# CHAPTER 1. INTRODUCTION

## 1.1 Purpose

The purpose of this NUREG-series report is to introduce the principles of fire dynamics and illustrate how fire protection inspectors can apply those principles in a risk-informed manner to better determine whether credible fire scenarios are possible. In this context, we broadly define the term “fire dynamics” as the scientific study of hostile fires. The dynamic nature of fire is a quantitative and mathematically complex subject. It combines physics, chemistry, mathematics, and engineering principles and can be difficult to comprehend for those who have a limited background in these areas. With the objective of quantitatively describing fire and related processes (i.e., ignition, flame spread, fire growth, and smoke movement) and their effects in an enclosure, the Fire Dynamics Tools (FDT$^s$) have been developed to assist fire protection inspectors in solving fire hazard problems in nuclear power plants (NPPs).

The goal of this report is to provide insights into fire dynamics, without using the sophisticated mathematics that are normally associated with the study of fire dynamics. Nonetheless, inspectors will need a working knowledge of algebra, reading graphs, scientific notation, formulas, and use of some simple mathematics functions to understand the quantitative aspect of fire phenomena. A better understanding of these processes will improve the quality of fire protection inspections conducted by the U.S. Nuclear Regulatory Commission (NRC).

## 1.2 Objective

The primary objective of this report is to provide a basic calculation methodology for use in assessing potential fire hazards in the NRC-licensed NPPs. The methodology uses simplified, quantitative fire hazard analysis (FHA) techniques to evaluate the potential for credible fire scenarios. One purpose of these evaluations is to determine whether a potential fire can cause critical damage to safe-shutdown components, either directly or indirectly by igniting intervening combustibles. The methodology used in this report is founded on material fire property data implemented in scientific calculations. In addition, the associated techniques have been assessed to ensure applicability and accuracy, and were derived primarily from the principles developed in the Society of Fire Protection Engineers (SFPE) *Handbook of Fire Protection Engineering*, and the National Fire Protection Association (NFPA) *Fire Protection Handbook*. The FHA methods have been implemented as Microsoft Excel® spreadsheets, which incorporate simple, empirical correlations and detailed mathematical equations based on fire dynamics principles. They also build on numerous tables of material fire property data, which have been assembled for NPPs. The combination of these spreadsheets and data tables forms the basis for the FDT$^s$.

## 1.3 Regulatory Background on Fire Protection for Nuclear Power Plants

The primary objectives of fire protection programs (FPPs) at U.S. NPPs are to minimize both the probability of occurrence and the consequences of fire. To meet these objectives, the FPPs for operating NPPs are designed to provide reasonable assurance, through defense-in-depth (DID), that a fire will not prevent the performance of necessary safe-shutdown functions and that radioactive releases to the environment in the event of a fire will be minimized. Section II, “General Requirements,” of Appendix R to Title 10, Part 50, of the *Code of Federal Regulations* (10 CFR

Part 50), states that the fire protection program shall extend the DID concept to fire protection in fires areas that are important to safety, with the following objectives:

(1) Prevent fires from starting.

(2) Rapidly detect, control, and extinguish those fires that do occur.

(3) Protect structures, systems, and components that are important to safety so that a fire that is not promptly extinguished by the fire suppression activities will not prevent the safe shutdown of the plant.

The first element of this DID approach deals with preventing fires from starting. This can be accomplished by limiting fire sources that could initiate a fire at an NPP, and preventing any existing ignition sources from causing self-sustaining fires in combustible materials. Despite the nuclear industry's best efforts to eliminate or at least control ignition sources, accidental (and purposeful) sources of ignition often exist and can result in hostile fires. This is an important aspect of a total fire safety program, which should not be overlooked.

The second element of the prevention element deals with rapidly detecting, controlling, and extinguishing those fires that do occur. This can be achieved by preventing significant fires from occurring, given the inadvertent or purposeful introduction of an ignition source. If all structures and contents comprised totally noncombustible materials, this would not pose a problem. However, this is not the case. Buildings and their contents are composed of a variety of materials of various degrees of combustibility. Materials with higher thresholds of ignition and less hazardous combustion are continually being developed. Regardless, at least in some cases, the higher resistance to ignition can also result in a higher resistance to fire extinction (Hill, 1982). Electrical cables are a good example. While cables qualified to the Institute of Electrical and Electronic Engineers (IEEE) Standard 383 are more fire-resistant, they are also more difficult to extinguish once they ignite. In any case, the prevention of hostile fires will likely never be the total solution to the fire safety problem in NPPs.

The second element of the DID approach involves limiting fire spread through fire detection and fire suppression. There are various approaches to this element. In the event of a significant fire, its spread might be limited in the following ways:

- early human detection and manual suppression
- provision and maintenance of adequate fire detection and automatic fire suppression systems
- a combination of manual and automatic detection and suppression systems

Heat and smoke detectors; fire alarm systems; Halon 1301, carbon dioxide ($CO_2$), and dry chemical fire suppression systems; automatic sprinkler, foam, and water spray systems; portable fire extinguishers; hose stations, fire hydrants, and water supply systems; and fire brigades are all part of the second element of the DID approach. Each is highly developed in modern fire protection designs, and is constantly being further refined as fire technology advances. Nonetheless, the DID concept recognizes that the first two elements of fire defense are not always entirely successful in meeting the fire challenge.

The third element of the DID approach involves designing NPP structures, systems, and components (SSCs) to prevent significant damage in the event that the first two elements fail, either partially or fully. This goal may be fulfilled in the following ways:

- Isolate combustible elements by spatial separation, such that a fire in one fuel package will not propagate to any other fuel package.
- Isolate combustible elements by fire-resistant barriers to prevent fires from propagating from one area to another. In particular, fire-rated horizontal and vertical barrier systems will limit fire spread from compartment to compartment.

The NRC's regulatory framework for FPPs at U.S. NPPs is described in a number of regulatory and supporting guidelines, including but not limited to General Design Criterion (GDC) 3, as specified in Appendix R to Title 10, Part 50, of the *Code of Federal Regulations* (10 CFR Part 50); 10 CFR 50.48; Appendix R to 10 CFR Part 50; Regulatory Guide (RG) 1.189 and other regulatory guides, generic communications (e.g., generic letters, bulletins, and information notices), NUREG-series reports; the standard review plan (NUREG-0800); and associated branch technical positions (BTPs).

## 1.4 Fire Hazard Analysis for Nuclear Power Plants

As previously stated, fire protection for NPPs relies on the DID concept to achieve the required degree of reactor safety by using redundant levels of administrative controls, fire protection systems and features, and safe-shutdown capability. An FHA should be performed to assess the fire hazard and demonstrate that the NPP will maintain its ability to perform safe shutdown functions and minimize radioactive material releases to the environment in the event of a fire.

RG 1.189 lists the following objectives for an FHA:

- Consider potential in situ and transient fire hazards.
- Determine the consequences of fire in any location in the plant, paying particular attention to the impact on the ability to safely shut down the reactor or the ability to minimize and control the release of radioactivity to the environment.
- Specify measures for fire prevention, fire detection, fire suppression, and fire containment, as well as alternative shutdown capability for each fire area containing SSCs that are important to safety in accordance with NRC guidelines and regulations.

## 1.5 Fire Protection Inspection Findings

Fire protection inspection findings are generally classified as weaknesses associated with one or more objectives of the DID elements introduced above. If a given inspection does not yield any DID-related findings against a fire protection feature or system, the fire protection feature and system are considered to be capable of performing their intended functions and operating in their normal (standby) state.

## 1.6 Fire Scenario Development for Nuclear Power Plants

In the broadest sense, a fire scenario can be thought of as a specific chain of events that begins with the ignition of a fire and ends either with successful plant shutdown or core damage. The fire is postulated to occur at a specific location in a specific fuel package, and to progress through various stages of fire growth, detection, and suppression. In this process, the fire may damage some set of plant equipment (usually electrical cables). For a given fire source, the FHA may postulate damage to various sets of equipment, depending on how long the fire burns and how large the initial fire is presumed to be. The postulated or predicted fire damage may either directly or indirectly cause the initiating event (such as a plant trip, loss of offsite power, etc.).

When inspectors develop a fire scenario, they should postulate the worst-case, realistic fire, provided that the compartment and configuration of the fire area, room, or zone can support such a fire. For example, a large cabinet fire is one in which fire damage initially extends beyond the cabinet in which the fire originated. The fire damage attributed to a large cabinet fire often extends into the overhead cabling, an adjacent cabinet, or both. A large fire for a pump or motor can often be based initially upon the largest (worst-case) oil spill from the equipment. If the configuration of the compartment, combustibles, etc., supports further growth of the large fire, the fire scenario should postulate that growth. Since scenarios that describe large fires are normally expected to dominate the risk-significance of an inspection finding, scenarios with small fires typically are not included unless they spread and grow into large fires.

## 1.7 Process of Fire Development

Fire hazards to NPP equipment can arise from many sources, including (but not limited to) thermal damage, fouling, and corrosivity. Fire is essentially a chemical reaction involving solids, liquids, and gases that ignite and undergo a rapid, self-sustaining oxidation process, accompanied by the evolution of heat and light of varying intensities. However, the chemical and physical reactions that take place during a fire are extremely complex and often difficult to describe completely. The most common fires start as a result of the ignition of solid or liquid fuels (combustible materials). Solid and liquid fuels typically become volatile and serve as suppliers of gaseous fuel to support combustion. In the physical model (illustrated in Figure 1-1) the process of fire development begins when the fuel surface starts to heat up as a result of heat transfer from the adjacent surroundings. As the temperature of the fuel surface increases in response to this heat input, the fuel surface begins to emit fuel vapors. The fuel vapors mix (by convection and diffusion) with oxygen in the adjacent boundary layer, ignite (through a chemical reaction), and release additional heat. Some of this liberated heat energy may further increase the surface temperature of the fuel and thereby accelerate the fire growth process.

Many materials react with oxygen to some degree; however, various materials differ in their respective rates of reaction. The difference between slow-and rapid-oxidation reactions is that the latter occur so rapidly that heat is generated faster than it is dissipated, causing the material being oxidized (fuel) to reach its ignition temperature. Once a material reaches its ignition temperature, it ignites and continues to burn until either the fuel or the oxygen is consumed. The heat released during combustion is usually accompanied by a visible flame. However, some materials (such as charcoal) smolder, rather than producing a visible flame. A familiar slow-oxidation reaction is the rusting of iron. Such a reaction releases heat so slowly that the temperature hardly increases more than a few degrees above the temperature of the surroundings. These reactions typically do not cause fires and are not considered combustion.

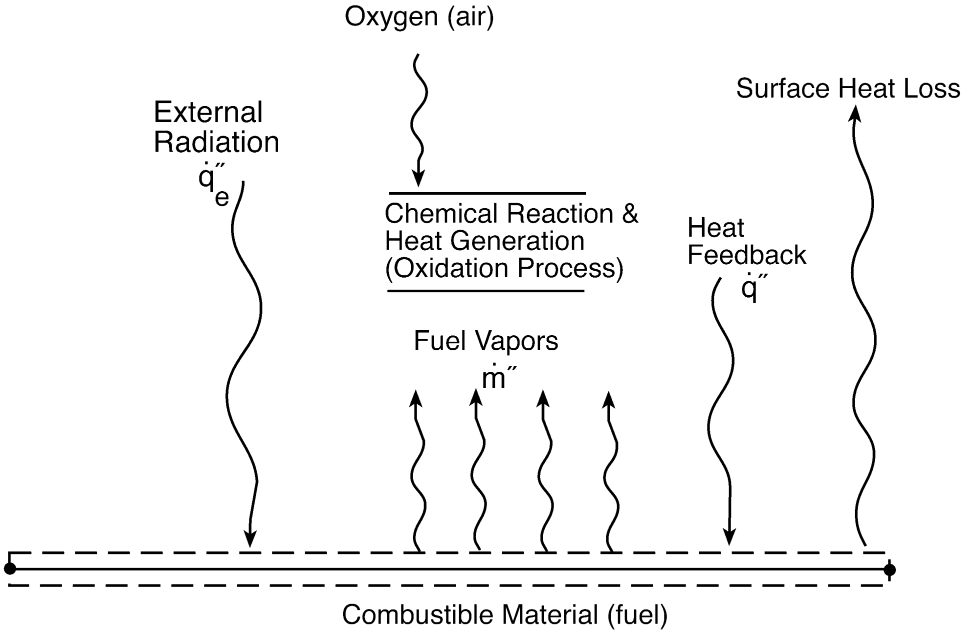

Figure 1-1 Physical Process of Combustion and Fire

Generally, three components are required to support combustion. These three components— fuel, oxygen, and heat source—are depicted in Figure 1-2, which is commonly called the fire triangle. The fire triangle shows that for combustion to occur, fuel, an oxidizing agent, and a heat source must be present in the same place at the same time. If any one of the legs of the triangle is removed, the combustion process will not be sustained. This is the most basic description of the fire phenomenon. It is applicable for most scenarios, with the exception of fire extinguishment involving dry chemicals and Halons.

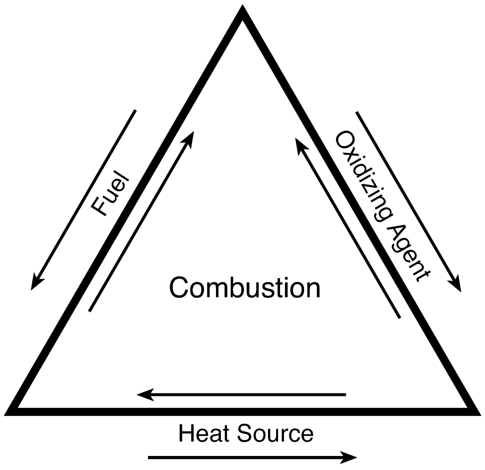

Figure 1-2 The Fire Triangle

## 1.8 The Fire Hazards

The fire load of NPPs is different than that of fossil-fuel power plants and many other industrial plants. An NPP does not have a constant flow of fuel (e.g., coal or oil) as the hazard. However, an NPP may have similar fire hazards, such as grouped electrical cables and lubricating oils (e.g., turbine, reactor coolant pumps). Table 1-1 lists the combustibles and hazardous materials that are commonly present in NPPs.

| **Table1-1. Common Combustible and Hazardous Materials in NPPs** |
|---|
| **Combustible solid fuels**<br>Cable insulation and jackets<br>Other thermal and electric insulation materials ( e.g., pipe insulation)<br>Building materials<br>Combustible metal deck and roof assemblies<br>Filtering materials including charcoal and high-efficiency particulate air (HEPA) filters<br>Packing materials and waste containers<br>Flexible materials used in connection with a seismic design, including flexible joints<br>Sealing materials (e.g., asphalt, silicone foam, neoprene, etc.)<br>Solidification agents for packing compacted radioactive waste conditioning (e.g., bitumen)<br>Low-level radioactive waste material (e.g., paper, plastic, anti-C-zone clothing, rubber shoes and gloves, overalls, etc.) |
| **Combustible and flammable liquid fuels**<br>Lubricants, hydraulic oil, and control fluids<br>Conventional fuels for emergency power units, auxiliary boilers, etc.<br>Paints and solvents |
| **Explosive and flammable gaseous fuels**<br>Hydrogen to cool the generators<br>Propane or other fuel gases, such as those used for starting boilers, burning radwaste, etc.<br>Oxygen and hydrogen radiolysis of reactor coolant water within the pressure vessel and addition of hydrogen for improved recombination<br>Hydrogen generated in battery room as a result of overcharging a battery |

The quantities and locations of these combustibles vary among NPPs. More importantly, identification of these combustibles and their characteristics only partially identifies the associated fire hazard. The bearing that the fire hazards have on nuclear safety must also be considered in defining the *total* fire hazard. Nuclear safety factors include maintaining the safe-shutdown capability and preventing radiation releases that exceed acceptable limits.

Fire hazards related to NPPs include (but are not limited) to the following examples:

- fire hazard associated with electrical cable insulation
- fire hazard of ordinary combustibles
- oil fire hazards associated with large reactor coolant pump motors
- oil fire hazard involving emergency turbine-driven feedwater pumpsdiesel fuel fire hazard at diesel-driven generators
- fire hazard involving charcoal in filter units
- fire hazard associated with flammable offgases
- fire hazard of protective coatings
- fire hazard of turbine lube oil and hydrogen seal oil

- hydrogen cooling gas fire hazard in turbine generator buildings
- fire hazard associated with electrical switchgear, motor control centers (MCCs), electrical cabinets, load centers, inverter, circuit boards, and transformers

### 1.8.1 Combustible Materials Found in Nuclear Power Plants

Combustible materials may be found in both large and small concentrations in NPPs. One can assume that outbreaks of fire may occur as a result of a variety of ignition sources. In general, the combustible materials in an NPP can be divided into four broad fuel categories, including (1) transient solid and liquid fuels, (2) in situ combustible consisting both solid and liquid fuels, (3) liquid fuels used in NPP equipment, and (4) explosive and flammable gases, as described in the following sections.

#### 1.8.1.1 Transient Combustibles

Solid transient fuels include general trash, paper waste, wood, plastics, cloth, and construction/modification materials. By contrast, liquid transient fuels commonly include cleaning solvents, paints, and lubricants being transported through the NPP for maintenance of plant equipment. These fuels are generally found in small quantities in most NPP areas at any given time.

#### 1.8.1.2 In Situ Combustibles

The most common category of potential fuels found in NPPs is that of in situ solid fuel elements. Of these, the largest single potential fuel source is cable insulation and jacketing materials. Several factors combine to support the conclusion that cable insulation and jacketing material far and away represent the most important materials to be considered in an NPP FHA, although any other plastic compounds installed in the NPP must also be included in the FHA. Cable insulation and jackets are typically manufactured using organic compounds and, therefore, they will burn under the proper circumstances.

The fire hazard associated with electrical cable insulation and jackets in NPPs is similar to that of other occupancies (e.g., telephone exchange) that use cable trays to support a large number of power, control, and instrument cables. However, an additional factor in NPPs is the added hazard associated with loss of reactor safety system redundancy.

A wide variety of cable insulation and jacketing materials can be commonly found in any given NPP. Cable insulation and jackets commonly encountered in an NPP include materials based on the following compounds:

- acrylonitrile-butadiene-styrene (ABS)
- chlorinated polyvinylchloride (CPVC)
- chlorosulfonated polyethylene rubber (CSP) (Hypalon®)
- chlorotrifluoroethylene (CTEF) (Kel-F®)
- cross-linked polyolefin (XLPO) including the more specific class of cross-linked polyethylene (XLPE)
- ethylenetetrafluoroethylene (ETFE) (Tefzel®)
- ethylene-propylene rubber (EPR)
- fluorinated polyethylene propylene (FEP) (Teflon®)
- neoprene or chloroprene rubber (CR)

- polycarbonate (PC)
- polyethylene (PE)
- polyethylene fluoride (PEF)
- polyethersulphone (PES)
- polypropylene (PP)
- polystyrene (PS)
- polytetrafluoroethylene (PTEF) (Teflon®)
- polyurethane (PU)
- polyvinyl chloride (PVC)
- silicone and silicone/rubber compounds
- styrene-butadiene rubber (SBR)
- tetrafluoroethylene (TFE) (Teflon®)

#### 1.8.1.3 Liquid Fuels

Liquid fuels include lubricating and cooling oils, cleaning solvents, and diesel fuels. These items are commonly used in pumps, motor generators, hydraulic-operated equipment, diesel-driven engines, transformers, and other equipment that require lubrication and cooling with heat transferring oils. Fires involving such types of equipment are relatively common and usually results from leakage or overheating.

#### 1.8.1.4 Explosive and Flammable Gases

Explosive and flammable gases are often present in an NPPs. The most common is hydrogen, which is present as a blanket inside the main generator and a byproduct of reactor operation (through dissociation of water). Battery rooms in NPPs are also a source of hydrogen gas production.

