe through a septum covering one of them. The desired level of humidity (ranging from 0-5 vol%) was obtained by drawing the purge gas through a water bath at the required temperature before reaching the box.

The HCl remaining airborne was determined by drawing (10-20) 50 cm^3 samples of box atmosphere with a disposable syringe, attached to a Luer-Lok^R and a 15 cm stainless steel needle. The gas samples were dissolved in 2 cm^3 of a standard 10^{-4} M HCl solution and the amount of HCl contained in the solution was determined directly, using a calibrated Orion model 94-17B chloride ion selective electrode with a double junction reference electrode and an Orion 701 digital voltmeter.

A new wall surface was normally used for each experiment, except for those cases where repeat exposures of a surface were to be investigated (all at 0% humidity). In some cases the same surface was used for a succession of experiments, in order to investigate whether its activity changed. These were called repeat exposures, and were carried out with painted PMMA, painted gypsum board and unpainted gypsum board. Details of these exposures are:

Painted PMMA:	9 times 7 cm^3 HCl, @ 298 K
Painted gypsum board:	9 times 3 cm^3 HCl, + once 7 cm^3, HCl, all @ 353 K
Unpainted gypsum board :	8 times 7 cm^3 HCl + twice 10 cm^3 HCl + 400 cm^3 HCl added between experiments and the box purged + 99 g HCl added between experiments and the box not purged, all @ 373 K

In most of the experiments with very active surfaces (MAR, UPGB, CT and CB), it was impossible to obtain adequate kinetic results in the minimum time frame required to obtain the first two measurements, viz. 30 s, if all six walls were constructed of the corresponding surface. Therefore, small "chips" of the appropriate surfaces were placed on the floor of chambers lined with PMMA walls and kept at fairly high temperatures.

Experiments in 200 L chamber

These experiments have been described elsewhere [22-24] and need not be discussed in detail here. A cable, coated with plasticised PVC, was decomposed electrically in a 171 L PMMA chamber. The electrical current was sufficient to destroy the PVC completely. The chamber was lined, additionally, with surfaces of painted gypsum board, ceiling tile, cement block, and Marinite^R, viz. the same materials as used in the 3 L experiments. The techniques used for measuring atmospheric HCl were: soda lime tubes (already described elsewhere [22] and syringes (described above). Data developed earlier showed that the HCl concentration was adequately characterised by the measurements made.

DESCRIPTION OF MODEL

Fire models are, in general, of two types: zone or field models. Simplistically, a zone model divides the compartments into "zones" of similar temperatures and gas concentrations whereas a field model calculates these values for each volume element. This results in the zone model requiring less computational power and being able to solve, approximately, more complex scenarios.

The basic zone model used in this work for the decay of HCl during the transport of fire gases has been described elsewhere before [25, 29-31]. To recap briefly, the model assumes that a fire creates uniformly mixed "zones" within a given compartment. This is associated with flows between connected compartments, in a multi-compartment scenario, resulting from the fire itself. The model was developed with the objective of incorporating it into an overall zone model for fire and smoke transport, such as the NIST fire and smoke transport model F.A.S.T. [33].

The model describes three processes: HCl transport within the gas phase, its adsorption onto surfaces and its reaction with, or disappearance into, surfaces. In order to do so, the model needs a large number of inputs. These inputs consist of: volumes of all zones, temperatures of gases (or smoke) and surfaces, humidity (water content of gaseous layer or smoke), mass transfer coefficients between gas and surfaces, and, in the case of multi-compartment applications, mass exchange rates between compartments.

In addition to the processes described in the model, the modelling equations require an HCl generation term. This HCl generation term is non zero in those compartments where HCl is being produced by some process, e.g., injection or burning PVC, and zero in other compartments.

The terms used in the equations for this work have been discussed before [29-32] and it would be redundant to repeat them in detail.

Two sets of applications are considered in this paper, i.e., static experiments carried out in 3 L and 200 L containers. In the 200 L volume cases, the HCl is generated from the electrical overload of PVC-coated electrical cables. The HCl generation from this same burning PVC wire jacket and insulation has already been, first, modelled as a generic case [25] and then, by forcibly preventing decay, as a function of wire temperature and of percentage of total PVC combusted [32]. The temporary prevention of HCl decay was achieved by intense heating of non sorptive glass walls.

In the 3 L volume cases, measured amounts of HCl gas were injected rapidly into the container at the beginning (time zero) of the experiment. The HCl concentration was then followed by periodic measurements until no more airborne HCl was detected in the chamber. In the model, HCl injection is handled as an initial condition for HCl concentration in the gas. This results in an HCl generation term which is zero for the entire experimental time, except for the initial instant.

In previous work [31], values for the surface specific parameters which model the HCl decay on a surface were reported for five different kinds of surfaces, i.e. PMMA, painted gypsum board (PGB), MAR, CB and CT. Since then, the model has been revised and extended to cover a broader range of temperature and humidity conditions [29, 30]. The new form for the gas/surface partition coefficient (K) is now equation (I) (representing a reversible process):

$$K = b1 * EXP[1500 / T] / \{1 + b2 * EXP[1500 / T] * [HCl]\} *$$

$$\{1 + b3 * [H2O]{**}b4\} / \{[H2O]s - [H2O]\}{**}b5 \quad (I)$$

The disappearance rate of HCl from or into the surface (kr) is now given by equation (II):

$$kr = b6 * EXP[-1786 / (1.99 * T)] \qquad (II)$$

In these equations, T is the gas temperature (in K), [HCl] is the bulk gas phase HCl concentration, [H2O] and [H2O]s are the gas concentrations of water at a particular period and at saturation respectively, and b1-b6 are surface parameters.

The original expression of the generation function was purely empirical [28]. In the work where the decay of HCl was forcibly prevented (sometimes described as "generation without decay" [32]), the generation function for HCl from burning PVC wire insulation was formulated on more theoretical grounds, as described above. The first series of papers describing surface parameters for the revised model had only reported results for PGB surfaces [29-30]. In these cases, the surface parameters were determined by fitting the model to full scale experiments in room/corridor/room and room/corridor scenarios. Surface parameters using the revised model for the other surfaces have not as yet been reported in the literature.

REAPPLICATION OF (REVISED) MODEL TO 3 L AND 200 L EXPERIMENTS

In this work, the revised HCl decay model was first fit to the experiments containing only PMMA, since PMMA forms part of the exposed surface in many of the experiments involving the other surfaces. The non-linear parameter estimation technique has been described previously [25]. Briefly, the surface parameters b1-b6 for PMMA (equations (I) and (II)) were picked to minimise the sum of the squares of the differences between predicted and measured values for both the 200 L and the 3 L experiments, for those cases in which PMMA was the only surface involved. A well-known optimisation strategy [Marquardt, 34] was used to vary the parameters. Once this was accomplished, the parameters obtained for PMMA were used to determine the new surface parameters for CT, CB and MAR from the experiments where each one of these surfaces formed a portion of the total exposed surface, the remaining being PMMA.

The new parameters for PGB, which had already been determined from the full scale room/corridor/room experiments [31], were used in the model to simulate the 3L and 200 L experiments involving PGB surfaces. No adjustment of the PGB parameters was permitted. In spite of this, the agreement between data and model predictions was good. The results are given in Table 1.

The root mean square correlation coefficients, RSQ200 and RSQ3, for the 200 L and 3 L data respectively, for PGB are considered good since there was no parameter adjustment for either the HCl generation function or the surface decay parameters. The overall fit for PMMA is considered to be very good.

In modelling the 3 L experiments, it was found to be important to account for the samples of chamber atmosphere (50 mL volume) that were withdrawn to measure the HCl concentration, in the experimental procedure. Typically, between 10 and 20 samples were withdrawn per experiment, which represents 17-33% of the total chamber volume. Since the box was not 100% air tight, each sample withdrawn, would be replaced, in a short time, by an equal volume of room air, carrying with it the ambient humidity (ca. 50 % relative humidity). The resulting modification of humidity in the experimental box, and dilution effect on the remaining HCl, were found to be important effects, particularly when the atmosphere was initially totally dry.

Data for the other surfaces were somewhat limited, so that, in many cases, the humidity effect, represented by b3, b4 and b5, could not be accurately evaluated, as denoted in Table 1. Because of the very high activity of these surfaces for HCl decay, even experiments where one full wall of the 3 L chamber was constructed of the very sorptive material, were too fast to permit experimental kinetic details to be calculated. Thus, involving them typically employed a very small area, or "chip", of the active surface with the remainder being PMMA. The parameters given for these surfaces in Table 1 are conservative estimates, in the sense that the actual HCl decay on these surfaces is at least as fast as predicted by the model when using these values. The rates of decay were calculated by fitting the slowest possible decay rate consistent with the experimental measurements.

Figure 1 shows experimental and calculated results of 200 L chamber burns with four surfaces, viz. CB, CT, PGB and PMMA. They illustrate the good fit achieved by the model and the difference in reactivity of the different surfaces. Figure 2 shows the range of reactivity between the various surfaces investigated in the 3 L box, from PMMA to MAR or CB. Figures 3 and 4 compare model predictions with experimental results for two of the 3 L box tests, one with painted PMMA and one with PGB surfaces respectively. These figures show, again, the good fit provided by the model. The curves addressing Model, 0 from these figures need to be compared here with the corresponding data. The other pair of curves and data in the figure, corresponding to ageing experiments, will be discussed later.

APPLICATION OF MODEL TO AGEING EXPERIMENTS

The surface parameters for the HCl decay model given in Table 1 all represent surfaces that have not experienced previous exposure to HCl. For some materials, repeated exposure of a surface to HCl results in a decreased activity of that surface for HCl decay, as has previously been reported [26]. This is illustrated in Figures 3 and 4, where the same PPMMA and PGB surfaces are shown, after having been exposed to a large dose of HCl. The curves referred to in this section are those described as Data (or Model), 1.336 x 10^-6 (Figure 3) and 9.8 x 10^-7 (Figure 4). To account for this reduction in surface activity in the model, it seems reasonable, at least as a first approximation, to expect that either the gas-surface HCl partition coefficient, K (in equation (1)), or the HCl rate of disappearance, kr (in equation (2)), would be affected by the repeated exposure. A multiplying factor of the form shown in equation (III),

[1 - (D / Dmax) ** p] (III)

was tried. In this equation, D is the known amount of HCl that has been previously absorbed by the surface, in kg mol HCl/m^2 of surface; Dmax is a fitted parameter, that represents a measure of the maximum amount of HCl a surface can absorb before its activity for HCl effectively goes to zero; and p is an exponent that allows for non-linearity in the loss of activity with increasing total exposure.

For each of the three surfaces subjected to repeated exposures of HCl, viz. PPMMA, PGB and UPGB, equation (III) was tried as a factor for K and kr, in turn, and the parameters Dmax and p were determined by a least squares fit of model predictions to the data. The results are given in Table 2.

In Table 2. it can be seen that Dmax for PGB is almost three times larger than Dmax for PPMMA. There is a strong non-linear effect of HCl exposure for both surfaces. On the other hand, Dmax for UPGB is about three orders of magnitude greater than Dmax for the other 2 surfaces. In fact, however, the value of Dmax for UPGB has no statistical significance, since it represents simply a conservative lower boundary. Any other value of Dmax, higher than the one in Table 2, would result in similar accuracy. The amount of HCl injected into this box, when the walls were UPGB, was equivalent to an HCl absorption at least as high as 10^-3 g mol HCl/cm^2 (corresponding to 100 times an initial HCl concentration of 100,000 ppm in a 3 L box) i.e. it was equivalent to filling the 3 L box with pure HCl 10 times). In all these measurements made in the box with UPGB walls the surface behaved like an unexposed surface.

Table 2. also indicates that for PGB and UPGB it is K, in the model, which seems to lose activity, while for PPMMA it is kr which loses activity. When fits for equation (III) were attempted, they were done first assuming that it would multiply K.

On doing this fit for PPMMA, by letting Dmax and p vary until the best fit was achieved, the maximum correlation coefficient obtained was only 0.67. It was then decided to try the same multiplicative factor on kr and a much better fit was obtained (RSQ = 0.90). Figure 5 illustrates the differences in fit for painted PMMA. The experiments used are the same as those in Figure 3, but in this case the time frame used is longer. Figure 5 contains the experimental data for the first exposure to HCl (Data; Dose = 0), and for the final repeat exposure (Data; Dose = 1.33 x 10^-6). It also contains the fitted curves resulting from applying the multiplying factor in equation (III) to the disappearance rate (kr) (modify kr) and to the partition coefficient (modify K). However, Figure 5 does not contain the fitted curve for the unexposed surface.

For PGB, however, when equation (III) multiplied K, the maximum correlation coefficient was 0.91, while the maximum correlation coefficient was only 0.52 when it multiplied kr. These results are illustrated in Figure 6 for PGB, showing that the differences in fit are qualitative as well as quantitative. The experiments in Figure 6 are the same as those in Figure 4, and the differences between the Figures is the same as that between Figures 3 and 5.

Figure 5 shows experimental data for the fraction of HCl remaining in the atmosphere with an unexposed PPMMA surface and with the same surface after it has been exposed to 1.336 E-6 gmol HCl/cm^2. It also shows the fitted curves for the surface exposed to that amount of HCl, assuming that equation (III) multiplies either K or kr. Figure 6 shows similar data for HCl decay at an unexposed PGB surface, and at the same surface after a total absorption of 9.8 E-7 gmol HCl/cm^2. It also shows the model predictions for a surface previously exposed to 9.8 E-7 gmol/cm^2 for modification, by equation (III), of K and kr. It is apparent that the modification of kr leads to a much better prediction of HCl decay data on PPMMA. On the other hand, the opposite behaviour is found for PGB: the modification of K is the appropriate solution.

The major effect of previous HCl exposure for PGB seems to be in a decrease of the capability of the surface to hold as much HCl in equilibrium with a given concentration of HCl in the gas phase. For PPMMA the initial partitioning of HCl between gas and surface is hardly affected by previous exposure to HCl, whereas the rate of decay on the surface appears to be greatly reduced. The prediction of the model, where kr has been modified by (III), gives a much better match to the data than the case where K has been modified. The model used for Figure 4 is the one giving the best fit in Figure 6, i.e. that where equation (III) multiplies K. The fitted curve in Figure 3 is the one that gives the best fit in Figure 5, i.e. the multiplicative factor is applied to kr. When considering the reasons for the differences in the effects on PGB and PPMMA it is worth remembering that there may be an added temperature effect, since the PGB was exposed at a temperature 55 K higher than the PPMMA.

HALF-LIFE RESULTS

Figure 7 shows model predictions for the half life of HCl concentration in the atmosphere of a 3 L box in contact with the various surfaces where the exposure parameters are given in Table 2. For comparison purposes, the single value for unexposed unpainted PMMA is also included in the figure. Figure 7 expresses the accumulated HCl the surface has been exposed to as gmol HCl/cm^2. All results are for surfaces starting with an HCl concentration in equilibrium with the gas.

The effect of this is that the rapid decay, as the initially bare surface loads up with HCl from the gas until equilibrium is reached, is eliminated from the half life calculations. This is correct, since that initial HCl decay is essentially a mass transfer rate controlled phenomena [35].

For unexposed surfaces, it can be seen that the decay is most rapid on UPGB, followed closely by PGB. Painted PMMA is almost a factor of 10 longer in half life, and regular PMMA is 2-3 times longer still. The non-linear effect of repeated exposures to HCl is clearly shown for both PGB and PPMMA. Also clearly shown is the fact that repeated exposure to HCl has no effect on HCl decay on UPGB, at least up to 1 E-6 gmol HCl/cm^2 (which is equivalent to 10,000 ppm of HCl initially in the gas phase in a 3 L box being absorbed on the walls). In fact, UPGB shows essentially no effect up to at least three orders of magnitude greater exposure to HCl than that in Figure 7.

DISCUSSION OF REPEATED EXPOSURE RESULTS

It is clear from the results that paint reduces the activity of a gypsum board surface, which is, by itself, a very active surface. At the same time, paint increases the activity of PMMA, which, by itself, is an inactive surface. Therefore, the activity of paint unexposed to HCl is clearly intermediate between those of gypsum board and PMMA. It is also apparent that the activity of paint is very sensitive to HCl exposure, since gypsum board by itself shows no effect resulting from

HCl exposure up to very high doses, whereas PGB is quite sensitive to repeated HCl exposure. In these experiments, it was found that the surface parameters for PMMA which determine K also gave an excellent fit to the data for PPMMA. On the other hand, the kr determined by the data for PPMMA is very much greater than kr for PMMA. This indicates that kr for paint itself is much greater than kr for PMMA. However, kr for the paint is greatly affected by HCl exposure, perhaps because the paint layer is thin. This is indicated as a decrease in kr for PPMMA with repeated HCl exposure, as shown in Figure 5.

Examination of the results in Table 1. reveals the following: K for paint is very much smaller than R for UPGB, while K for PGB lies somewhere between the other two. This implies that the paint layer is somewhat permeable to HCl, giving a surface K that is some kind of average of the individual surface partition coefficients. Loss of reactivity in the paint itself would not have as great an effect on the overall kr as it did for PPMMA, because kr for gypsum board dominates even when the paint is unexposed.

From Figure 6, it is apparent that, in contrast to PMMA, K was reduced for PGB with repeated HCl exposures. It is possible that this was a combined effect of HCl and temperature on the paint, causing it to lose active surface sites for HCl adsorption with additional exposures. As noted in Table 2, the PGB repeated exposure experiments were conducted at 353 K, whereas the PPMMA experiments were at 298 K. It is impossible, at this time, to do more than speculate on the effects of the increased temperature.

CONCLUSIONS

In view of the interest in the toxicity of smoke in fire and of the frequent presence of HCl in fire atmospheres, it is very important to understand the lifetime of HCl in different scenarios. Several series of experiments have been carried out to measure the rate of decay of HCl in fire atmospheres. The two chambers used had volumes of 3 L and of 200 L.

A model, described earlier for transport and decay of HCl, in a fire atmosphere, was used to develop surface parameters for a number of common construction surfaces: unpainted gypsum board, ceiling tile, cement block, Marinite^R, PMMA and painted PMMA, based on parameters for painted gypsum board. The model was applied to predict HCl concentrations in experiments involving either burning PVC or pure HCl. No changes were introduced into the model.

The predicted HCl concentrations were compared with those of actual experiments. The model results fit the experimental results well. Most of these surfaces (CT, CB, MAR, UPGB) had such a rapid rate of decay that conservative lower boundary rates only could be calculated.

Half lives of HCl on he various surfaces were also calculated. They varied over 3 orders of magnitude between PMMA and unpainted gypsum board.

Experiments were made to investigate the effect of repeat exposure of three surfaces on HCl decay. Repeat exposure has no effect on the ability of unpainted gypsum board to react with HCl. It decreases the rate of decay of HCl within a painted PMMA surface and it decreases the partition coefficient between surface and gas for painted gypsum board. In both cases, however, HCl still decays.

The concentrations of other combustion gases, such as carbon monoxide, decrease only by physical entrainment and dilution processes. Thus, the relative toxic importance of HCl, as compared to carbon monoxide, decreases as the smoke layer moves away from the fire zone.

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Table 1. Surface Parameters for Revised HCl Decay Model

Surface	b1	b2	b3	b4	b5	b6	RSQ200	RSQ3
Painted Gypsum	0.63	0.7×10^7	0.63×10^5	1.021	0.431	3.52	84	72
PMMA	0.0096	0.5×10^3	0.70×10^4	0.99	0.431	1.23	93	73
Ceiling Tile	0.40	0.2×10^4	10*	1*	0.431*	7.36	83	65
Cement Block	1.8	0.2×10^6	10*	1*	0.431*	2.98	80	65
Marinite(R)	1.9	0.5×10^4	10*	1*	0.431*	1.80	72	65
Unpainted Gypsum	1.5	0.2×10^6	10*	1*	0.431*	10.00	ND	99**
Painted PMMA	0.0096	0.5×10^3	0.70×10^4	1.0	0.431	5.28	ND	98**

* insufficient data to accurately determine humidity effect
** parameters for these surfaces estimated; minimum values only
ND: 200 L data were not determined

Table 2. Surface Parameters Describing Effects of Repeated HCl Exposure

Surface	Temperature K	Humidity %	Dmax	p g mol/cm^2	RSQ	Note
PGB	353	0	8.1×10^{-6}	0.26	0.91	(a)
PPMMA	298	0	3.0×10^{-6}	0.084	0.90	(b)
UPGB	373	0	5.1×10^{-3}	1	0.88	(c)

Notes: (a) PGB: factor (III) multiplies K; (b) PPMMA: factor (III) multiplies kr; (c) UPGB: factor (III) multiplies K, exponent b is at least this large; fit for Dmax was not significant

Nomenclature

[HCl]: gas concentration of HCl, expressed as total mass of HCl, in kg.
K: partition, or gas/wall equilibrium, coefficient for HCl, in 1/m.
kr: decay rate coefficient of HCl inside the surface, in 1/min.
$[H_2O]$: concentration of water, in kg/m^3.
$[H_2O]_s$: saturation concentration of water, also in kg/m^3.
b1: fitted surface parameter representing the temperature dependency, in m.
b2: fitted surface parameter, also representing temperature dependency, but expressed in m^3/kg.
T: temperature (in K).
b3: fitted surface parameter, representing dependency on humidity, with units of $(m_3/kg)^{b4}$.
b4: fitted surface parameter, also representing dependency on humidity, dimensionless.
b5: fitted surface parameter, also representing dependency on humidity, and also dimensionless.
b6: parameter representing the pre-exponential fraction of the temperature dependency of the decay rate coefficient, kr, in 1/min.

Figure Legends

Figure 1: Generation and Decay of Hydrogen Chloride in the 200 L Box, in the presence of various surfaces, sited in the floor of the box. HCl is generated by decomposition of wire coated with plasticised PVC.

Figure 2: Generation and Decay of Hydrogen Chloride in the 3 L Box, in the presence of various surfaces, either comprising all walls of box or as chips sited in the floor of the box. HCl is introduced by injection into the box.

Figure 3: Effect of Ageing of 3 L Box with Painted PMMA Walls on Hydrogen Chloride Decay, Before and After Injection of large Amounts of HCl.

Figure 4: Effect of Ageing of 3 L Box with Painted Gypsum Walls on Hydrogen Chloride Decay, Before and After Injection of large Amounts of HCl.

Figure 5: Hydrogen Chloride Decay in a Painted PMMA 3 L Box, Data Before and After Injection of large Amounts of HCl, and Predictions Assuming Correction Factor is to be Applied to partition coefficient (K) and to decay rate coefficient (kr).

Figure 6: Hydrogen Chloride Decay in a Painted Gypsum 3 L Box, Data Before and After Injection of large Amounts of HCl, and Predictions Assuming Correction Factor is to be Applied to partition coefficient (K) and to decay rate coefficient (kr).

Figure 7: Comparison of the Half Lives of Hydrogen Chloride in the Presence of Various Surfaces, Computed After the Surface has Reached Equilibrium With HCl. The Single Value for PMMA is also plotted for comparison purposes.

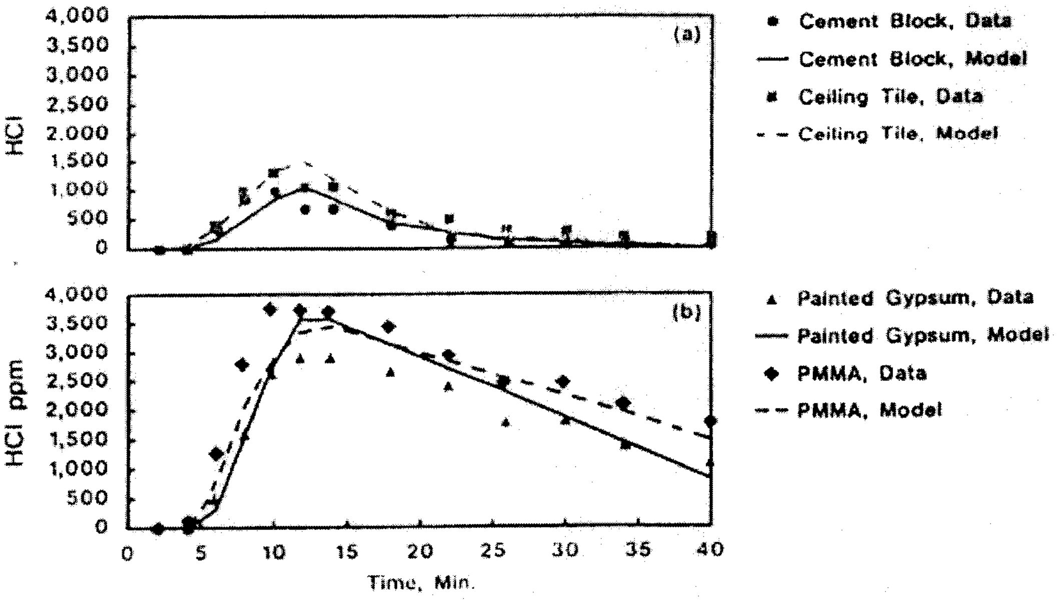

Figure 1. Generation and decay of hydrogen chloride in the 200 l box, in the presence of various surfaces, sited in the floor of the box. HCl is generated by decomposition of wire coated with plasticized PVC.

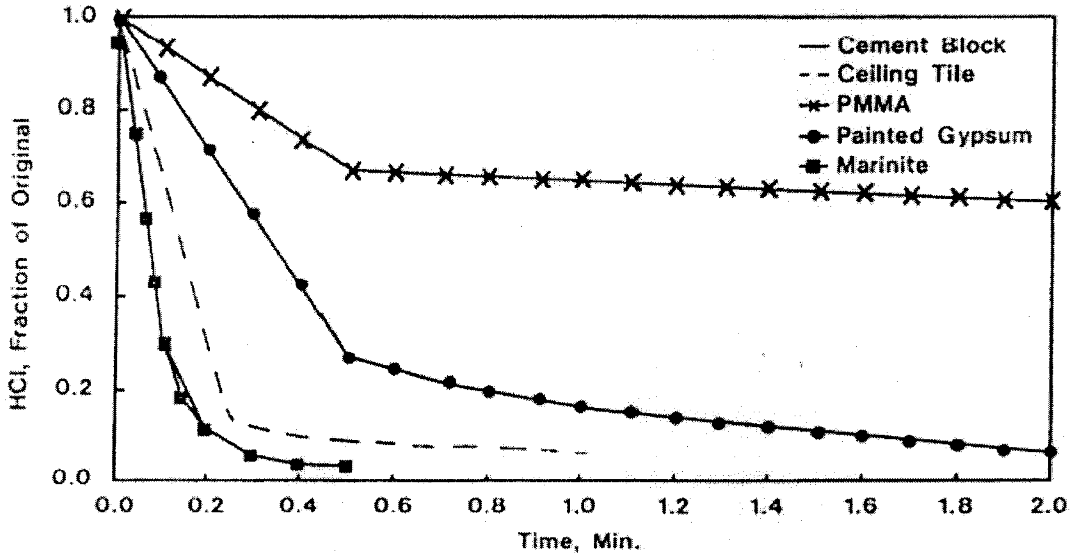

Figure 2. Generation and decay of hydrogen chloride in the 3 l box, in the presence of various surfaces, either comprising all walls of box or as chips sited in the floor of the box. HCl is introduced by injection into the box.

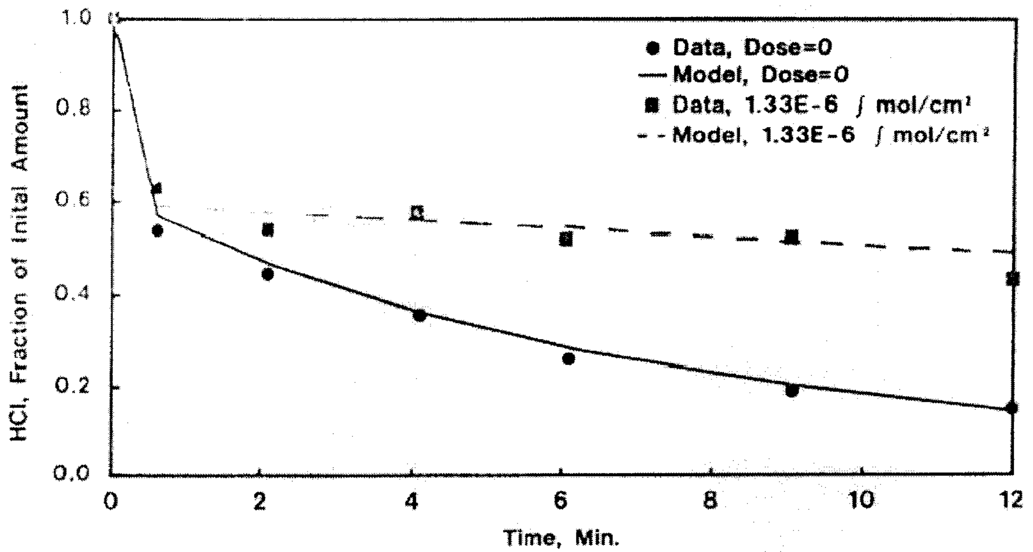

Figure 3. Effect of ageing of 3 l box with painted PMMA walls on hydrogen chloride decay, before and after injection of large amounts of HCl.

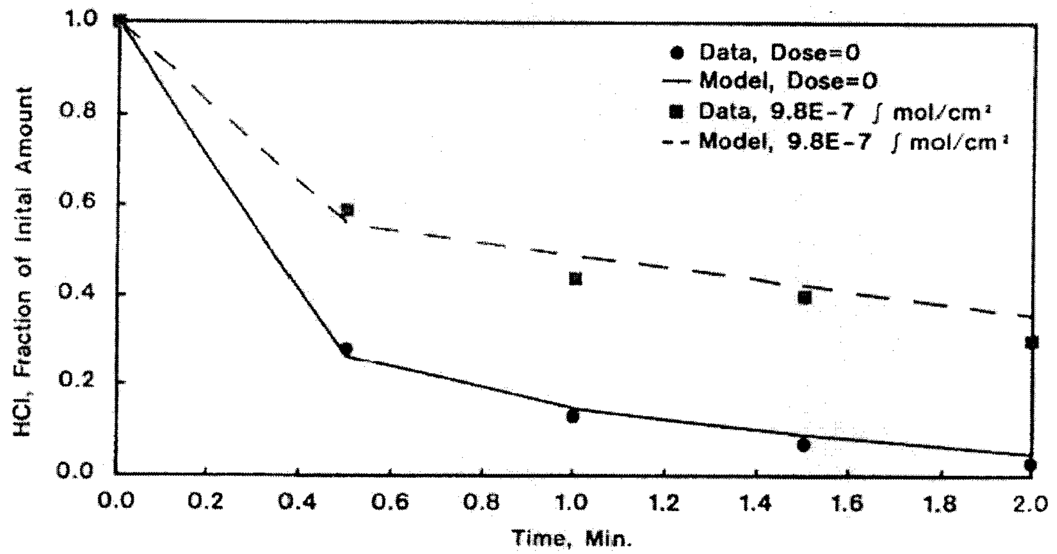

Figure 4. Effects of ageing of 3 l box with painted gypsum walls on hydrogen chloride decay, before and after injection of large amounts of HCl.

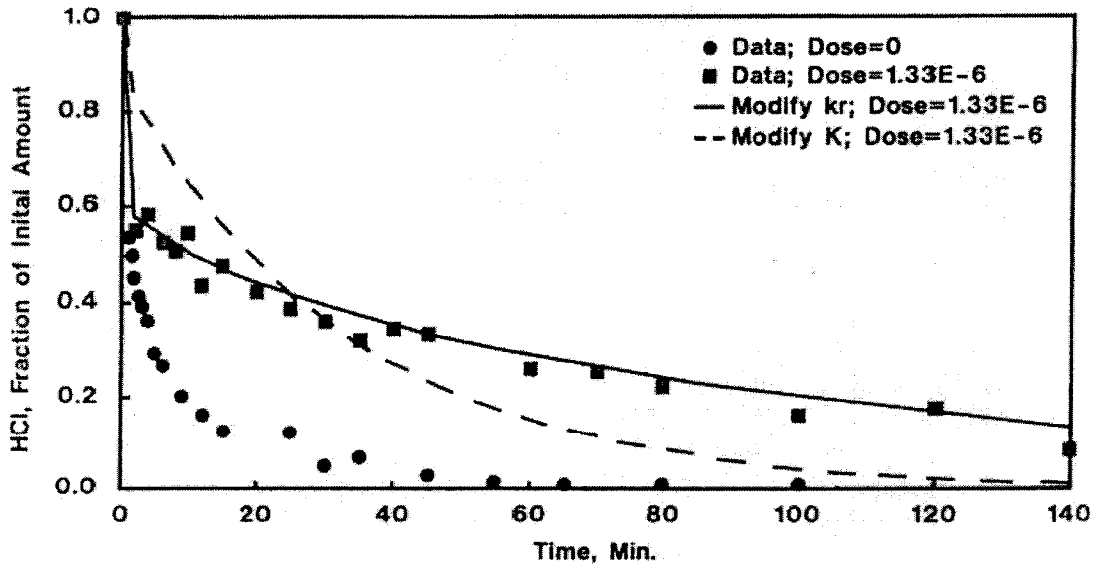

Figure 5. Hydrogen chloride decay in a painted PMMA 3 l box, data before and after injection of large amounts of HCl, and predictions assuming correction factor is to be applied to partition coefficient (K) and to decay rate coefficient (k_r).

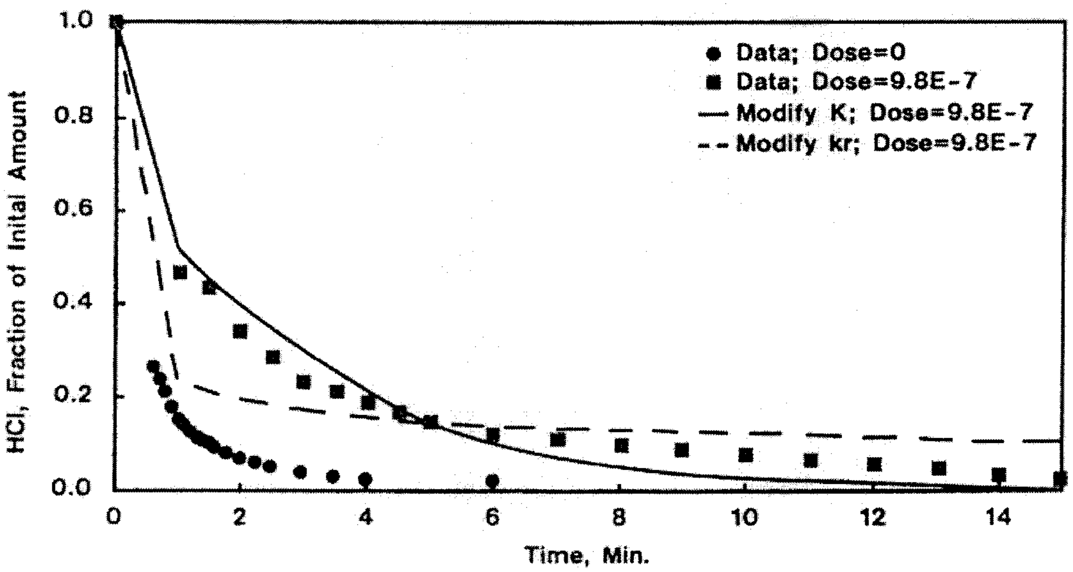

Figure 6. Hydrogen chloride decay in a painted gypsum 3 l box, data before and after injection of large amounts of HCl, and predictions assuming correction factor is to be applied to partition coefficient (K) and to decay rate coefficient (k_r).

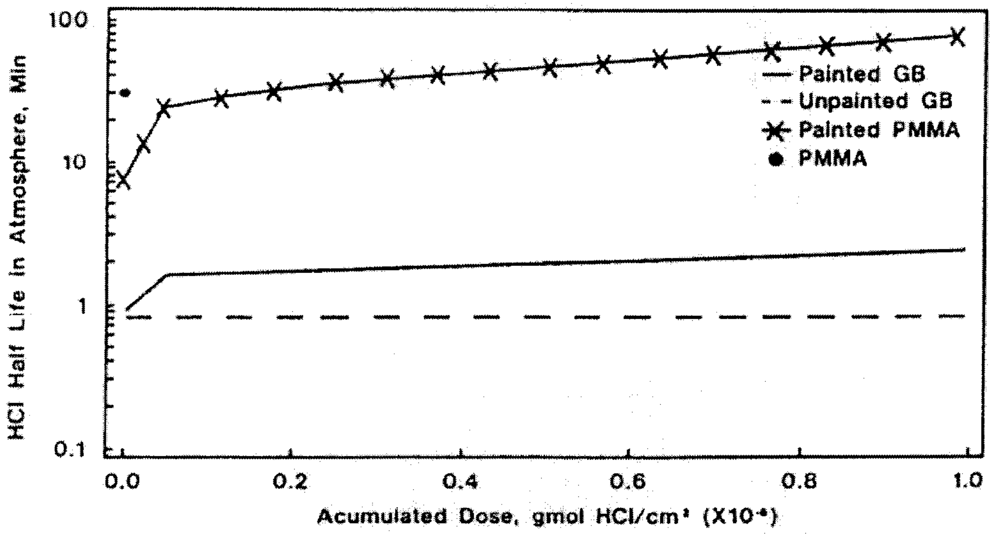

Figure 7. Comparison of the half-lives of hydrogen chloride in the presence of various surfaces, computed after the surface has reached equilibrium with HCl. The single value for PMMA is also plotted for comparison purposes.

GBH Attachment 27

AB59-COMM-7-27

THE HYDROGEN CHLORIDE GENERATION AND DEPOSITION CAPABILITY IN HAZARD I

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ABSTRACT

The new hydrogen chloride (HCl) generation and deposition capability in version 1.1 of Hazard I is analyzed. A background and a technical review of the HCl decay model are given. This is followed by general information on the use of this capability, including: (1) guidelines for simulating HCl generation, (2) the surfaces for which the parameters needed for modeling currently exist and (3) the importance of humidity in the deposition process.

The first general conclusion is that HCl has not been included in the tenability calculations. Thus, the use of HAZARD I for fires where HCl is a major combustion product must be restricted to the use of FAST, a subsection of HAZARD I.

The next overall concern is that the initial ambient humidity, as calculated by the software, is much higher than is realistic. This will cause predictions of excessive HCl decay, and can be solved very easily by the developers of the HAZARD I software.

The model has been applied to several full scale tests, in room-corridor-room and room-plenum scenarios. The results are compared to the experimental data, to earlier predictions, obtained by using the HCl deposition model and FAST separately, and to the results to be obtained in the absence of HCl decay.

Finally, a demonstration run is made, showing the predictive power of the new HCl capability, in a realistic fire scenario (two story residence). The HCl decay application in HAZARD I showed how HCl levels are much lower, particularly remote from the fire, than would have been the case if HCl had not undergone decay.

The overall results of this analysis indicate that the version of HAZARD I released is an excellent first step in the use of the HCl decay and generation model. However, a few difficulties still exist. Some of them are easily solvable (e.g. the overall wall surfaces present) while some others are more inherent in the method (e.g. no deposition on floors).

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INTRODUCTION

A large amount of work has demonstrated the tendency for hydrogen chloride (HCl) to decay relatively fast in fire atmospheres [1-16]. The decay of HCl occurs at most gas-solid interfaces, by HCl adsorption onto most solid surfaces, followed by a combination of reaction and diffusion.

The phenomenon of HCl decay is a fire safety issue because HCl is a significant product resulting from the combustion of widely used synthetic products, particularly those based on poly(vinyl chloride) (PVC) [17-18]. Measurements of HCl concentrations made in real instrumented accidental fires gave values that did not exceed 280 ppm [19-21], due, at least in part, to the decay process for HCl during the transport of smoke and fire gases. Therefore, HCl decay must be taken into account so as not to overestimate the fire hazard of materials containing PVC.

The Vinyl Institute and BFGoodrich have had a program in progress for several years, involving many experimental series of studies, to develop a model for HCl transport and decay in fire atmospheres [22-30]. These studies demonstrated the reactivity of most common construction surfaces (e.g. cement block, ceiling tile, gypsum board) toward HCl. Peak gas HCl concentrations found were always much lower than chlorine content of the burning materials would indicate. This was followed by eventual total HCl disappearance from the atmosphere.

From the beginning of the modeling work, the intent has been to formulate the model in a manner consistent with the treatment of convective heat transfer in multi-compartment fire models, particularly FAST [31]. This would, ultimately, allow the HCl transport and decay model to be incorporated into such models. This has now happened, with the incorporation of the model into the version of FAST which is used in HAZARD I, version 1.1. The purpose of the present work is to, briefly, review the technical basis of the model, establish its validity by comparing computational results from it with data generated in two full scale fire tests, and then demonstrate its usage in a hypothetical private residence fire scenario. Finally, some guidelines are indicated for using the model in the context of HAZARD I.

MODEL DESCRIPTION

The model for HCl decay during the transport of fire gases has been described in detail [32-34]. Briefly, it assumes: that the HCl concentration is uniform in the bulk gas phase, that transport across the gas boundary layer is described by a mass transfer coefficient, and that partitioning of HCl at the gas/wall interface is described by a surface specific equilibrium coefficient. The rate of disappearance of HCl into the wall is described by a first order rate constant which is specific to the surface material.

In most applications of the model [30, 32-35], the experimental layout permits the approximation that large surface areas can be treated uniformly, e.g., the entire ceiling in a room. Thus, the model can be formulated in terms of ordinary differential equations with time as the independent variable. This treatment is consistent with "zone modelling" of convective heat transfer in multi-compartment fire models [31].

MATHEMATICAL FORMULATION

The gas transport equation for HCl is

```
~~{d[HCl]} over {dt}~=~~~-~kc*~A~*~ ( ~[HCl] ~-~{[HCl] sub w} over {Ke}~ )
~~~~~~~~~~~(1)
```

where the left hand side represents the rate of HCl gas phase concentration change, and the right hand side represents the rate of HCl transfer from the gas to the wall. The variable A represents the area of the surface where the decay is taking place. The constants kc and Ke are the mass transfer coefficient through the gas phase and the HCl partition coefficient (equilibrium constant) between the wall and the gas phase. The calculation of flows in and out of every compartment is not explicitly shown in Equation (1), but is calculated by FAST.

The mass transfer coefficient, kc, has units of distance/time. In general, it is a function of the local velocity field and the diffusivity of the transferring species. The similarity of convective mass and heat transfer has been known in the field of transport phenomena for a long time. In its sinplest form, this similarity can be expressed as a relation between the convective heat and mass transfer coefficients, known as the Reynolds analogy [36]. Fire driven flows generally meet the conditions assumed in the "Reynolds analogy". Thus, in the FAST implementation of the HCl transport and decay model, the "Reynolds Analogy" is used to obtain kc from the convective heat transfer coefficient. It has been shown that, in most practical situations, the decay rate of HCl from fire gases is not very sensitive to the convective mass transfer rate [37]. The predicted values of kc should, therefore, be sufficiently accurate in the great majority of cases.

The wall conservation equation for HCl is

```
~{d[HCl] sub w} over {dt}~=~kc~*~~(~[HCl]~-~{{[HCl]} sub w} over {Ke}~)~-
~kr~*~{[HCl]} sub w~~~~~~~~(2)
```

where the left hand side corresponds to the HCl surface concentration rate of change, the first term on the right hand side is the rate of transfer of HCl from the gas to the wall, and the second term is the rate of HCl disappearance of HCl into the wall (first order kinetics). The equilibrium gas concentration at the gas/surface interface (which is not explicitly calculated) is given by equation (3):

```
~~~{[HCl] sub i} ~=~{{[HCl]} sub w} over {Ke}~~~~~~~~~(3)
```

In general, Ke and kr are functions of temperature, humidity and HCl concentration, as well as the specific type of surface material [30, 32-34].

The effect of water (humidity) is to increase the number of surface sites available for HCl adsorption, leading to a multiplicative functional form for the effect of water on HCl adsorption; i.e.,

```
~~Ke~=~F1~([HCl],~T)~*~F2(H sub 2 O])~~~~~~~~~~(4)
```

F1 represents the partition coefficient at zero humidity, i.e.:

```
F1~=~{b1~*~e sup {12500/R*T}~*~[HCl]} over {1~+~b2~*~e sup
{12500/R*T}~*~[HCl]}~~~~~~~~~~~~~~~~~~~~~~~~~~~~~(5a)
```

In the case of painted gypsum board, the values for b1 and b2 are, respectively, 0.0063 m and 192 m^3/kg. At the other extreme, when the HCl-H_2O binary reaches saturation conditions in the gas phase, any surface will have an infinite capacity to adsorb HCl. There are, thus, two limiting conditions for F2:

```
~~F2(0)~=~1;~~~~F2({[H sub 2 O]} sub s)~~      ~~ INF ~~~~~~~(5b)
```

With these limiting conditions, the final form for F2 is:

```
~~F2~=~1~+~{b5~*~{[H sub 2 O]} sup {b6}} over {{({[H sub 2 O]} sub s~-~[H sub 2 O])}
sup {b7}}~~~~~~~~(6)
```

The fitted values, for painted gypsum board, for the constants b5, b6 and b7 are shown in Table 1.

The expression for the saturation concentration of water, $[H_2O]_s$, was developed [25] by linear regression of "data" points generated from a rigorous vapor/liquid phase dissociation equilibrium model for the hydrogen chloride-water system (ASPEN-PLUS^R software package for the modeling of chemical processes [34]). Equation (7) shows how to calculate the saturated water concentration from the polynomial expressions described in reference [30]. These expressions are 5th order in [HCl], 3rd order in temperature and also contain combined temperature/ concentration terms, all of which are a function of ambient temperature.

```
~{[H sub 2 O]} sub s~~=~{0.556~*~10 sup {-4}~*~(Polynomial Expression)} over
{R~*T}~~~~~~(7)
```

The term kr in equation (2) is the coefficient for the decay rate of HCl on the surface, which is assumed to be a first order process in the surface concentration $[HCl]_W$. Previously [25], kr was assumed to be a constant independent of temperature, with a different value for each type of surface. However, when investigating larger temperature ranges [30], it became obvious that some temperature dependency was needed, and an Arrhenius form was assumed for this dependency. The expression obtained for kr is:

```
~~kr~=~b3~*~e sup {{-b4} over {(R*T)}}~~~~~~~~~~(8)
```

Table 1 shows the surface parameters (b1-b7) for the majority of the surfaces used in the experiments carried out.

GENERATION OF HYDROGEN CHLORIDE

Equation (1) can also include a generation term, which is only non zero in the burn room. In one study [38], a specific HCl generation function was developed for electrical decomposition of flexible PVC coated onto wire. In a couple of other studies, involving burning of rigid PVC, generation functions were developed on the basis of the mass loss rate of PVC (measured) and the chlorine content of the PVC [30, 32]. In some cases HCl was injected directly, in which case the generation function is simply the rate of introduction of HCl into the compartment [30, 32, 35]. Other equations can be developed depending on the scenario and the source of the HCl.

SURFACES

Hydrogen chloride decay has been studied on a variety of surfaces, the principal ones are painted gypsum board (PGB) and poly(methyl methacrylate) (PMMA). The other surfaces studied are: concrete, unpainted gypsum board, ceiling tile, Marinite®, painted PMMA, and two wire materials: copper and carbon steel. HAZARD I contains, in the file THERMAL.TPF, surface parameters for PGB, under the label GYPSUM. The technical reference to HAZARD I (version 1.1) also contains the surface coefficients for PMMA, ceiling tile, concrete and Marinite®. Further details of the parameters for the other surfaces can be found in Table 1 and in the references to this paper, particularly numbers 34 and 38.

SCENARIOS USED TO ASSESS HCL DECAY IN HAZARD I

In this work, the HAZARD I, version 1.1, software was applied to three cases:

(a) The fire involved the thermal decomposition of PVC by electrical overload of 9.14 m of PVC-coated building wire, laid on the floor of a simulated plenum above a room. The dimensions of the plenum were 2.4 x 3.7 m, with a 1.2 m height, and it had painted gypsum board walls and ceiling and ceiling tile floor. The plenum floor was simply ceiling tiles laid on metal tracks, above a standard room (3.7 x 2.4 x 2.4 m) [23].

(b) The fire involved injection of pure HCl into a standard room (3.7 x 2.4 x 2.4 m, burn room), with painted gypsum walls and a normal door. The fire source was a series of 3 burners (a radiant panel generating 2,700 W, a small propane pilot flame (generating 174 W) and a sand box burner generating 5,800 W. The room was connected, via a 26 m long (by 2.4 x 2.4 m) corridor to two other doors. One door led to the open air and the other one led to another room (target room, identical to the burn room) [30].

(c) The fire is scenario 5, Christmas tree fire, in the example cases for the HAZARD I method [39]. It involves a townhouse, which has two floors. For HAZARD use, on the lower floor there are two "compartments" (the burn room (8.2 x 4.9 x 2.4 m) and the hall (2.1 x 5.2 x 2.4 m)), a set of stairs (in two more "compartments": a low (1.2 x 2.1 x 2.4 m) and a high (1.2 x 3.0 x 4.9 m) level) and on the higher floor there are two more "compartments" (bedrooms 1 (5.3 x 3.3 x 2.4 m) and 2 (2.9 x 6.1 x 2.4 m)). In reality the house has, of course, several compartments and furniture, but is divided in this way for calculation purposes. The walls and ceilings are painted gypsum board and the floors are concrete (lower floor) and wood (Douglas fir, upper floor). The first item ignited is a natural Christmas tree, which eventually ignites a "bean bag chair" (vinyl covered, with polystyrene foam beads). For this application 454 g of polystyrene beads were replaced by an equal mass of rigid PVC. The generation of HCl was calculated on the basis of a 56% HCl content of the PVC. The HCl generation was based on the assumption that this PVC formulation contained no fillers or other HCl retention catalysts; this is a simplistic approximation. It was assumed, for simplicity, that the replacement of polystyrene by PVC had no effect on heat release or other fire performance.

PROCEDURE

Examples a and b had already been analyzed, prior to this work, using the "old model", i.e. the stand alone version of the HCl transport and decay model. Thus, the work presented here involved carrying out the following:

(I) running HAZARD I in the scenario in question (labelled HAZARD D, for decay, in the illustrations);

(II) running HAZARD I in the same scenario but forcing HCl not to decay (by creating a new TPF file where the surface parameters for PGB were assigned zero values) (labelled HAZARD ND);

(III) comparing both results with those of the "old model" and with the experimental data.

In example (b), additional work was also made. The corridor, which is 26 m long, was treated once as a single compartment and once subdivided into four virtual compartments, and the results compared. This was done for two reasons. First, the experimental data included HCl concentration measurements taken at 4 locations along the corridor, and a comparison with that data was desirable. Second, it was felt that a 26 m corridor was too large to be taken as a single compartment.

In example (c), the HAZARD I software was run 3 times:

(I) in the normal way (labelled Decay);

(II) forcing HCl not to decay (by creating a new TPF file where the surface parameters for PGB were assigned zero values) (labelled No Decay);

(III) after increasing the wall surface area of every compartment by 50%, without changing the compartment volumes, the floor or the ceiling area (labelled Enhanced Decay).

TENABILITY: HAZARD I OR FAST?

One of the final outcomes of a HAZARD I run is the expected mortality in the fire, or the time available for escape. This is accomplished based on one of several tenability criteria, addressing heat, smoke toxicity or a combination of both. One tenability criterion is based on the N-gas model, which uses a combination of the toxic potencies of various primary toxic gases: carbon monoxide, carbon dioxide, hydrogen cyanide and low oxygen. Unfortunately this does not include HCl, although NIST has already developed a modified formula for the N-gas model which does include HCl [40]. Thus, it is not possible, today, to assess the effect of chlorinated materials on the toxicity of the smoke atmosphere using this criterion. This is an easily solvable problem. There is, unfortunately, an added problem. One further criterion for assessing tenability via smoke toxicity is the use of a generic smoke toxic potency, and the calculation of tenability based on overall mass loss (Ct). This is, normally, a very adequate calculation. Indeed, it is probably a better calculation than one based on individual toxic potencies. However, in this case it will lead to an added hazard because the tenability is calculated based on mass lost by the fuel burnt and not on the amount of smoke present. The difference between the two is, of course, the amount of HCl that has decayed. This is a problem that is less easily solved, but is a small issue.

The consequence of this incomplete consideration of the issue of HCl decay in HAZARD I is that HAZARD I cannot yet really address fires where HCl is a major combustion product. For such fires, however, a series of measurements of gas concentrations can still be obtained from the application of FAST, a subsection of HAZARD I. The validity of this version of FAST for measuring HCl decay will be analyzed in the subsequent sections of this paper.

RESULTS AND DISCUSSION

Humidity:

The first observation that was made addressed the issue of humidity. The humidity function included in HAZARD I to calculate the initial water content of the atmosphere is incorrect. Use of that equation leads to an exceedingly high initial humidity, ca. 10 times higher than is reasonable. This is, of course, of limited importance for most fire hazard calculations, but it would dramatically increase the rate of hydrogen chloride decay. This was addressed in the present work by changing, manually, the initial humidity, and pressing on with the calculations.