Gases can be categorized as flammable and nonflammable. In addition, some gases are not flammable but support combustion. For example, oxygen does not burn; however, most fires burn more rapidly if the oxygen concentration is increased.

A general word of caution about gaseous fuels: when a compressed gas, like butane, is released, the visible vapor cloud indicates that the gas is colder than the air temperature and, consequently, condensing the moisture in the air. It appears much like a fog; however, this visible cloud is not the extent of the gaseous vapor. This is because the vapor disappears from view as it warms up, but may still linger in the area. Thus, it is possible to stand in an invisible gaseous vapor with a concentration that is within the flammable range. If the vapor were to ignite, the person could be burned severely, if not killed.

## 1.9 Location of the Fire

Exposure fires involving transient combustibles are assumed to have an equal probability of occurring anywhere in a space or an enclosure, while fires involving fixed combustibles are assumed to occur at the site of the fixed combustible. Since the hazard is greater when a fire is located directly beneath a target (e.g., cable tray or electrical cabinet), this placement is normally evaluated for scenarios involving transient combustibles. For fixed combustibles, the actual geometry between the source and the target is evaluated to determine whether the target is located in the fire plume or ceiling jet region.

## 1.10 Risk-Informed, Performance-Based Fire Protection

Risk-informed, performance-based fire protection is an integration of decision-based and quantitative risk assessment with a defined approach for quantifying the performance success of fire protection systems (FPSs) (Barry, 2002).

Performance-based fire safety engineering is defined as “An engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and growth effluents; and (4) a quantitative assessment of the effectiveness of design alternatives against objectives,” (Custer and Meacham, 1997).

One primary difference between prescriptive and performance-based designs is that a fire safety goal, life safety, property protection, mission continuity, and environmental impact are explicitly stated in the performance-based design, while prescriptive requirements may inhibit fire safety components from the design. Performance-based fire protection design is widely gaining acceptance by various countries around the world including United States. The application of performance-based approach to fire safety analysis will certainly continue to gain widespread acceptance in the future as an alternative to prescriptive building and fire codes.

Risk is a quantitative measure of fire incident loss potential in terms of both the event likelihood and aggregate consequences. In the risk-informed approach, the analyst considers the likelihood that a fire will occur, as well as its potential severity of a fire and consequences. For example, based on the knowledge and experience of the equipment operator, a fire in a given turbine generator is likely to occur 80 percent of the time. Similarly based on the knowledge and experience of the fire protection engineer, the sprinkler system protecting that generator is 90-percent likely to contain and control that fire. Because the risk-informed, performance-based methodology quantifies the likelihood of a fire hazard and the likelihood that the fire protection system will contain or control the fire, it provides a more realistic prediction of the actual risk.

The risk-informed, performance-based approach presents a more realistic predication of potential fire hazards for a given system or process or for an entire operation. The performance-based approach provides solutions based on performance to established goals, rather than on prescriptive requirements with implied goals. Solutions are supported by operator and management about processes, equipment, and components; the buildings or structural housing them; operation data and maintenance personnel; and the fire protection systems in place. Published performance data pertaining to these aspects are also incorporated into the analysis.

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# CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL AND FORCED VENTILATION

## 2.1 Objectives

This chapter has the following objectives:

- Explain the different stages of a compartment fire.
- Identify the types of forced and natural ventilation systems.
- Explain how the various types of forced ventilation systems work.
- Describe how to calculate the hot gas layer temperature and smoke layer height for a fire in a compartment with both natural and forced ventilation systems.

## 2.2 Introduction

In evaluating the environmental conditions resulting from a fire in an enclosure, it is essential to estimate the temperature of the hot fire gases. These elevated temperatures can often have a direct impact on nuclear power plant (NPP) safety. A temperature estimate is also necessary in order to predict mass flow rates in and out through openings, thermal feedback to the fuel and other combustible objects, and thermal influence (initiating stimulus) on detection and suppression systems. Heat from a fire poses a significant threat to the operation of NPPs, both when the component and equipment come in contact with heated fire gases and when heat is radiated from a distance.

## 2.3 Compartment Fire Growth

A compartment or enclosure fire is usually a fire that is confined to a single compartment within a structure. Ventilation is achieved through open doors and windows, as well as heating, ventilation, and air conditioning (HVAC) systems. Such a fire typically progresses through several stages (or phases) as a function of time, as discussed in the next section.

### 2.3.1 Stages of Compartment Fires

Initially, fire in a compartment can be treated as a freely burning, unconfined fire. This treatment is a valid approximation until thermal feedback or oxygen depletion in the compartment becomes significant. In many ventilated spaces, the ventilation is stopped automatically under fire conditions, either through the shutdown of fan units or the closing of fire doors and dampers. In other spaces, however, ventilation systems may continue to operate or unprotected openings may remain open. The course of compartment fires, and the conditions that result, depend on the following variables (among others):

- fire heat release rate (HRR) of the combustible
- enclosure size
- enclosure construction
- enclosure ventilation

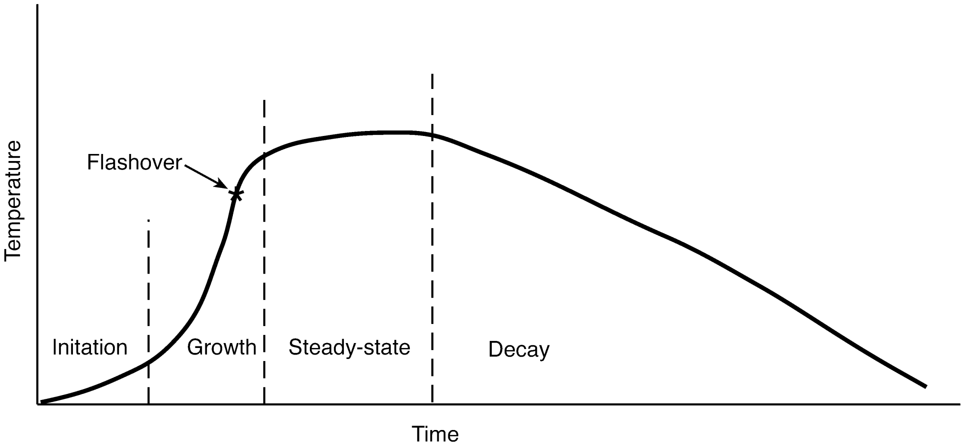
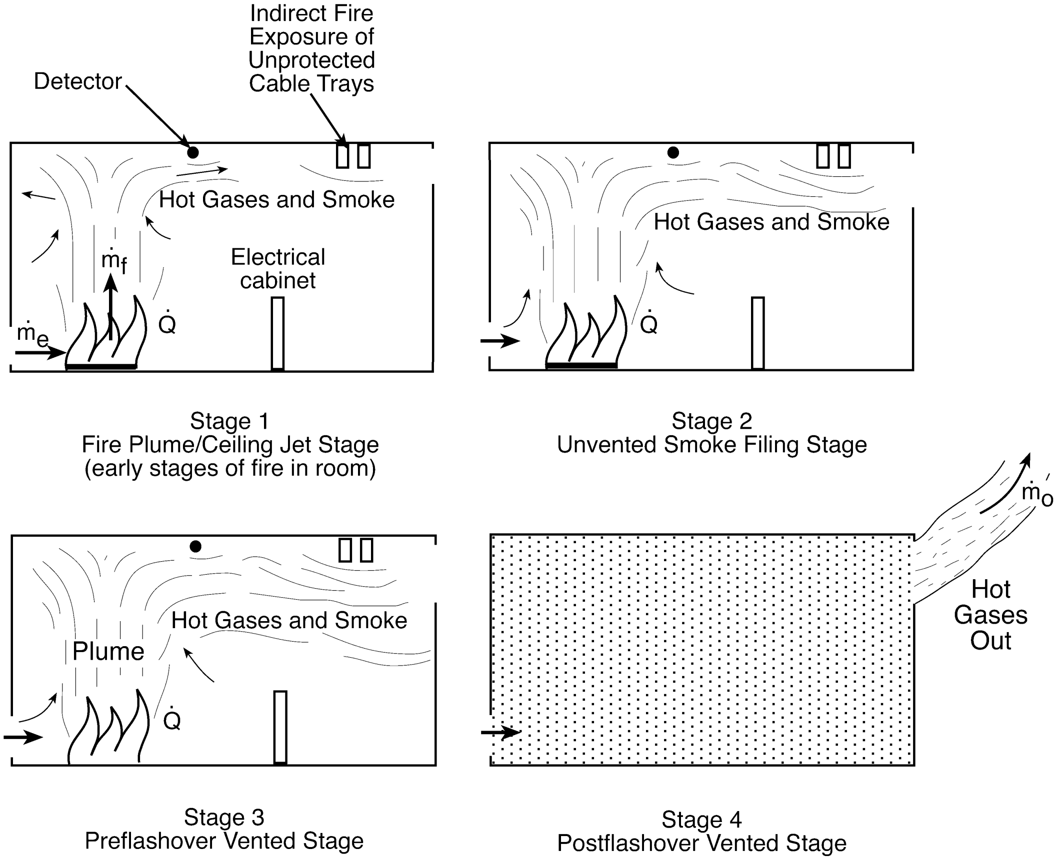


Figure 2-1 Typical Stages of Fire Development



Stage 1
Fire Plume/Ceiling Jet Stage
(early stages of fire in room)

Stage 2
Unvented Smoke Filing Stage

Stage 3
Preflashover Vented Stage

Stage 4
Postflashover Vented Stage

Figure 2-2 Stages of Compartment Fire

Conceptually, compartment fires can be considered in terms of the four stages illustrated in Figures 2-1 and 2-2. The initial stage of compartment fires is the fire plume/ceiling jet phase. During this stage, buoyant hot gases rise to the ceiling in a plume above the fire and spread radially beneath the ceiling as a relatively thin jet. As the plume gases rise to the ceiling, they entrain cool, fresh air. This entrainment decreases the plume temperature and combustion product concentrations, but increases the volume of smoke. The plume gases impinge upon the ceiling and turn to form a ceiling jet, which can continue to extend radially until it is confined by enclosure boundaries or other obstructions (such as deep solid beams at the ceiling level).

Once the ceiling jet spreads to the full extent of the compartment, the second stage of compartment fires ensues. During this stage, a layer of smoke descends from the ceiling as a result of air entrainment into the smoke layer and gas expansion attributable to heat addition to the smoke layer. The gas expansion, in turn increases the average temperature of the smoke layer. However, the continuing entrainment of cool, fresh air into the smoke layer tends to slow this temperature increase.

The duration of this second stage (an unventilated compartment smoke filling phase) depends on the HRR of the fuel, the size and configuration of the compartment, the heat loss histories, and the types and locations of ventilation openings in the compartment. In closed compartments, the smoke layer continues to descend until the room is filled with smoke or until the fire source burns out, as a result of either fuel consumption or oxygen depletion. In ventilated compartments, the smoke layer descends to the elevation where the rate of mass flow into the smoke layer is balanced by the rate of flow from the smoke layer through natural or mechanical ventilation.

The preflashover vented fire stage begins when smoke starts to flow from the compartment. Ventilation may occur naturally through openings in compartment boundaries (such as doorways), or it may be forced by mechanical air handling systems. The smoke layer may continue to expand and descend during the preflashover vented fire stage.

The final stage of compartment fires, known as the postflashover vented phase, represents the most significant hazard, both within the fire compartment and as it affects remote areas of a building. This stage occurs when thermal conditions within the compartment reach a point at which all exposed combustibles ignite, virtually simultaneously in many cases, and air flow to the compartment is sufficient to sustain intense burning. During this stage, the rate of air flow into the compartment and, consequently, the peak rate of burning within the compartment, become limited. The ventilation is limited by the sizes, shapes, and locations of boundary openings for naturally ventilated spaces, or by the ventilation rate from mechanically ventilated spaces. With adequate ventilation, flames may fill the enclosure volume and result in a rapid change from a developing compartment fire to full compartment involvement. This point is commonly referred to as “flashover.” Flashover is the point in compartment fire development which can evolve as a rapid transition from a slowly growing to fully developed fire. The underlying mechanism in this phenomenon is essentially a positive feedback from the fire environment to the burning fuel. The formation of a hot ceiling layer at the early stages of a fire leads to radiative feedback to the fuel, which, in turn, increases the burning rate and the temperature of the smoke layer. If heat losses from the compartment are insufficient, a sharp increase in the fire’s power (i.e., flashover) will eventually occur.

The International Organization for Standardization (ISO) formally defines flashover as "the rapid transition to a state of total surface involvement in a fire of combustion material within an enclosure." In fire protection engineering, the term is used as the demarcation point between the preflashover and postflashover stages of a compartment fire. Flashover is not a precise term, and several variations in its definition can be found in the literature. The criteria given usually require that the temperature in the compartment reaches 500 to 600 °C (932 to 1,112 °F), the radiation heat transfer to the floor of the compartment is 15 to 20 kW/m$^2$ (1.32 to 1.76 Btu/ft$^2$-sec), or flames appear from the compartment openings. In a compartment with one opening, flashover is principally described by four stages. Specifically, the hot buoyant plume develops at the first stage following ignition, and then reaches the ceiling and spreads as a ceiling jet during the second stage. During the third and fourth stages, the hot layer expands and deepens, while flow through the opening is established.

Flashover usually causes the fire to reach its fully developed state, in which all of the fuel within the room becomes involved. However, all of the fuel gases may not be able to combust within the room because the air supply is limited. Such an air-limited fire is commonly termed "ventilation-limited" or "ventilation-controlled", as opposed to a "fuel-limited" fire, which is a fire that has an ample supply of oxygen and is limited by the amount of materials (fuel) burning.

### 2.3.2 Ventilation-Limited or Ventilation-Controlled Fires

A ventilation-limited or ventilation-controlled fire is one that experiences low oxygen concentration as a result of insufficient air supply. The hot fire gases typically have nearly zero oxygen.

### 2.3.3 Fuel-Limited Fires

In contrast to a ventilation-limited fire, a fuel limited fire is a compartment fire in which the air supply is sufficient to maintain combustion, but the amount of fuel that is burning limits the fire size.

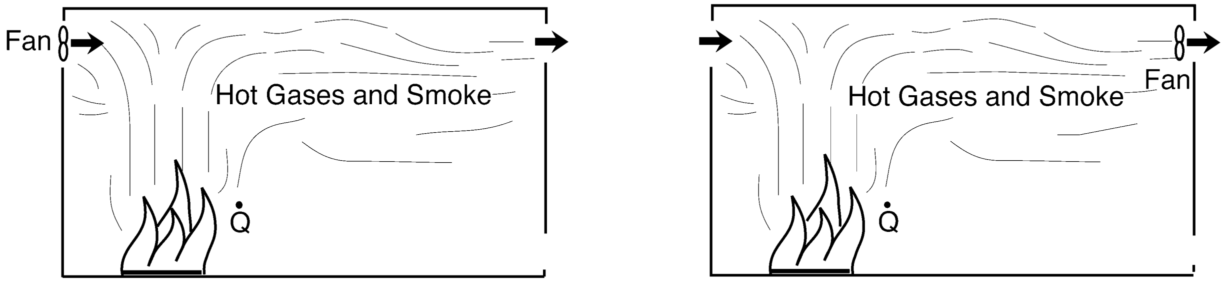
## 2.4 Compartment Ventilation

General ventilation system design controls heat, odors, and hazardous chemical contaminants. General ventilation can be provided by mechanical systems, by natural draft, or by a combination of the two. Examples of combination systems include (1) mechanical supply with air relief through louvers and/or other types of vents and (2) mechanical exhaust with air replacement inlet louvers and/or doors. Natural ventilation is a controlled flow of air caused by thermal and wind pressure.

Mechanical or forced ventilation is accomplished with fans to create the pressure differentials to produce the desired flows of air. Exhaust in the ventilation process that draws noxious air entrained particulate and vapors from a compartment, collect them into ducts for transport to the outside or to equipment that cleans the air before discharging it to the outside or returning it to the area of origin. In a closed area, exhaust cannot operate at the flows required without having an equal supply of makeup air available. "Makeup air" and "replacement air" are the terms commonly used to refer to the air that has to be brought into a space to limit pressure gradients so that the exhaust process can operate as designed. This air may be brought directly into a space via ducts or indirectly via openings from adjacent areas. The quantity of makeup air must be of a sufficient flow rate to allow the exhaust system to operate within its pressure differential design parameters, yet not be so great as to create a positive pressure within the compartment.

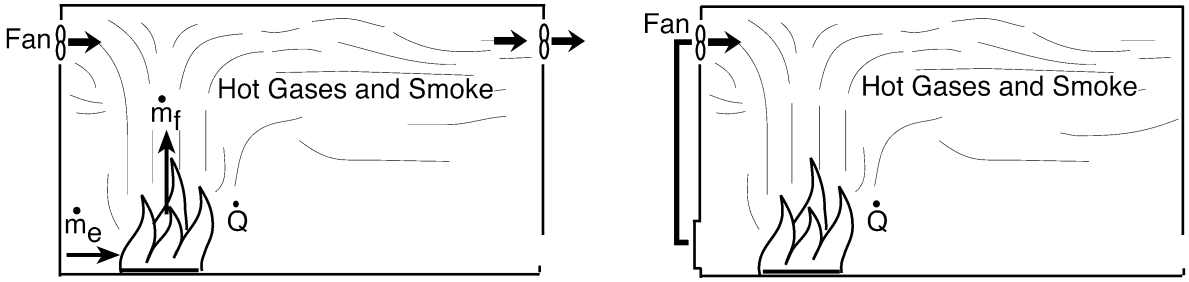
Mechanically ventilated compartments are a common environment for fire growth in NPP structures. A fire in a forced-ventilation compartment is markedly different than in a compartment with natural ventilation. An important factor is that the stratified thermal hot gas layer induced by the fire in a naturally ventilated compartment may be unstable in a forced ventilation compartment. Normally, a ventilating system recirculates most of the exhaust air. If normal operation were to continue during a fire, this recirculation could result in smoke and combustion products being mixed with supply air, and the contaminated mixture being delivered throughout the ventilation zone. To prevent this, dampers are often placed in the system. Upon fire detection in an engineered smoke control system, the damper positions are changed so that all exhaust from the fire zone is dumped, and 100-percent makeup air is drawn from outside the building.

The following four general types of mechanical ventilation systems are commonly encountered, as illustrated in Figure 2-3.



Push System

Pull System



Push-Pull System

Recirculation System

Figure 2-3 Types of Mechanical Ventilation Systems

### 2.4.1 Definitions

- *Push Systems* - Push systems mechanically supply fresh (outside) air into a compartment at the design volumetric flow rate of the system, while air expulsion occurs freely through transfer grills, registers, or diffusers in the compartment.
- *Pull Systems* - Pull systems mechanically extract hot gases (smoke) from a compartment. Pull systems are designed to extract smoke from a compartment based on the volumetric flow rate of the system. The density of smoke is normally less than that of ambient air because the smoke is at an elevated temperature.
- *Push-Pull Systems* - Push-pull systems both inject and extract air mechanically, with the supply and exhaust fan units typically sized and configured to produce balance supply and exhaust rates under normal operation. Push-pull systems cannot continue to operate at their balanced design flow rate under fire conditions. If the supply and exhaust fan units continue to inject and extract air at the same balanced design volumetric flow rates, the rate of mass injection will exceed the rate of mass extraction because of the difference in the densities of the supply and exhaust streams.
- *Recirculation Systems* - Recirculation systems typically use a single fan unit to mechanically extract air from a space, condition it, and return it to the same space.
- *Volume Flow Rate* handled by the fan is the number of cubic feet of air per minute (cfm) expressed at fan inlet conditions.
- *Fan Total Pressure Rise* is the fan total pressure at the outlet minus the fan total pressure at all inlet (in. of water).
- *Fan Velocity Pressure* is the pressure corresponding to the average velocity determined from the volume flow rate and fan outlet area (in. of water).
- *Fan Static Pressure Rise* is the fan total pressure rise diminished by the fan velocity pressure. The fan inlet velocity head is assumed to be equal to zero for fan rating purposes (in. of water).