Case a:

Figure 1 shows the results of the application of HAZARD I to case a. A clear very large difference can be seen between the HCl concentrations found with the "decay" and "no decay" applications of the model, indicating that the decrease in HCl concentration is due to the reactivity of HCl and not to simple mass transfer and smoke flows. More surprising is the difference between the HAZARD I results and those obtained previously. It is interesting that HAZARD I predicts much less HCl decay than is shown by the experimental data, or than was shown by the "old model". In consequence, HAZARD I does not predict this scenario too well.

One of the most important reasons, probably, for this discrepancy is the fact that the "hot layer" never reaches the floor level in HAZARD I, while it clearly did so in the actual experiment. Thus, HCl decay on a very substantial fraction of the surface (the ceiling tile floor) is ignored. This is made even more important since the rate of HCl decay on ceiling tile is considerably faster than on PGB.

Another concern has to do with the mass flows. This fire involved over 9 m of cable, stretched throughout the floor, but HAZARD I requires it to be a "point source", thereby requiring the smoke (and HCl) to travel much further to any wall surface.

Case b:

Figures 2-7 address the case where the corridor was subdivided into 4 virtual compartments. As the smoke flows along the corridor it moves from CORR 1 up to CORR 4. The HCl concentrations are plotted for every compartment, for 5 cases: Hazard D, Old Model D, Hazard ND, Old Model ND and Data. In every case, for the Decay calculation, the predictions of HAZARD I and of the old model are very comparable, and adequately track the experimental data. The No Decay calculations show considerably higher HCl concentrations, particularly as the smoke moves along the corridor. As expected, there is little HCl decay in the burn room, but very low concentrations in the target room: peak HCl values decrease by a factor of 3-4.

Figures 8 and 9 show a curious mathematical result of these calculations, which does not reflect experimental reality. In the period of 2-5 min, the burn room and corridor compartment 1 (and partially 2) in the corridor show a peak HCl concentration, which is probably fictitious. This must result from some mass flow calculation, because it is found both in the decay and no decay uses of HAZARD I.

Figures 10-13 are analogous to Figures 2-7, except that the corridor is now a single compartment. The difference between Figures 12 and 13 is that the calculated results are compared to the data at opposite ends of the corridor. Clearly these predictions are much less satisfactory than those made with the 4 virtual compartments.

Overall, however, HAZARD I does satisfactorily predict this scenario, with the caveats that subdivision of a long corridor into several "virtual compartments" is important, and that a few excessively high values are found early on.

Case c:

An analysis was made of the "compartments" in this "packaged" example found in the HAZARD I reference guide. During this analysis it was noticed that the "compartments" are simply one way in which the same floor and ceiling area, and the same compartment height could be distributed along walls. It was, moreover, observed that some other walls present in the house (bathrooms, closets, kitchen, furniture) were not being used, although they would clearly have served as added sinks for HCl. A simple arithmetical calculation shows that the dimensions of these compartments can easily be changed, within the same house scenario, to achieve higher wall surfaces. Thus, HAZARD I was run in the "enhanced decay" mode, where every "compartment" has 50% more walls, but the same floor and ceiling surfaces and the same overall volume. This value of 50% was picked at random, to investigate the effect of increased wall surface area on HCl decay.

This example found in HAZARD I has a total fire duration of 30 min. It was quite straightforward to run this example as is, without modification. However, when it was attempted to run this case with HCl added, the run was not completed, and the simulation stopped soon after the fire had reached 20 min, but had clearly not yet died. Interestingly, repeat calculations with the same input stopped at the same time, but when the input was changed somewhat (going from Decay to No Decay to Enhanced Decay) the runs stopped at different times.

Figures 14-19 present the results of these analyses, together with the temperature of the upper layer. The results speak for themselves: there is considerable decay as the smoke moves away from the burn room, particularly when it reaches the second floor. This was an expected, and pleasing, result.

The effect of increasing the "compartment" wall surface area was much more unexpected. The "enhanced decay" HCl concentration is consistently very much lower than that normally calculated by HAZARD I. This indicates that, from the point of view of HCl decay, care must be taken to include, when designing the "compartments" in the burn room, a proper set of values for the wall surface areas, to avoid seriously underestimating HCl decay.

CONCLUSIONS

This work shows that the HCl transport and decay model has been adequately introduced into the FAST subsection of the new HAZARD I software. The FAST fire model can, thus, be used to predict HCl decay in a large series of realistic residential (and small commercial or industrial) fire scenarios.

The work points out a few areas where improvement is still desirable. Moreover, the work also points out that HAZARD I cannot, yet, be used to determine tenability in fires where HCl is a major combustion product. This deficiency is, however, easily solvable because NIST already has determined the way to incorporate HCl into the toxic potency fractional effective dose calculations.

This work points out, once again, with an example of a realistic residential fire scenario, how much the phenomenon of HCl decay lowers the HCl concentrations, particularly in rooms remote from the fire.

GLOSSARY

d[HCl]/dt:	rate of change of HCl atmospheric concentration, in kg/(m^3 s).
[HCl]:	concentration of HCl in the gas phase, in kg/m^3.
$[HCl]_i$:	concentration of HCl at the interface, in kg/m^3.
kc:	convective mass transfer coefficient; in m/s.
$[HCl]_w$:	concentration of HCl on the wall, in kg/m^2.
Ke:	HCl partition (or gas/wall equilibrium), coefficient, in m.
kr:	HCl decay rate coefficient inside the surface, in 1/s.
F1:	term denoting partition coefficient dependency on [HCl] and temperature; it represents adsorptivity of the surface for HCl in absence of water, in 1/m.

F2: term denoting partition coefficient dependency on water concentration; it represents added capacity for HCl adsorption as a function of the water present in the gas; dimensionless function.

V: gas volume of compartment, in m^3.

A: surface area where decay takes place, in m^2.

$[H_2O]$: concentration of water, in kg/m^3.

$[H_2O]_s$: saturation concentration of water, also in kg/m^3.

b1: fitted surface parameter, representing the temperature dependency, in m.

b2: fitted surface parameter, also representing temperature dependency, but expressed in m^3/kg.

b3: fitted surface parameter, representing the first order reaction pre-exponential factor, in 1/s.

b4: fitted surface parameter, representing the activation energy, in J/g mol.

b5: fitted surface parameter, representing dependency on humidity, in units of $(m^3/kg)^{b7-b6}$.

b6: fitted surface parameter, also representing dependency on humidity; it is dimensionless.

b7: fitted surface parameter, also representing dependency on humidity; it is dimensionless.

T: temperature, in K.

R: ideal gas constant, 8.314 J K^{-1} mol^{-1}.

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Table 1. Surface Coefficients for HCl Decay

Surface	b1	b2	b3	b4	b5	b6	b7
	(m)	(m^3/kg)	(1/s)	a	b	(-)	(-)
Painted Gypsum	6.3E-03	191.8	0.0587	7476	193	1.021	0.431
PMMA	9.6E-05	0.0137	0.0205	7476	29	1.0	0.431
Ceiling Tile	4.0E-03	0.0548	0.123	7476	30	1.0	0.431
Cement Block	1.8E-02	5.48	0.497	7476	30	1.0	0.431
Marinite®	1.9E-02	0.137	0.030	7476	30	1.0	0.431

a: (J/ g mol); b: (m^3/kg)^(b7-b6)

The HCl Decay Model Equations

The gas transport equation for HCl is:

$$d[HCl]_i/dt = G_i(t) - (\Sigma)_j\ m_{ij}*[HCl]_i/(V_i*M_i) +$$

$$- k_c*A_i*\{([HCl]_i/V_i)-([HCl_w]_i/A_i)/K_{ei}\}$$

The wall decay equation for HCl is:

$$d[HCl_w]_i/dt = k_c*A_i*\{([HCl]_i/V_i) - \qquad (2)$$

$$- ([HCl_w]_i/A_i)/K_{ei}\} - k_{ri}*[HCl_w]_i$$

The generation term, $G_i(t)$, is non-zero only in the burn room, where HCl is being produced by combustion of PVC. The generation rate is the product of the total mass loss rate involved in the fire times a value representing the fraction of that total mass which is HCl. The function $G_i(t)$ was determined to match the actual generation rate of HCl, from the measured rate of mass loss of the burning PVC sample.

The mass transfer coefficient, k_c, was assigned a constant value of 0.68 m/min for all cases, a typical value, as derived from the convective heat transfer coefficient used by FAST in this situation. The rate of mass exchanges between compartments, m_{ij}, are taken directly from the calculations of FAST.

The partition coefficient for HCl, K_{ei}, expresses the relation between the concentration of HCl in the gas phase that is in equilibrium with a given amount of HCl adsorbed on a surface. This has been based on previous work [32], but a larger range of temperature and absolute humidity has been used here, as described in reference 30.

The difference between the old model of K_e and the present version is that the previous function, purely empirical, treated the enhanced adsorption of HCl on surfaces in the presence of humidity as an additive effect. The new model now views the presence of water as increasing the number of surface sites for HCl adsorption, leading to a multiplicative functional form for the effect of water on HCl adsorption; i.e.,

$$K_e=F1([HCl],T)*F2([H_2O]) \qquad (3)$$

Both the old and new expressions for F1, representing the partition coefficient at zero humidity, are identical, i.e.:

$$F1=b1*\exp[1500/(R*T)]/\{1+b2*\exp[1500/(R*T)]*[HCl]/V\} \quad (4a)$$

In the case of painted gypsum board, the values for b1 and b2 are, respectively, 0.0063 m and 192 m^3/kg. At the other extreme, when the HCl-H_2O binary reaches saturation conditions in the gas phase, any surface will have an infinite capacity to adsorb HCl. There are, thus, two limiting conditions for F2:

$$F2(0)=1;\ F2([H_2O]s)=>\text{infinity} \quad (4b)$$

In between these limiting conditions, the final form for F2 is:

$$F2=1+\{c1*[H_2O]^{c2}\}/\{[H_2O]_s-[H_2O]\}^{c3} \quad (5)$$

The fitted values, for painted gypsum board, for the constants c1, c2 and c3 are, respectively: 193 [in units of $(m^3/kg)^{c2-c3}$], 1.021 and 0.431.

The expression for the saturation concentration of water, $[H_2O]_s$, was developed [25] by linear regression of "data" points generated from a rigorous vapor/liquid phase dissociation equilibrium model for the hydrogen chloride-water system (ASPEN-PLUS^R software package for the modeling of chemical processes [33]). Equation (6) shows how to calculate the saturated water concentration from the polynomial expressions presented in the earlier paper [30].

$$[H_2O]_s = \{0.556E\text{-}04 * (\text{Polynomial Expression})\}/(R*T) \quad (6)$$

The term k_r in equation (2) is the coefficient for the decay rate of HCl on the painted gypsum surfaces, which is assumed to be a first order process in the surface concentration $[HCl]_w$. Previously [25], k_r was assumed to be a constant independent of temperature, with a different value for each type of surface. However, when investigating larger temperature ranges [30], it became obvious that some temperature dependency was needed, and an Arrhenius form was assumed for this dependency. The expression obtained for k_r is:

$$k_r=3.52*\exp[-1786./(R*T)] \quad (7)$$

FIGURE 1

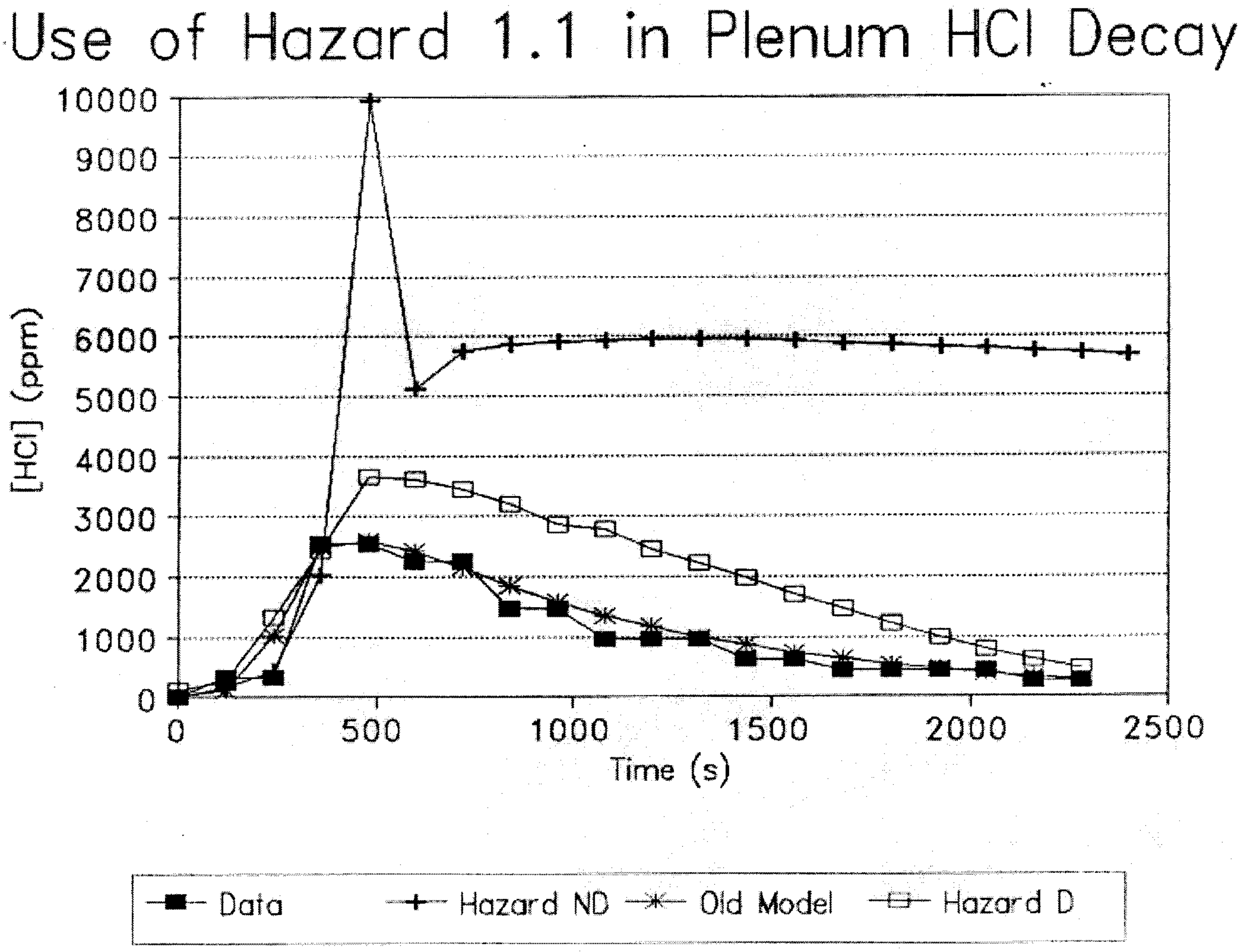
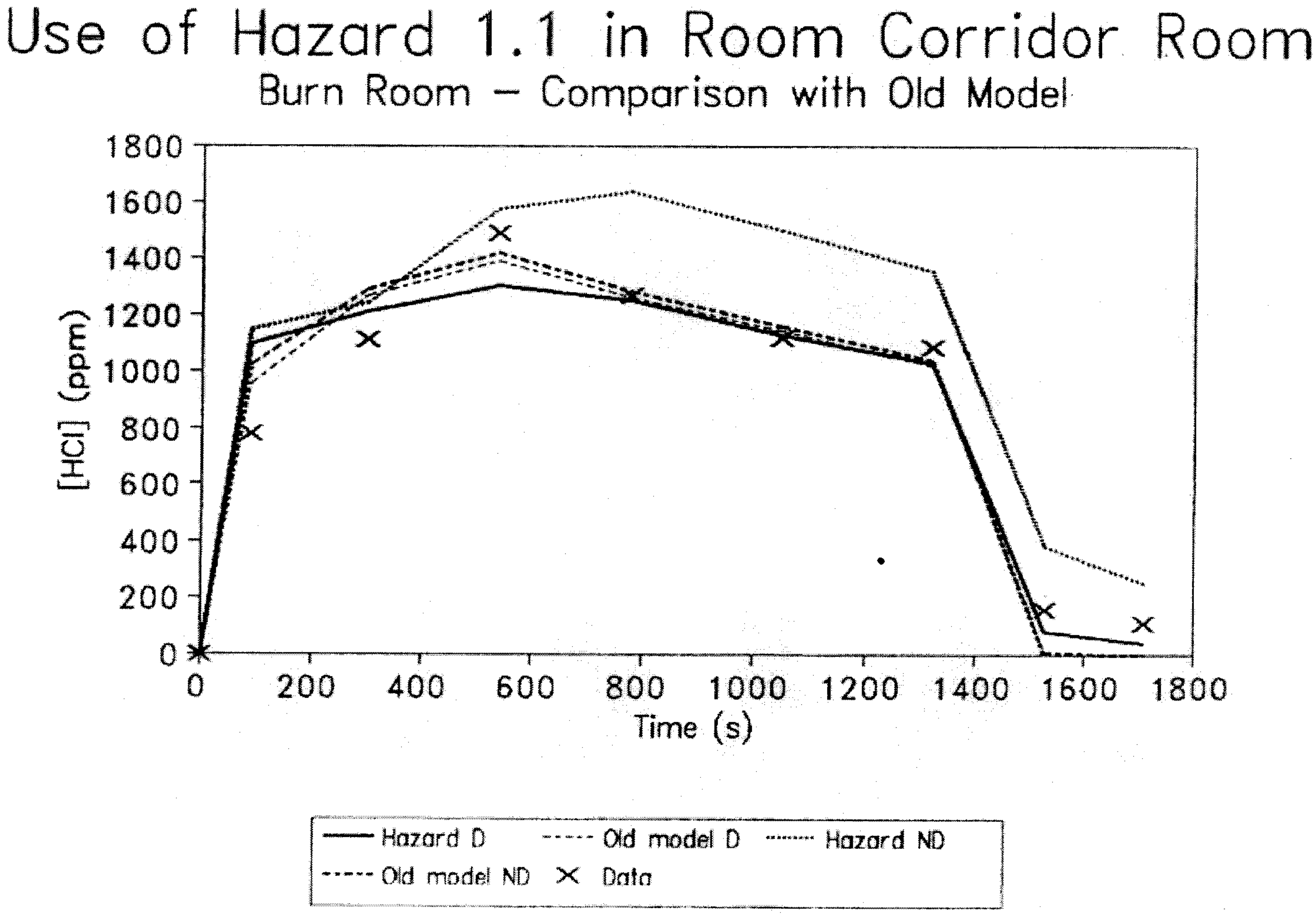

Use of Hazard 1.1 in Plenum HCl Decay
[HCl] (ppm)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
2500
Time (s)
Data
Hazard ND
Old Model
Hazard D

FIGURE 2



Use of Hazard 1.1 in Room Corridor Room
Burn Room – Comparison with Old Model
[HCl] (ppm)
1800
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)
Hazard D
Old model D
Hazard ND
Old model ND
Data

FIGURE 3

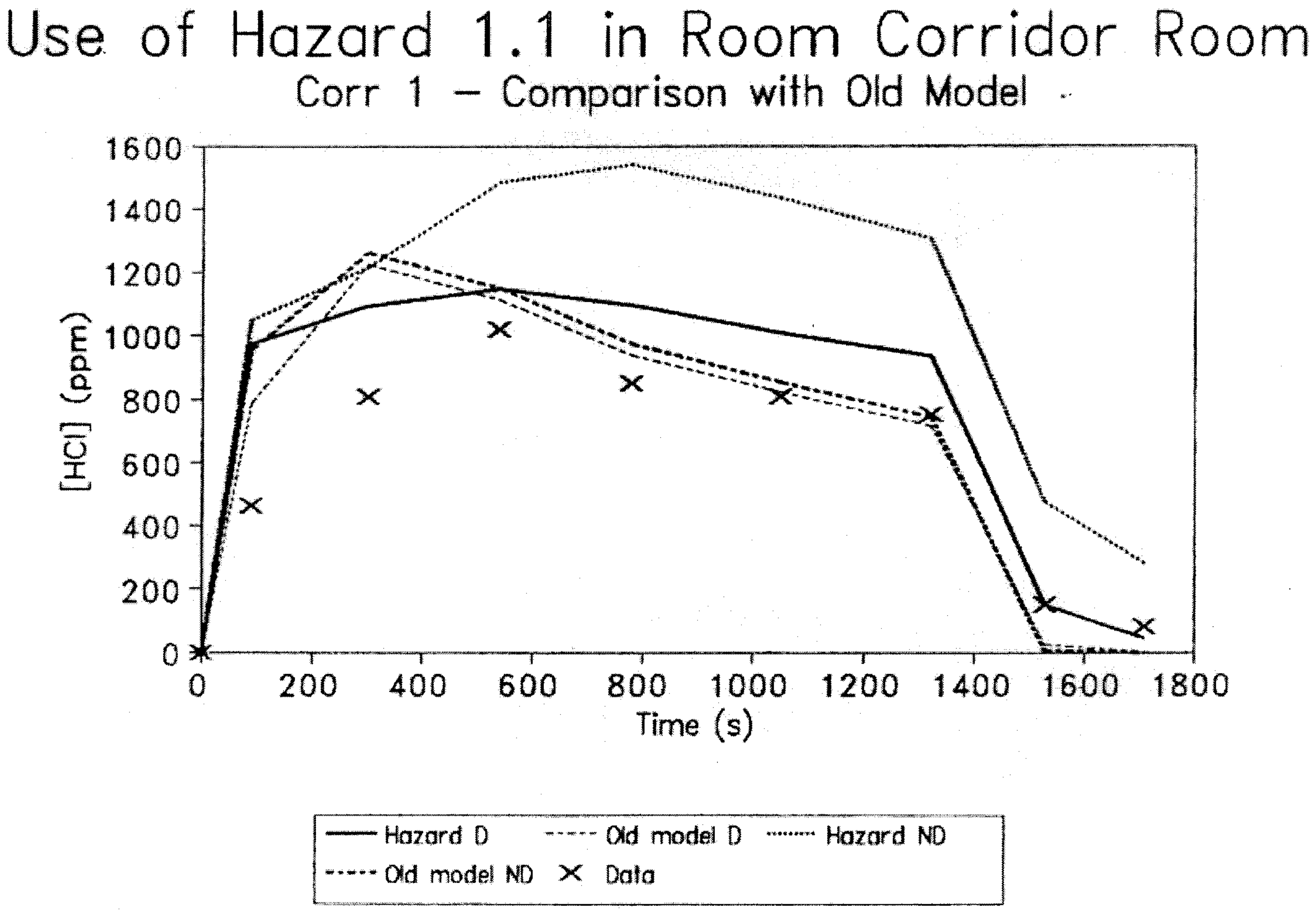

Use of Hazard 1.1 in Room Corridor Room
Corr 1 – Comparison with Old Model
[HCl] (ppm)
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)
Hazard D
Old model D
Hazard ND
Old model ND
Data

FIGURE 4

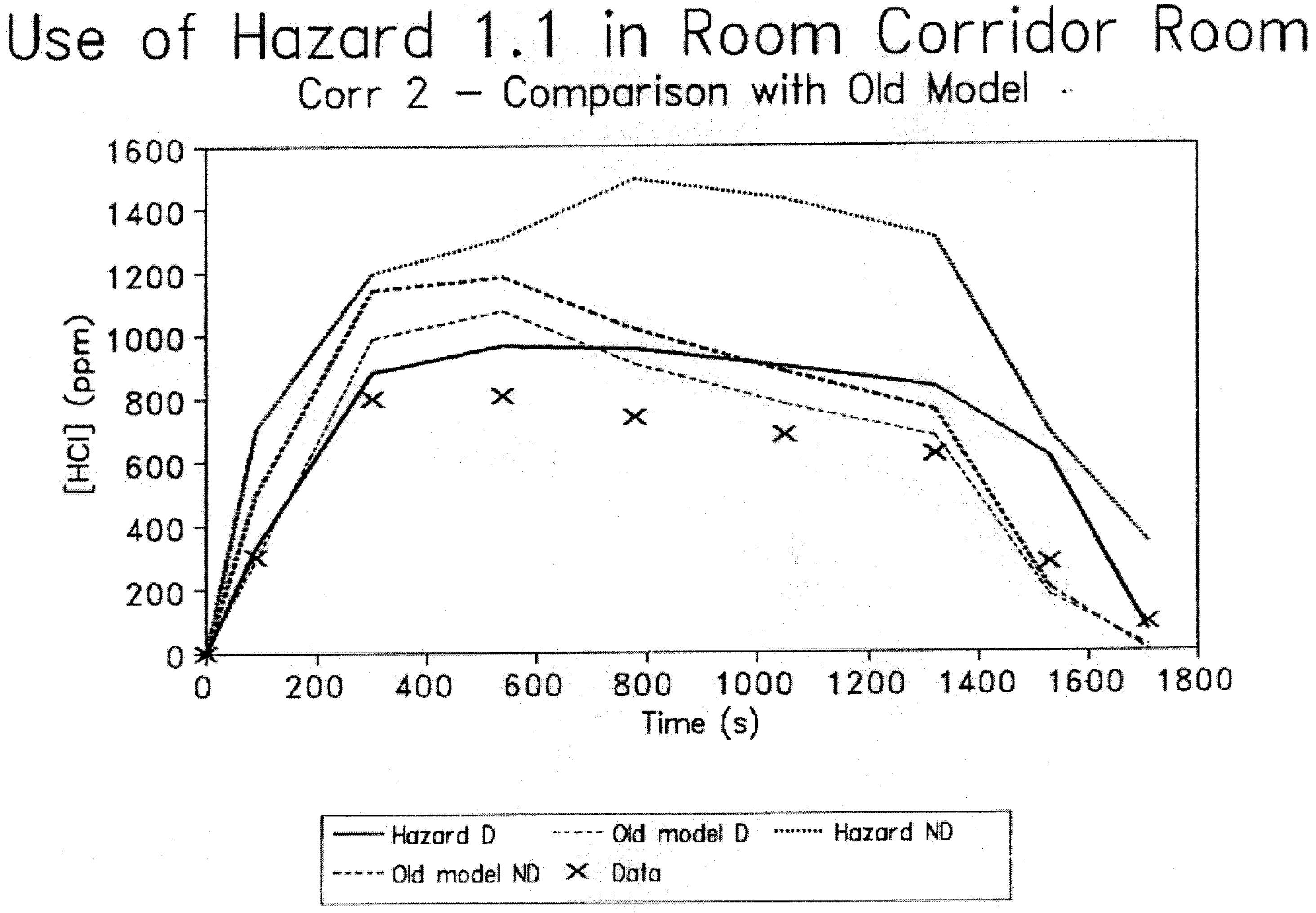

Use of Hazard 1.1 in Room Corridor Room
Corr 2 – Comparison with Old Model
[HCl] (ppm)
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)
Hazard D
Old model D
Hazard ND
Old model ND
Data

FIGURE 5

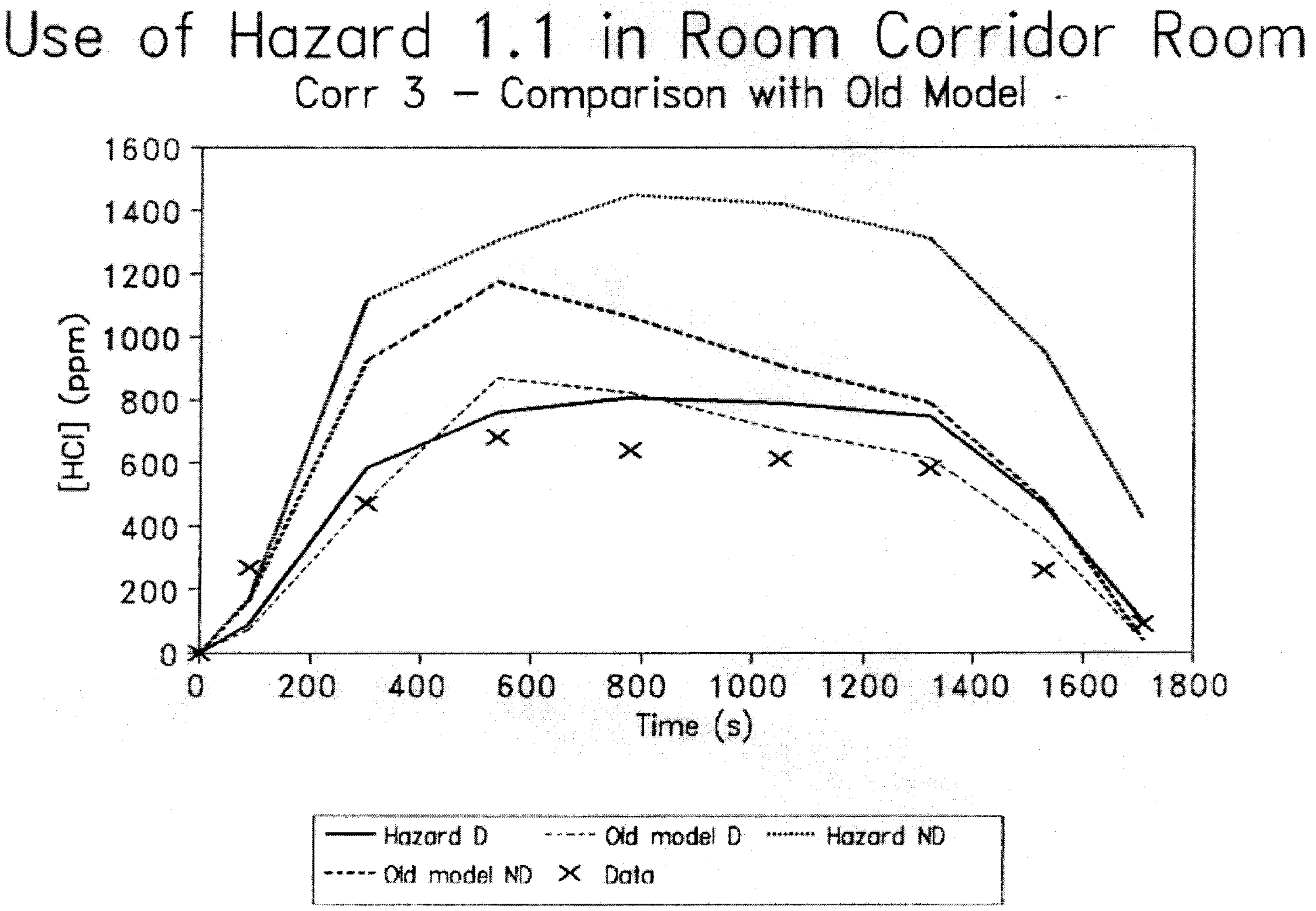

Use of Hazard 1.1 in Room Corridor Room
Corr 3 – Comparison with Old Model
[HCl] (ppm)
0
200
400
600
800
1000
1200
1400
1600
Time (s)
0
200
400
600
800
1000
1200
1400
1600
1800
Hazard D
Old model D
Hazard ND
Old model ND
Data

FIGURE 6

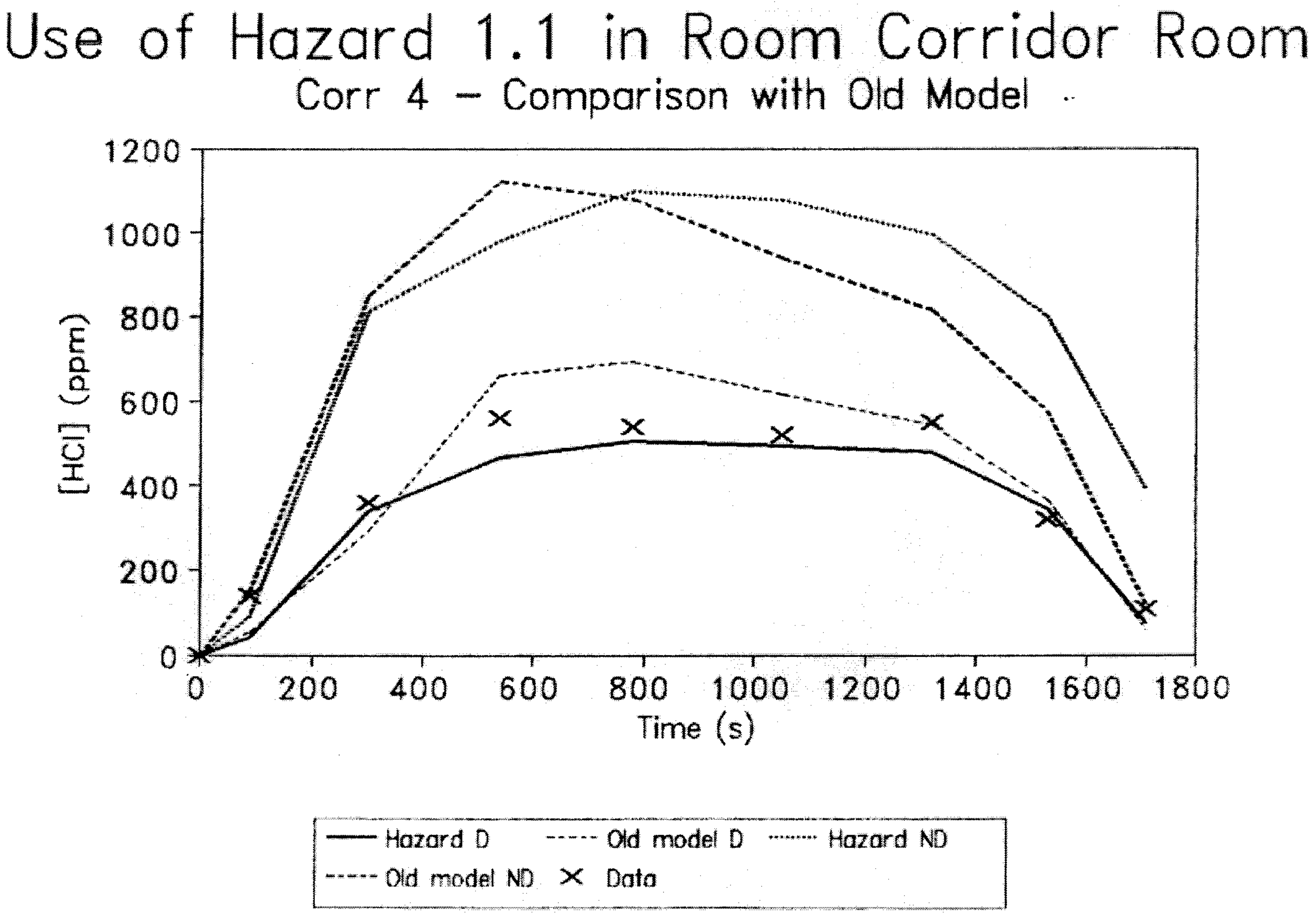

Use of Hazard 1.1 in Room Corridor Room
Corr 4 – Comparison with Old Model
1200
1000
800
600
400
200
0
[HCl] (ppm)
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)
Hazard D
Old model D
Hazard ND
Old model ND
Data

FIGURE 7

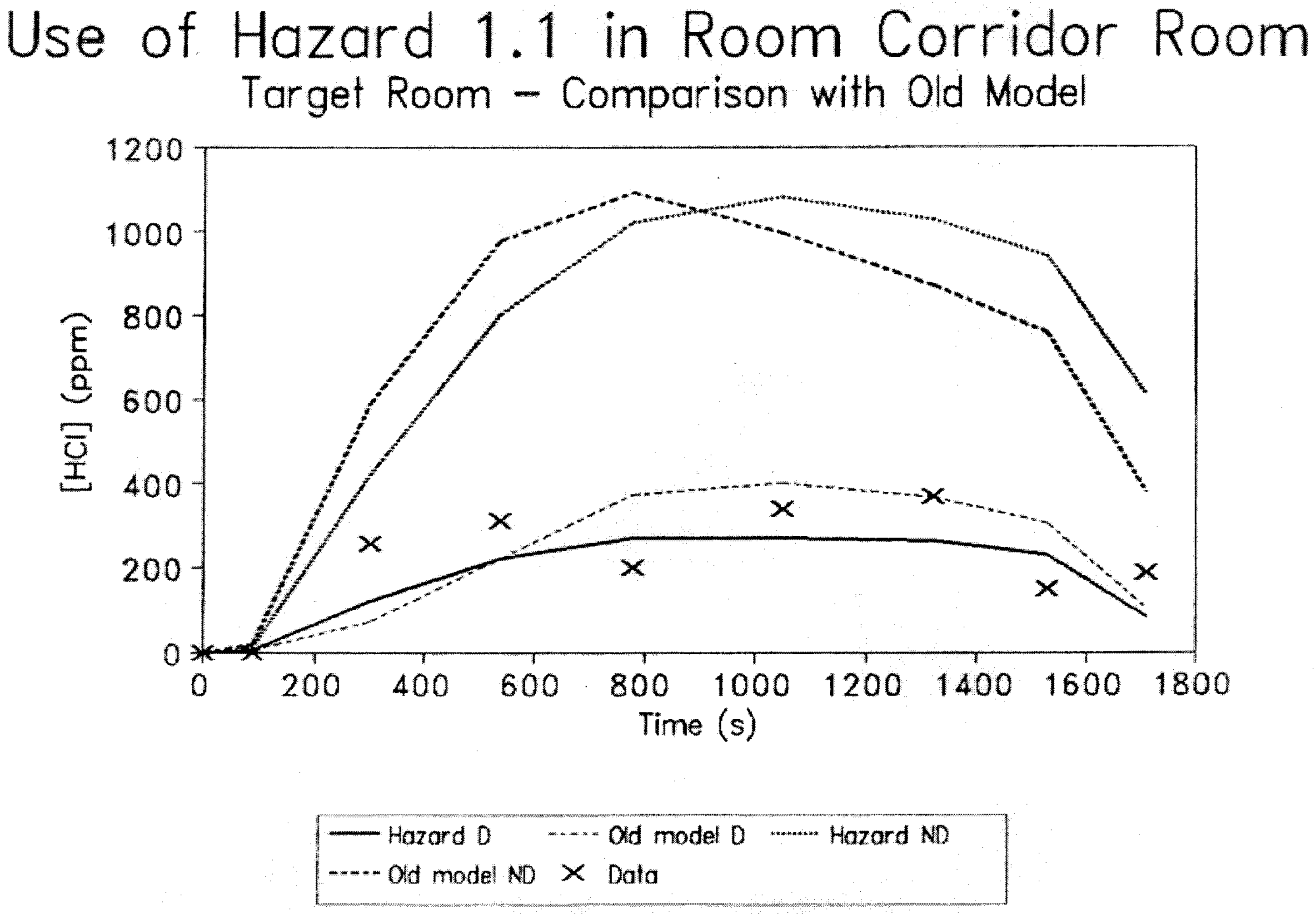

Use of Hazard 1.1 in Room Corridor Room
Target Room – Comparison with Old Model
[HCl] (ppm)
0
200
400
600
800
1000
1200
Time (s)
0
200
400
600
800
1000
1200
1400
1600
1800
Hazard D
Old model D
Hazard ND
Old model ND
Data

FIGURE 8

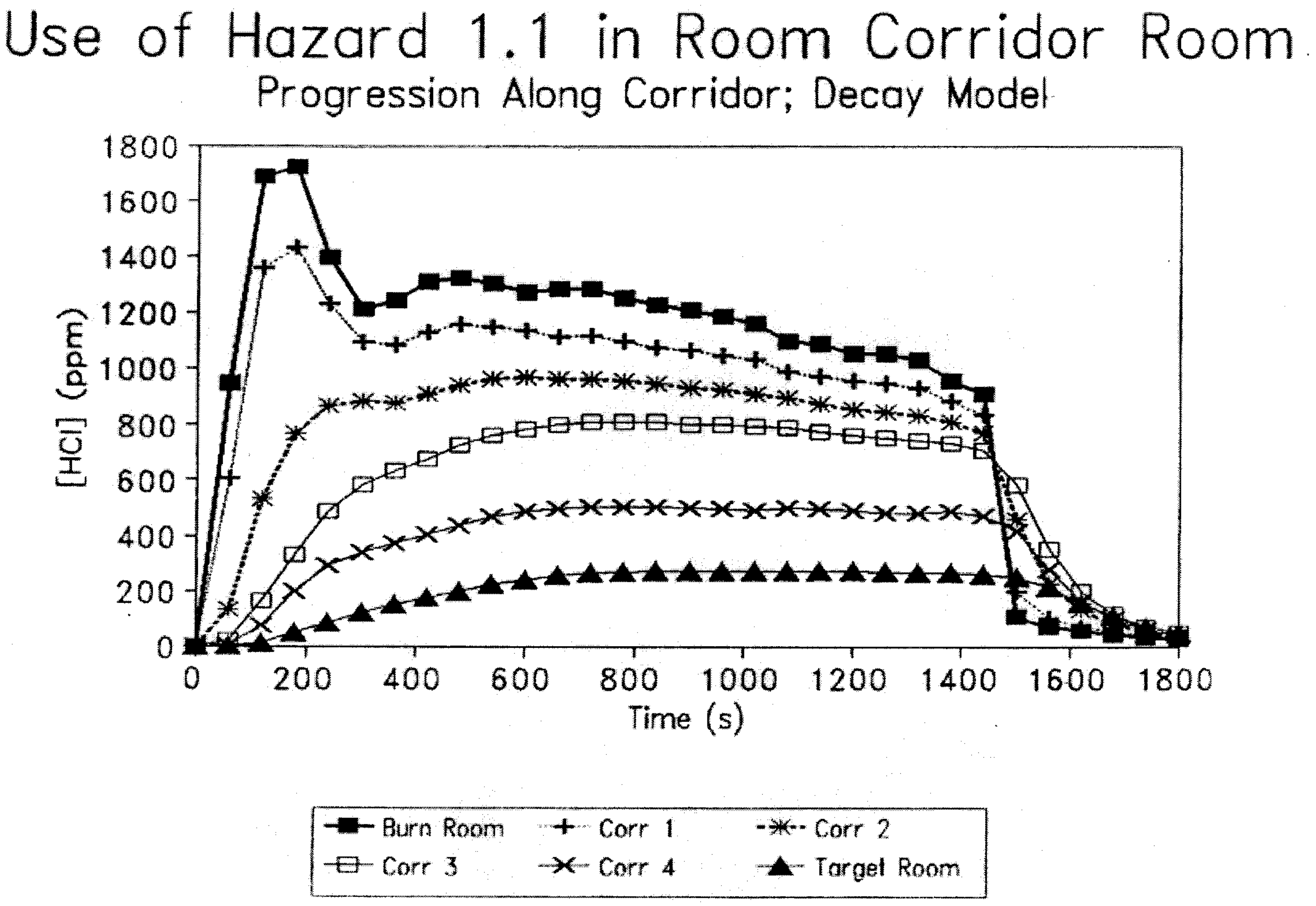

Use of Hazard 1.1 in Room Corridor Room
Progression Along Corridor; Decay Model
[HCl] (ppm)
1800
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)
Burn Room
Corr 1
Corr 2
Corr 3
Corr 4
Target Room

FIGURE 9

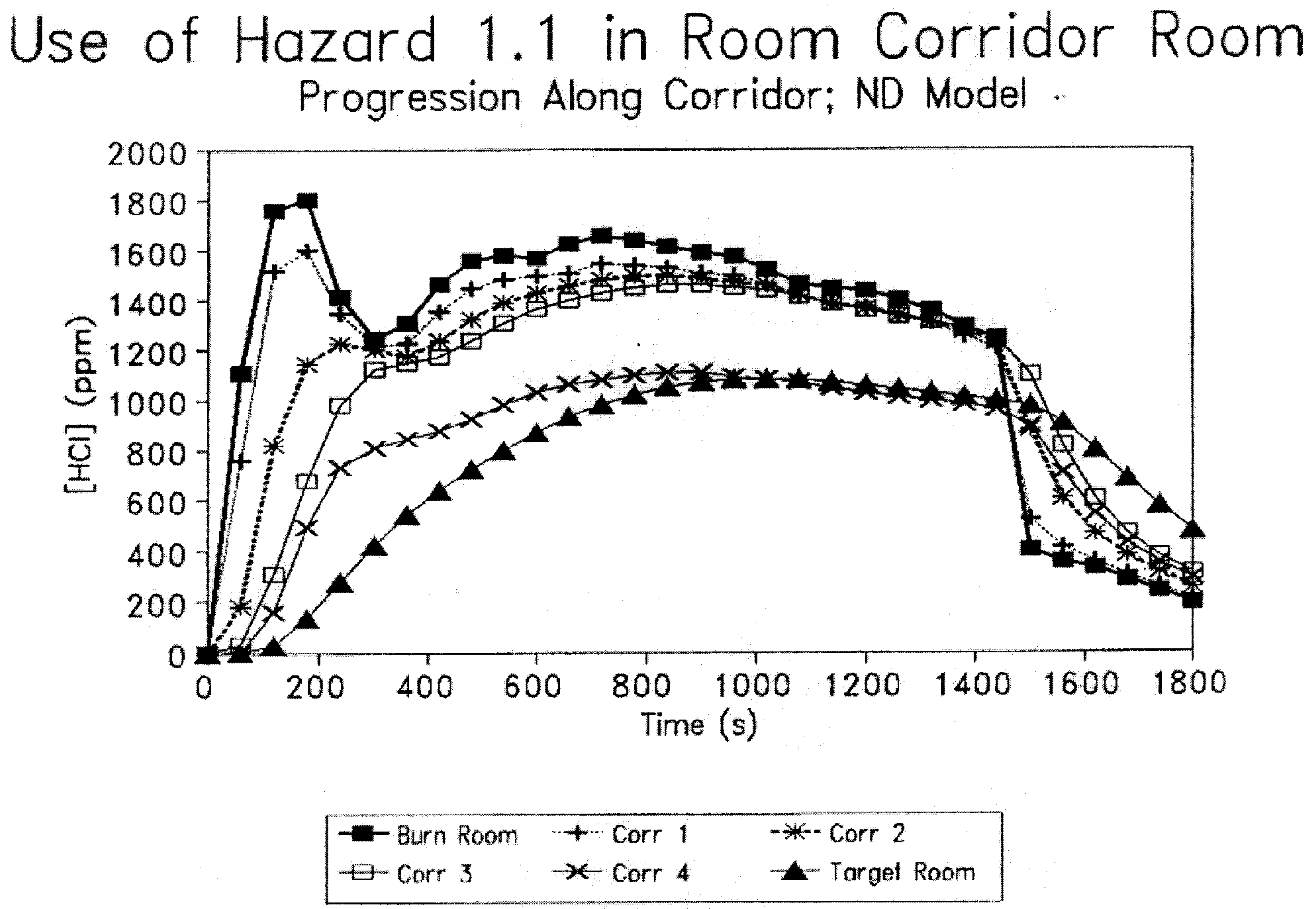

Use of Hazard 1.1 in Room Corridor Room
Progression Along Corridor; ND Model
2000
1800
1600
1400
1200
1000
800
600
400
200
0
[HCl] (ppm)
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)
Burn Room
Corr 1
Corr 2
Corr 3
Corr 4
Targel Room

FIGURE 10

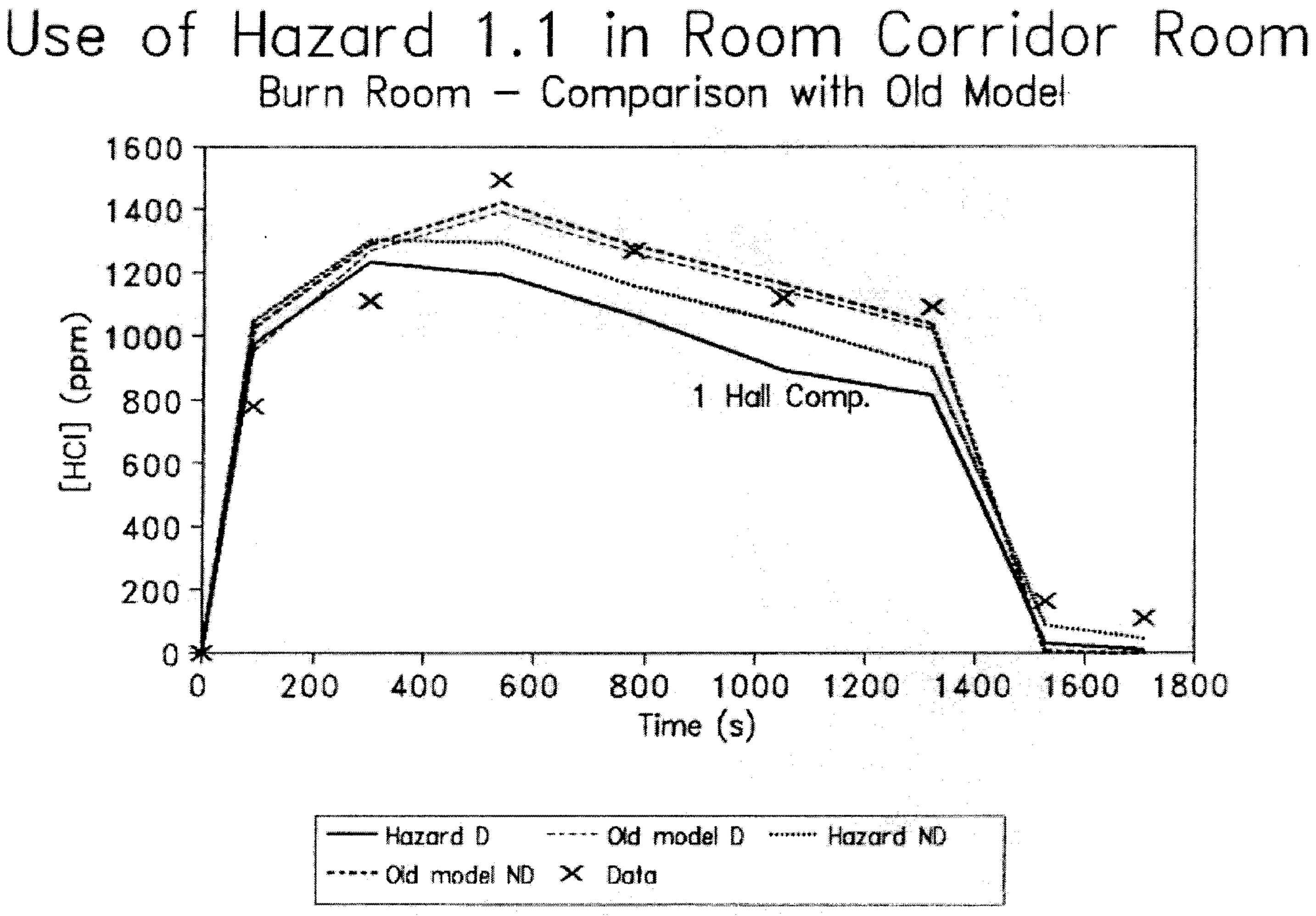

Use of Hazard 1.1 in Room Corridor Room
Burn Room – Comparison with Old Model
[HCl] (ppm)
1600
1400
1200
1000
800
600
400
200
0
Time (s)
0
200
400
600
800
1000
1200
1400
1600
1800
1 Hall Comp.
Hazard D
Old model D
Hazard ND
Old model ND
Data