## 2.5 Temperature

When discussing gases, temperature is a measure of the mean kinetic energy of the molecules in a gas. Temperature defines the conditions under which heat transfer occurs. A gas temperature, $T_g$, describes precisely the state of the average molecular energy in that gas. However that description is not particularly useful for the purposes of describing the physical phenomena that are relevant to fire science. In a broad sense, temperature can be thought of as a measure of the state of a system. Materials behave differently at different temperatures. Water, for example, at atmospheric pressure, is solid below 0 °C (32 °F), liquid between 0 °C (32 °F) and 100 °C (212 °F), and gaseous above 100 °C (212 °F). Similarly, plastic materials begin to gasify at a certain temperature. At a slightly higher temperature, they gasify enough to ignite, and at still higher temperatures, they may self-ignite. For our purpose, then, temperature can be viewed as an indicator of the state of an object system.

There are standard ways to define temperature. The most common are the Fahrenheit and Celsius scales of temperature. Related to these scales is the Kelvin absolute temperature scale[1]. The correspondence between the scales is illustrated in Table 2-1.

Table 2-1. Temperature Conversions

| **Original Unit** | **Conversions** | | |
|---|---|---|---|
| | **Celsius, $T_C$** | **Fahrenheit, $T_F$** | **Kelvin, $T_K$** |
| **Celsius, $T_C$** | - | 9/5 ($T_C$) + 32 | $T_C$ + 273.15 |
| **Fahrenheit, $T_F$** | 5/9 ($T_F$ - 32) | - | 5/9 ($T_F$ + 459.7) |
| **Kelvin, $T_K$** | $T_K$ - 273.15 | 9/5 ($T_K$ - 255.37) | - |

The difference between the relative temperature scale and its absolute counterpart is the starting point of the scale. That is, 0 °C is equal to 273 Kelvin and each degree on the Celsius scale is equal to 1 degree on the Kelvin scale. By contrast, the English unit temperature scale and SI (metric) unit temperature scale differ in two main ways. Specifically, zero is defined differently in Celsius than in Fahrenheit, and one degree Fahrenheit represents a different quantity of heat than one degree Celsius for a given heat capacity and mass. It is important to remember that these temperature scales are arbitrary, but they relate to important physical processes and the effect of temperature on an object is what we are really interested in.

Table 2-2 lists the critical temperatures for different exposure conditions and the resultant effects on humans.

Table 2-2. Critical Temperatures for Different Exposure Conditions and Effects on Humans [Chartered Institution of Building Services Engineers (CIBSE) Guide E. With permission.]

| **Type and Period of Heat Exposure** | **Temperature °C (°F)** | **Effect** |
|---|---|---|
| Radiation | 185 (365) | Severe skin pain |
| Conduction (metal) (1 second) | 60 (140) | Skin burns |
| Convection (30 minutes) | 100 (212) | Hyperthermia |
| Convection (< 5 minutes) | 120 (248) | Skin and lungs are burned by hot gases |
| Convection (<1 minute) | 190 (374) | Skin and lungs are burned by hot gases |

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[1] The Rankine scale is used for absolute zero in the English units. Since most fire dynamics equations will be solved in SI units, it will not be discussed here.

In order to calculate or predict the temperatures in a compartment, a description or analytical approximation of the fire phenomena must be created in quantitative terms. This approximation is described in terms of physical equations for chemistry, physics, mathematics, fluid mechanics, and heat and mass transfer, which can be solved to predict the temperature in the compartment. Such an approximation, therefore, is an idealization of the compartment fire phenomena (i.e., ignition, flame spread, and burning rate).

## 2.6 Estimating Hot Gas Layer Temperature

This section presents methods predicting the temperature achieved by the hot gas layer in an enclosure fire; these methods are currently the most widely accepted in the fire protection engineering literature. Nonetheless, the methods employ assumptions and limitations, which must be understood before using any of the methods presented.

### 2.6.1 Natural Ventilation: Method of McCaffrey, Quintiere, and Harkleroad (MQH)

The temperatures throughout a compartment in which a fire is burning are affected by the amount of air supplied to the fire and the location at which the air enters the compartment. Ventilation-limited fires produce different temperature profiles in a compartment than well-ventilated fires.

A compartment with a single rectangular wall opening (such as a door or window) is commonly used for room fire experiments. They also are commonly involved in real fire scenarios, where a single door or vent opening serves as the only path for fire-induced natural ventilation to the compartment. The hot gas layer that forms in compartment fires descends within the opening until a quasi-steady balance is struck between the rate of mass inflow to the layer and the rate of mass outflow from the layer.

A complete solution of the mass flow rate in this scenario requires equating and solving two non-linear equations describing the vent flow rate and the plume entrainment rate as a function of the layer interface height (the layer in a compartment that separates the smoke layer from the clear layer). If it is nonvented, the smoke layer gradually descends as the fire increases, thereby lowering the smoke interface and (possibly) eventually filling the compartment. McCaffrey, Quintiere, and Harkleroad (MQH) (1981) (also reported by Walton and Thomas, 1995 and 2002) have developed a simple statistical dimensionless correlation for evaluating fire growth in a compartment (hot gas layer temperature) with natural ventilation. This MQH correlation is based on 100 experimental fires (from 8 series of tests involving several types of fuel) in conventional-sized rooms with openings. The temperature differences varied from T = 20 °C (68 °F) to 600 °C (1,112 °F). The fire source was away from walls (i.e., data was obtained from fires set in the center of the compartment). The larger the HRR $(\dot{Q})$, and the smaller the vent, the higher we expect the upper-layer gas temperature to increase.

The approximate formula for the hot gas layer temperature increase, $T_g$, above ambient ($T_g$ - $T_a$) is as follows:

$$\Delta T_g = 6.85\left[\frac{\dot{Q}^2}{\left(A_v\sqrt{h_v}\right)\left(A_T h_k\right)}\right]^{\frac{1}{3}} \qquad (2\text{-}1)$$

Where:

$T_g$ = upper layer gas temperature rise above ambient ($T_g$ - $T_a$) (K)
$\dot{Q}$ = heat release rate of the fire (kW)
$A_v$ = total area of ventilation opening(s) ($m^2$)
$h_v$ = height of ventilation opening (m)
$h_k$ = heat transfer coefficient ($kW/m^2$-K)
$A_T$ = total area of the compartment enclosing surfaces ($m^2$), excluding area of vent opening(s).

The above equation can be used for multiple vents by summing the values, as follows:

$$\left(\sum_{i=1}^{n}\left(A_v\sqrt{h_v}\right)\right)_i$$

where n is the number of vents, and can be used for different construction materials by summing the $A_T$ values for the various wall, ceiling, and floor elements.

The compartment interior surface area can be calculated as follows:

$A_T$ = ceiling + floor 2 ($w_c$ x $l_c$)
+ 2 large walls 2 ($h_c$ x $w_c$)
+ 2 small walls 2 ($h_c$ x $l_c$)
- total area of vent opening(s) ($A_v$)

$$A_T = [2\,(w_c \text{ x } l_c) + 2\,(h_c \text{ x } w_c) + 2\,(h_c \text{ x } l_c)] - A_v \qquad (2\text{-}2)$$

Where:

$A_T$ = total compartment interior surface area ($m^2$), excluding area of vent opening(s)
$w_c$ = compartment width (m)
$l_c$ = compartment length (m)
$h_c$ = compartment height (m)
$A_v$ = total area of ventilation opening(s) ($m^2$)

For very thin solids, or for conduction through a solid that continues for a long time, the process of conduction becomes stationary (steady-state). The heat transfer coefficient, $h_k$, after long heating times, can be written as follows:

$$h_k = \frac{k}{\delta} \qquad (2\text{-}3)$$

Where:

k = thermal conductivity (kW/m-K) of the interior lining
= thickness of the interior lining (m)

This equation is useful for steady-state applications in which the fire burns longer than the time required for the heat to be transferred through the material until it begins to be lost out the back (cold) side. This time is referred to as the thermal penetration time, $t_p$, which can be calculated as:

$$t_p = \left(\frac{\rho\, c_p}{k}\right)\left(\frac{\delta}{2}\right)^2 \qquad (2\text{-}4)$$

Where:

= density of the interior lining (kg/m$^3$)
$c_p$ = thermal capacity of the interior lining (kJ/kg-K)
k = thermal conductivity of the interior lining (kW/m-K)
= thickness of the interior lining (m)

However, if the burning time is less than the thermal penetration time, $t_p$, the boundary material retains most of the energy transferred to it and little will be lost out the non-fire (cold) side. The heat transfer coefficient, $h_k$, in this case, can then be estimated using the following equation for $t < t_p$:

$$h_k = \sqrt{\frac{k\rho c}{t}} \qquad (2\text{-}5)$$

Where:

k c = interior construction thermal inertia [(kW/m$^2$-K)$^2$-sec]
(thermal property of the material responsible for the rate of temperature increase)
t = time after ignition in seconds (characteristic burning time)

By contrast, for $t \geq t_p$, the heat transfer coefficient is estimated from Equation 2-3.

As indicated above, the k c parameter is a thermal property of the material responsible for the rate of temperature increase. This is the product of the material thermal conductivity (k), the material density ( ), and the heat capacity (c). Collectively, k c is known as the material thermal inertia. For most materials, c does not vary significantly, and the thermal conductivity is largely a function of the material density. This means that density tends to be the most important material property. Low-density materials are excellent thermal insulators. Since heat does not pass through such materials, the surface of the material actually heats more rapidly and, as a result, can ignite more quickly. Good insulators (low-density materials), therefore, typically ignite more quickly than poor insulators (high-density materials). This is the primary reason that foamed plastics are so dangerous in fires; they heat rapidly and ignite in situations in which a poor insulator would be slower to ignite because of its slower response to the incident heat flux. The thermal response properties (k c), for a variety of generic materials have been reported in the literature. These values have been derived from measurements in the small-scale lateral ignition and flame spread test (LIFT) apparatus (ASTM E1321). Table 2-3 lists typical thermal properties of variety of materials.

Table 2-3. Thermal Properties of Compartment Enclosing Surface Materials
(Klote and Milke, 2002, © ASHRAE. With permission.)

| **Materials** | **Thermal Inertia k c $(kW/m^2\text{-}K)^2$-sec** | **Thermal Conductivity k (kW/m-K)** | **Thermal Capacity c (kJ/kg-K)** | **Density $(kg/m^3)$** |
|---|---|---|---|---|
| Aluminum (pure) | 500 | 0.206 | 0.0895 | 2710 |
| Steel (0.5% Carbon) | 197 | 0.054 | 0.465 | 7850 |
| Concrete | 2.9 | 0.0016 | 0.75 | 2400 |
| Brick | 1.7 | 0.0008 | 0.8 | 2600 |
| Glass, Plate | 1.6 | 0.00076 | 0.8 | 2710 |
| Brick/Concrete Block | 1.2 | 0.00073 | 0.84 | 1900 |
| Gypsum Board | 0.18 | 0.00017 | 1.1 | 960 |
| Plywood | 0.16 | 0.00012 | 2.5 | 540 |
| Fiber Insulation Board | 0.16 | 0.00053 | 1.25 | 240 |
| Chipboard | 0.15 | 0.00015 | 1.25 | 800 |
| Aerated Concrete | 0.12 | 0.00026 | 0.96 | 500 |
| Plasterboard | 0.12 | 0.00016 | 0.84 | 950 |
| Calcium Silicate Board | 0.098 | 0.00013 | 1.12 | 700 |
| Alumina Silicate Block | 0.036 | 0.00014 | 1.0 | 260 |
| Glass Fiber Insulation | 0.0018 | 0.000037 | 0.8 | 60 |
| Expanded Polystyrene | 0.001 | 0.000034 | 1.5 | 20 |

### 2.6.2 Natural Ventilation (Compartment Closed): Method of Beyler

Beyler (1991) (also reported by Walton and Thomas, 2002) developed a correlation based on a nonsteady energy balance to the closed compartment, by assuming that the compartment has sufficient leaks to prevent pressure buildup. For constant HRR, the compartment hot gas layer temperature increase, $T_g$, above ambient ($T_g$ - $T_a$) is given by the following equation:

$$\Delta T_g = T_g - T_a = \frac{2K_2}{K_1^2}\left(K_1\sqrt{t} - 1 + e^{-K_1\sqrt{t}}\right) \qquad (2\text{-}6)$$

Where:

$$K_1 = \frac{2\left(0.4\sqrt{k\rho c}\right)}{mc_p} \qquad\qquad K_2 = \frac{\dot{Q}}{mc_p}$$

And:

$T_g$ = upper layer gas temperature rise above ambient ($T_g$ - $T_a$) (K)
k = thermal conductivity of the interior lining (kW/m-K)
= density of the interior lining (kg/$m^3$)
c = thermal capacity of the interior lining (kJ/kg-K)
$\dot{Q}$ = heat release rate of the fire (kW)
m = mass of the gas in the compartment (kg)
$c_p$ = specific heat of air (kJ/kg-k)
t = exposure time (sec)

### 2.6.3 Forced Ventilation: Method of Foote, Pagni, and Alvares (FPA)

Foote, Pagni, and Alvares (FPA) (1985) (also reported by Walton and Thomas, 1995 and 2002) developed another method, which follows the basic correlations of the MQH method, but adds components for forced-ventilation fires. This method is based on temperature data that were obtained from a series of tests conducted at the Lawrence Livermore National Laboratory (LLNL). Fresh air was introduced at the floor and pulled out the ceiling by an axial fan. Test fires from 150 to 490 kW were used, producing ceiling jet temperatures from 100 to 300 °C (212 to 572 °F). The approximate constant HRR and ventilation rates were chosen to be representative of possible fires in ventilation-controlled rooms with seven room air changes per hour, which was roughly between 200 and 575 cfm.

The upper-layer gas temperature increase above ambient is given as a function of the fire HRR, the compartment ventilation flow rate, the gas-specific heat capacity, the compartment surface area, and an effective heat transfer coefficient. The nondimensional form of the resulting temperature correlation is as follows:

$$\frac{\Delta T_g}{T_a} = 0.63 \left(\frac{\dot{Q}}{\dot{m} c_p T_a}\right)^{0.72} \left(\frac{h_k A_T}{\dot{m} c_p}\right)^{-036} \qquad (2\text{-}7)$$

Where:

$T_g$ = hot gas layer temperature rise above ambient ($T_g$ - $T_a$) (K)
$T_a$ = ambient air temperature (K)
$\dot{Q}$ = HRR of the fire (kW)
$\dot{m}$ = compartment mass ventilation flow rate (kg/sec)
$c_p$ = specific heat of air (kJ/kg-K)
$h_k$ = heat transfer coefficient (kW/$m^2$-K)
$A_T$ = total area of compartment enclosing surfaces ($m^2$)

The above correlation for forced-ventilation fires can be used for different construction materials by summing the $A_T$ values for the various wall, ceiling, and floor elements.

### 2.6.4 Forced Ventilation: Method of Deal and Beyler

Deal and Beyler (1990) (also reported by Walton and Thomas, 2002) developed a simple model of forced ventilated compartment fires. The model is based on a quasi-steady simplified energy equation with a simple wall heat loss model. The model is only valid for times up to 2000 seconds. The approximate compartment hot gas layer temperature increase, $T_g$, above ambient ($T_g$ - $T_a$) is given by the following equation:

$$\Delta T_g = T_g - T_a = \frac{\dot{Q}}{\dot{m} c_p + h_k A_T} \qquad (2\text{-}8)$$

Where:

$T_g$ = hot gas layer temperature rise above ambient ($T_g$ - $T_a$) (K)
$T_a$ = ambient air temperature (K)
$\dot{Q}$ = HRR of the fire (kW)
$\dot{m}$ = compartment mass ventilation flow rate (kg/sec)
$c_p$ = specific heat of air (kJ/kg-K)
$h_k$ = convective heat transfer coefficient (kW/$m^2$-K)
$A_T$ = total area of compartment enclosing surfaces ($m^2$)

The convective heat transfer coefficient is given by the following expression:

$$h_k = 0.4 \max \left( \sqrt{\frac{k\rho c}{t}},\ \frac{k}{\delta} \right) \qquad (2\text{-}9)$$

Where:

k = thermal conductivity of the interior lining (kW/m-K)
= density of the interior lining (kg/m$^3$)
c = thermal capacity of the interior lining (kJ/kg-K)
t = exposure time (sec)
= thickness of the interior lining (m)

## 2.7 Estimating Smoke Layer Height

When a fire occurs in a compartment, within few seconds of ignition, early flame spread can quickly lead to a flaming, free-burning fire. If left unchecked, the fire continues to grow. Besides releasing energy, the combustion process also yields a variety of other products, including toxic and nontoxic gases and solids. Together, all of these products are generally referred to as the “smoke” produced by the fire.

As the flame spreads across the fuel surface, the fire size, which can be described as the HRR, increases. As the size increases, the radiation heat transfer from the flame to the fuel surface increases, and this increases the burning rate. If the flame has not involved the entire surface area, this increased fire size accelerates the flame spread. Above the flame zone, a buoyant plume is formed. The plume entrains ambient air, which both cools the gas and increases the flow rate. In a typical compartment, the plume strikes the ceiling and forms a ceiling jet, which in turn strikes a wall, and the compartment begins to fill with hot smoke from the ceiling downward. The plume continues to entrain ambient air, adding mass to the layer until it reaches the upper gas layer. Here, as the gas layer descends, less mass is entrained into it. Thus, the amount of gas flow from the plume is a function of the fire size and the height over which entrainment occurs.

As previously stated, the temperature and composition of gas entering the hot gas layer are driven by the fire source and the plume. Once the hot gas enters this hot layer, it cools by losing energy to surrounding surfaces (i.e., ceiling, walls) by conduction, and cools by radiating heat energy to the floor and the cool gas layer near the floor. The rate of descent of the hot gas layer is driven by the size of the compartment and the amount of mass flow from the plume. Since the plume mass flow is a function of the height beneath the gas layer, the layer descends at a progressively slower rate as it gets closer to the fire source.

The plume essentially mixes cool air with the combustion products, thereby increasing the total flow into the hot gas layer, while reducing its temperature and the concentration of gases flowing into it. The plume can only add mass to the upper layer by entrainment along the plume axis below the hot gas layer position. Once it penetrates the hot gas layer, it entrains hot gas, helping to mix the layer, but not increasing its depth.

One of the most important processes that occurs during the early stages of a compartment fire is the filling of the compartment with smoke. Although the hot layer gas temperatures are relatively low [< 200 °C (392 °F)], the composition of the smoke relative to visibility and toxicity and the vertical position of the layer are of interest. Figure 2-4 shows this process schematically.

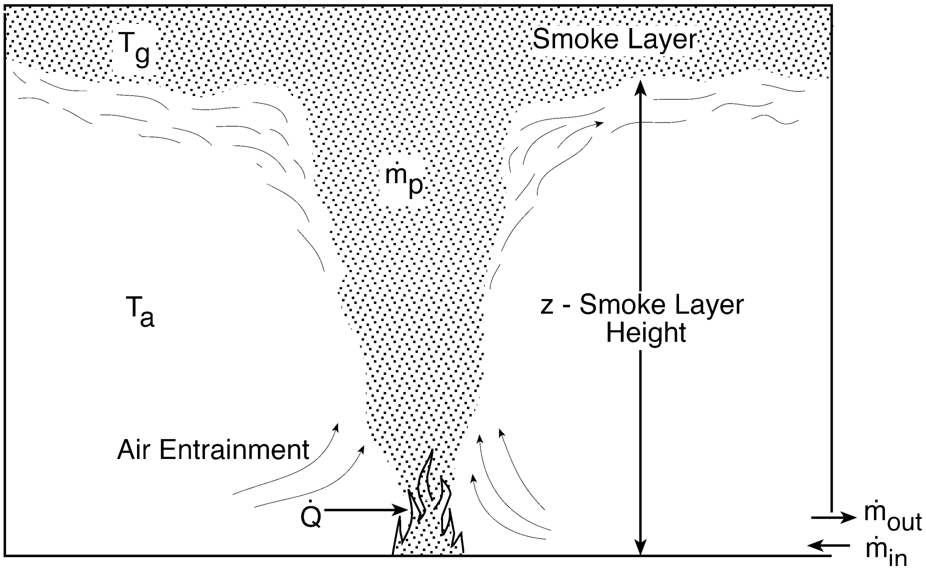


Figure 2-4 Smoke Filling in a Compartment Fire

### 2.7.1 Smoke Layer

The smoke layer can be described as the accumulated thickness of smoke below a physical or thermal barrier (e.g., ceiling). The smoke layer is typically not a homogeneous mixture, and it does not typically have a uniform temperature. However, for first-order approximations, the calculation methods presented below assume homogeneous conditions. The smoke layer includes a transition zone that is nonhomogeneous and separates the hot upper layer from the smoke-free air (i.e., two zones).

### 2.7.2 Smoke Layer Interface Position

Figure 2-5 depicts the theoretical boundary (or interface) between a smoke layer and the smoke-free air. In practice, the smoke layer interface is an effective boundary within a transition buffer zone, which can be several feet thick. Below this effective boundary, the smoke density in the transition zone decreases to zero.

### 2.7.3 Natural Ventilation (Smoke Filling): The Non-Steady-State Yamana and Tanaka Method

In a compartment with larger openings (windows or doors), there will be little or no buildup of pressure attributed to the volumetric expansion of hot gases, with the exception of rapid accumulation of mass or energy. Thus, for the first-order approximations, pressure is assumed to remain at the ambient pressure. The opening flows are thus determined by the hydrostatic pressure differences across the openings, and mass flows out of and into the compartment. We also assume that the upper layer density ( $_g$), is some average constant value at all times throughout the smoke-filling process.

Assuming a constant average density in the upper hot gas layer has the advantage that we can form an analytical solution of the smoke-filling rate, where the HRR does not need to be constant (that is, it can be allowed to change with time), and we can use the conservation of mass to arrive at the expression for the smoke-filling rate. When this is done, the height of the smoke layer as a function of time is known, and we can use the conservation of energy to check the stipulated value of $\rho_g$.

Yamana and Tanaka (1985) (also reported by Karlsson and Quintiere, 1999b) developed the expression for the height of the smoke layer interface, z, in terms of time, as follows:

$$z = \left( \frac{2\ k\ \dot{Q}^{\frac{1}{3}}\ t}{3\ A_c} + \frac{1}{h_c^{\frac{2}{3}}} \right)^{-\frac{3}{2}} \qquad (2\text{-}10)$$

Where:

$z$ = height (m) of the smoke layer interface above the floor

$\dot{Q}$ = heat release rate of the fire (kW)

$t$ = time after ignition (sec)
$A_c$ = compartment floor area ($m^2$)
$h_c$ = compartment height (m)

And:

$k$ = a constant given by the following equation:

$$k = \frac{0.21}{\rho_g} \left( \frac{\rho_a^2 g}{c_p T_a} \right)^{\frac{1}{3}} \qquad (2\text{-}11)$$

Where:

$\rho_g$ = hot gas density $kg/m^3$
$\rho_a$ = ambient density = 1.20 $kg/m^3$
$g$ = acceleration of gravity = 9.81 $m/sec^2$
$c_p$ = specific heat of air = 1.0 kJ/kg-K
$T_a$ = ambient air temperature = 298 K.

Substituting the above numerical values in Equation 2-11, we get the following expression:

$$k = \frac{0.076}{\rho_g} \qquad (2\text{-}12)$$

Where density of the hot gas ($\rho_g$), layer is given by:

$$\rho_g = \frac{353}{T_g} \qquad (2\text{-}13)$$

Where:

$T_g$ = hot gas layer temperature (K) calculated from Equation 2-1

*Calculation Procedure*

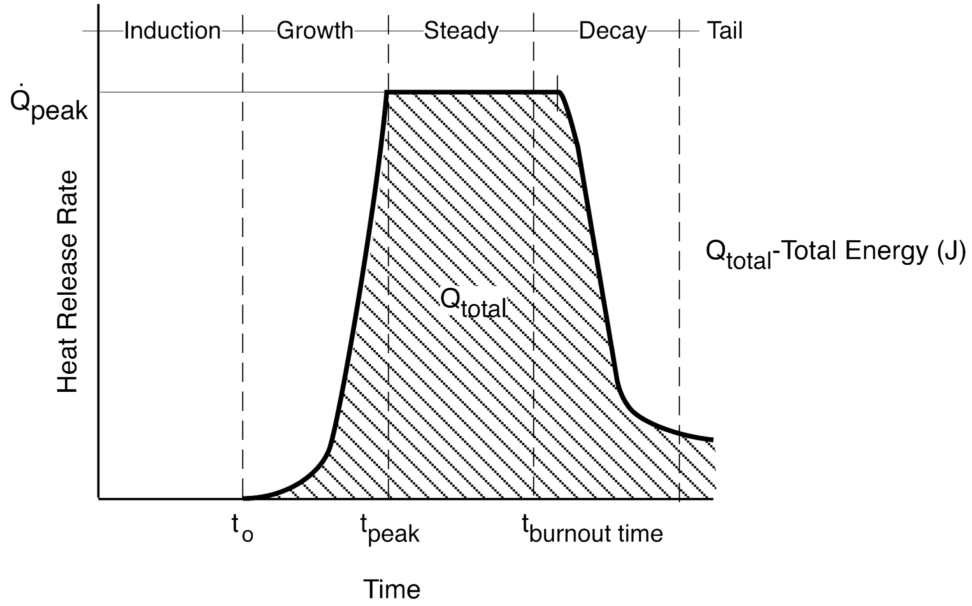
(1) Calculate $_g$ from Equation 2-13.
(2) Calculate the constant k from Equation 2-12.
(3) Calculate the smoke layer height (z) at the some time (t) from Equation 2-10 given HRR.

## 2.8 Data Sources for Heat Release Rate

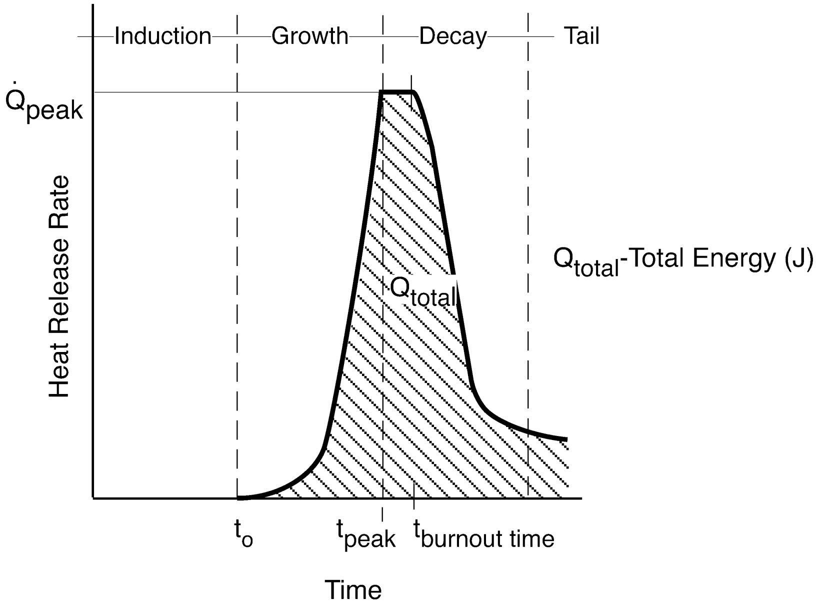
When an object burns, it releases a certain amount of energy per unit of time. For most materials, the HRR of a fuel changes with time, in relation to its chemistry, physical form, and availability of oxidant (air), and is ordinarily expressed as kW (kJ/sec) or Btu/sec and denoted by $\dot{Q}$ (1,000 kW = 1 MW) (1 BTU/sec = 1.055 kW).

Figure 2-5 illustrates the general features of typical HRR histories. HRR commonly demonstrates an acceleratory growth stage, which may follow an induction stage of negligible growth. Objects may or may not exhibit the period of fairly steady burning illustrated in Figure 2-5 (a); this depends on whether fuel burnout begins after the fuel surface is fully involved. Materials that do not begin to burn out before the fuel surface is fully involved (peak HRR) demonstrate the fairly steady burning period exhibited in Figure 2-5 (a) until burnout begins; materials that begin to burn out before the peak HRR is achieved are characterized by heat release curves with distinct peaks, as illustrated in Figure 2-5 (b). In either case, at some time following attainment of peak HRR, a decay stage associated with fuel burnout usually occurs. This decay stage frequently gives way to a tail stage of relatively low HRR. This tail stage, which may persist for an extended time, is normally attributable to the glowing combustion that follows flaming combustion for char-forming products.

The total energy released by a material is equal to the area under the time-HRR curve. This area is influenced by the energy released during the tail stage, which may contribute a considerable portion of the total energy released, but at such a slow rate that it does not constitute the significant hazard.



(a) Burnout Time > Time to Peak HRR



(b) Burnout Time < Time to Peak HRR

Figure 2-5 General Representation of Heat Release Rate Histories for a Fuel Package

## 2.9 Identification of Fire Scenario

The first step in an FHA is to identify which target(s) to evaluate within an enclosure or compartment. Normally, the target is a safety-related component that is being evaluated for a particular scenario. However, if exposed, intervening combustibles exist between the fire source and the safety-related component, they can become the targets for further evaluation.

Electrical cables typically serve as the primary target for most NPP analyses. The nuclear industry has defined two general types of electrical cables, referred to as IEEE-383 qualified and unqualified. These terms refer to cables that either pass or fail the IEEE-383 fire test standard, respectively. A damage threshold temperature of 370 °C (700 °F) and a critical heat flux of 10 $kW/m^2$ (1 $Btu/ft^2$-sec) have been selected for IEEE-383 qualified cable. A damage threshold temperature of 218 °C (425 °F) and a critical heat flux of 5 $kW/m^2$ (0.5 $Btu/ft^2$-sec) have been selected for IEEE-383 unqualified cable. These values are reported in several studies, including NUREG/CR-4679, Electrical Power Research Institute (EPRI), “Fire-Induced Vulnerability Evaluation (FIVE) Methodology,” and the U.S. Department of Transportation (DOT) study reported in “Combustibility of Electrical Wire and Cable for Rail Rapid Transient Systems,” DOT-TSC-UMAT-83-4-1, May 1983.

The second step in an FHA is to identify the location of credible exposure fire sources relative to the target being evaluated. Exposure fires involving transient combustibles are assumed to have an equal probability of occurring anywhere in a space, while exposure fires involving fixed combustibles are assumed to occur at the site of the fixed combustible. Since the hazard is greater when a fire is located directly beneath a target, this placement is evaluated for scenarios involving exposure fires with transient combustibles. For fixed combustibles, the actual geometry between the source and the target is evaluated to determine whether the target is located in the fire plume region.

Representative unit HRR values for a number of fuels present in the NPP (e.g., electrical cables, electrical cabinets, flammable/combustible liquids, and transient combustibles) have been measured and reported in various reports by Lee (1985), Nowlen (1986 and 1987), Chavez (1987), and Babrauskas (1991). Flammable/combustible liquid spill fires and trash fires are the most commonly postulated transient fuel exposure fires in NPPs. Electrical cable fires and electrical cabinet fires are the most commonly postulated fixed fuel fires. Tables 2-4 through 2-10 show the HRR and other data for common fixed and transient combustible materials found in NPPs.

Table 2-4. Measured Heat Release Rate Data for Cable Jacketing Material (Lee, 1981)

| **Fuel** | **HRR per Unit Area** $\dot{Q}''$ **(kW/m²)** | **Heat of Combustion** $H_c$ **(kJ/kg)** |
|---|---|---|
| PE/PVC (Polyethylene/Polyvinylchloride) | 590 | 24,000 |
| XPE/FRXPE (Crosslinked Polyethylene/Fire Retardant Crosslinked Polyethylene) | 475 | 28,300 |
| XPE/Neoprene | 300 | 10,300 |
| PE, Nylon/PVC, Nylon | 230 | 9,200 |
| Tefzel™ - ETFE (Ethylenetetrafluoroethylene) | 100 | 3,200 |

Table 2-5. Measured Heat Release Rate Data for Electrical Cabinets (Nowlen, 1986 and 1987)

| **Fuel** | **Peak HRR*** $\dot{Q}$ **(kW)** |
|---|---|
| Electrical Cabinet Filled with IEEE-383 Qualified Cables (Vertical doors open) | 55 |
| Electrical Cabinet Filled with IEEE-383 Qualified Cables (Vertical doors closed) | No data |
| Electrical Cabinet Filled with IEEE-383 Unqualified Cables (Vertical doors open) | 1,000 |
| Electrical Cabinet Filled with IEEE-383 Unqualified Cables (Vertical doors closed, vent grills only) | 185 |
| *Note: HRR contributions in the electrical cabinet are based solely on the cable insulation material, and neglect the energy release based on the current (amperes squared multiplied by time.) | |

Table 2-6. Measured Heat Release Rate Data for Transient Combustible Materials (Flammable/Combustible Liquids)

| **Fuel** | **HRR per Unit Area** $\dot{Q}''$ **(kW/m$^2$)** |
|---|---|
| Diesel oil | 1,985 |
| Gasoline | 3,290 |
| Kerosene | 2,200 |
| Transformer oil | 1,795 |
| Lube oil lubrication<br>(used in reactor coolant pump (RCP) motors and turbine) | For lubricating oil, use HRR of transformer oil. Lubricating oil has burning characteristics similar to transformer oil. |

Table 2-7. Measured Heat Release Rate Data for Transient Combustible Materials (Trash) (Lee, 1985)

| **Fuel** | **Peak HRR** $\dot{Q}$ **(kW)** |
|---|---|
| 9.1 kg computer paper crumpled up in two plastic trash bags | 110 |
| 11.4 kg rags, 7.7 paper towels. 5.9 kg plastic gloves and taps, and 5.9 kg methyl alcohol, mixed in two 50-gallon trash bags | 120 |
| 13.6 kg computer paper crumpled up and divided in two 7.5 kg (50 gallon) plastic trash cans | 110 |
| 4.6 kg crumpled up computer paper and 31.8 kg folded computer paper, evenly divided into two bags | 40 |

Table 2-8. Measured Heat Release Rate Data
for Transient Combustible Materials (Plywood and Wood Pallet)
(Karlsson and Quintiere, 1999a, © CRC Press, LLC. With permission.)

| **Fuel** | **HRR per Unit Area** $\dot{Q}''$ **(kW/m$^2$)** |
|---|---|
| Douglas fir plywood | 124 |
| Fire-retardant treated plywood | 81 |
| Wood pallets, stacked 1½ ft high | 1,420 |
| Wood pallets, stacked 5 ft high | 3,970 |
| Wood pallets, stacked 10 ft high | 6,800 |
| Wood pallets, stacked 16 ft high | 10,200 |

Table 2-9. Ignition Thresholds (Pilotless within 30 seconds)
(Naval Ship's Technical Manual, S9086-S3-STM-010/CH-555, 1993)

| **Material** | **Hot Air (Oven Effect) °C (°F)** | **Hot Metal Contact (Frying Pan Effect) (kW/m$^2$)** | **Radiant Heat Flux (kW/m$^2$)** |
|---|---|---|---|
| Paper | 230 (450) | 250 (480) | 20 |
| Cloth | 250 (480) | 300 (570) | 35 |
| Wood | 300 (570) | 350 (660) | 40 |
| Cables | 375 (700) | 450 (840) | 60 |

Table 2-10. Thermal Effects on Electronics
(Naval Ship's Technical Manual, S9086-S3-STM-010/CH-555, 1993)

| **Temperature °C (°F)** | **Effects** |
|---|---|
| 50 (120) | Computer develop faults |
| 150 (300) | Permanent computer damage |
| 250 (480) | Data transmission cable fail |

## 2.10 Assumptions and Limitations

The methods discussed in this chapter have several assumptions and limitations.

*The following assumptions and limitations apply to **all** forced and natural convection situations:*

(1) These methods best apply to conventional-size compartments. They should be used with caution for large compartments.

(2) These methods apply to both transient and steady-state fire growth.

(3) The HRR must be known; it does not need to be constant, and can be allowed to change with time.

(4) Compartment geometry assumes that a given space can be analyzed as a rectangular space with no beam pockets. This assumption affects the smoke filling rate within a space if the space has beam pockets. For irregularly shaped compartments, equivalent compartment dimensions (length, width, and height) must be calculated and should yield slightly higher layer temperatures than would actually be expected from a fire in the given compartment.

(5) These methods predict average temperatures and do not apply to cases in which predication of local temperature is desired. For example, this method should not be used to predict detector or sprinkler actuation or the material temperatures resulting from direct flame impingement.

(6) Caution should be exercised when the compartment overhead are highly congested with obstructions such as cable trays, conduits, ducts, etc.

(7) A single heat transfer coefficient may be used for the entire inner surface of the compartment.

(8) The heat flow to and through the compartment boundaries is unidimensional ( i.e., corners and edges are ignored, and the boundaries are assumed to be infinite slabs).

(9) These methods assume that heat loss occurs as a result of mass flowing out through openings. Consequently, these methods do not apply to situations in which significant time passes before hot gases begin leaving the compartment through openings. This may occur in large enclosures (e.g., turbine building), where it may take considerable time for the smoke layer to reach the height of the opening.

*The following assumptions and limitations apply only to **natural convection** situations:*

(10) The correlations hold for compartment upper layer gas temperatures up to approximately 600 °C (1,112 °F) only for naturally ventilated spaces in which a quasi-steady balance develops between the rates of mass inflow and outflow from the hot gas layer.

(11) These correlations assume that the fire is located in the center of the compartment or away from the walls. If the fire is flush with a wall or in a corner of the compartment, the MQH correlation is not valid with coefficient 6.85.

(12) The smoke layer height correlation assumes an average constant value of upper layer density throughout the smoke-filling process.

(13) The correlation does not allow the vent to be placed in the ceiling.

(14) At the EPRI Fire Modeling Workshop, August 26, 2002 in Seattle, Washington, Mark Salley asked Professor James G. Quintiere (one of the authors of the MQH method) what limits apply to compartment size when using the MQH equation. Professor Quintiere replied that the correlation will work for ***any*** size compartment since it is a dimensionless equation. Professor Quintiere also stated that $\dot{Q}$ should be limited by the following expressions:

$$\dot{m}_f \Delta H_c \leq \ 3000 \frac{kJ}{kg} \quad \text{or} \quad 0.5 A_v \sqrt{h_v} \leq \ 3000 \frac{kJ}{kg}$$

Where:

$\dot{m}_f$ = mass loss rate of fuel (kg/sec)

$H_c$ = heat of combustion (kJ/kg)
$A_v$ = area of ventilation opening ($m^2$)
$h_v$ = Height of ventilation opening (m)

*The following assumptions and limitations apply only to* ***forced convection*** *situations:*

(15) These correlations assume that the test compartment is open to the outside at the inlet, and its pressure is fixed near 1 atmosphere.

(16) These correlations do not explicitly account for evaluation of the fire source.

(17) These correlations assume that the fire is located in the center of the compartment or away from the walls. If the fire is flush with a wall or in a corner of the compartment, the Foot, Pagni, and Alvares (FPA) correlation is not valid with coefficient 0.63.

## 2.11 Required Input for Spreadsheet Calculations

The user must obtain the following values before attempting a calculation using the natural or forced ventilation spreadsheets:

(1) Compartment width (ft)
(2) Compartment length (ft)
(3) Compartment height (ft)
(4) Interior lining material thickness (in)
(6) Fire heat release rate, HRR (kW)

The user must obtain the following values before attempting a calculation using the natural ventilation spreadsheets:

(7) Vent width (ft)
(8) Vent height (ft)
(9) Top of vent from floor (ft)

The user must obtain the following values before attempting a calculation using the forced ventilation spreadsheets:

(10) Forced ventilation rate (cfm)

## 2.12 Cautions

(1) Use the appropriate spreadsheet (02.1_Temperature_NV.xls, 02.2_Temperature_FV.xls, or 02.3_Temperature_CC.xls) in the CD ROM for calculation.