FIGURE 11

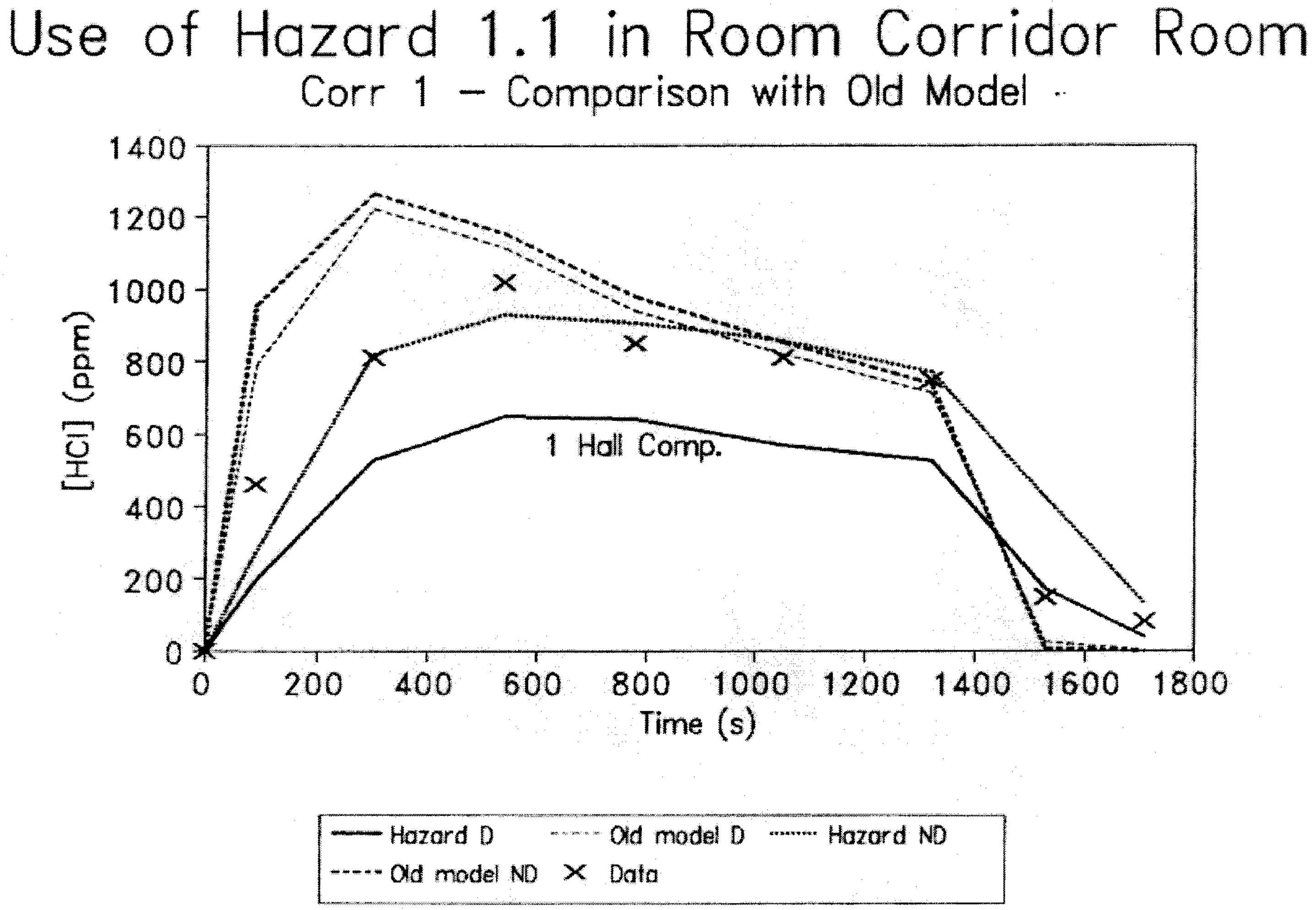
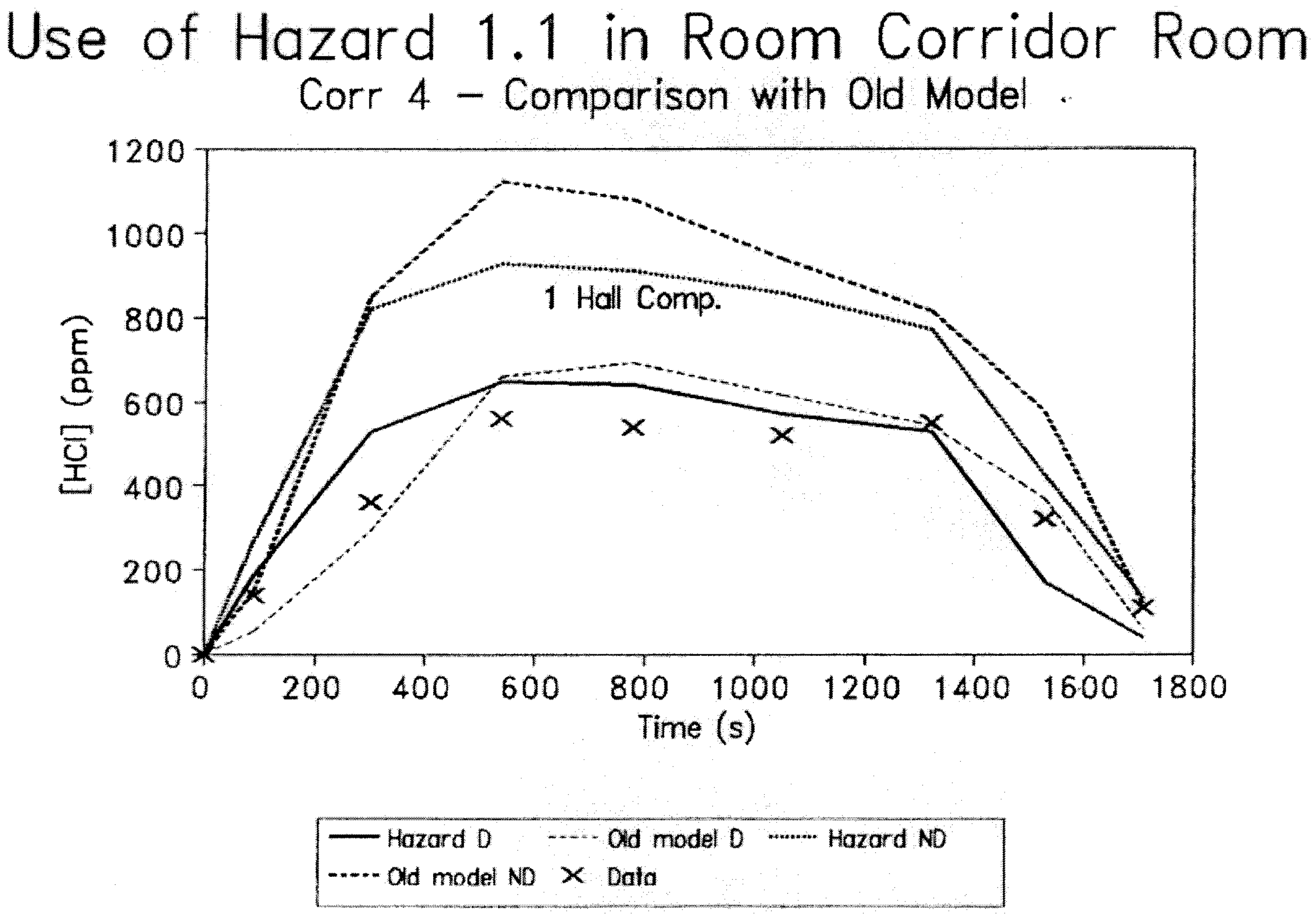

Use of Hazard 1.1 in Room Corridor Room
Corr 1 – Comparison with Old Model
[HCl] (ppm)
1400
1200
1000
800
600
400
200
0
1 Hall Comp.
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)
Hazard D
Old model D
Hazard ND
Old model ND
Data

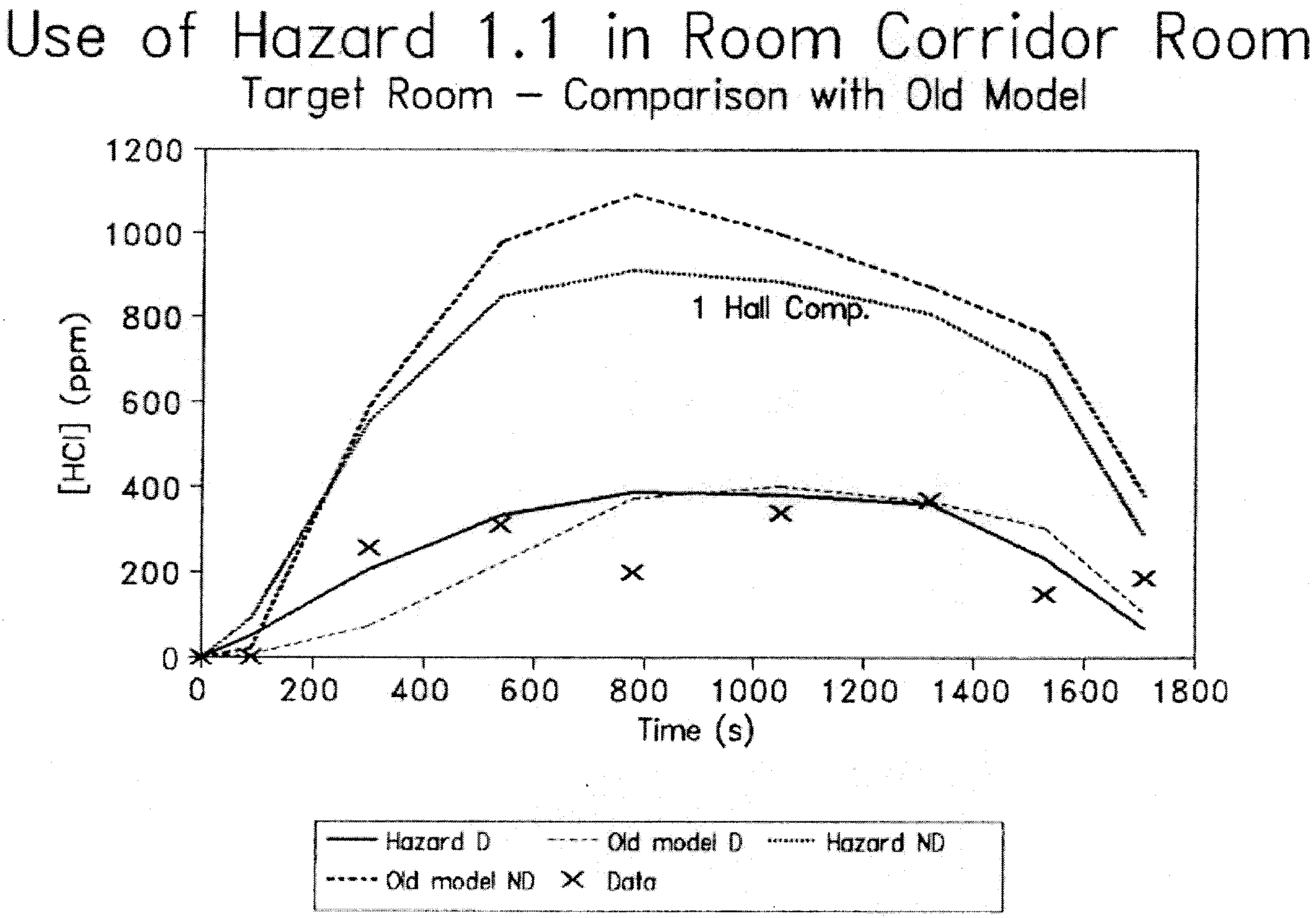
FIGURE 12



Use of Hazard 1.1 in Room Corridor Room

Corr 4 – Comparison with Old Model

FIGURE 13



Use of Hazard 1.1 in Room Corridor Room
Target Room – Comparison with Old Model
[HCl] (ppm)
0
200
400
600
800
1000
1200
Time (s)
0
200
400
600
800
1000
1200
1400
1600
1800
1 Hall Comp.
Hazard D
Old model D
Hazard ND
Old model ND
Data

FIGURE 14

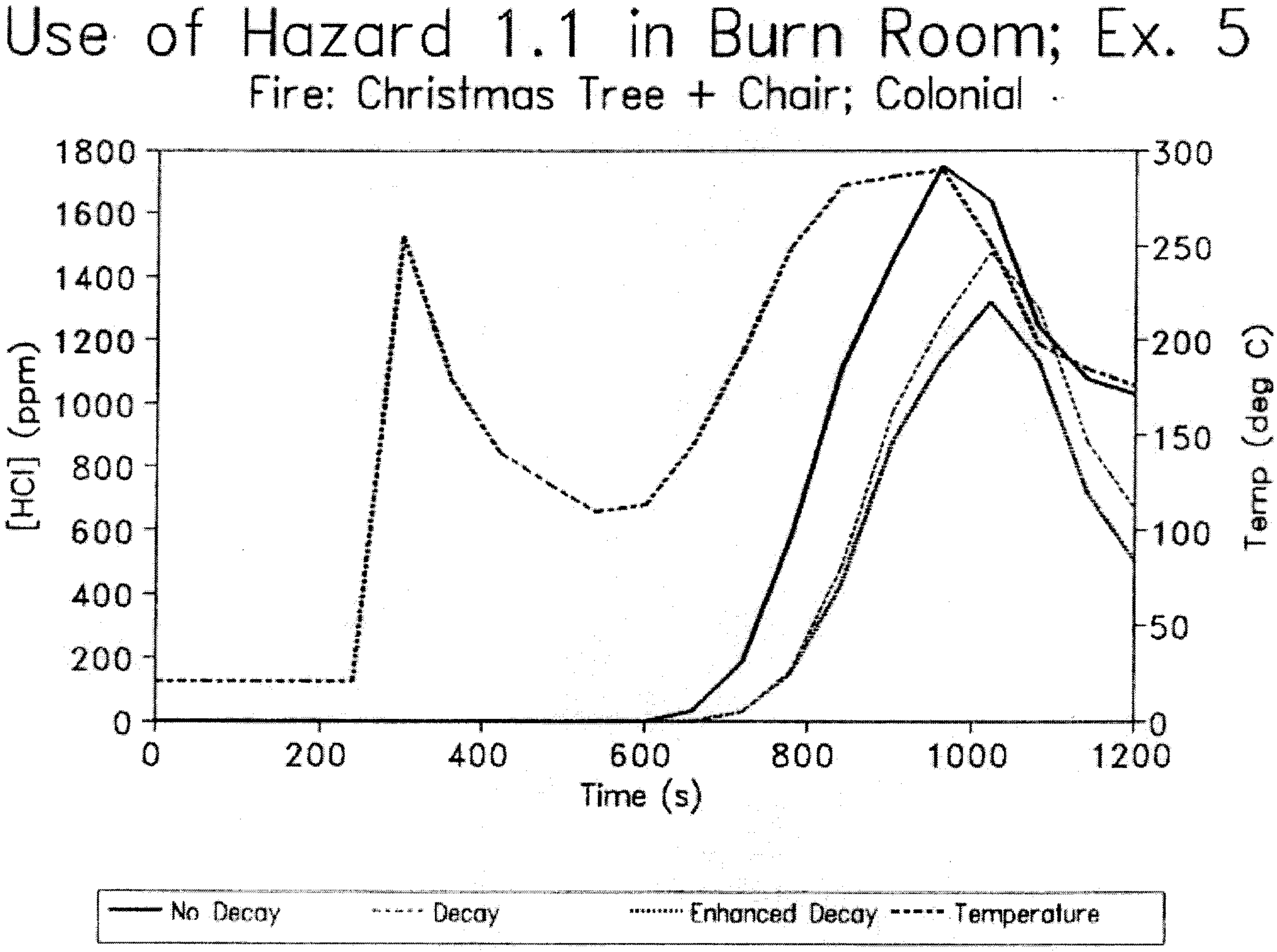
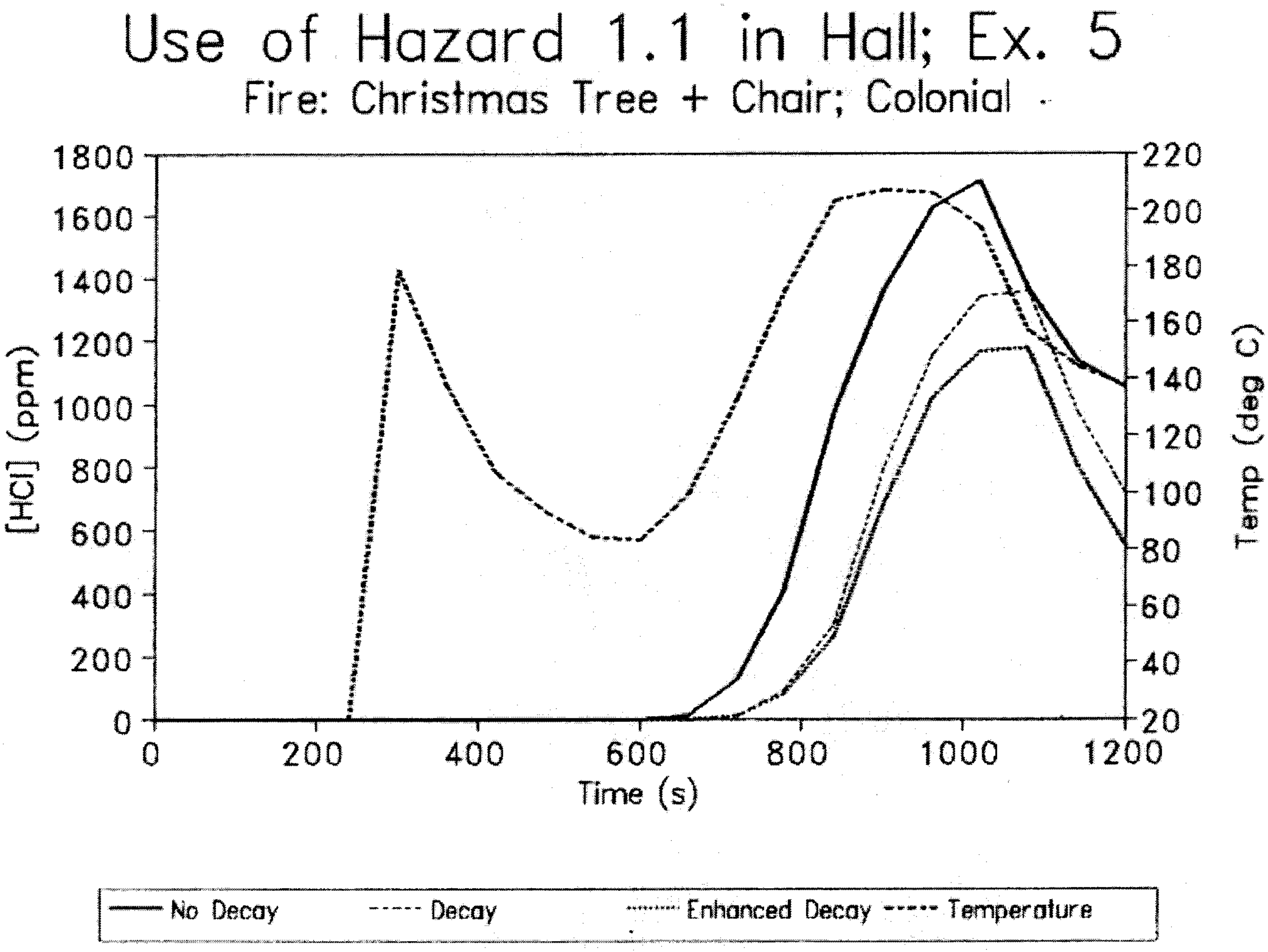

Use of Hazard 1.1 in Burn Room; Ex. 5
Fire: Christmas Tree + Chair; Colonial
[HCl] (ppm)
0
200
400
600
800
1000
1200
1400
1600
1800
Temp (deg C)
0
50
100
150
200
250
300
Time (s)
0
200
400
600
800
1000
1200
No Decay
Decay
Enhanced Decay
Temperature

FIGURE 15



Use of Hazard 1.1 in Hall; Ex. 5
Fire: Christmas Tree + Chair; Colonial
[HCl] (ppm)
0
200
400
600
800
1000
1200
1400
1600
1800
Temp (deg C)
20
40
60
80
100
120
140
160
180
200
220
Time (s)
0
200
400
600
800
1000
1200
No Decay
Decay
Enhanced Decay
Temperature

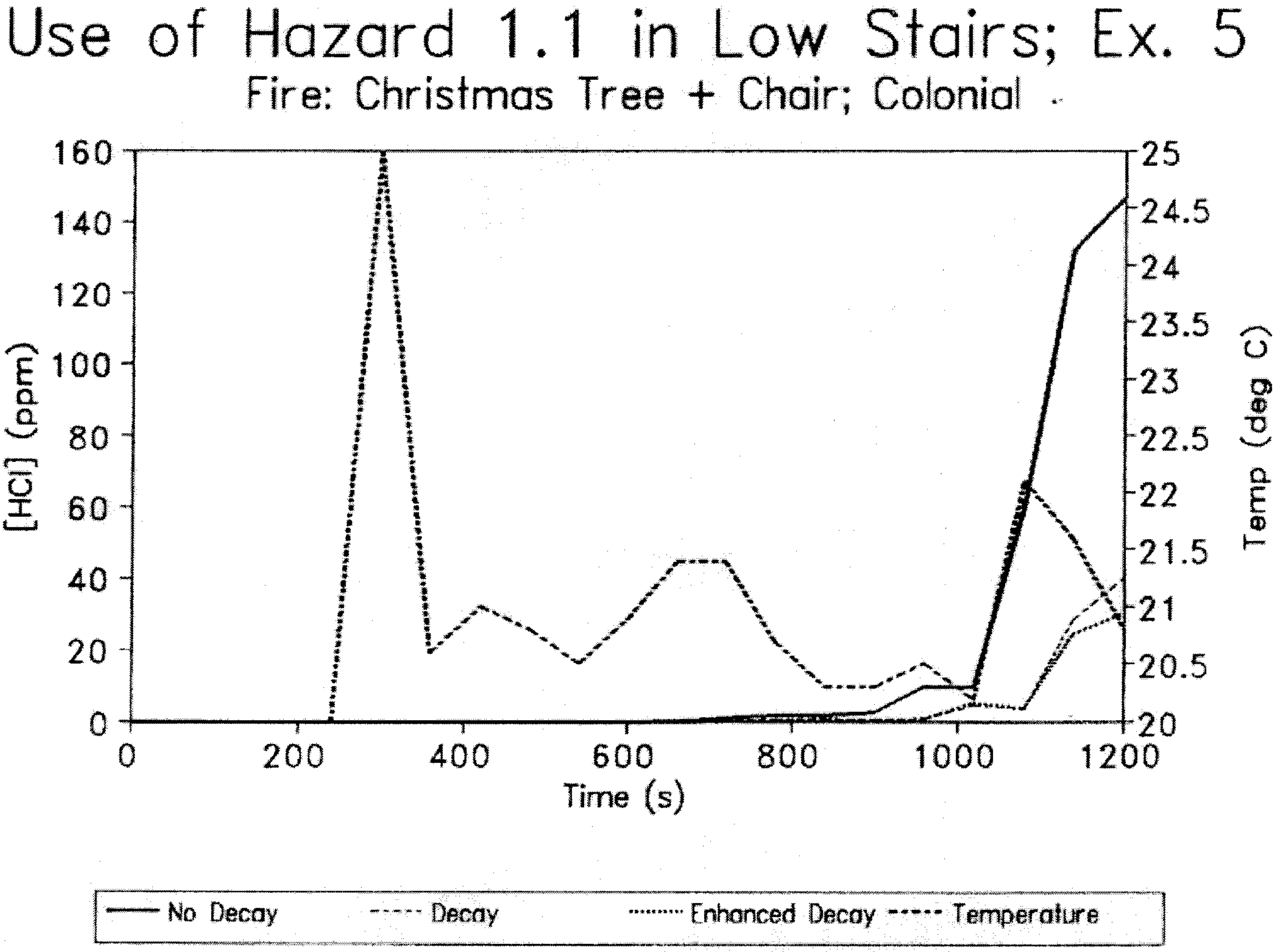

Use of Hazard 1.1 in Low Stairs; Ex. 5
Fire: Christmas Tree + Chair; Colonial
[HCl] (ppm)
0
20
40
60
80
100
120
140
160
Temp (deg C)
20
20.5
21
21.5
22
22.5
23
23.5
24
24.5
25
Time (s)
0
200
400
600
800
1000
1200
No Decay
Decay
Enhanced Decay
Temperature