(2) Make sure to input values using correct units.

(3) The smoke layer height is a conservative estimate and is only intended to provide an indication of where the hot gas layer is located. Calculated smoke layer heights below the vent height are not creditable since the calculation does not account for smoke exiting the vent!

## 2.13 Summary

Determination of hot gas layer temperatures and smoke layer height associated with compartment fires provides a means of assessing an important aspect of fire hazard, namely the likelihood of hazardous conditions when structural elements are in danger of collapsing, and the thermal feedback to fuel sources or other objects.

When doors and/or windows provide the air for the fire, natural ventilation occurs, and the MQH correlation applies to the prediction of hot gas temperature. The correlation is relatively straightforward, and it yields reasonable results when applied to most situations. Specifically, the correlation gives the temperature increase of the hot gas layer as a function of three primary variables:

(1) fire size ( $\dot{Q}$ , HRR)
(2) energy losses to the walls ($h_k$, $A_T$)
(3) energy loss through vents ($A_v\sqrt{h_v}$)

Forced ventilation can have a significant effect on fire growth, the temperature profile in the compartment, the spread of toxic fire gases, and the descent of the hot gas layer in a multi-room building. The magnitude of this effect, of course, depends on the HRR of the combustibles and the amount and configuration of the forced ventilation. Depending on the arrangement of the supply and exhaust vents, forced ventilation affects the compartment's thermal environment and sensitive equipment, as it relates to the descent of the hot gas layer. For situations involving forced ventilation, the FPA correlation is applied to the prediction of hot gas temperature. Specifically the FPA correlation gives the temperature increase of the hot gas layer as a function of three primary variables:

(1) fire size ( $\dot{Q}$ , HRR)
(2) energy losses to the walls ($h_k$, $A_T$)
(3) energy loss through vents ( $\dot{m}_f\ c_pT_a$)

The depth (or height) of the growing smoke layer increases with time, but it does not change once the smoke layer has reached equilibrium. Unsteady fires do not have a plateau or upper limit for the rate of heat release. In addition, unsteady fires may have a less rapid buildup of pressure. One approach is to relate the interface of a growing smoke layer for an unsteady fire to a $t^2$ fire profile.

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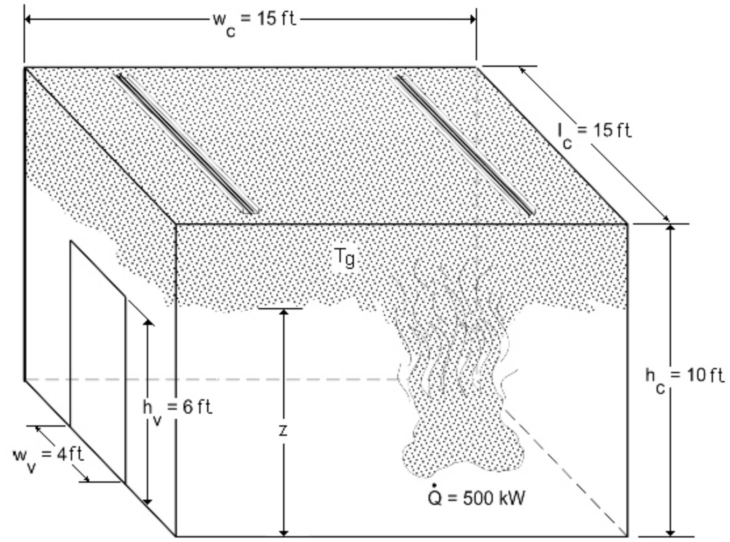
## 2.16 Problems

### 2.16.1 Natural Ventilation

**Example Problem 2.16.1-1**

**Problem Statement**

Consider a compartment that is 15 ft wide x 15 ft long x 10 ft high ($w_c$ x $l_c$ x $h_c$), with a simple vent that is 4 ft wide x 6 ft tall ($w_v$ x $h_v$). The fire is constant with an HRR of 500 kW. Compute the hot gas layer temperature in the compartment and smoke layer height at 2 minutes assuming that the compartment interior boundary material is (a) 1 ft thick concrete and (b) 1.0 inch thick gypsum board. Assume that the top of the vent is 6 ft.



Example Problem 2-1: Compartment with Natural Ventilation

**Solution**

Purpose:

For two different interior boundary materials determine following:

(1) The hot gas layer temperature in the compartment ($T_g$) at t = 2 min after ignition

(2) The smoke layer height (z) at t = 2 min after ignition

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)

(2) Simple rectangular geometry (no beam pockets)

(3) One-dimensional heat flow through the compartment boundaries

(4) Constant heat release rate (HRR)

(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet ($FDT^s$) Information:

Use the following $FDT^s$:

(a) For concrete: 02.1_Temperature_NV.xls (click on *Temperature_ NV Thermally Thick*)

(b) For gypsum board: 02.1_Temperature_NV.xls (click on *Temperature_ NV Thermally Thin*)

**Note:** Since concrete thickness is greater than one inch, it is necessary to use the correlations for thermally thick material. However, since the gypsum board thickness is equal to 1 inch, it is necessary to use correlations for thermally thin material.

$FDT^s$ Input Parameters: (for both spreadsheets)

- Compartment Width ($w_c$) = 15 ft
- Compartment Length ($l_c$) = 15 ft
- Compartment Height ($h_c$) = 10 ft
- Vent Width ($w_v$) = 4 ft
- Vent Height ($h_v$) = 6 ft
- Top of Vent from Floor ($V_T$) = 6 ft
- Interior Lining Thickness ($\delta$) = 12 in.(concrete) and 1 in. (gypsum board)
- Ambient Air Temperature ($T_a$) = 77 °F
- Specific Heat of Air ($c_p$)= 1 kJ/kg-K
- Material: Select **Concrete** and **Gypsum Board** on the respective $FDT^s$
- Fire Heat Release Rate $(\dot{Q})$ = 500 kW
- Time after ignition (t) = 2 min

**Results***

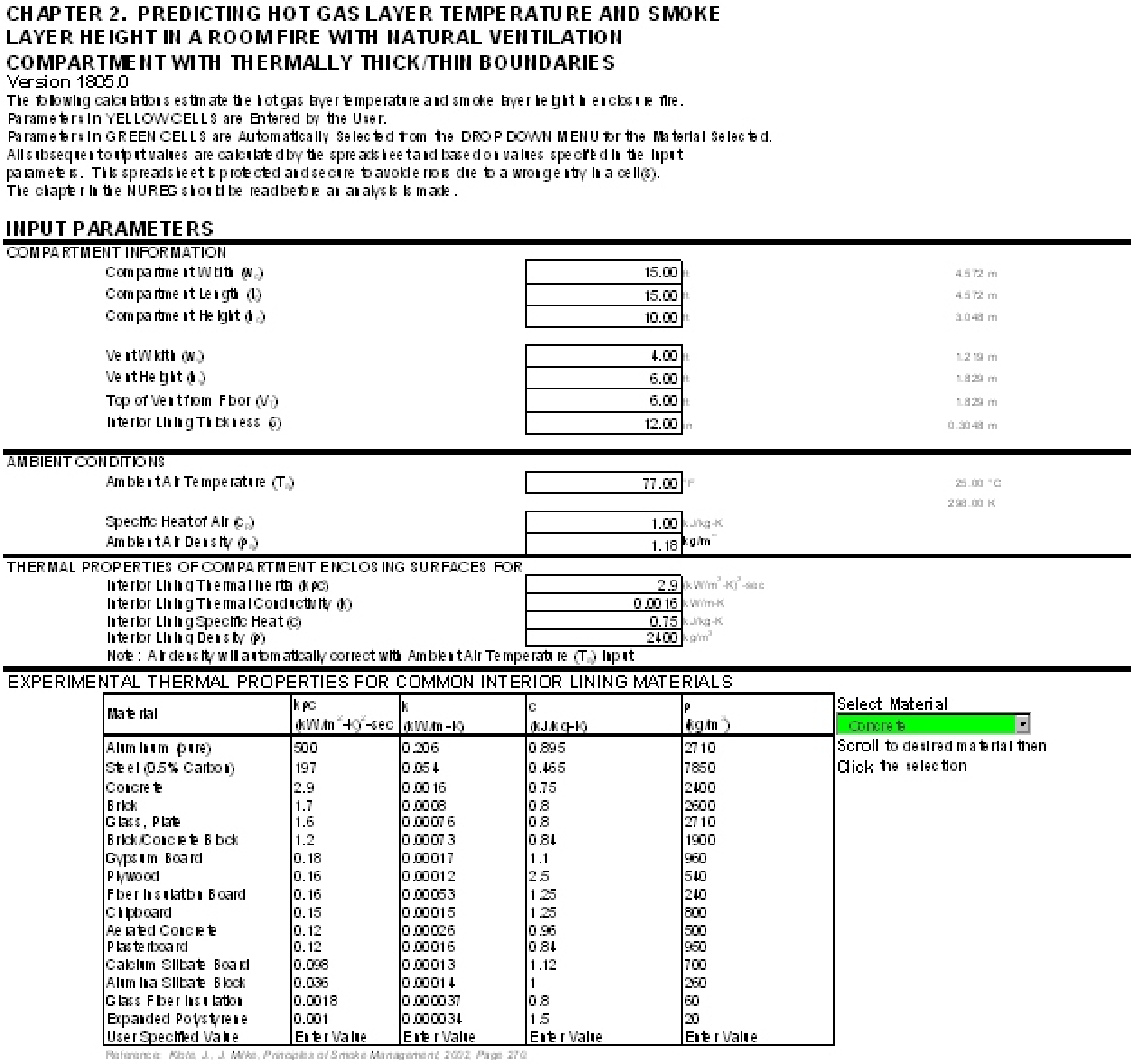
| Interior Boundary Material | Hot Gas Layer Temperature ($T_g$)<br>°C (°F)<br>(Method of MQH) | Smoke Layer Height (z)<br>z m (ft)<br>(Method of Yamana and Tanaka) |
|---|---|---|
| Concrete | 147 (296) | 1.83 (6.00)<br>(smoke exiting vent, $z < V_T$) |
| Gypsum Board | 218 (425) | 1.83 (6.00)<br>(compartment filled with smoke |

*see spreadsheet on next page at t = 2 min

## Spreadsheet Calculations

(a) Boundary Material: Concrete

FDT$^s$: 02.1_Temperature_NV.xls



### CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

### INPUT PARAMETERS

COMPARTMENT INFORMATION

| | | | |
|---|---|---|---|
| Compartment Width ($w_c$) | 15.00 | ft | 4.572 m |
| Compartment Length ($l_c$) | 15.00 | ft | 4.572 m |
| Compartment Height ($h_c$) | 10.00 | ft | 3.048 m |
| Vent Width ($w_v$) | 4.00 | ft | 1.219 m |
| Vent Height ($h_v$) | 6.00 | ft | 1.829 m |
| Top of Vent from Floor ($V_T$) | 6.00 | ft | 1.829 m |
| Interior Lining Thickness ($\delta$) | 12.00 | in | 0.3048 m |

AMBIENT CONDITIONS

| | | | |
|---|---|---|---|
| Ambient Air Temperature ($T_a$) | 77.00 | °F | 25.00 °C<br>298.00 K |
| Specific Heat of Air ($c_p$) | 1.00 | kJ/kg-K | |
| Ambient Air Density ($\rho_a$) | 1.18 | kg/m$^3$ | |

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

| | | |
|---|---|---|
| Interior Lining Thermal Inertia ($k\rho c$) | 2.9 | (kW/m$^2$-K)$^2$-sec |
| Interior Lining Thermal Conductivity ($k$) | 0.0016 | kW/m-K |
| Interior Lining Specific Heat ($c$) | 0.75 | kJ/kg-K |
| Interior Lining Density ($\rho$) | 2400 | kg/m$^3$ |

Note : Air density will automatically correct with Ambient Air Temperature ($T_a$) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

| Material | $k\rho c$<br>(kW/m$^2$-K)$^2$-sec | $k$<br>(kW/m-K) | $c$<br>(kJ/kg-K) | $\rho$<br>(kg/m$^3$) |
|---|---|---|---|---|
| Aluminum (pure) | 500 | 0.206 | 0.895 | 2710 |
| Steel (0.5% Carbon) | 197 | 0.054 | 0.465 | 7850 |
| Concrete | 2.9 | 0.0016 | 0.75 | 2400 |
| Brick | 1.7 | 0.0008 | 0.8 | 2600 |
| Glass, Plate | 1.6 | 0.00076 | 0.8 | 2710 |
| Brick/Concrete Block | 1.2 | 0.00073 | 0.84 | 1900 |
| Gypsum Board | 0.18 | 0.00017 | 1.1 | 960 |
| Plywood | 0.16 | 0.00012 | 2.5 | 540 |
| Fiber Insulation Board | 0.16 | 0.00053 | 1.25 | 240 |
| Chipboard | 0.15 | 0.00015 | 1.25 | 800 |
| Aerated Concrete | 0.12 | 0.00026 | 0.96 | 500 |
| Plasterboard | 0.12 | 0.00016 | 0.84 | 950 |
| Calcium Silicate Board | 0.098 | 0.00013 | 1.12 | 700 |
| Alumina Silicate Block | 0.036 | 0.00014 | 1 | 260 |
| Glass Fiber Insulation | 0.0018 | 0.000037 | 0.8 | 60 |
| Expanded Polystyrene | 0.001 | 0.000034 | 1.5 | 20 |
| User Specified Value | Enter Value | Enter Value | Enter Value | Enter Value |

Select Material

Concrete

Scroll to desired material then Click the selection

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270.

---

**FIRE SPECIFICATIONS**

Fire Heat Release Rate (Q) 500.00 kW

Calculate

---

## METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2})\,(A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)
$Q$ = heat release rate of the fire (kW)
$A_v$ = area of ventilation opening ($m^2$)
$h_v$ = height of ventilation opening (m)
$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)
$A_T$ = total area of the compartment enclosing surface boundaries excluding area of vent openings ($m^2$)

Area of Ventilation Opening Calculation

$A_v$ = $(w_v)\,(h_v)$
Where $A_v$ = area of ventilation opening ($m^2$)
$w_v$ = vent width (m)
$h_v$ = vent height (m)
$A_v$ = 2.23 $m^2$

Thermal Penetration Time Calculation

$t_p$ = $(\rho c_p/k)\,(\delta/2)^2$
Where $t_p$ = thermal penetration time (sec)
$\rho$ = interior construction density ($kg/m^3$)
$c_p$ = interior construction heat capacity (kJ/kg-K)
$k$ = interior construction thermal conductivity (kW/m-K)
$\delta$ = interior construction thickness (m)
$t_p$ = 26128.98 sec

Heat Transfer Coefficient Calculation

$h_k$ = $\sqrt{(k\rho c/t)}$ for $t < t_p$ or $(k/\delta)$ for $t > t_p$
Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)
$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec
(a thermal property of material responsible for the rate of temperature rise)
$t$ = time after ignition (sec)
See table below for results

Area of Compartment Enclosing Surface Boundaries

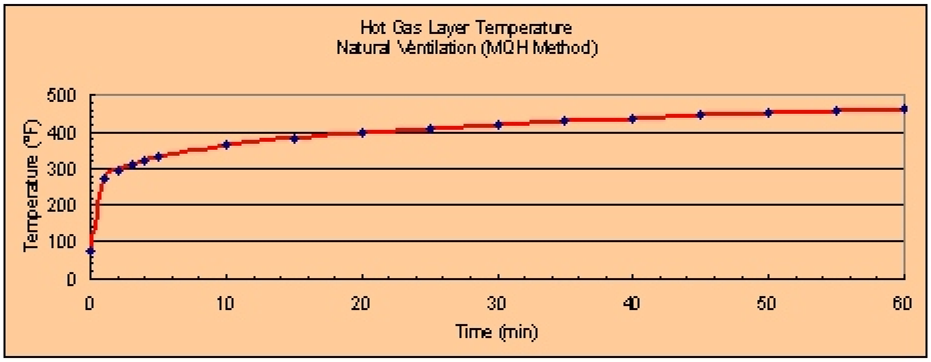
$A_T$ = $[2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$
Where $A_T$ = total area of the compartment enclosing surface boundaries excluding area of vent openings ($m^2$)
$w_c$ = compartment width (m)
$l_c$ = compartment length (m)
$h_c$ = compartment height (m)
$A_v$ = area of ventilation opening ($m^2$)
$A_T$ = 35.32 $m^2$

Compartment Hot Gas Layer Temperature With Natural Ventilation

$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2})\,(A_T h_k)]^{1/3}$
$\Delta T_g$ = $T_g - T_a$
$T_g$ = $\Delta T_g + T_a$

**Results**

| Time After Ignition (t) | | $h_k$ | $\Delta T_g$ | $T_g$ | $T_g$ | $T_g$ |
|---|---|---|---|---|---|---|
| (min) | (sec) | (kW/m$^2$-K) | (K) | (K) | (°C) | (°F) |
| 0 | 0.00 | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.22 | 108.34 | 406.34 | 133.34 | 272.02 |
| 2 | 120 | 0.16 | 121.61 | 419.61 | 146.61 | 295.90 |
| 3 | 180 | 0.13 | 130.11 | 428.11 | 155.11 | 311.20 |
| 4 | 240 | 0.11 | 136.50 | 434.50 | 161.50 | 322.70 |
| 5 | 300 | 0.10 | 141.67 | 439.67 | 166.67 | 332.01 |
| 10 | 600 | 0.07 | 159.02 | 457.02 | 184.02 | 363.24 |
| 15 | 900 | 0.06 | 170.14 | 468.14 | 195.14 | 383.26 |
| 20 | 1200 | 0.05 | 178.50 | 476.50 | 203.50 | 398.30 |
| 25 | 1500 | 0.04 | 185.26 | 483.26 | 210.26 | 410.47 |
| 30 | 1800 | 0.04 | 190.98 | 488.98 | 215.98 | 420.76 |
| 35 | 2100 | 0.04 | 195.95 | 493.95 | 220.95 | 429.71 |
| 40 | 2400 | 0.03 | 200.36 | 498.36 | 225.36 | 437.64 |
| 45 | 2700 | 0.03 | 204.33 | 502.33 | 229.33 | 444.79 |
| 50 | 3000 | 0.03 | 207.95 | 505.95 | 232.95 | 451.31 |
| 55 | 3300 | 0.03 | 211.28 | 509.28 | 236.28 | 457.30 |
| 60 | 3600 | 0.03 | 214.37 | 512.37 | 239.37 | 462.86 |



## ESTIMATING SMOKE LAYER HEIGHT
## METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{2/3}))^{-3/2}$

Where
$z$ = smoke layer height (m)
$Q$ = heat release rate of the fire (kW)
$t$ = time after ignition (sec)
$h_c$ = compartment height (m)
$A_c$ = compartment floor area (m$^2$)
$k$ = a constant given by $k = 0.076/\rho_g$
$\rho_g$ = hot gas layer density (kg/m$^3$)
$\rho_g$ is given by $\rho_g = 353/T_g$
$T_g$ = hot gas layer temperature (K)

Compartment Area Calculation
$A_c$ = $(w_c)\ (l_c)$
Where
$A_c$ = compartment floor area (m$^2$)
$w_c$ = compartment width (m)
$l_c$ = compartment length (m)
$A_c$ = 20.90 m$^2$