FIGURE 17

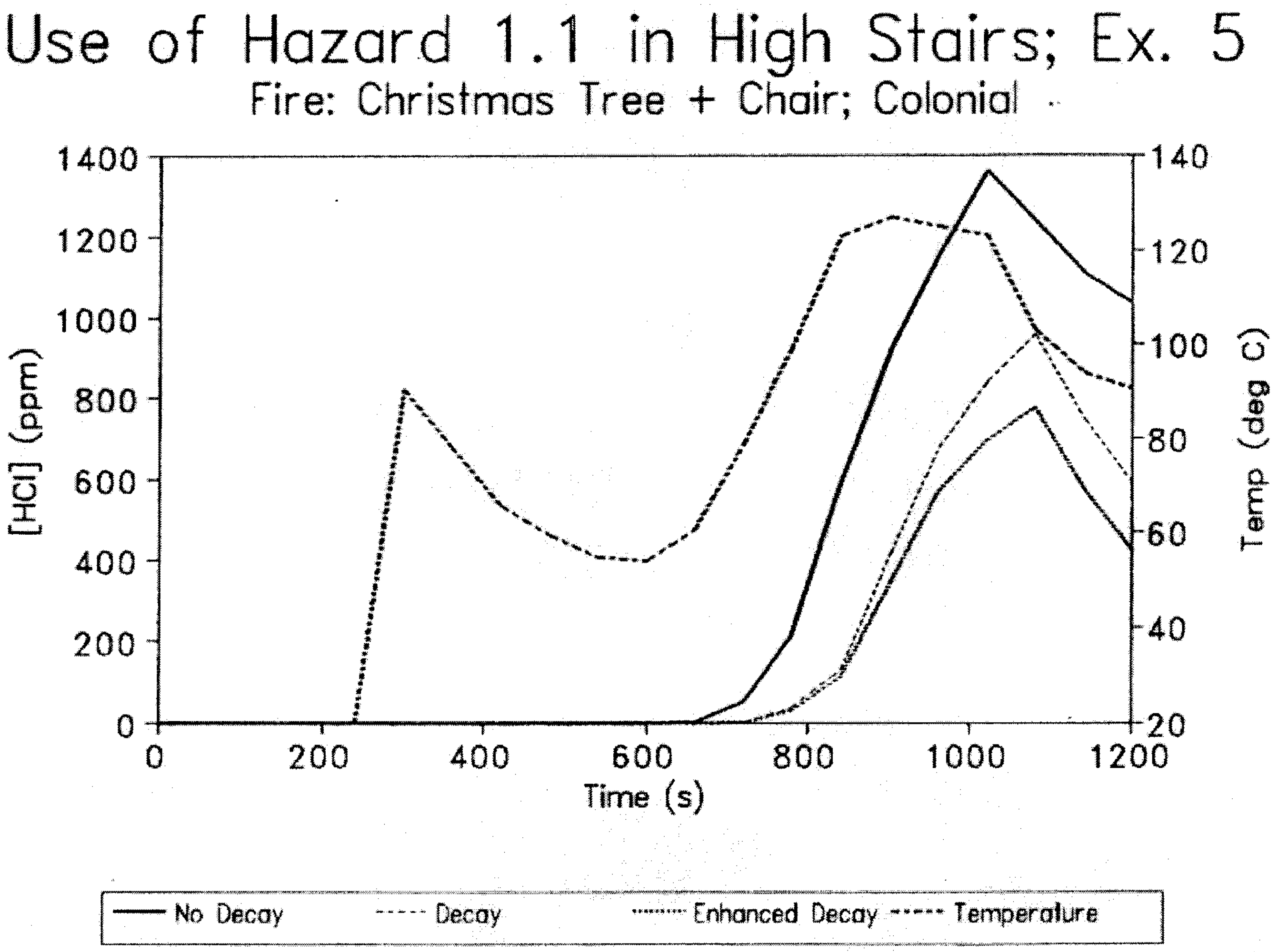
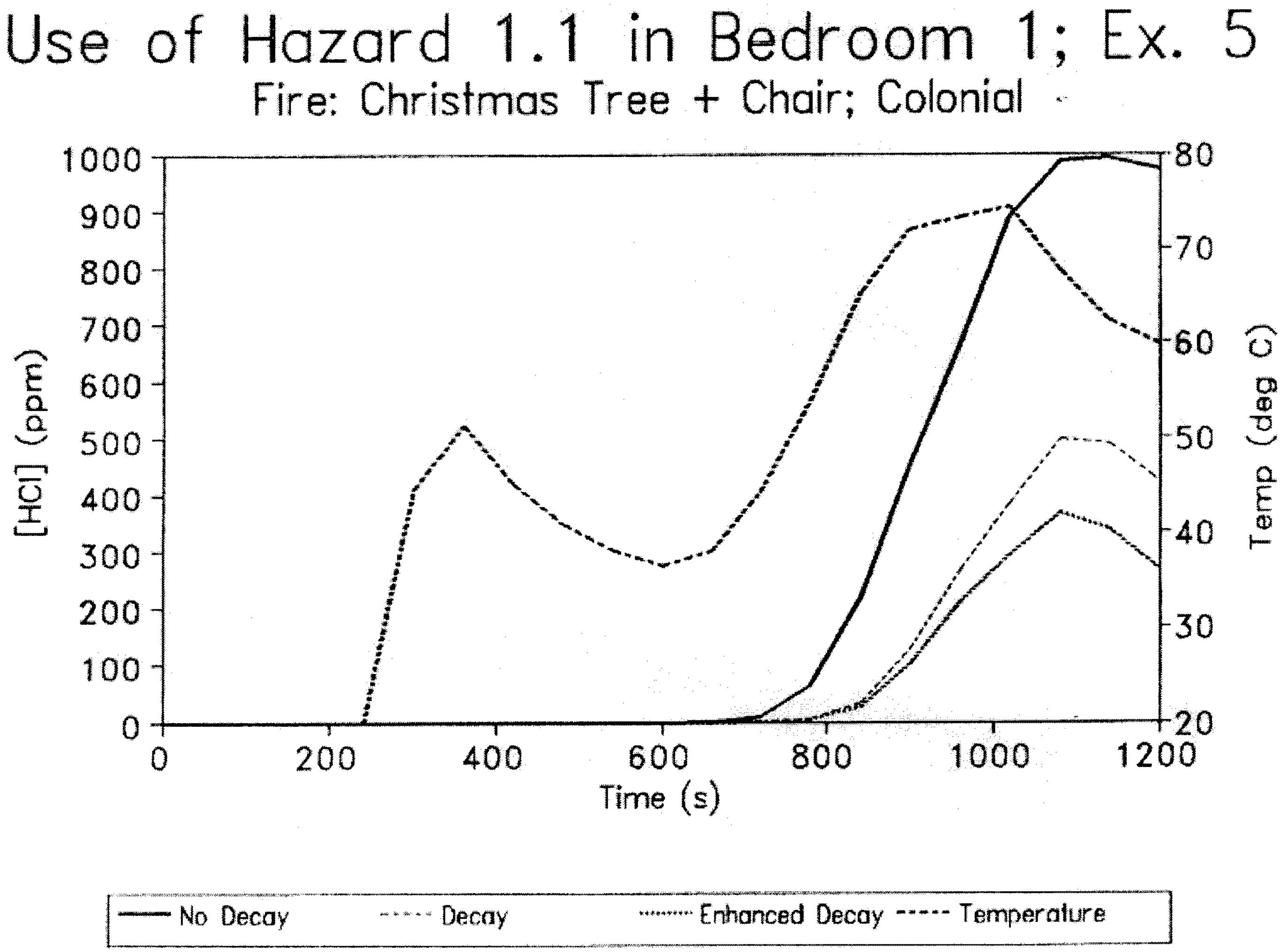
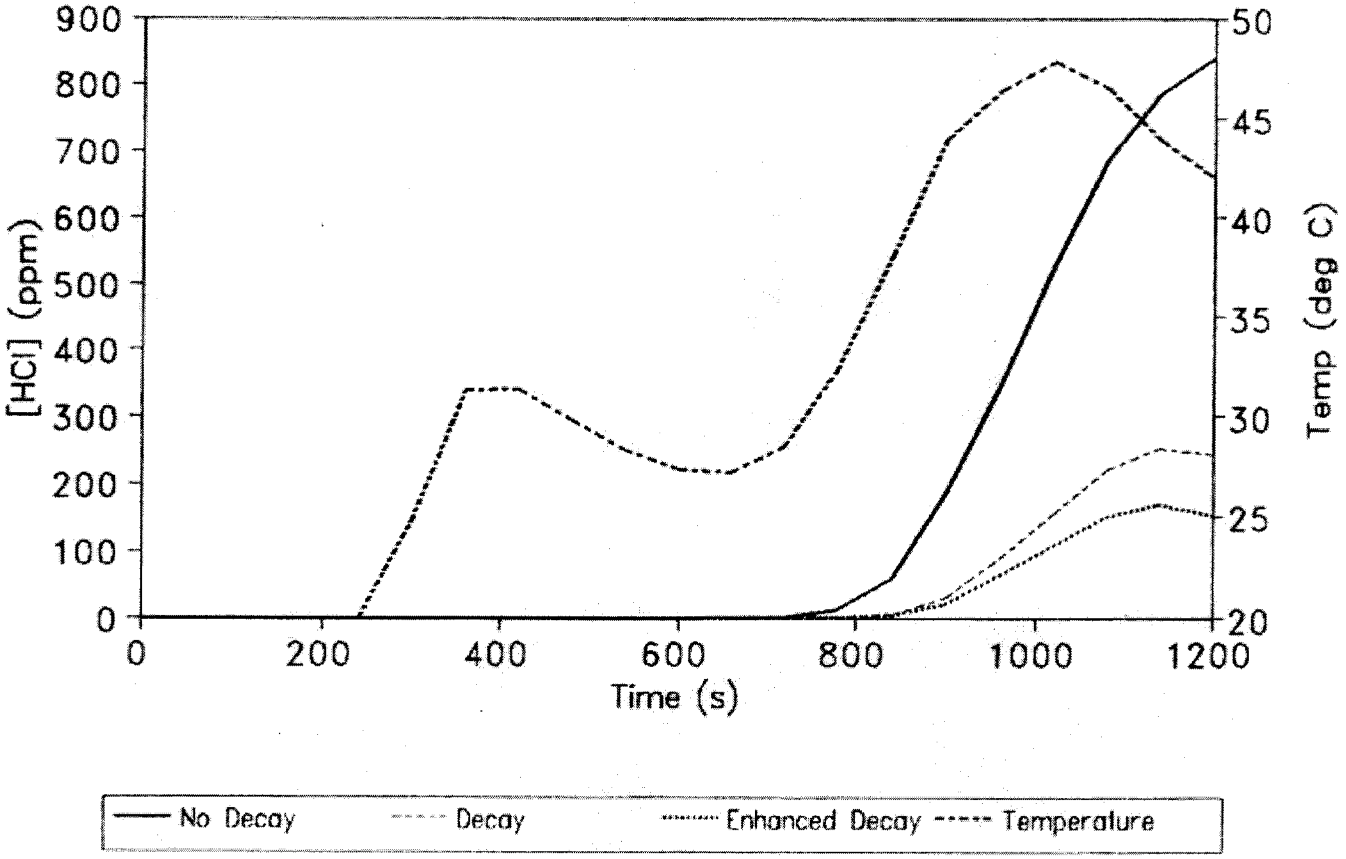

Use of Hazard 1.1 in High Stairs; Ex. 5
Fire: Christmas Tree + Chair; Colonial
[HCl] (ppm)
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
Time (s)
140
120
100
80
60
40
20
Temp (deg C)
No Decay
Decay
Enhanced Decay
Temperature

FIGURE 18


Use of Hazard 1.1 in Bedroom 1; Ex. 5
Fire: Christmas Tree + Chair; Colonial
[HCl] (ppm)
1000
900
800
700
600
500
400
300
200
100
0
Temp (deg C)
80
70
60
50
40
30
20
0
200
400
600
800
1000
1200
Time (s)
No Decay
Decay
Enhanced Decay
Temperature

Use of Hazard 1.1 in Bedroom 2; Ex. 5

Fire: Christmas Tree + Chair; Colonial



GBH Attachment 28

AB59-COMM-7-28

Application of a Transport and Decay Model for Hydrogen Chloride to Hydrogen Chloride Generation in the Presence of Various Fluids and Surfaces, but Without Poly(vinyl Chloride)

F. Merrill Galloway[1] and Marcelo M. Hirschler[2]

"Application of a transport and decay model for hydrogen chloride to hydrogen chloride generation in the presence of various fluids and surfaces, but without poly(vinyl chloride)", F.M. Galloway and M.M. Hirschler, Fire and Materials, 18, 31-43 (1994).

ABSTRACT

In a total of 63 experiments, all of them carried out in a 200 L plastic chamber, a large amount of HCl (800 - 1,000 mL) was injected. In no case was the HCl generated from decomposition of poly(vinyl chloride). The chamber contained a variety of surfaces. Furthermore, various fluids were injected into the chamber together with the HCl. The fluids used were: water, ethylene glycol, ethylene glycol/water 50/50 mixture, a model for airborne smoke particulates (and several partial models for such synthetic smoke) and mineral oil. The surfaces used were PMMA, painted gypsum board, ceiling tile and soot.

The results showed the efficiency of many of these fluids as sinks for HCl: hydrophilic fluids are good HCl sinks, with water and synthetic smoke being the most effective.

A previously developed zone model for HCl transport and decay, contained within the NIST fire model Hazard 1.1, and used most often to investigate HCl formation from PVC combustion or pyrolysis, was used to predict the results of the experiments in this work. The correlation between experimental and predicted atmospheric HCl concentrations was made without fitting any new parameters. The results were excellent.

This work shows that the HCl transport and decay model is robust enough that it can be applied to a number of scenarios where HCl is present, even in the absence of PVC. The model is, thus, of particular use in fire hazard assessment.

1. INTRODUCTION

The phenomenon of hydrogen chloride (HCl) decay (i.e. the fact that HCl does not remain in the atmosphere for a long time) has been studied for a long time. This includes studies by different authors, starting in the late 1960's and going through the early 1980's. BFGoodrich and the Vinyl Institute, however, started a comprehensive program in the mid 1980's, studying all reasonable facets of the issue. This has resulted in several publications, the most important of which

---

[1] BFGoodrich, 9921 Brecksville Road, Brecksville, OH, 44141

[2] Safety Engineering Laboratories, 38 Oak Road, Rocky River, OH, 44116

are references # 17-31. Thus, HCl does not remain for long in a fire atmosphere. Rather, its atmospheric concentration decreases, at a rate dependent on external conditions. The decay of HCl takes place at most gas-solid interfaces, by adsorption onto the solid material followed by a mixture of reaction and diffusion.

The main importance of the decay of HCl is in connection with the toxicity of fire atmospheres, because HCl is a major product resulting from the combustion of a widely used synthetic material, poly(vinyl chloride) (PVC) [32-33]. PVC is present in about one third of all fires, because of its wide range of applications [34-35]. Interestingly, the highest HCl concentration measured in a set of real fires where gas analyses were made was only 280 ppm [34-36]. Therefore, when fire hazard is assessed, HCl decay is an aspect that needs to be taken into account.

The BFGoodrich/Vinyl Institute program has involved many experimental series of studies, to investigate the lifetime of HCl in a fire atmosphere, accompanied by appropriate modelling work. The work has shown that HCl reacts very rapidly with common construction surfaces (e.g. cement block, ceiling tile, gypsum board), particularly if they are sorptive. Moreover, atmospheric HCl concentrations peak at values much lower than would have been predicted from the chlorine content of the burning material. Moreover, HCl soon disappears completely from the atmosphere. The overall model developed, which accounts for the generation (usually from decomposition of PVC), transport and decay of HCl in a fire, has been validated with several large- and small-scale experiments. Large scale experiments used involved the following scenarios: room-plenum, room-corridor, room-corridor-room and a heating-ventilating-air conditioning (HVAC) system. In small scale scenarios, the phenomenon of HCl generation under conditions where decay was kept artificially at a minimum was also examined.

It was, thus, decided that there was one potential gap in the model: the effect of surfaces and fluids (simulating smoke and other fluids potentially present in a fire) on HCl generated in the absence of PVC.

2. EXPERIMENTAL

2.1 Apparatus

A plastic (poly(methyl methacrylate), PMMA) chamber, with external dimensions of 1.22 m long, 0.43 m wide and 0.33 m high was used for all experiments (total volume: 172 L). Air circulation in the chamber was purely due to convection and gravity; there was no forced air movement.

The chamber was positioned vertically (i.e. standing on one of the 0.33 m x 0.43 m ends) during the majority of the experiments. However, it was also positioned horizontally in some experiments (i.e. standing on a 0.33 m x 1.22 m end). Finally in some experiments involving carbon black the chamber was sited horizontally, but tipped 90 degrees, so that it was lying on a 1.22 m x 0.43 m surface.

Hydrogen chloride was injected into the chamber via a specially-constructed syringe made of glass and polytetrafluoroethylene and capable of delivering up to 1,500 cm^3 of a gas. It entered the chamber through a back wall (i.e. one of the 0.33 m x 1.22 m surfaces, which was never at the bottom). Rubber septa covered sampling ports in the plastic walls located in the center of the front vertical side (i.e. the other 0.33 m x 1.22 m surface) and also in the center of the top panel (i.e. the free 0.33 m x 0.43 m end). Again, neither of these surfaces was ever placed at the bottom.

2.2 Materials

The pure chemicals used were reagent grade: hydrogen chloride, deionized water, ethylene glycol. Other materials used were:

- mineral oil. This was used to simulate the hydrophobic constituents of smoke.
- polyacrylic acid (Carbopol™ 940 or Carbopol™ 941, BFGoodrich products). This is a commercial polymeric emulsifier which allows suspensions (apparently homogeneous) to be created with mixtures of water and carbon black or water and mineral oil.
- carbon black (Monarch 700 (Cabot: 200 m^2/g surface area; 18 x 10^{-9} m particle diameter) or Raven 410 (Citco: 23 m^2/g surface area; 70 x 10^{-9} m particle diameter)). This was used to simulate soot.

Synthetic smoke was manufactured in two steps:

- Carbopol™/carbon black suspension, containing 78.9% water, 19.7% of 0.5% 940 Carbopol™ solution and 1.7% of Raven carbon black.
- In one experiment the Raven carbon black was replaced by Monarch carbon black.
- Synthetic smoke, containing 59.2% water, 18.4% of 1.0% 941 Carbopol™ solution, 1.9% of Monarch carbon black, 10% surfactant and 19.5% mineral oil.

Surfaces used were all identical to those described in earlier work, viz. painted gypsum board (PGB), poly(methyl methacrylate) (PMMA) and ceiling tile (back side, CT). The paint used was a Satin Latex Wall Paint matte flat, and two thick layers were applied.

2.3 Procedure

In most experiments 1,000 cm^3 of HCl gas were introduced into the PMMA chamber. Samples of HCl, 50 cm^3 in volume, were taken from the sampling ports mentioned, using gas tight syringes. The first sample was taken 10 s after HCl entered the chamber, and the remaining samples were collected after selected intervals. Test duration was approximately one hour.

Conditions within the chamber were varied from one experiment to another. Different surfaces were placed into the chamber, on the floor, side or top of the chamber. The exposed areas of the added surfaces ranged from 0.43 x 0.33 m to 1.22 x 0.33 m, and several combinations of locations were used. In a few cases the temperature in the laboratory was raised or lowered from the standard value of 23 °C.

Between experiments the chamber was purged with dry air (passing through silica gel), forced through with an air circulation pump. No air purge was deemed necessary when a PGB or CT surface was used, since the surfaces were already saturated with water from the standard laboratory atmosphere (50 % relative humidity).

Fluids were injected using an ultrasonic atomiser (Sonotek), fed by a peristaltic pump (Gilson Minipuls II), with speed control display. Fluid injection was usually started simultaneously with HCl injection. The volume of fluid injected was calibrated, gravimetrically, for every fluid. Carbon black, when used on its own, was spread on the floor of the chamber, prior to closing it.

2.4 HCl analysis

A small amount (2 cm^3) of a dilute (10^{-4} M) HCl solution was added to the gas sample collected in the syringe. This was shaken for a sufficiently long period (ca. 30 s) to ensure total dissolution of HCl gas into the aqueous solution. The solution was then placed into a custom-made, minimum volume, polytetrafluorethylene sample holder. The HCl concentration was then measured using an Orion Expandable Ion Analyzer EA920, with chloride ion selective electrodes. Corrections were made to account for the HCl solution added.

Table 1 details all the experiments carried out, and the conditions used for them.

3. MODEL FORMULATION

The model for decay of HCl from the atmosphere onto various surfaces has been described in detail elsewhere [25, 27]. Briefly, it assumes a uniform HCl concentration in the bulk gas phase, with transport across the gas boundary layer, described by a mass transfer coefficient, and partitioning of the HCl at the gas/wall interface, described by a surface specific equilibrium coefficient. The model also assumes that HCl "disappears" into the wall surface following first order reaction rate kinetics. The corresponding first order rate constant, which is specific to the surface material, describes the rate of HCl reaction with the surface. This model is used without modification in the examples in this paper for HCl decay on fixed chamber surfaces.

3.1 Extension of the Model to Liquid Droplets

The model was extended to simulate HCl transport to the liquid phase droplets as follows. The pump/atomizer combination (Minipuls) continuously injected the droplets. However, for the purpose of modelling, the droplets were accumulated into one minute groupings; i.e., all drops injected in a given one minute interval were assumed to have been injected simultaneously and to have completely uniform characteristics. Thus, if in a given experiment fluid injection continued for 20 min, there would be twenty such groups of droplets. The total mass of the droplets in each group is determined by the pumping rate. Since the pumping rate was essentially constant during a given experiment, each group had the same total initial mass. The number of drops in a group is determined by the drop diameter. This initial diameter was determined indirectly from the data, as described in the results section. Since the same atomizer was used throughout, the initial drop diameter was assumed to be constant from group to group, and experiment to experiment. It was further assumed that each drop remained distinct and eventually fell to the bottom of the chamber (rather than drifting into the sides, which some surely did). All of these simplifications regarding droplet dynamics are justifiable, as will be seen in the results section.

3.2 Transport of HCl between gas and droplet phases

Transport of HCl between the gas and droplet phases can be written in terms of a mass transfer coefficient as [37]:

$$F_{HCl} = k * A * ([HCl]_g - [HCl]_e) \tag{1}$$

where F_{HCl} is the inter-phase transfer rate of HCl, in g mol/min, k is the mass transfer coefficient, in cm/min, A is the total area of a droplet group, in cm^2, $[HCl]_g$ is the gas phase HCl concentration, in g mol cm^{-3} and $[HCl]_e$ is the gas phase concentration of HCl that is in equilibrium with the given droplet phase concentration of HCl, in g mol cm^{-3}. Thus, as defined here, transport of HCl from the gas to the droplet phase is positive. At any given time, $[HCl]_g$ and A are known, as is the droplet phase HCl concentration. In order to calculate F_{HCl}, values for k and $[HCl]_e$ are needed. The mass transfer coefficient k can be calculated from a correlation for mass transfer from spheres [38]:

$$\frac{(k * D_d)}{D_g} = 2 + [D_d * v_d \frac{r_g}{u_g}]^{0.5} * [\frac{u_g}{(r_g * D_g)}]^{0.33} \tag{2}$$

where D_d is the droplet diameter, D_g is the diffusivity of HCl in air, v_d is the droplet settling velocity, r_g is the gas density and u_g is the gas viscosity. All of these quantities are known or can be estimated by standard correlations; thus, k can be calculated from equation (2). In order to compute $[HCl]_e$, given the concentration of HCl in the droplet phase, the equilibrium distribution of HCl between gas and droplet phases must be known. In the cases where the droplets are pure water, an empirical correlation relating HCl molarity to HCl partial pressure is used [39]. In this case, the transport of water to/from the droplets is also handled exactly the same as for HCl.

3.3 Use of Henry's Law

In the cases where the droplets are not pure water, the partial pressure of HCl in equilibrium with the droplet phase is assumed to be defined by Henry's law:

$$P_{HCl} = H_{HCl} * X_{HCl} \tag{3}$$

where P_{HCl} is the partial pressure of HCl, in atm, X_{HCl} is the mol fraction of HCl in the droplet phase, based on HCl and water only, and H_{HCl} is the Henry's law constant for HCl in that particular liquid, also in atm. H_{HCl} is a parameter to be determined from the data. In this case, the partial pressure of water is determined from Raoult's Law:

$$P_{wat} = X_{wat} * P^{\circ}_{wat} \tag{4}$$

where P_{wat} is the partial pressure of water, in atm, X_{wat} is the mol fraction of water in the droplet phase, based on HCl and water only, and P°_{wat} is the vapor pressure of pure water at the system temperature.

3.4 Diffusion and mass transfer

Strictly speaking, equation (1) assumes not only a well mixed gas phase, but a well mixed droplet phase as well. Seinfeld [40] has considered characteristic diffusion times in droplets, and estimates them to be much less than 1 s for the size droplets considered here (on the order of 10 micro m diameter; see results section). Thus, the assumption of a well mixed droplet phase is well justified.

In addition to transport of HCl and water between the gas and droplet phases, as governed by equation (1) and an analogous equation for water, the position of the droplets in each group is followed as determined by the settling velocity of the droplets. When a group of droplets reaches the floor of the chamber, they are assigned to a "liquid film" phase, which is composed of all the droplet groups that have reached the floor. HCl and water equilibria are computed in the same way as for the droplets, based on the concentrations that exist in the liquid film. However, the mass transfer coefficient that governs transport is the one determined for the bottom surface of the chamber, and the area is the area of the bottom surface of the chamber. Thus, the product

$$k * A$$

for the liquid film phase is much smaller than it typically is for a droplet group.

In summary of the model extension to include a droplet phase, equation (1) simply becomes an additional source/sink term, representing transport to/from the droplet phase, for the previous model which included transport only to bounding surfaces.

4. COMPUTATIONAL METHODS

The model formulation results in equations for the time dependent concentrations of HCl and water in the gas phase and up to twenty droplet groups. Equations for HCl concentration also result for the top, side and bottom surfaces. In addition, there are equations for the vertical position of each droplet group, until it reaches the bottom of the chamber. These equations were numerically integrated using the fourth order Runge-Kutta method [41], with a step size of 0.005 min.

Parameter estimation, typically Henry's law constants and mass transfer coefficients to chamber surfaces in this investigation, was performed using the Marquardt method [42]. The objective function is the sum of the squares of the differences between measured and predicted gas phase HCl concentrations at various times during the experiments.

5. RESULTS

5.1 Empirical observations of effects

Figures 1-7 give a visual analysis of the major trends discovered. A few simple interpretations can be drawn easily from them.

5.2 Effect of carbon black

Figure 1 shows the effect of carbon black spread on the floor of the test chamber: it is clear that the presence of carbon black strongly increases the efficiency of the PMMA surface as an active sink for HCl. Moreover, this efficiency is a function of the amount of carbon black present (i.e. the number of layers).

5.3 Effect of surface location

Figures 2 and 3 show the effect of the mass transfer to the various locations in the chamber: B (bottom), T (top) and SL (side), for two types of surfaces: ceiling tile and painted gypsum board. When analyzing these effects, it must be remembered too that the different sides of the chamber have different dimensions, which will be taken into account in the subsequent analysis. Clearly, as was already found in earlier studies, ceiling tile is more sorptive toward HCl than painted gypsum board. Thus, surface location effects appear to be more noticeable with the less sorptive surface (painted gypsum board), where all curves are very easily distinguishable from each other.

Figure 4 compares the same effect of surface location in the presence of an added fluid (water, with the minipuls setting at 300): in this case the effect of the fluid overwhelms the effect of the surface location and all curves are identical.

5.4 Effect of water

Figure 5 shows the effect of water added, and also the effect of ambient temperature. It is clear that the effect of temperature is much smaller than the effect of water, but that temperature does, indeed, play a role, as had been found before. As the temperature increases, HCl decay becomes slower.

5.5. Effects of different fluids

Figures 6 and 7 address the different types of fluids. Figure 6 compares the effect of a Carbopol™/carbon black (CP/CB) solution, which is a very mediocre attempt to simulate smoke, with that of synthetic smoke, which also contains mineral oil and is, thus, a better simile for smoke. It appears that the synthetic smoke is a much more effective fluid to absorb HCl than the CP/CB solution. This is a curious result, because the principal additional component of synthetic smoke is mineral oil, a hydrophobic solvent, which has virtually no effect on HCl decay.

Figure 7 shows how mineral oil is almost inert towards HCl, after an initial very fast decay. The CP solution is less effective than ethylene glycol, which, in turn, is less effective than the ethylene glycol-water mixture. The synthetic smoke, at a 4 times lower pumping rate (minipuls setting of 125 rather than 600) is about as effective as ethylene glycol. A caveat is needed, however: the minipuls setting does not describe the mass flow rate of the fluid, as will be discussed later.

5.6 Determination of Initial Drop Size

An estimate of drop size is needed since drop size appears in the mathematical model formulation. Two of the experiments involving only PMMA surfaces and pure water as the droplet liquid were performed by introducing the liquid droplets for some time prior to injection of the HCl sample. The introduction of droplets was stopped simultaneously with the HCl injection. Thus, the only droplets effective in removing HCl from the gas phase would be the ones that had not yet settled to the bottom. The liquid film formed on the bottom would absorb HCl from the gas, but at a much slower rate than the equivalent amount of water in the droplet phase. The amount of water still in the droplet phase at the time of HCl injection depends on the droplet settling velocity, which in turn is proportional to droplet diameter squared. These simulations showed that a value of 26 micro m gives a predicted decay rate that is too slow, indicating that too many of the droplets had already settled out. Conversely, a value of 7.8 micro m predicts a decay rate that is too rapid, indicating too many droplets still traveling through the gas. The value of 10 micro m for the initial droplet diameter gave the correct decay rate; thus, this value was used in the rest of the simulations for initial droplet size.

With an initial droplet diameter of 10 micro m, the surface area of the droplet phase is large, as is the product, k * A, in equation (1). In order to preserve stability of the numerical integration without imposing an impractically small integration step size, an upper limit of 100,000 (cm^3/min) was placed on k * A. This is equivalent to a relaxation time on the order of 1 min for the approach to equilibrium between the gas phase and the droplet phase. Since the decay times in most of the experiments is of the order of 10 min, making the upper limit for k * A larger would not significantly change the results.

6. DISCUSSION

6.1 Grouping of Experiments for Simulation

Table 2 is a summary of how the experiments were grouped for simulation. It describes, too, which parameters were regressed and their resulting values for each group of experiments. Table 3 summarizes how the mass transfer coefficients were determined for each case. Parameters for fluid delivery equations are in Table 4.

6.2 Experiments with vertical chamber, added surfaces but no fluid

Case 1 consisted of eight experiments (numbers 38-45), in which an active surface of painted gypsum or ceiling tile was placed on a side, the bottom or the top of the 200 L chamber. The chamber was vertically placed in these experiments. No droplets (no fluid) were introduced in these experiments. Since parameters characterizing the sorptive capacity of these surfaces for HCl had been determined from previous work [30], the only unknown parameters in the model were the mass transfer coefficients for the side, bottom and top walls of the chamber. These were found, by regression, to be 8.7, 19.8 and 0.25 cm/min, respectively. In previous work [23], using the same size chamber but with a heated wire (and burning wire insulation) running across the bottom which created natural convection currents, corresponding values of 15, 50 and 90 cm/min were determined. Since there was nothing except slight temperature differences between the walls and interior gas to set up convection currents in the examples of Case 1, it is not surprising that the values found in the previous case were higher. The upward buoyant plume was reasoned to be responsible for the maximum mass transfer to the top surface in the previous case. The explanation for the relative values of k to the various surfaces in the present case is not clear. However, it could be conjectured that because of the lack of any other strong convective driving forces, the initial density difference between the injected (essentially horizontally) HCl and the air inside the chamber was the dominant driving force, causing an initial downward flowing plume of HCl to be created. This case, and the following one, involved the tests with the highest experimental error because the lack of droplet injection, to create gas circulation, means that HCl is unevenly distributed in the chamber.

6.3 Experiments with horizontal chamber, no added surfaces and no fluid

Case 2 consisted of three experiments (numbers 1, 2 and 4), involving only PMMA surfaces and again no droplet phase, with the chamber placed horizontally. The mass transfer coefficients found in Case 1 were used for the analysis. Previously determined surface parameters for PMMA were also used [30]. However, these parameters are for a PMMA surface exposed to a relatively low concentration level of HCl. It has been observed before [30] that when surfaces are exposed to very large amounts of HCl, or the same surface is repeatedly exposed to HCl, that surface gradually loses its capacity to absorb HCl. This had been modelled by using a multiplying factor containing two parameters (D_{max}, or DOSEMAX, maximum amount of HCl a surface can absorb before its activity is reduced to zero, in kg mol HCl m^{-2}; and p, a non-dimensional exponent allowing for non linearity). This multiplier, whose corresponding equation is:

$$[1 - (\frac{D}{D_{\max}})^{p}] \tag{5}$$

can affect the gas-surface HCl partition coefficient (as it does for painted gypsum board), or the first order reaction rate constant, (as it does for painted PMMA) [30]. The concentrations of HCl used in the experiments in the present work were about ten times greater than what had been used to determine the surface parameters for PMMA previously. Thus, Case 2 experiments were used to fit HCl exposure parameters for PMMA. The exposure was assumed to affect the rate of disappearance of HCl from the surface, which had been found to be the case for painted PMMA. Using the previous nomenclature, the regressed values were found to be:

$D_{max} = 0.67$ E-6 (gmol/cm^2)

$p = 0.33$ (nd)

6.4 Experiments with horizontal chamber and carbon black

Case 3 contained two experiments (numbers 25 and 27), in which two differing amounts of carbon black were spread on the bottom surface (the chamber was horizontal). The two experiments represent a case where a thin layer (perhaps single layer thickness) and a very thick layer are laid on the chamber floor. The carbon black was modelled as other surfaces in previous investigations had been modelled. However, since there was not enough data under different conditions to determine a complete set of parameters for carbon black, it was assigned most of the parameters previously determined for ceiling tile, except for two of them. These were: (1) a parameter which, for a given condition of gas phase HCl concentration, temperature and humidity, is directly proportional to the amount of HCl adsorbed on the given surface per unit area (this is the surface area of the bottom of the horizontal chamber which the carbon black layer is covering, not the theoretical surface area of the particles themselves), and (2) a parameter which describes the rate of disappearance of HCl from the surface, by reaction with and/or diffusion into the material. A value for the parameter of type (1) was regressed for each amount of carbon black. However, only one type (2) parameter was regressed, reasoning that, although the capacity to adsorb HCl onto the surface should somehow be dependent on the amount of carbon black used, the rate of disappearance from the surface is independent of the amount of carbon black. Since no droplets were involved in these experiments, the mass transfer coefficients from Case 1 were assumed to apply, even though the chamber was horizontal. Values of 1.54 and 0.171 (in cm) were found for the first parameter (S1, S1' in Table 2) for the 157 g and 20 g carbon black cases, respectively. Since these capacity parameters are in almost the same ratio as the amounts of carbon black used, it indicates that the thickness of the loosely packed particle layer was not enough to prevent essentially equal exposure of all the carbon black particles to the HCl in the gas. The value determined for the second parameter (S2 in Table 2) was 0.21 (in 1/min). By way of comparison, the corresponding values for ceiling tile that had been determined previously are 0.40 and 7.36, respectively [30]. Thus, the surface capacity values for carbon black bracket that for ceiling tile, but the surface disappearance rate is more than an order of magnitude smaller.

6.5 Experiments with a vertical chamber and water, but no added surface

Case 4 involved PMMA surfaces and a droplet phase of pure water, and consisted of ten experiments at various pumping rates and times (numbers 6-10, 22, 23, 28, 61 and 63). The chamber was vertical. Previously determined surface parameters for PMMA were used. As indicated in the Model Formulation section, an empirical correlation for HCl-water vapor-liquid equilibrium was used [40]. No parameters were fit in the simulation runs. It was observed in this, and in the remaining experiments involving the introduction of a liquid droplet phase with the chamber vertical, that the mass transfer rate to the walls was generally enhanced in proportion to the pumping rate of the liquid droplets. This is not surprising, since the pumping of liquid, in the form of droplets, into the chamber would create additional convective currents. A linear correlation was found between the total surface averaged mass transfer coefficient and the fluid pumping rate, of the form:

$$k = 11.15 * LR - 2.107 \qquad (6)$$

where k is the average mass transfer coefficient (in cm/min) and LR is the pumping rate (in g/min). This was used to compute the side wall mass transfer coefficient in all droplet experiments where the chamber was vertical. Because of the additional convective currents, it was reasoned that the difference in mass transfer to the bottom and side walls would not be as large as it was in the non-fluid cases, Cases 1-3. Thus, the 2.3 ratio of bottom to side mass transfer coefficients was reduced somewhat, to 1.6. Similarly, it was reasoned that there would also not be as large a difference between mass transfer to the sides and top as had been the case in the non-fluid cases where mass transfer to the top was very small. Thus, the 0.03 ratio of top to side mass transfer coefficients was increased to 0.3. These ratios proved to yield satisfactory results in all the vertical chamber experiments involving a liquid droplet phase.

The relationship between the pump (Minipuls) setting and the fluid delivery rate (LR, in g/min) for water was determined to be a linear one, as follows:

$$LR = 0.11 + 0.1173 \, x \, 10^{-2} * PS \qquad (7)$$

6.6 Experiments with a vertical chamber, no added surface and water

Case 5 involved surfaces of PMMA, painted gypsum and ceiling tile in various configurations, and a droplet phase of pure water. There were a total of nine experiments (numbers 31-37, 46, 47), and the chamber was vertical. No parameters were fit in the simulation runs. The fluid delivery rate and mass transfer coefficient equations are identical to those in Case 4.

6.7 Experiment with a vertical chamber, no added surface and water-ethylene glycol solution

Case 6 was similar to Case 5. The droplet phase was a water-ethylene glycol solution. There was only one experiment, number 14, also with the chamber vertical. The fitted Henry's law constant was 0.017 (in atm). This case has the same mass transfer coefficient equation (equation 6), but a new fluid delivery rate equation, similar to equation 7, but with different parameters. Those parameters are shown in Table 4, together with those for the other cases.

6.8 Experiment with a vertical chamber, no added surfaces and ethylene glycol

Case 7 was similar to Case 5, with a droplet phase of pure ethylene glycol. There were two experiments (numbers 11, 12) and the chamber was also vertical. The fitted Henry's law constant was 0.022 (in atm). Just like case 6, there is a new fluid delivery rate equation, but still the same mass transfer coefficient one.

6.9 Experiment with a vertical chamber, no added surfaces and mineral oil

The experiment with mineral oil (number 13, see Figure 7) was not fitted. It represented an attempt to investigate the effect of a hydrophobic fluid, and it was found that the fluid had almost no effect alone. The decay could be represented by two straight lines: one initial fast decay (found in all experiments) and a very slow subsequent decay, probably unrelated to the mineral oil.

6.10 Experiments with a vertical chamber, no added surfaces and Carbopol™ solution

Case 8 was similar to Case 5, with a droplet phase of Carbopol™ in water, also in a vertical chamber. There were two experiments (numbers 15 and 29), and the fitted Henry's law constant was 0.022 (in atm). The parameters for the new fluid delivery equation are also in Table 4.

6.11 Experiments with a vertical chamber, no added surfaces and a Carbopol™/carbon black solution

Case 9 involved only PMMA surfaces in a vertical box. The droplet phase was the Carbopol™/carbon black liquid. There were five experiments (numbers 16, 18-21) using various pumping times and rates. The Henry's law constant for HCl was regressed, and found to have the value 0.018 (in atm). Again, equation parameters are found in Table 4.

Case 11 was similar to Case 5, with a droplet phase of Carbopol™ and carbon black in water, differing only in the type of carbon black used (Monarch, with higher surface area, rather than Raven). There was only one experiment, number 60. Since the same kind of carbon black was used as in the synthetic smoke case, Case 6, the same Henry's law constant, 0.0086 atm, was assigned. Thus, no parameters were fit.

6.12 Experiments with a vertical chamber, added surfaces and synthetic smoke

Case 10 was similar to Case 5, except that the fluid used was synthetic smoke. The droplet phase was a suspension which represented the best attempt to include several components of smoke in a fire: a water phase, a hydrophobic phase and soot. There were eight experiments (numbers 30, 54-59, 62) in a vertical chamber. The Henry's law constant had a fitted value of 0.0086 (in atm). In this case, equation 6 is valid for the mass transfer coefficient. However, the fluid delivery rate equation depends on the value of the pump setting. It is a linear equation for pump settings above 300, and a quadratic equation (Equation 8) for pump settings lower than 300 (see table 4):

$$LR = 0.858 + 0.38 *10^{-2} * PS - 0.6035 * 10^{-5} * P \tag{8}$$

6.12 Experiments with a horizontal chamber, added surfaces and synthetic smoke or water

Case 12 involved various combinations of PMMA, painted gypsum and ceiling tile surfaces, in a horizontal chamber. The droplet phase was pure water in some of the experiments and synthetic smoke in the others. There were a total of five experiments (numbers 48, 49, 51-53). Because the long dimension of the chamber was in the horizontal plane, the correlation between mass transfer coefficient and liquid droplet pumping rate used in Cases 3-10 was not applicable. A value for the mass transfer coefficient to the side walls (i.e., the vertical walls, with the chamber in the horizontal position) was the only parameter fit. The same ratios between bottom and side, and top and side, for the mass transfer coefficients, that were used in Cases 3-10 were again used. The value for the Henry's law constant for synthetic smoke found in Case 6 was used here. The equations for fluid delivery rate used were those in case 4 for water and in case 10 for synthetic smoke.

6.13 Comparisons of the effects of various fluids

Returning to Figures 6 and 7, it is now clear that the comparison should really have been made between cases with equal fluid delivery rates. The fluid delivery rates were calculated for experiments # 11, 16, 30 and 58, using the parameters in Table 4. The results are:

11: 1.03 g/min (setting 600; Ethylene glycol)
16: 1.14 g/min (setting 1000; CP/CB solution)
30: 1.02 g/min (setting 125; synthetic smoke)
58: 4.66 g/min (setting 1000; synthetic smoke)

Analyzing these fluid delivery rates, it appears that the main reason for the difference between CP/CB solution and synthetic smoke is the higher fluid delivery rate for the latter, at the same Minipuls setting. However, the Henry's law constant (see next paragraph) is slightly lower for synthetic smoke, indicating that it is, somewhat, more effective than CP/CB solution. In Figure 7, a comparison of the efficiency of ethylene glycol and synthetic smoke was actually done at very similar fluid delivery rates. This indicates that their reactivity towards HCl is similar, but that of synthetic smoke is somewhat higher, as shown by the lower Henry's law constant.

The Henry's law constants determined for the various liquids employed in these experiments can be put into perspective by comparing them with the equivalent Henry's law constant for HCl in pure water at the same temperature. Of course, the Henry's law constant for HCl in water is not a constant at a given temperature, but rather it is a strong function of concentration, since the system is highly non-ideal. Table 5 shows the variability of the Henry's law constant for HCl and water, with molarity, at 23 °C, based on the correlation given by Schotte [39].

In fact, the values in Table 5 are correlated very well by the following equation:

$$\log_{10}[H_{HCl}] = 0.364 * m - 5.102 \tag{9}$$

Typically, with the amount of water and HCl introduced in the experiments, the molarity of HCl would be about 3. Thus, a typical Henry's law constant for water, for comparison with the other liquid mixtures, would be 1 E-4. This is two orders of magnitude smaller than the values found for the various mixtures, indicating that pure water is much more effective in absorbing HCl than any of the other fluids used.

7. CONCLUSIONS

The present work addressed the effect of various fluids, potentially present in fire atmospheres. It is clear from the results that the presence of most fluids enhances decay. In particular, plain water and smoke particulates (as represented by the synthetic smoke) are very effective sinks of HCl, in that order. At the other extreme, mineral oil is almost totally impervious to reaction with HCl. These results are, of course, not particularly surprising. More unexpectedly, ethylene glycol, a polar organic solvent, is a very effective sink of HCl, indicating that all hydrophilic fluids can be sinks for HCl.

In these experiments, the mass transfer rate to the walls increased with increasing fluid delivery rate. The mass transfer rate to the droplet phase is very high in every case. Thus, droplets of the more reactive fluids, like water, are very effective in removing HCl from the atmosphere.

Soot deposits are an important sink of HCl, their main effect being to create a more active surface. The reactivity of sooty surfaces appears to increase as soon as there is some soot present.

Finally, the principal aspect of the present work was the modelling. The model for HCl transport and decay of hydrogen chloride has been applied to predict atmospheric HCl concentrations in a number of cases wherein no PVC is present with excellent correlation results. This indicates that the model is robust enough that it goes beyond the generation of HCl from PVC, as had been the case in many of the previous series of experiments.

GLOSSARY

A	surface area of a group of droplets (cm^2)
D_d	droplet diameter (cm)
D_g	molecular diffusivity of HCl in air (cm^2/s)
D_{max}	maximum amount of HCl a surface can absorb
F_{HCl}	inter-phase transfer rate of HCl (g mol/min)
H_{HCl}	Henry's Law constant for HCl (atm)
$[HCl]_e$	equilibrium gas phase HCl concentration (g mol/cm^3)
$[HCl]_g$	gas phase HCl concentration (g mol/cm^3)
k	mass transfer coefficient (cm/min)
LR	fluid delivery rate (g/min)
m	HCl molarity in water (g mol/L)
p	non dimensional multiplier for surface saturation
P_{HCl}	HCl partial pressure (atm)
P^o_{wat}	vapor pressure of pure water (atm)
PS	Minipuls pump setting
r_g	gas density (g/cm^3)
u_g	gas viscosity (g/cm s)
v_d	droplet settling velocity (cm/s)
X_{HCl}	mol fraction of HCl in water
X_{wat}	mol fraction of water in the droplet phase

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Table 1. Details of All Experiments

Exper. #	Fluid	Minipuls Setting	Time min	Surface	Chmb Ornt	Comment
1	NONE	NA	NA	NA	HORZ	
2	NONE	NA	NA	NA	HORZ	
3	WATER	NOT USED	6	NA	HORZ	
4	NONE	NA	NA	NA	HORZ	
5	WATER	NOT USED	5	NA	HORZ	
6	WATER	600	5	NA	HORZ	
7	WATER	600	12	NA	VERT	
8	WATER	300	20	NA	VERT	
9	WATER	300	10	NA	VERT	
10	WATER	900	20	NA	VERT	
11	ETH. GLYCOL	600	20	NA	VERT	
12	ETH. GLYCOL	300	20	NA	VERT	
13	MIN. OIL	600	20	NA	VERT	
14	ETH. GLY./WATER	600	20	NA	VERT	50/50
15	CP SOLN	600	20	NA	VERT	
16	CP/CB	1000	20	NA	VERT	
17	CP/CB	1000	5	NA	VERT	
18	CP/CB	300	20	NA	VERT	
19	CP/CB	1000	20	NA	VERT	BI
20	CP/CB	1000	10	NA	VERT	
21	CP/CB	1000	5	NA	VERT	
22	WATER	1000	20	NA	VERT	BI
23	WATER	1000	10	NA	VERT	BI
24	CB RAVEN	NA	20	NA	VERT	5 g
25	CB MONARCH	NA	NA	NA	HORZ T	157 g
26	CB MONARCH	NA	NA	NA	HORZ T	10 g
27	CB MONARCH	NA	NA	NA	HORZ T	20 g
28	WATER	600	20	NA	VERT	
29	CP SOLN	100	20	NA	VERT	
30	SYNTH SMOKE	125	20	NA	VERT	
31	WATER	300	5	PGB-B	VERT	
32	WATER	300	20	PGB-B	VERT	
33	WATER	300	20	PGB-T	VERT	
34	WATER	300	20	PGB-T&B	VERT	
35	WATER	300	20	CT-B	VERT	
36	WATER	300	20	CT-T	VERT	
37	WATER	300	20	CT-T&B	VERT	
38	NONE	NA	NA	PGB-B	VERT	
39	NONE	NA	NA	PGB-T	VERT	
40	NONE	NA	NA	PGB-T&B	VERT	
41	NONE	NA	NA	CT-B	VERT	
42	NONE	NA	NA	CT-T	VERT	
43	NONE	NA	NA	CT-SL	VERT	
44	NONE	NA	NA	PGB-SL	VERT	

Table 1 (Continued). Details of All Experiments

Exper. #	Fluid	Minipuls Setting	Time min	Surface		Chmb Ornt	Comment
	45	NONE	NA	NA	CT-T&B	VERT	
	46	WATER	300	20	CT-SL	VERT	
	47	WATER	300	20	PGB-SL	VERT	
	48	WATER	300	20	PGB-SB	HORZ	
	49	WATER	300	20	CT-SB	HORZ	
	50	SYNTH SMOKE	600	11	CT-SB	HORZ	
	51	SYNTH SMOKE	600	10	PGB-SB	HORZ	
	52	SYNTH SMOKE	300	12	PGB-SB	HORZ	
	53	SYNTH SMOKE	300	10	CT-SB	HORZ	
	54	SYNTH SMOKE	300	10	CT-T&B	VERT	
	55	SYNTH SMOKE	300	10	PGB-T&B	VERT	
	56	SYNTH SMOKE	600	10	CT-T&B	VERT	
	57	SYNTH SMOKE	600	10	PGB-T&B	VERT	
	58	SYNTH SMOKE	1000	20	NA	VERT	
	59	SYNTH SMOKE	1000	10	CT-T&B	VERT	
	60	CP/CB #	1000	20	NA	VERT	
	61	WATER (LOW T)	600	20	NA	VERT	
	62	SYNTH SMOKE	1000	10	PGB-T&B	VERT	
	63	WATER (HIGH T)	600	20	NA	VERT	

Low T: 14.7 deg C; High T: 29.4 deg C; T: top of chamber; B: bottom of chamber. BI: Before injection; SL: Side of vertical chamber; SB: bottom of vertical chamber; CP/CB #: containing Monarch carbon black; HORZ T: Carbon black on side of box, which is acting as bottom.

TABLE 2

Summary of Results

Case		Parameters Regressed	Regressed Values	Correlation Coefficient
1.	Mixed Surfaces & Locations/ No Fluid	MTC-side MTC-bottom MTC-top	8.7 19.8 0.25	0.55
2.	PMMA Surfaces/No Fluid	DOSEMX p	0.67 E-6 0.33	0.42
3.	PMMA Surfaces/ Carbon Layer/ No Fluid/ Horiz Chamber	S1 S1' S2	1.54 0.17 0.21	0.93
4.	PMMA Surfaces/water	None		0.74
5.	Mixed Surfaces/water	None		0.74
6.	PMMA Surfaces/ Glycol: water fluid	Henry's Const.	0.017	0.90
7.	PMMA Surfaces/ Glycol Fluid	Henry's Const.	0.022	0.74
8.	PMMA Surfaces/ CP Fluid	Henry's Const.	0.022	0.88
9.	PMMA Surfaces/ CP:CB Fluid	Henry's Const.	0.018	0.80
10.	PMMA Surfaces/ SynSmk Fluid	Henry's Const.	0.0086	0.78
11.	PMMA Surfaces/ CP:CBM Fluid/ Horiz Chamber	None		0.85
12.	Mixed Surfaces/ SynSmk & Water Fluids/Horiz Chamber	MTC-side	21.1	0.66

Note: CP:CBM fluid: is the one using Monarch carbon black.

TABLE 3

Summary of Mass Transfer Coefficients

Case	Range of Pump Settings	Pumping Rate	Mass Transfer Coefficients
		(g/min)	(cm/min)
1	0	0	Side: 8.7 Bottom: 19.8 Top: 0.25
2	0	0	(Same as 1)
3	0	0	(Same as 1)
4	300-1000	Equation 7	Side: Equation 6 Bottom: 1.6 * Side Top: 0.3 * Side
5	300	(Same as 4)	(Same as 4)
6	600	See Table 4	(Same as 4)
7	300-600	See Table 4	(Same as 4)
8	600-1000	See Table 4	(Same as 4)
9	300-1000	See Table 4	(Same as 4)
10	125-1000	See Table 4	(Same as 4)
11	1000	(Same as 10)	(Same as 4)
12	300-600	(As 4 for water; as 10 for synsmk)	S:21.1 B:1.6*S T:.3*S

PS: pump setting
S: side of chamber
B: bottom of chamber
T: top of chamber
LR: liquid rate

Table 4. Parameters for Fluid Delivery Equations

Case	Intercept	Slope
4	0.110	0.117 E-2
6	0.153	0.128 E-2
7	0.196	0.139 E-2
8	0.174	0.844 E-3
9	0.183	0.952 E-3
10	0.858	0.380 E-2 (for PS > 300)*
11	0.858	0.380 E-2 (for PS > 300)*
12	0.110	0.117 E-2 (for water)
12	0.858	0.380 E-2 (for PS > 300)* (for synthetic smoke)

*: for PS < 300 : LR = 0.093 + 0.814 E-2 * PS - 0.6035 E-5 * PS^2

Table 5
Effective Henry's Law Constant for HCl in Water at 23 C

HCl Molarity	Henry's Constant (atm)
1	1.5E-5
3	1.1E-4
5	6.5E-4
9	1.3E-2

Figure Legends

Figure 1: Effect of carbon black on HCl decay, with no added surfaces and no fluid. Legend indicates experiment number and the amount of carbon black added.

Figure 2: Effect of the location of the added surface (painted gypsum board) on HCl decay, with no fluid. Legend indicates experiment number and added surface location: B (bottom of horizontal chamber), T (top of horizontal chamber), T&B (top and bottom of horizontal chamber), SL (side of vertical chamber) and no PGB (no added surface).

Figure 3: Effect of the location of the added surface (ceiling tile) on HCl decay, with no fluid. Legend indicates experiment number and added surface location: B (bottom of horizontal chamber), T (top of horizontal chamber), T&B (top and bottom of horizontal chamber), SL (side of vertical chamber) and no PGB (no added surface).

Figure 4: Effect of the location of the added surface (painted gypsum board (PGB) or ceiling tile (CT)) on HCl decay, with water added at a Minipuls setting of 300. Legend indicates experiment number and added surface location: PGB B (PGB at bottom of horizontal chamber), PGB T (PGB at top of horizontal chamber), PGB T&B (PGB at top and bottom of horizontal chamber), CT B (CT at bottom of horizontal chamber), CT T (CT at top of horizontal chamber) and CT T&B (CT at top and bottom of horizontal chamber).

Figure 5: Effect of temperature and water (Minipuls at 600, for 20 min) on HCl decay, with no added surfaces. Legend indicates experiment number and the other variation: norm T (23 °C, water), low T (14.7 °C, water), high T (29.4 °C, water), dry, nor (23 °C, no water).

Figure 6: Effect of fluid used (at a Minipuls setting of 1000) on HCl decay, with no added surfaces. Legend indicates experiment number and the fluid used: CP/CB (Carbopol™/carbon black solution), ss (synthetic smoke) and none (no fluid).

Figure 7: Effect of fluid used (at a Minipuls setting of 600) on HCl decay, with no added surfaces. Legend indicates experiment number and the fluid used: Etgl (ethylene glycol), etgl/wt (ethylene/glycol water solution), minol (mineral oil), CP sol (Carbopol™ solution), ss 125 (synthetic smoke, at a Minipuls setting of 125) and None (no fluid).