Hot Gas Layer Density Calculation
$\rho_g$ = $353/T_g$

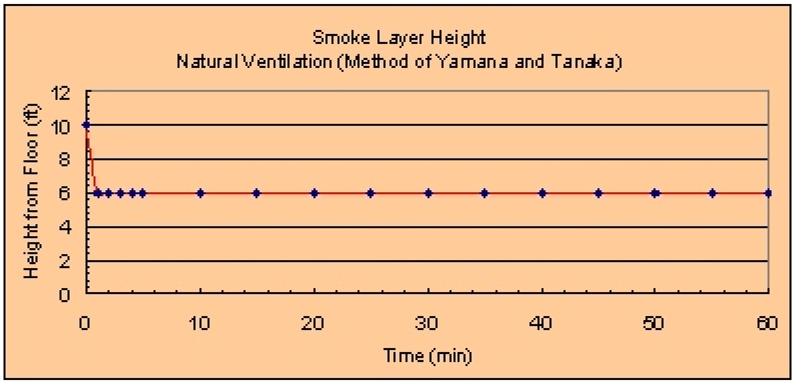
Calculation for Constant K
$k$ = $0.076/\rho_g$

Smoke Gas Layer Height With Natural Ventilation
$z$ = $[(2kQ^{1/3}t/3A_c] + (1/h_c^{2/3}))^{-3/2}$

**Results**

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

| Time (min) | $\rho_g$ (kg/m$^3$) | Constant (k) (kW/m-K) | Smoke Layer height z (m) | Smoke Layer height z (ft) | |
|---|---|---|---|---|---|
| 0 | 1.18 | 0.064 | 3.05 | 10.00 | |
| 1 | 0.87 | 0.087 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 2 | 0.84 | 0.090 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 3 | 0.82 | 0.092 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 4 | 0.81 | 0.094 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 5 | 0.80 | 0.095 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 10 | 0.77 | 0.098 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 15 | 0.75 | 0.101 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 20 | 0.74 | 0.103 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 25 | 0.73 | 0.104 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 30 | 0.72 | 0.105 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 35 | 0.71 | 0.106 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 40 | 0.71 | 0.107 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 45 | 0.70 | 0.108 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 50 | 0.70 | 0.109 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 55 | 0.69 | 0.110 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 60 | 0.69 | 0.110 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |



**NOTE**

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

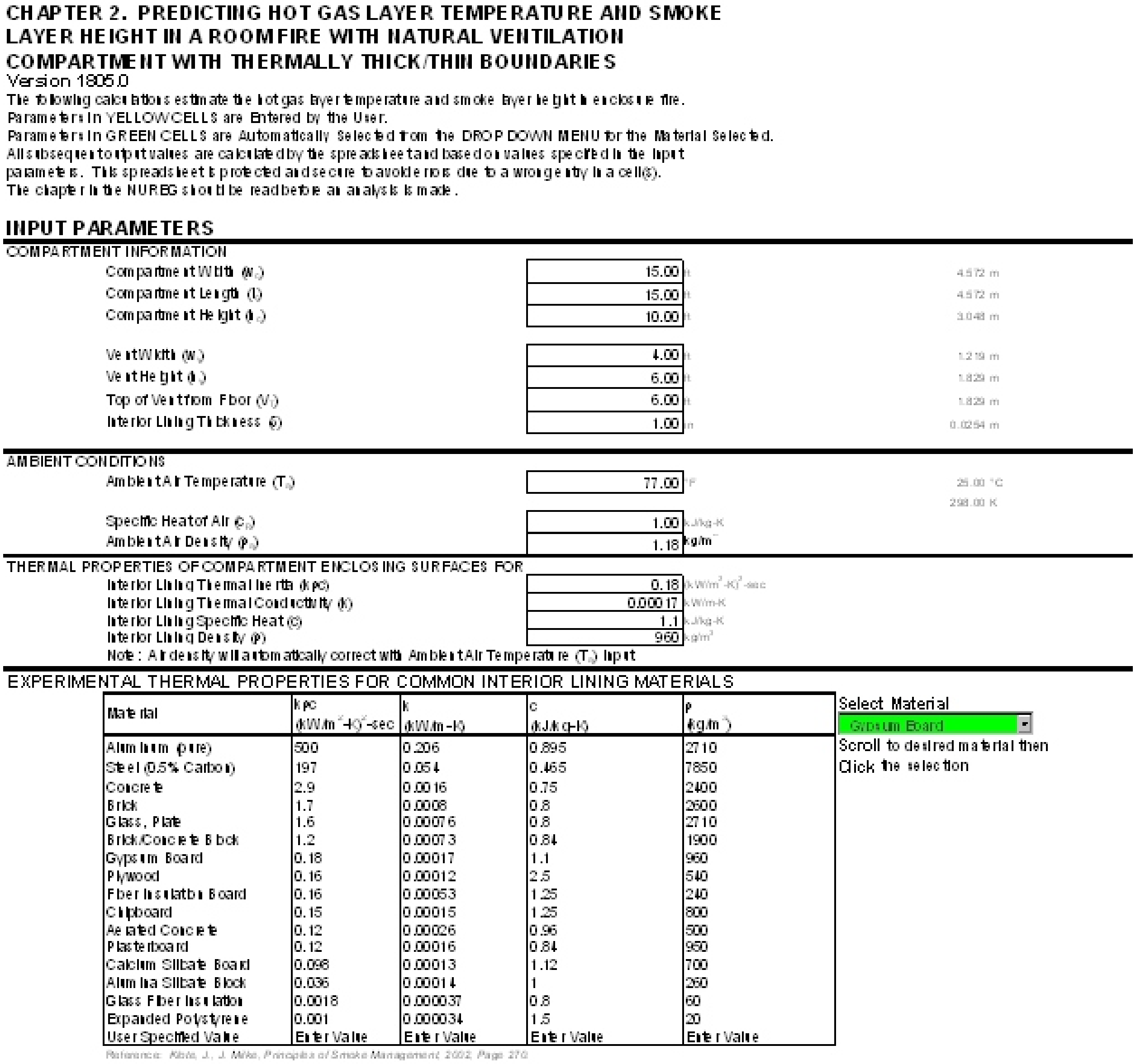
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

(b) Boundary Material: Gypsum Board

FDT$^s$: 02.1_Temperature_NV.xls



## CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

### INPUT PARAMETERS

COMPARTMENT INFORMATION

| | | | |
|---|---|---|---|
| Compartment Width ($w_c$) | 15.00 | ft | 4.572 m |
| Compartment Length ($l_c$) | 15.00 | ft | 4.572 m |
| Compartment Height ($h_c$) | 10.00 | ft | 3.048 m |
| Vent Width ($w_v$) | 4.00 | ft | 1.219 m |
| Vent Height ($h_v$) | 6.00 | ft | 1.829 m |
| Top of Vent from Floor ($V_T$) | 6.00 | ft | 1.829 m |
| Interior Lining Thickness ($\delta$) | 1.00 | in | 0.0254 m |

AMBIENT CONDITIONS

| | | | |
|---|---|---|---|
| Ambient Air Temperature ($T_a$) | 77.00 | °F | 25.00 °C<br>298.00 K |
| Specific Heat of Air ($c_p$) | 1.00 | kJ/kg-K | |
| Ambient Air Density ($\rho_a$) | 1.18 | kg/m$^3$ | |

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

| | | |
|---|---|---|
| Interior Lining Thermal Inertia ($k\rho c$) | 0.18 | (kW/m$^2$-K)$^2$-sec |
| Interior Lining Thermal Conductivity ($k$) | 0.00017 | kW/m-K |
| Interior Lining Specific Heat ($c$) | 1.1 | kJ/kg-K |
| Interior Lining Density ($\rho$) | 960 | kg/m$^3$ |

Note: Air density will automatically correct with Ambient Air Temperature ($T_a$) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

| Material | $k\rho c$ (kW/m$^2$-K)$^2$-sec | $k$ (kW/m-K) | $c$ (kJ/kg-K) | $\rho$ (kg/m$^3$) |
|---|---|---|---|---|
| Aluminum (pure) | 500 | 0.206 | 0.895 | 2710 |
| Steel (0.5% Carbon) | 197 | 0.054 | 0.465 | 7850 |
| Concrete | 2.9 | 0.0016 | 0.75 | 2400 |
| Brick | 1.7 | 0.0008 | 0.8 | 2600 |
| Glass, Plate | 1.6 | 0.00076 | 0.8 | 2710 |
| Brick/Concrete Block | 1.2 | 0.00073 | 0.84 | 1900 |
| Gypsum Board | 0.18 | 0.00017 | 1.1 | 960 |
| Plywood | 0.16 | 0.00012 | 2.5 | 540 |
| Fiber Insulation Board | 0.16 | 0.00053 | 1.25 | 240 |
| Chipboard | 0.15 | 0.00015 | 1.25 | 800 |
| Aerated Concrete | 0.12 | 0.00026 | 0.96 | 500 |
| Plasterboard | 0.12 | 0.00016 | 0.84 | 950 |
| Calcium Silicate Board | 0.098 | 0.00013 | 1.12 | 700 |
| Alumina Silicate Block | 0.036 | 0.00014 | 1 | 260 |
| Glass Fiber Insulation | 0.0018 | 0.000037 | 0.8 | 60 |
| Expanded Polystyrene | 0.001 | 0.000034 | 1.5 | 20 |
| User Specified Value | Enter Value | Enter Value | Enter Value | Enter Value |

Select Material

Gypsum Board

Scroll to desired material then Click the selection

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 270.

---

**FIRE SPECIFICATIONS**

Fire Heat Release Rate (Q) 500.00 kW

Calculate

---

## METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2}) (A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)
$Q$ = heat release rate of the fire (kW)
$A_v$ = area of ventilation opening ($m^2$)
$h_v$ = height of ventilation opening (m)
$h_k$ = convective heat transfer coefficient (kW/$m^2$-K)
$A_T$ = total area of the compartment enclosing surface boundaries excluding area of vent openings ($m^2$)

**Area of Ventilation Opening Calculation**

$A_v$ = $(w_v)\,(h_v)$
Where $A_v$ = area of ventilation opening ($m^2$)
$w_v$ = vent width (m)
$h_v$ = vent height (m)
$A_v$ = 2.23 $m^2$

**Thermal Penetration Time Calculation**

$t_p$ = $(\rho c_p/k)\,(\delta/2)^2$
Where $t_p$ = thermal penetration time (sec)
$\rho$ = interior construction density (kg/$m^3$)
$c_p$ = interior construction heat capacity (kJ/kg-K)
$k$ = interior construction thermal conductivity (kW/m-K)
$\delta$ = interior construction thickness (m)
$t_p$ = 1001.90 sec

**Heat Transfer Coefficient Calculation**

$h_k$ = $\sqrt{(k\rho c/t)}$ for $t < t_p$ or $(k/\delta)$ for $t > t_p$
Where $h_k$ = heat transfer coefficient (kW/$m^2$-K)
$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2\text{-sec}$
(a thermal property of material responsible for the rate of temperature rise)
$t$ = time after ignition (sec)
See table below for results

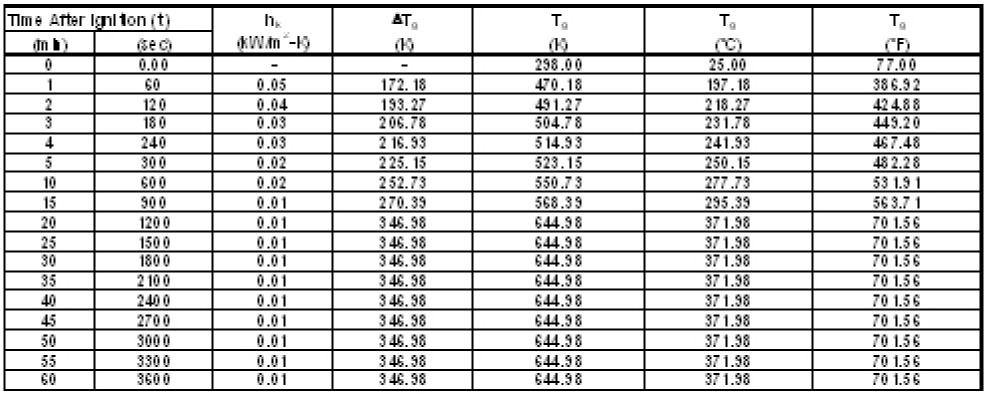
**Area of Compartment Enclosing Surface Boundaries**

$A_T$ = $[2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$
Where $A_T$ = total area of the compartment enclosing surface boundaries excluding area of vent openings ($m^2$)
$w_c$ = compartment width (m)
$l_c$ = compartment length (m)
$h_c$ = compartment height (m)
$A_v$ = area of ventilation opening ($m^2$)
$A_T$ = 95.32 $m^2$

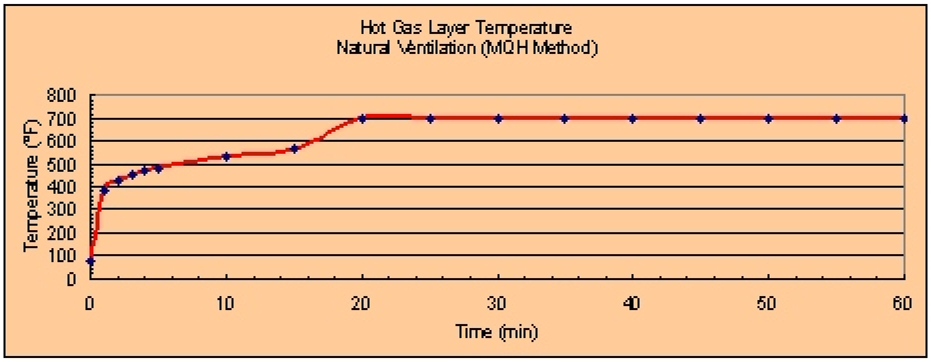
**Compartment Hot Gas Layer Temperature With Natural Ventilation**

$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2}) (A_T h_k)]^{1/3}$
$\Delta T_g$ = $T_g - T_a$
$T_g$ = $\Delta T_g + T_a$

**Results**



| Time After Ignition (t) | | $h_k$ (kW/m$^2$-K) | $\Delta T_g$ (K) | $T_g$ (K) | $T_g$ (°C) | $T_g$ (°F) |
|---|---|---|---|---|---|---|
| (min) | (sec) | | | | | |
| 0 | 0.00 | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.05 | 172.18 | 470.18 | 197.18 | 386.92 |
| 2 | 120 | 0.04 | 193.27 | 491.27 | 218.27 | 424.88 |
| 3 | 180 | 0.03 | 206.78 | 504.78 | 231.78 | 449.20 |
| 4 | 240 | 0.03 | 216.93 | 514.93 | 241.93 | 467.48 |
| 5 | 300 | 0.02 | 225.15 | 523.15 | 250.15 | 482.28 |
| 10 | 600 | 0.02 | 252.73 | 550.73 | 277.73 | 531.91 |
| 15 | 900 | 0.01 | 270.39 | 568.39 | 295.39 | 563.71 |
| 20 | 1200 | 0.01 | 346.98 | 644.98 | 371.98 | 701.56 |
| 25 | 1500 | 0.01 | 346.98 | 644.98 | 371.98 | 701.56 |
| 30 | 1800 | 0.01 | 346.98 | 644.98 | 371.98 | 701.56 |
| 35 | 2100 | 0.01 | 346.98 | 644.98 | 371.98 | 701.56 |
| 40 | 2400 | 0.01 | 346.98 | 644.98 | 371.98 | 701.56 |
| 45 | 2700 | 0.01 | 346.98 | 644.98 | 371.98 | 701.56 |
| 50 | 3000 | 0.01 | 346.98 | 644.98 | 371.98 | 701.56 |
| 55 | 3300 | 0.01 | 346.98 | 644.98 | 371.98 | 701.56 |
| 60 | 3600 | 0.01 | 346.98 | 644.98 | 371.98 | 701.56 |



## ESTIMATING SMOKE LAYER HEIGHT
## METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where $z$ = smoke layer height (m)
$Q$ = heat release rate of the fire (kW)
$t$ = time after ignition (sec)
$h_c$ = compartment height (m)
$A_c$ = compartment floor area ($m^2$)
$k$ = a constant given by $k = 0.076/\rho_g$
$\rho_g$ = hot gas layer density ($kg/m^3$)
$\rho_g$ is given by $\rho_g = 353/T_g$
$T_g$ = hot gas layer temperature (K)

Compartment Area Calculation
$A_c = (w_c)\ (l_c)$
Where $A_c$ = compartment floor area ($m^2$)
$w_c$ = compartment width (m)
$l_c$ = compartment length (m)
$A_c$ = 20.90 $m^2$

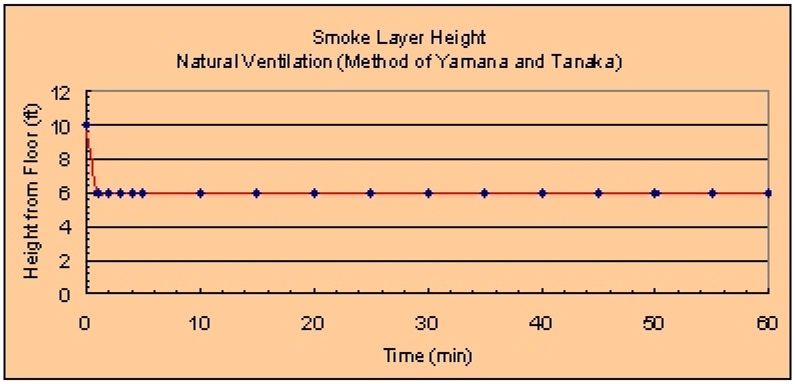
Hot Gas Layer Density Calculation
$\rho_g = 353/T_g$

Calculation for Constant K
$k = 0.076/\rho_g$

Smoke Gas Layer Height With Natural Ventilation
$z = [(2kQ^{1/3}t/3A_c] + (1/h_c^{2/3}))^{-3/2}$

**Results** Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

| Time (min) | $\rho_g$ ($kg/m^3$) | Constant (k) (kW/m-K) | Smoke Layer height z (m) | Smoke Layer height z (ft) | |
|---|---|---|---|---|---|
| 0 | 1.18 | 0.064 | 3.05 | 10.00 | |
| 1 | 0.75 | 0.101 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 2 | 0.72 | 0.106 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 3 | 0.70 | 0.109 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 4 | 0.69 | 0.111 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 5 | 0.67 | 0.113 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 10 | 0.64 | 0.119 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 15 | 0.62 | 0.122 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 20 | 0.55 | 0.139 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 25 | 0.55 | 0.139 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 30 | 0.55 | 0.139 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 35 | 0.55 | 0.139 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 40 | 0.55 | 0.139 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 45 | 0.55 | 0.139 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 50 | 0.55 | 0.139 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 55 | 0.55 | 0.139 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 60 | 0.55 | 0.139 | 1.83 | 6.00 | CAUTION: SMOKE IS EXITING OUT VENT |



**NOTE**

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

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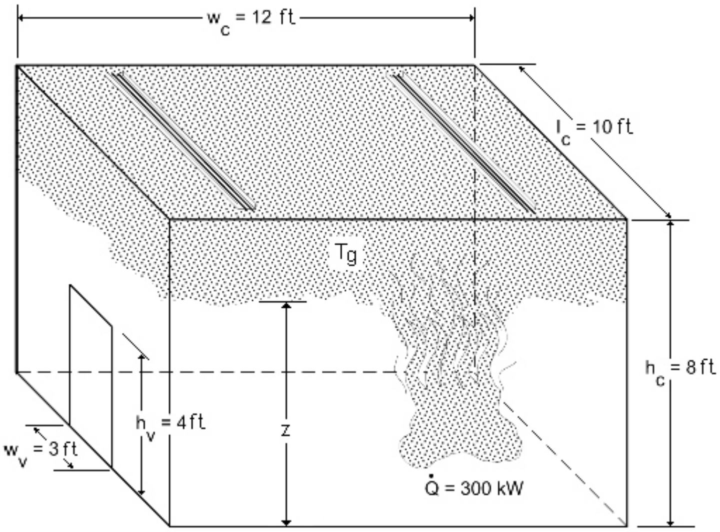
### Example Problem 2.16.1-2

**Problem Statement**

Consider a compartment that is 12 ft wide x 10 ft long x 8 ft high ($w_c$ x $l_c$ x $h_c$) with a simple vent 3 ft wide x 4 ft tall ($w_v$ x $h_v$). The construction is essentially 0.5 ft thick gypsum board. The fire is constant with an HRR of 300 kW. Assume that the top of the vent is 4 ft. Compute the hot gas temperature in the compartment, as well as the smoke layer height at 2 minutes.



Example Problem 2-2: Compartment with Natural Ventilation

**Solution**

Purpose:

(1) The hot gas layer temperature in the compartment ($T_g$) at t = 2 min after ignition
(2) The smoke layer height (z) at t = 2 min after ignition

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)
(2) Simple rectangular geometry (no beam pockets)
(3) One-dimensional heat flow through the compartment boundaries
(4) Constant Heat Release Rate (HRR)
(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet (FDT$^s$) Information:

Use the following FDT$^s$:

(a) 02.1_Temperature_NV.xls

**Note:** Since the gypsum board is greater than 1 inch, it is necessary to use the correlations for thermally thick material.

FDT$^s$ Input Parameters:

- Compartment Width ($w_c$) = 12 ft
- Compartment Length ($l_c$) = 10 ft
- Compartment Height ($h_c$) = 8 ft
- Vent Width ($w_v$) = 3 ft
- Vent Height ($h_v$) = 4 ft
- Top of Vent from Floor ($V_T$) = 4 ft
- Interior Lining Thickness ($\delta$) = 6 in
- Ambient Air Temperature ($T_a$) = 77 °F
- Specific Heat of Air ($c_p$)= 1 kJ/kg-K
- Material: Select **Gypsum Board** on the FDT$^s$
- Fire Heat Release Rate $(\dot{Q})$ = 300 kW

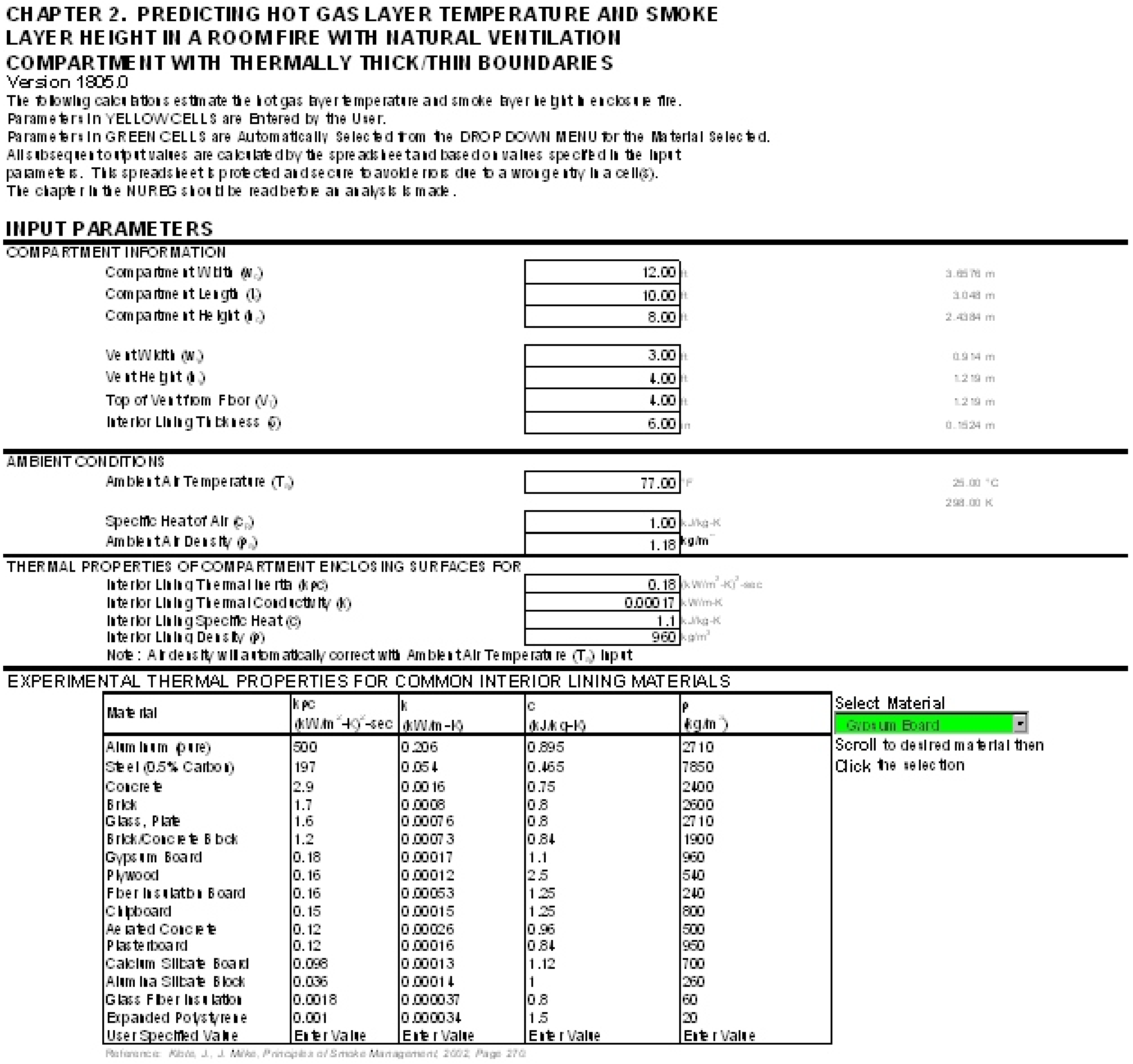
**Results***

| Hot Gas Layer Temperature ($T_g$) °C (°F) (Method of MQH) | Smoke Layer Height (z) m (ft) (Method of Yamana and Tanaka) |
|---|---|
| 249 (480) | 1.22 (4.00)<br>(smoke exiting vent, $z < V_T$) |

*see attached spreadsheet on next page at t = 2 min

## Spreadsheet Calculations

FDT$^s$: 02.1_Temperature_NV.xls



### CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

### INPUT PARAMETERS

COMPARTMENT INFORMATION

| | | | |
|---|---|---|---|
| Compartment Width ($w_c$) | 12.00 | ft | 3.6576 m |
| Compartment Length ($l_c$) | 10.00 | ft | 3.048 m |
| Compartment Height ($h_c$) | 8.00 | ft | 2.4384 m |
| Vent Width ($w_v$) | 3.00 | ft | 0.914 m |
| Vent Height ($h_v$) | 4.00 | ft | 1.219 m |
| Top of Vent from Floor ($V_T$) | 4.00 | ft | 1.219 m |
| Interior Lining Thickness ($\delta$) | 6.00 | in | 0.1524 m |

AMBIENT CONDITIONS

| | | | |
|---|---|---|---|
| Ambient Air Temperature ($T_a$) | 77.00 | °F | 25.00 °C<br>298.00 K |
| Specific Heat of Air ($c_p$) | 1.00 | kJ/kg-K | |
| Ambient Air Density ($\rho_a$) | 1.18 | kg/m$^3$ | |

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

| | | |
|---|---|---|
| Interior Lining Thermal Inertia ($k\rho c$) | 0.18 | (kW/m$^2$-K)$^2$-sec |
| Interior Lining Thermal Conductivity ($k$) | 0.00017 | kW/m-K |
| Interior Lining Specific Heat ($c$) | 1.1 | kJ/kg-K |
| Interior Lining Density ($\rho$) | 960 | kg/m$^3$ |

Note : Air density will automatically correct with Ambient Air Temperature ($T_a$) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

| Material | $k\rho c$<br>(kW/m$^2$-K)$^2$-sec | $k$<br>(kW/m-K) | $c$<br>(kJ/kg-K) | $\rho$<br>(kg/m$^3$) |
|---|---|---|---|---|
| Aluminum (pure) | 500 | 0.206 | 0.895 | 2710 |
| Steel (0.5% Carbon) | 197 | 0.054 | 0.465 | 7850 |
| Concrete | 2.9 | 0.0016 | 0.75 | 2400 |
| Brick | 1.7 | 0.0008 | 0.8 | 2600 |
| Glass, Plate | 1.6 | 0.00076 | 0.8 | 2710 |
| Brick/Concrete Block | 1.2 | 0.00073 | 0.84 | 1900 |
| Gypsum Board | 0.18 | 0.00017 | 1.1 | 960 |
| Plywood | 0.16 | 0.00012 | 2.5 | 540 |
| Fiber Insulation Board | 0.16 | 0.00053 | 1.25 | 240 |
| Chipboard | 0.15 | 0.00015 | 1.25 | 800 |
| Aerated Concrete | 0.12 | 0.00026 | 0.96 | 500 |
| Plasterboard | 0.12 | 0.00016 | 0.84 | 950 |
| Calcium Silicate Board | 0.098 | 0.00013 | 1.12 | 700 |
| Alumina Silicate Block | 0.036 | 0.00014 | 1 | 260 |
| Glass Fiber Insulation | 0.0018 | 0.000037 | 0.8 | 60 |
| Expanded Polystyrene | 0.001 | 0.000034 | 1.5 | 20 |
| User Specified Value | Enter Value | Enter Value | Enter Value | Enter Value |

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 270

Select Material

Scroll to desired material then Click the selection

**FIRE SPECIFICATIONS**

| | | |
|---|---|---|
| Fire Heat Release Rate (Q) | 300.00 | kW |
| | Calculate | |

## METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

*Reference: SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2})\,(A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

$Q$ = heat release rate of the fire (kW)

$A_v$ = area of ventilation opening ($m^2$)

$h_v$ = height of ventilation opening (m)

$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)

$A_T$ = total area of the compartment enclosing surface boundaries excluding area of vent openings ($m^2$)

**Area of Ventilation Opening Calculation**

$A_v = (w_v)\,(h_v)$

Where $A_v$ = area of ventilation opening ($m^2$)

$w_v$ = vent width (m)

$h_v$ = vent height (m)

$A_v =$ 1.11 $m^2$

**Thermal Penetration Time Calculation**

$t_p = (\rho c_p/k)\,(\delta/2)^2$

Where $t_p$ = thermal penetration time (sec)

$\rho$ = interior construction density ($kg/m^3$)

$c_p$ = interior construction heat capacity (kJ/kg-K)

$k$ = interior construction thermal conductivity (kW/m-K)

$\delta$ = interior construction thickness (m)

$t_p =$ 36068.24 sec

**Heat Transfer Coefficient Calculation**

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or $(k/\delta)$ for $t > t_p$

Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

$t$ = time after ignition (sec)

See table below for results

**Area of Compartment Enclosing Surface Boundaries**

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where $A_T$ = total area of the compartment enclosing surface boundaries excluding area of vent openings ($m^2$)

$w_c$ = compartment width (m)

$l_c$ = compartment length (m)

$h_c$ = compartment height (m)

$A_v$ = area of ventilation opening ($m^2$)

$A_T =$ 53.88 $m^2$

**Compartment Hot Gas Layer Temperature With Natural Ventilation**

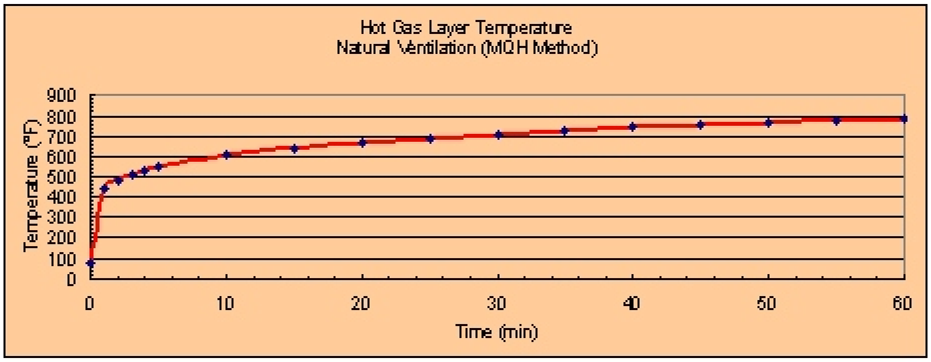
$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2})\,(A_T h_k)]^{1/3}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

**Results**

| Time After Ignition (t) |  | $h_k$ (kW/m$^2$-K) | $\Delta T_g$ (K) | $T_g$ (K) | $T_g$ (°C) | $T_g$ (°F) |
|---|---|---|---|---|---|---|
| (min) | (sec) |  |  |  |  |  |
| 0 | 0.00 | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.05 | 199.69 | 497.69 | 224.69 | 436.44 |
| 2 | 120 | 0.04 | 224.14 | 522.14 | 249.14 | 480.45 |
| 3 | 180 | 0.03 | 239.81 | 537.81 | 264.81 | 508.66 |
| 4 | 240 | 0.03 | 251.59 | 549.59 | 276.59 | 529.86 |
| 5 | 300 | 0.02 | 261.12 | 559.12 | 286.12 | 547.02 |
| 10 | 600 | 0.02 | 293.10 | 591.10 | 318.10 | 604.58 |
| 15 | 900 | 0.01 | 313.59 | 611.59 | 338.59 | 641.46 |
| 20 | 1200 | 0.01 | 328.99 | 626.99 | 353.99 | 669.19 |
| 25 | 1500 | 0.01 | 341.46 | 639.46 | 366.46 | 691.63 |
| 30 | 1800 | 0.01 | 351.99 | 649.99 | 376.99 | 710.59 |
| 35 | 2100 | 0.01 | 361.16 | 659.16 | 386.16 | 727.08 |
| 40 | 2400 | 0.01 | 369.28 | 667.28 | 394.28 | 741.71 |
| 45 | 2700 | 0.01 | 376.60 | 674.60 | 401.60 | 754.89 |
| 50 | 3000 | 0.01 | 383.28 | 681.28 | 408.28 | 766.90 |
| 55 | 3300 | 0.01 | 389.41 | 687.41 | 414.41 | 777.94 |
| 60 | 3600 | 0.01 | 395.10 | 693.10 | 420.10 | 788.18 |



## ESTIMATING SMOKE LAYER HEIGHT
## METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where
$z$ = smoke layer height (m)
$Q$ = heat release rate of the fire (kW)
$t$ = time after ignition (sec)
$h_c$ = compartment height (m)
$A_c$ = compartment floor area ($m^2$)
$k$ = a constant given by $k = 0.076/\rho_g$
$\rho_g$ = hot gas layer density ($kg/m^3$)
$\rho_g$ is given by $\rho_g = 353/T_g$
$T_g$ = hot gas layer temperature (K)

Compartment Area Calculation
$A_c$ = $(w_c)(l_c)$
Where
$A_c$ = compartment floor area ($m^2$)
$w_c$ = compartment width (m)
$l_c$ = compartment length (m)
$A_c$ = 11.15 $m^2$

Hot Gas Layer Density Calculation
$\rho_g$ = $353/T_g$

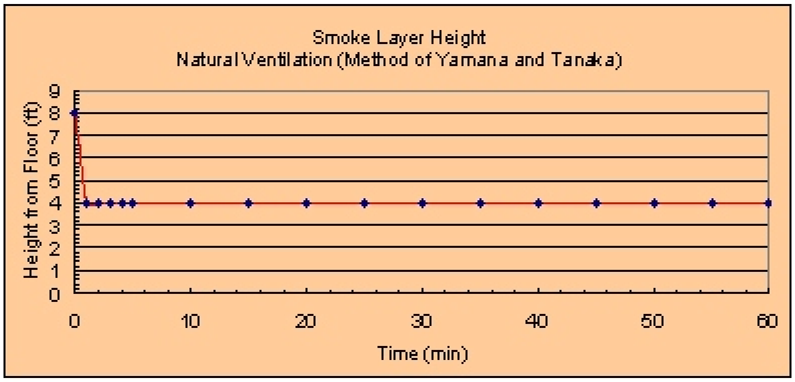
Calculation for Constant K
$k$ = $0.076/\rho_g$

Smoke Gas Layer Height With Natural Ventilation
$z$ = $[(2kQ^{1/3}t/3A_c] + (1/h_c^{2/3}))^{-3/2}$

**Results**

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

| Time (min) | $\rho_g$ ($kg/m^3$) | Constant (k) (kW/m-K) | Smoke Layer height z (m) | Smoke Layer height z (ft) | |
|---|---|---|---|---|---|
| 0 | 1.18 | 0.064 | 2.44 | 8.00 | |
| 1 | 0.71 | 0.107 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 2 | 0.68 | 0.112 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 3 | 0.66 | 0.116 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 4 | 0.64 | 0.118 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 5 | 0.63 | 0.120 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 10 | 0.60 | 0.127 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 15 | 0.58 | 0.132 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 20 | 0.56 | 0.135 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 25 | 0.55 | 0.138 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 30 | 0.54 | 0.140 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 35 | 0.54 | 0.142 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 40 | 0.53 | 0.144 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 45 | 0.52 | 0.145 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 50 | 0.52 | 0.147 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 55 | 0.51 | 0.148 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 60 | 0.51 | 0.149 | 1.22 | 4.00 | CAUTION: SMOKE IS EXITING OUT VENT |



**NOTE**

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

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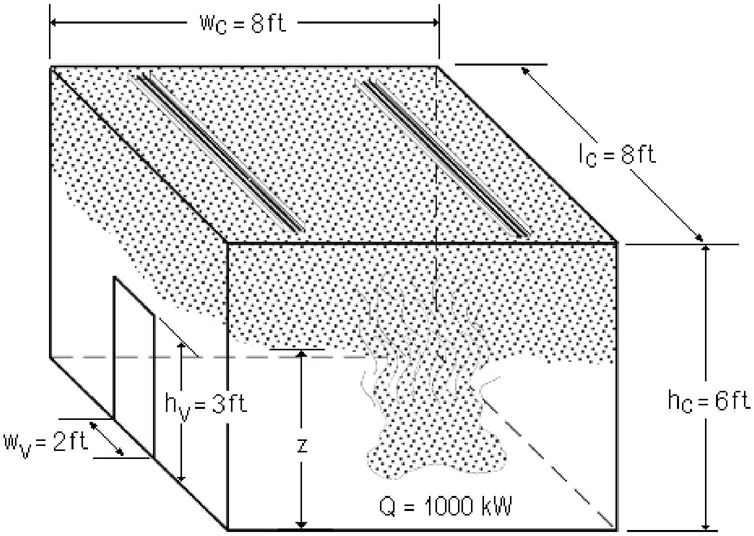
**Example Problem 2.16.1-3**

**Problem Statement**

Consider a compartment that is 8 ft wide x 8 ft long x 6 ft high ($w_c$ x $l_c$ x $h_c$) with a simple vent that is 2 ft wide x 3 ft tall ($w_v$ x $h_v$). The construction is essentially 0.75 ft thick concrete. The fire is constant with an HRR of 1,000 kW. Assume that the top of the vent is 3 ft. Compute the hot gas temperature in the compartment, as well as the smoke layer height at 3 minutes.



Example Problem 2-3: Compartment with Natural Ventilation

**Solution**

Purpose:

(1) Determine the hot gas layer temperature in the compartment ($T_g$) at t = 3 min after ignition

(2) Determine the smoke layer height (z) at t = 3 min after ignition

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)

(2) Simple rectangular geometry (no beam pockets)

(3) One-dimensional heat flow through the compartment boundaries

(4) Constant Heat Release Rate (HRR)

(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet (FDT$^s$) Information:

Use the following FDT$^s$:

(a) 02.1_Temperature_NV.xls

**Note:** Since concrete thickness is greater than 1 inch, it is necessary to use the correlations for thermally thick material.