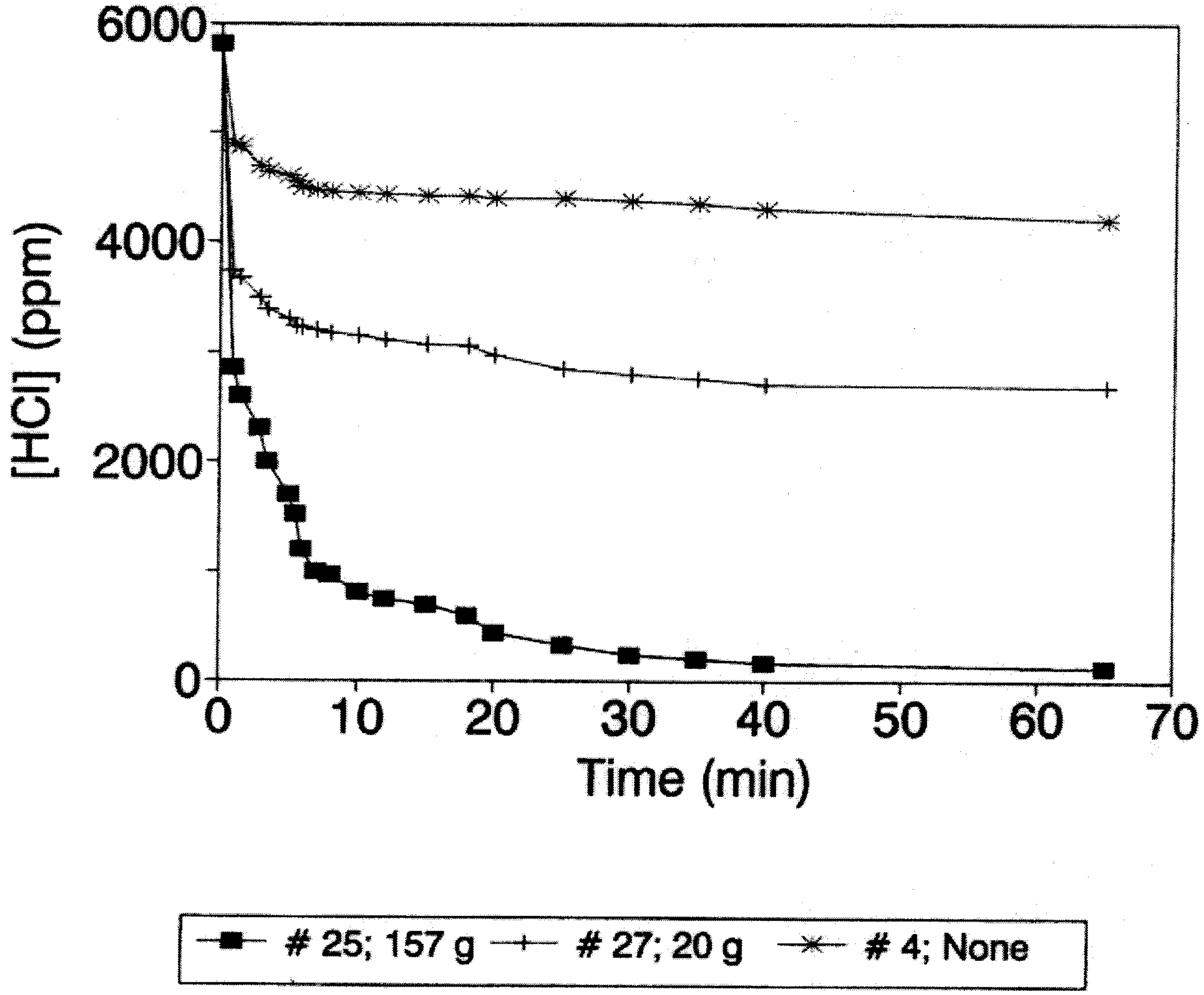

Figure 1. Effect of carbon black on HCl decay, with no added surfaces and no fluid. Legend indicates experiment number and the amount of carbon black added.

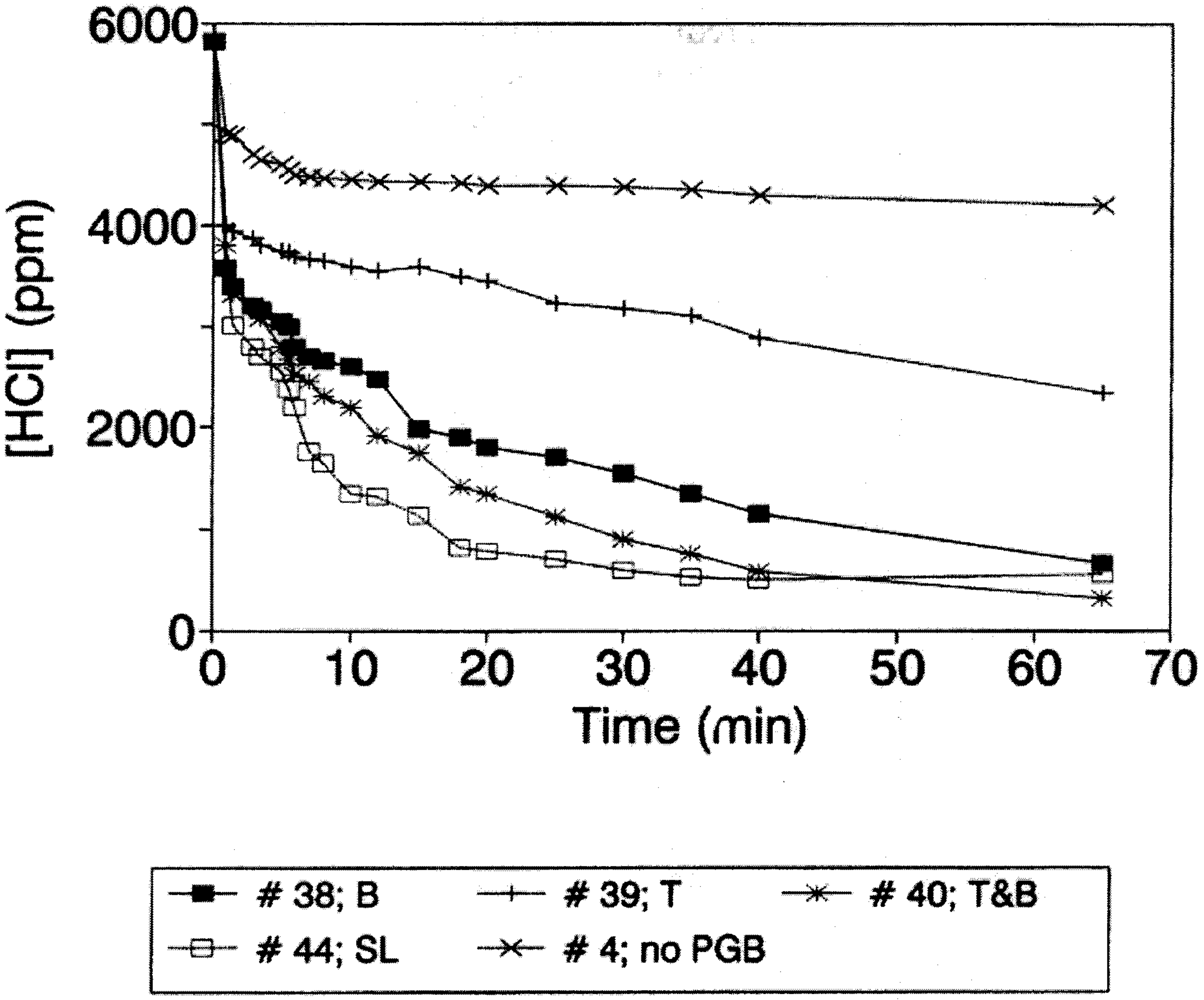

Figure 2. Effect of the location of the added surface (painted gypsum board) on HCl decay, with no fluid. Legend indicates experiment number and added surface location: B (bottom of horizontal chamber), T (top of horizontal chamber), T&B (top and bottom of horizontal chamber), SL (side of vertical chamber) and no PGB (no added surface).

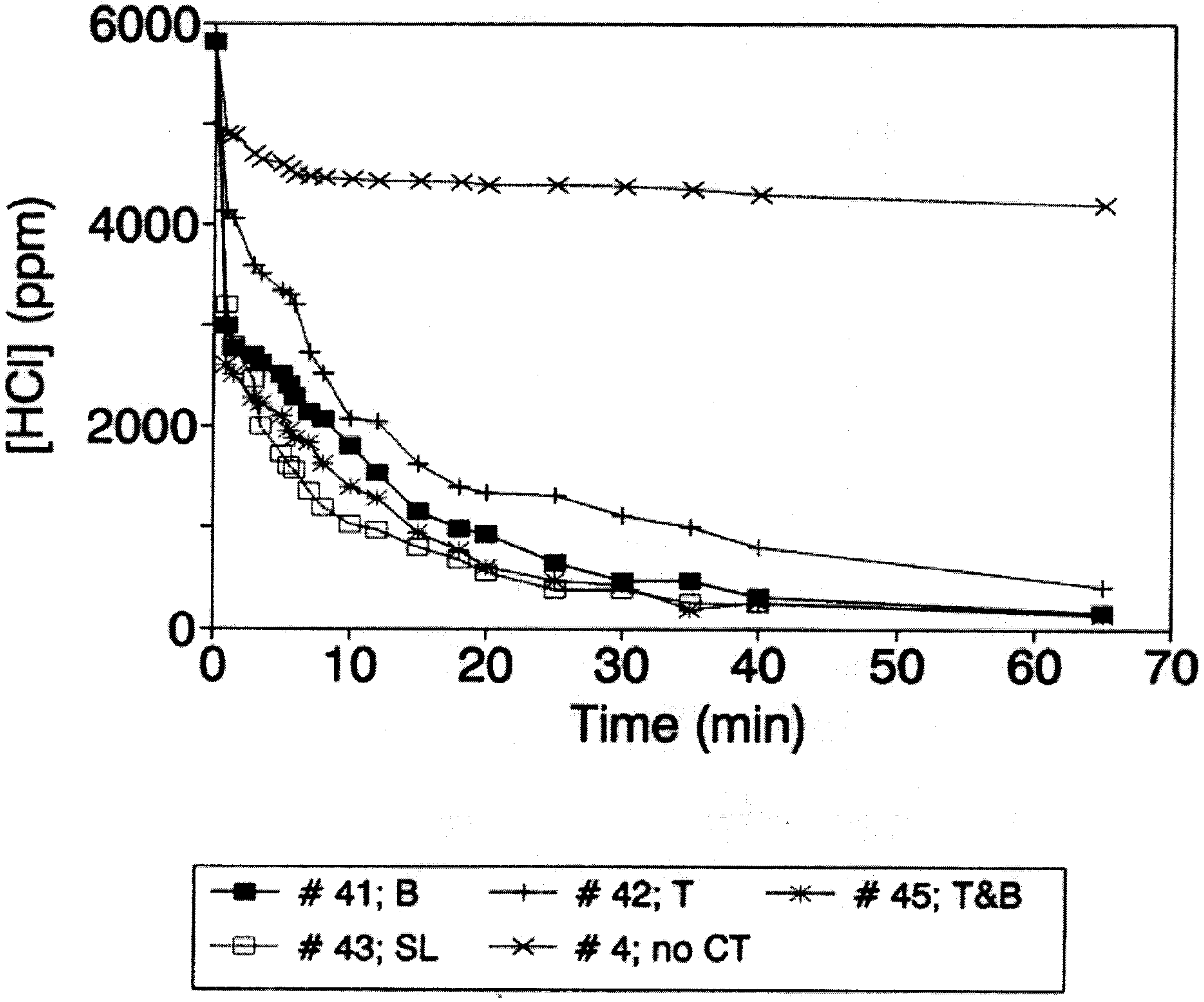

Figure 3. Effect of the location of the added surface (ceiling tile) on HCl decay, with no fluid. Legend indicates experiment number and added surface location: B (bottom of horizontal chamber), T (top of horizontal chamber), T&B (top and bottom of horizontal chamber), SL (side of vertical chamber) and no PGB (no added surface).

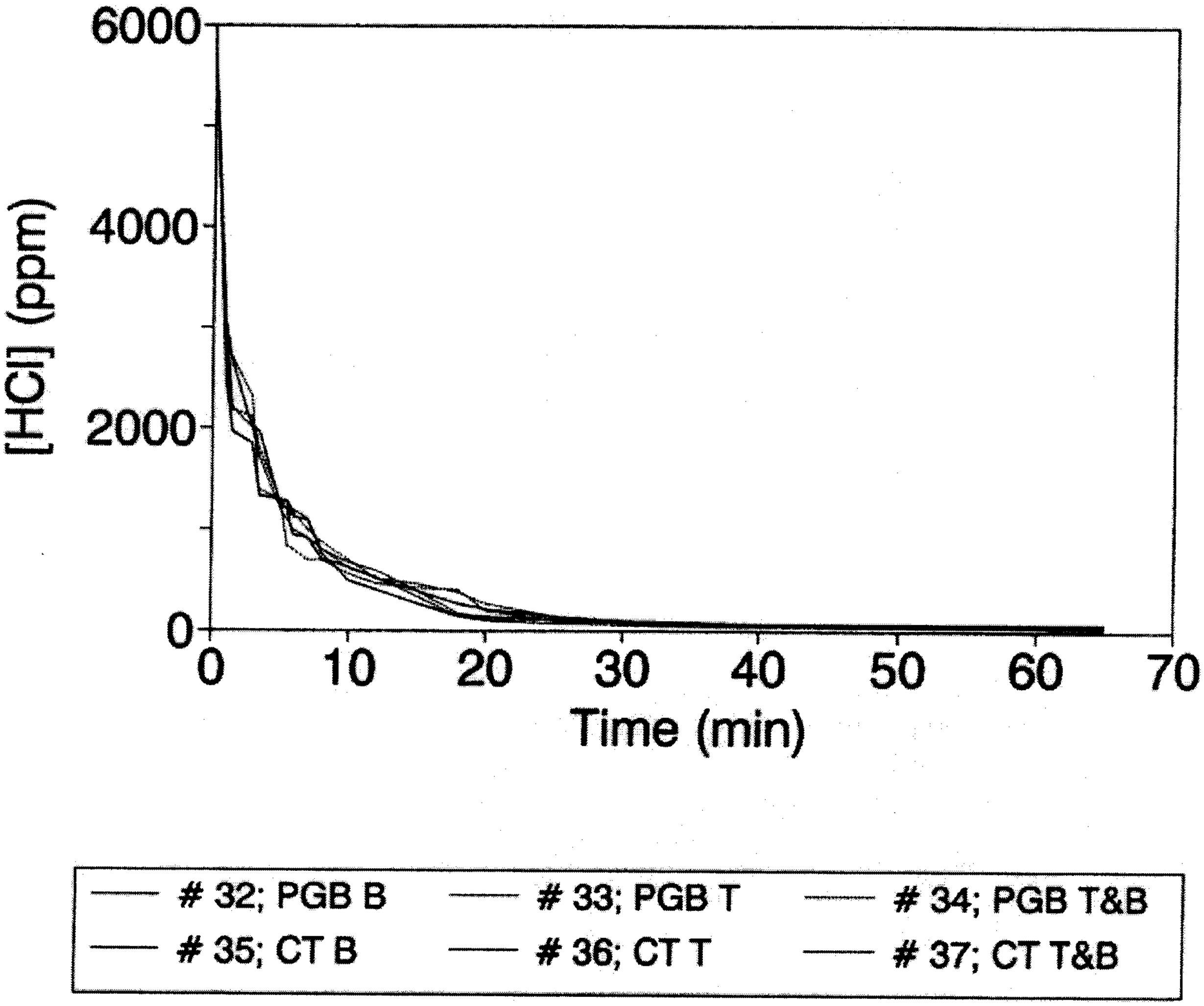

Figure 4. Effect of the location of the added surface (painted gypsum board (PGB) or ceiling tile (CT)) on HCl decay, with water added at a Minipuls setting of 300. Legend indicates experiment number and added surface location: PGB B (PGB at bottom of horizontal chamber), PGB T (PGB at top of horizontal chamber), PGB T&B (PGB at top and bottom of horizontal chamber), CT B (CT at bottom of horizontal chamber), CT T (CT at top of horizontal chamber) and CT T&B (CT at top and bottom of horizontal chamber).

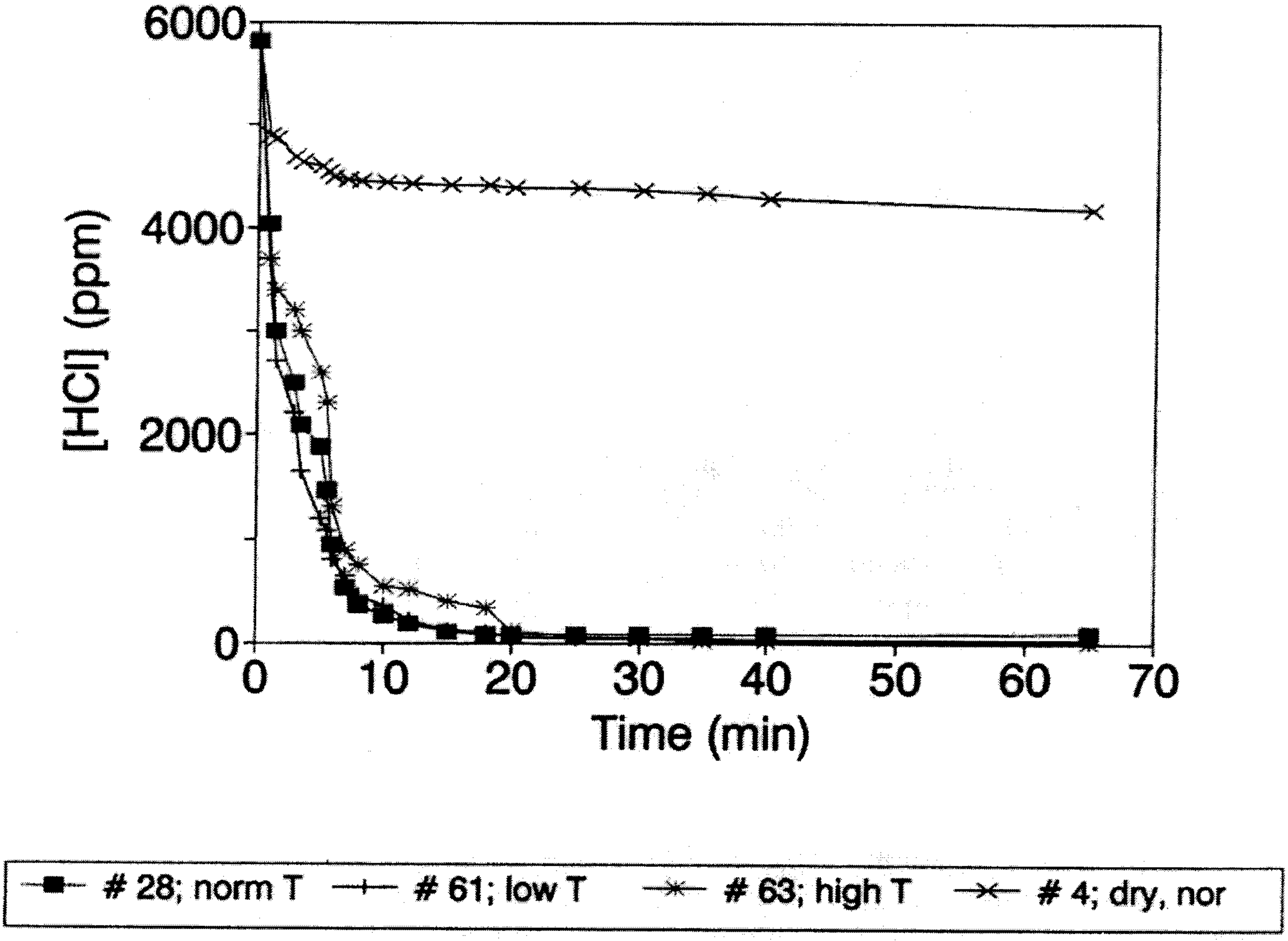

Figure 5. Effect of temperature and water (Minipuls at 600, for 20 min) on HCl decay, with no added surfaces. Legend indicates experiment number, and the other variation: norm T (23°C, water), low T (14.7°C, water), high T (29.4°C, water), dry, nor (23°C, no water).

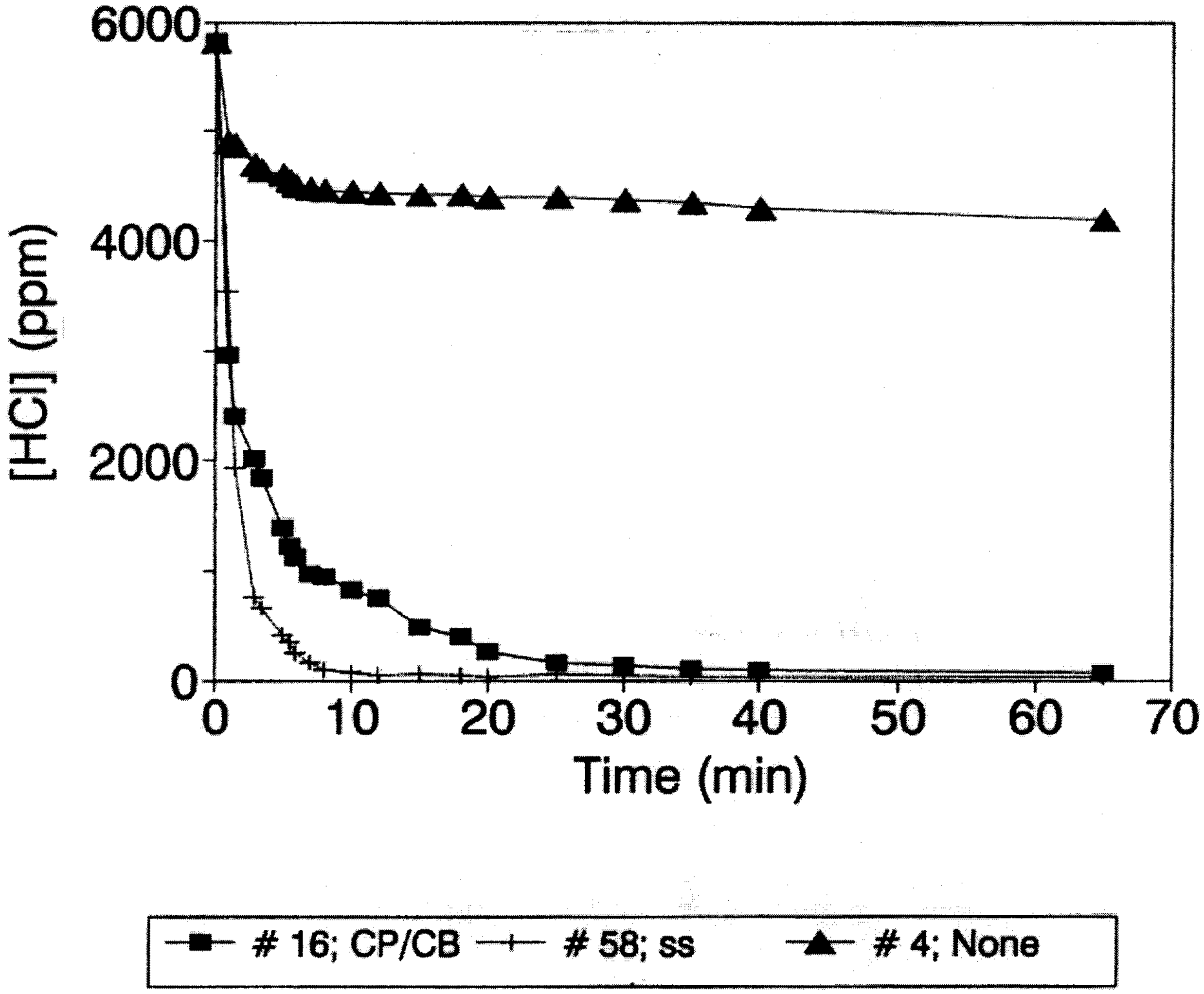

Figure 6. Effect of fluid used (at a Minipuls setting of 1000) on HCl decay, with no added surfaces. Legend indicates experiment number and the fluid used: CP/CB (Carbopol^{TM}/carbon black solution), ss (synthetic smoke) and none (no fluid).

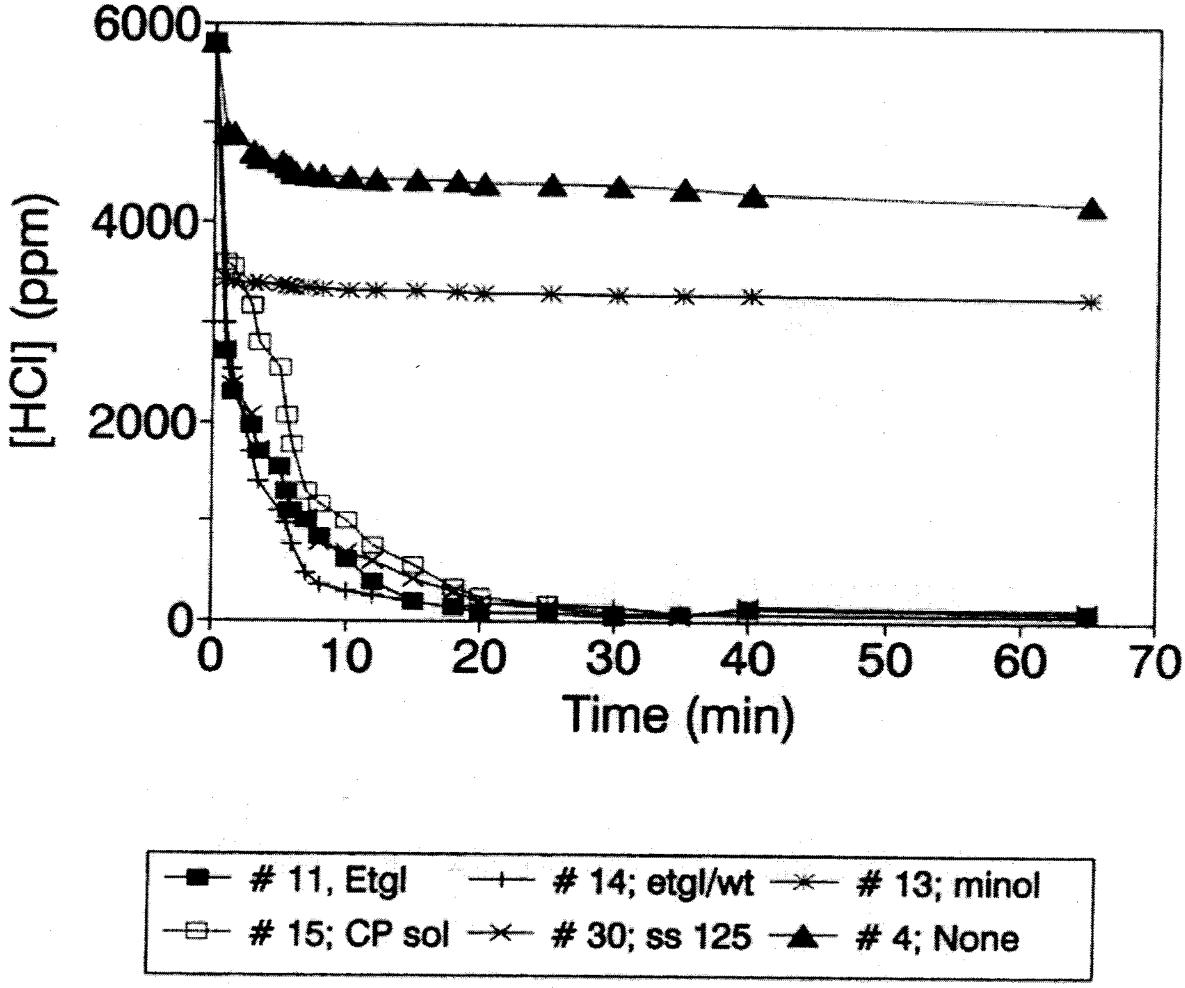

Figure 7. Effect of fluid used (at a minipuls setting of 600) on HCl decay, with no added surfaces. Legend indicates experiment number and the fluid used: Etgl (ethylene glycol), etgl/wt (ethylene/glycol water solution), minol (mineral oil), CP sol (Carbopol^{TM} solution), ss 125 (synthetic smoke, at a minipuls setting of 125) and None (no fluid).