FDT$^s$ Input Parameters:

- Compartment Width ($w_c$) = 8 ft
- Compartment Length ($l_c$) = 8 ft
- Compartment Height ($h_c$) = 6 ft
- Vent Width ($w_v$) = 2 ft
- Vent Height ($h_v$) = 3 ft
- Top of Vent from Floor ($V_T$) = 3 ft
- Interior Lining Thickness ($\delta$) = 9 in
- Ambient Air Temperature ($T_a$) = 77 °F
- Specific Heat of Air ($c_p$)= 1 kJ/kg-K
- Material: Select **Concrete** on the FDT$^s$
- Fire Heat Release Rate $(\dot{Q})$ = 1,000 kW

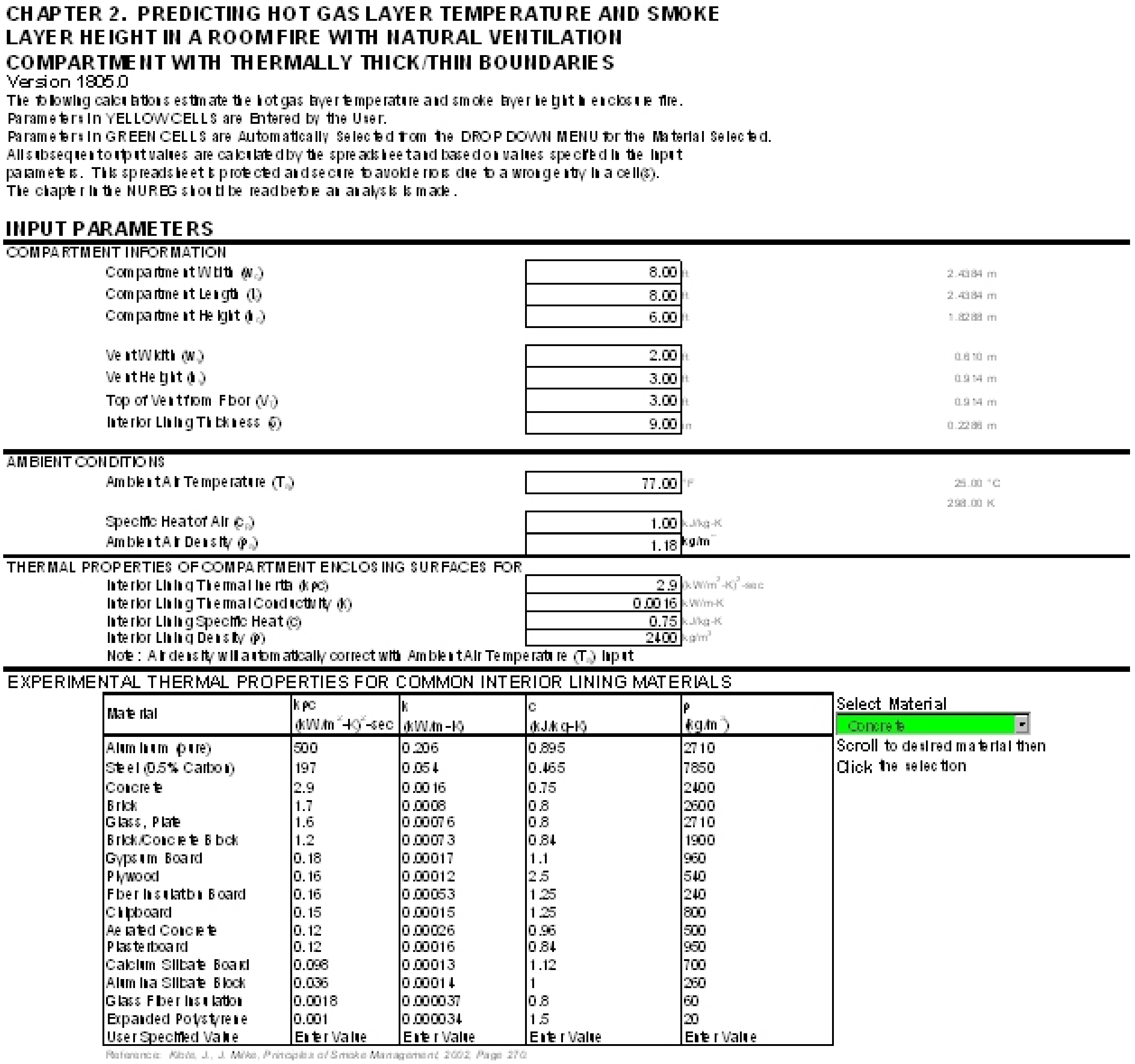
**Results*:**

| Hot Gas Layer Temperature ($T_g$) °C (°F) (Method of MQH) | Smoke Layer Height (z) m (ft) (Method of Yamana and Tanaka) |
|---|---|
| 571 (1,060) | 0.91 (3.00)<br>compartment filled with smoke) |

*see spreadsheet on next page at t = 3 min

## Spreadsheet Calculations

FDT$^s$: 02.1_Temperature_NV.xls



### CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

### INPUT PARAMETERS

COMPARTMENT INFORMATION

| | | | |
|---|---|---|---|
| Compartment Width ($w_c$) | 8.00 | ft | 2.4384 m |
| Compartment Length ($l_c$) | 8.00 | ft | 2.4384 m |
| Compartment Height ($h_c$) | 6.00 | ft | 1.8288 m |
| Vent Width ($w_v$) | 2.00 | ft | 0.610 m |
| Vent Height ($h_v$) | 3.00 | ft | 0.914 m |
| Top of Vent from Floor ($V_T$) | 3.00 | ft | 0.914 m |
| Interior Lining Thickness ($\delta$) | 9.00 | in | 0.2286 m |

AMBIENT CONDITIONS

| | | | |
|---|---|---|---|
| Ambient Air Temperature ($T_a$) | 77.00 | °F | 25.00 °C |
| | | | 298.00 K |
| Specific Heat of Air ($c_p$) | 1.00 | kJ/kg-K | |
| Ambient Air Density ($\rho_a$) | 1.18 | kg/m$^3$ | |

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

| | | |
|---|---|---|
| Interior Lining Thermal Inertia ($k\rho c$) | 2.9 | $(kW/m^2\text{-}K)^2\text{-sec}$ |
| Interior Lining Thermal Conductivity ($k$) | 0.0016 | kW/m-K |
| Interior Lining Specific Heat ($c$) | 0.75 | kJ/kg-K |
| Interior Lining Density ($\rho$) | 2400 | kg/m$^3$ |

Note: Air density will automatically correct with Ambient Air Temperature ($T_a$) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

| Material | $k\rho c$<br>$(kW/m^2\text{-}K)^2\text{-sec}$ | $k$<br>(kW/m-K) | $c$<br>(kJ/kg-K) | $\rho$<br>(kg/m$^3$) |
|---|---|---|---|---|
| Aluminum (pure) | 500 | 0.206 | 0.895 | 2710 |
| Steel (0.5% Carbon) | 197 | 0.054 | 0.465 | 7850 |
| Concrete | 2.9 | 0.0016 | 0.75 | 2400 |
| Brick | 1.7 | 0.0008 | 0.8 | 2600 |
| Glass, Plate | 1.6 | 0.00076 | 0.8 | 2710 |
| Brick/Concrete Block | 1.2 | 0.00073 | 0.84 | 1900 |
| Gypsum Board | 0.18 | 0.00017 | 1.1 | 960 |
| Plywood | 0.16 | 0.00012 | 2.5 | 540 |
| Fiber Insulation Board | 0.16 | 0.00053 | 1.25 | 240 |
| Chipboard | 0.15 | 0.00015 | 1.25 | 800 |
| Aerated Concrete | 0.12 | 0.00026 | 0.96 | 500 |
| Plasterboard | 0.12 | 0.00016 | 0.84 | 950 |
| Calcium Silicate Board | 0.098 | 0.00013 | 1.12 | 700 |
| Alumina Silicate Block | 0.036 | 0.00014 | 1 | 260 |
| Glass Fiber Insulation | 0.0018 | 0.000037 | 0.8 | 60 |
| Expanded Polystyrene | 0.001 | 0.000034 | 1.5 | 20 |
| User Specified Value | Enter Value | Enter Value | Enter Value | Enter Value |

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270.

Select Material

Concrete

Scroll to desired material then Click the selection

---

**FIRE SPECIFICATIONS**

Fire Heat Release Rate (Q) 1000.00 kW

Calculate

---

## METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2})\,(A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)
$Q$ = heat release rate of the fire (kW)
$A_v$ = area of ventilation opening ($m^2$)
$h_v$ = height of ventilation opening (m)
$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)
$A_T$ = total area of the compartment enclosing surface boundaries excluding area of vent openings ($m^2$)

Area of Ventilation Opening Calculation
$A_v$ = $(w_v)\,(h_v)$
Where $A_v$ = area of ventilation opening ($m^2$)
$w_v$ = vent width (m)
$h_v$ = vent height (m)
$A_v$ = 0.56 $m^2$

Thermal Penetration Time Calculation
$t_p$ = $(\rho c_p/k)\,(\delta/2)^2$
Where $t_p$ = thermal penetration time (sec)
$\rho$ = interior construction density ($kg/m^3$)
$c_p$ = interior construction heat capacity (kJ/kg-K)
$k$ = interior construction thermal conductivity (kW/m-K)
$\delta$ = interior construction thickness (m)
$t_p$ = 14697.55 sec

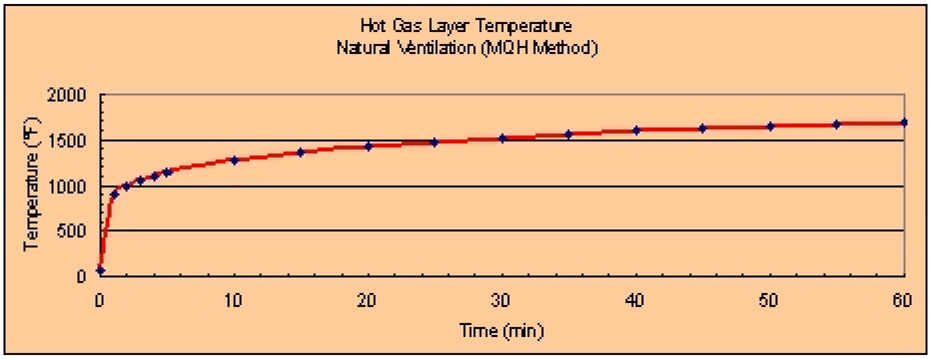
Heat Transfer Coefficient Calculation
$h_k$ = $\sqrt{(k\rho c/t)}$ for $t < t_p$ or $(k/\delta)$ for $t > t_p$
Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)
$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec
(a thermal property of material responsible for the rate of temperature rise)
$t$ = time after ignition (sec)
See table below for results

Area of Compartment Enclosing Surface Boundaries
$A_T$ = $[2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$
Where $A_T$ = total area of the compartment enclosing surface boundaries excluding area of vent openings ($m^2$)
$w_c$ = compartment width (m)
$l_c$ = compartment length (m)
$h_c$ = compartment height (m)
$A_v$ = area of ventilation opening ($m^2$)
$A_T$ = 29.17 $m^2$

Compartment Hot Gas Layer Temperature With Natural Ventilation
$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2})\,(A_T h_k)]^{1/3}$
$\Delta T_g$ = $T_g - T_a$
$T_g$ = $\Delta T_g + T_a$

**Results**

| Time After Ignition (t) | | $h_k$ | $\Delta T_g$ | $T_g$ | $T_g$ | $T_g$ |
|---|---|---|---|---|---|---|
| (min) | (sec) | (kW/m$^2$-K) | (K) | (K) | (°C) | (°F) |
| 0 | 0.00 | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.22 | 454.72 | 752.72 | 479.72 | 895.50 |
| 2 | 120 | 0.16 | 510.41 | 808.41 | 535.41 | 995.74 |
| 3 | 180 | 0.13 | 546.09 | 844.09 | 571.09 | 1059.97 |
| 4 | 240 | 0.11 | 572.91 | 870.91 | 597.91 | 1108.25 |
| 5 | 300 | 0.10 | 594.62 | 892.62 | 619.62 | 1147.32 |
| 10 | 600 | 0.07 | 667.44 | 965.44 | 692.44 | 1278.39 |
| 15 | 900 | 0.06 | 714.10 | 1012.10 | 739.10 | 1362.39 |
| 20 | 1200 | 0.05 | 749.18 | 1047.18 | 774.18 | 1425.52 |
| 25 | 1500 | 0.04 | 777.56 | 1075.56 | 802.56 | 1476.62 |
| 30 | 1800 | 0.04 | 801.56 | 1099.56 | 826.56 | 1519.80 |
| 35 | 2100 | 0.04 | 822.42 | 1120.42 | 847.42 | 1557.35 |
| 40 | 2400 | 0.03 | 840.92 | 1138.92 | 865.92 | 1590.66 |
| 45 | 2700 | 0.03 | 857.59 | 1155.59 | 882.59 | 1620.67 |
| 50 | 3000 | 0.03 | 872.79 | 1170.79 | 897.79 | 1648.02 |
| 55 | 3300 | 0.03 | 886.76 | 1184.76 | 911.76 | 1673.17 |
| 60 | 3600 | 0.03 | 899.72 | 1197.72 | 924.72 | 1696.49 |



## ESTIMATING SMOKE LAYER HEIGHT
## METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where $z$ = smoke layer height (m)
$Q$ = heat release rate of the fire (kW)
$t$ = time after ignition (sec)
$h_c$ = compartment height (m)
$A_c$ = compartment floor area ($m^2$)
$k$ = a constant given by $k = 0.076/\rho_g$
$\rho_g$ = hot gas layer density ($kg/m^3$)
$\rho_g$ is given by $\rho_g = 353/T_g$
$T_g$ = hot gas layer temperature (K)

Compartment Area Calculation
$A_c = (w_c)\ (l_c)$
Where $A_c$ = compartment floor area ($m^2$)
$w_c$ = compartment width (m)
$l_c$ = compartment length (m)
$A_c =$ 5.95 $m^2$

Hot Gas Layer Density Calculation
$\rho_g = 353/T_g$

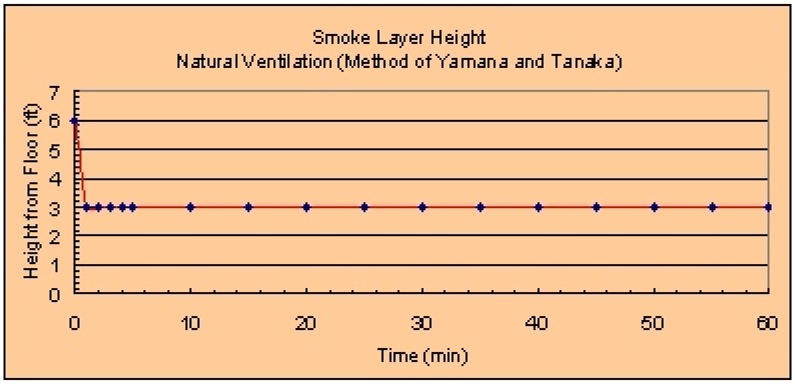
Calculation for Constant K
$k = 0.076/\rho_g$

Smoke Gas Layer Height With Natural Ventilation
$z = [(2kQ^{1/3}t/3A_c] + (1/h_c^{2/3}))^{-3/2}$

**Results**

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

| Time (min) | $\rho_g$ ($kg/m^3$) | Constant (k) (kW/m-K) | Smoke Layer height z (m) | Smoke Layer height z (ft) | |
|---|---|---|---|---|---|
| 0 | 1.18 | 0.064 | 1.83 | 6.00 | |
| 1 | 0.47 | 0.162 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 2 | 0.44 | 0.174 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 3 | 0.42 | 0.182 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 4 | 0.41 | 0.188 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 5 | 0.40 | 0.192 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 10 | 0.37 | 0.208 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 15 | 0.35 | 0.218 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 20 | 0.34 | 0.225 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 25 | 0.33 | 0.232 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 30 | 0.32 | 0.237 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 35 | 0.32 | 0.241 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 40 | 0.31 | 0.245 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 45 | 0.31 | 0.249 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 50 | 0.30 | 0.252 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 55 | 0.30 | 0.255 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |
| 60 | 0.29 | 0.258 | 0.91 | 3.00 | CAUTION: SMOKE IS EXITING OUT VENT |



**NOTE**

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

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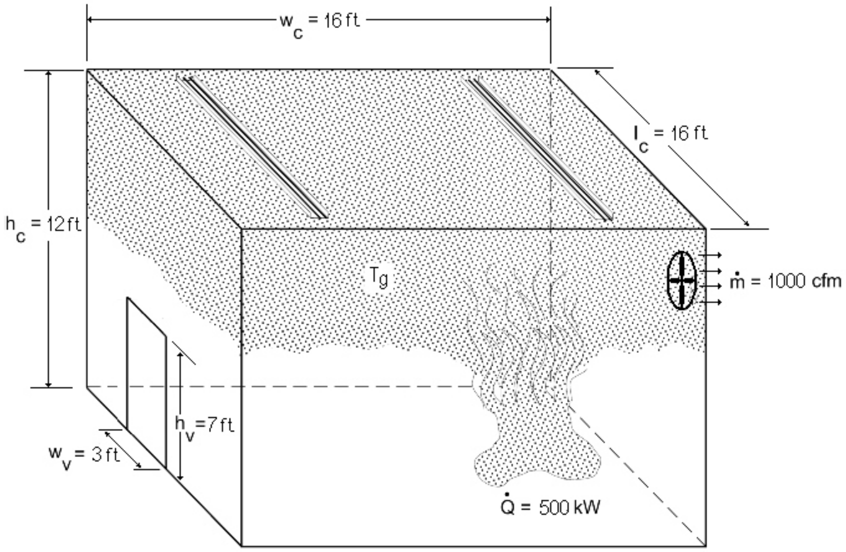
### 2.16.2 Forced Ventilation

### Example Problem 2.16.2-1

### Problem Statement

Consider a compartment that is 16 ft wide x 16 ft long x 12 ft high ($w_c$ x $l_c$ x $h_c$), with a vent opening that is 3 ft wide x 7 ft tall ($w_v$ x $h_v$). The forced ventilation rate is 1,000 cfm (exhaust). Calculate the hot gas layer temperature for a fire size of 500 kW at 2 minutes after ignition. The compartment boundaries are made of (a) 1 ft thick concrete and (b) 0.7 inch thick gypsum board.



Example Problem 2-4: Compartment with Forced Ventilation

### Solution

Purpose:

For two different interior lining materials determine the hot gas layer temperature in the compartment ($T_g$) at t = 2 min after ignition.

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)
(2) Simple rectangular geometry (no beam pockets)
(3) One-dimensional heat flow through the compartment boundaries
(4) Constant Heat Release Rate (HRR)
(5) The fire is located at the center of the compartment or away from the walls
(6) The bottom of the vent is at the floor level
(7) The compartment is open to the outside at the inlet (pressure = 1 atm)

Spreadsheet ($FDT^s$) Information:

Use the following $FDT^s$:

(a) For Concrete:

02.2_Temperature_FV.xls

(b) For Gypsum Board:

02.2_Temperature_FV.xls

**Note:** Since concrete thickness is greater than one inch, it is necessary to use the correlations for thermally thick material. However, since gypsum board thickness is less than 1 inch, it is necessary to use correlations for thermally thin material. Also, each spreadsheet has a different method to calculate the hot gas layer temperature ($T_g$). We are going to use both methods to compare the results.

$FDT^s$ Input Parameters: (for both spreadsheets)

- Compartment Width ($w_c$) = 16 ft
- Compartment Length ($l_c$) = 16 ft
- Compartment Height ($h_c$) = 12 ft
- Interior Lining Thickness ($\delta$) = 12 in (concrete) and .7in (gypsum board)
- Ambient Air Temperature ($T_a$) = 77 °F
- Specific Heat of Air ($c_p$)= 1 kJ/kg-K
- Material: Select **Concrete** and **Gypsum Board** on the respective $FDT^s$
- Compartment Mass Ventilation Rate (m) = 1,000 cfm
- Fire Heat Release Rate $(\dot{Q})$ = 500 kW
- Time after ignition (t) = 2 min.

**Results***

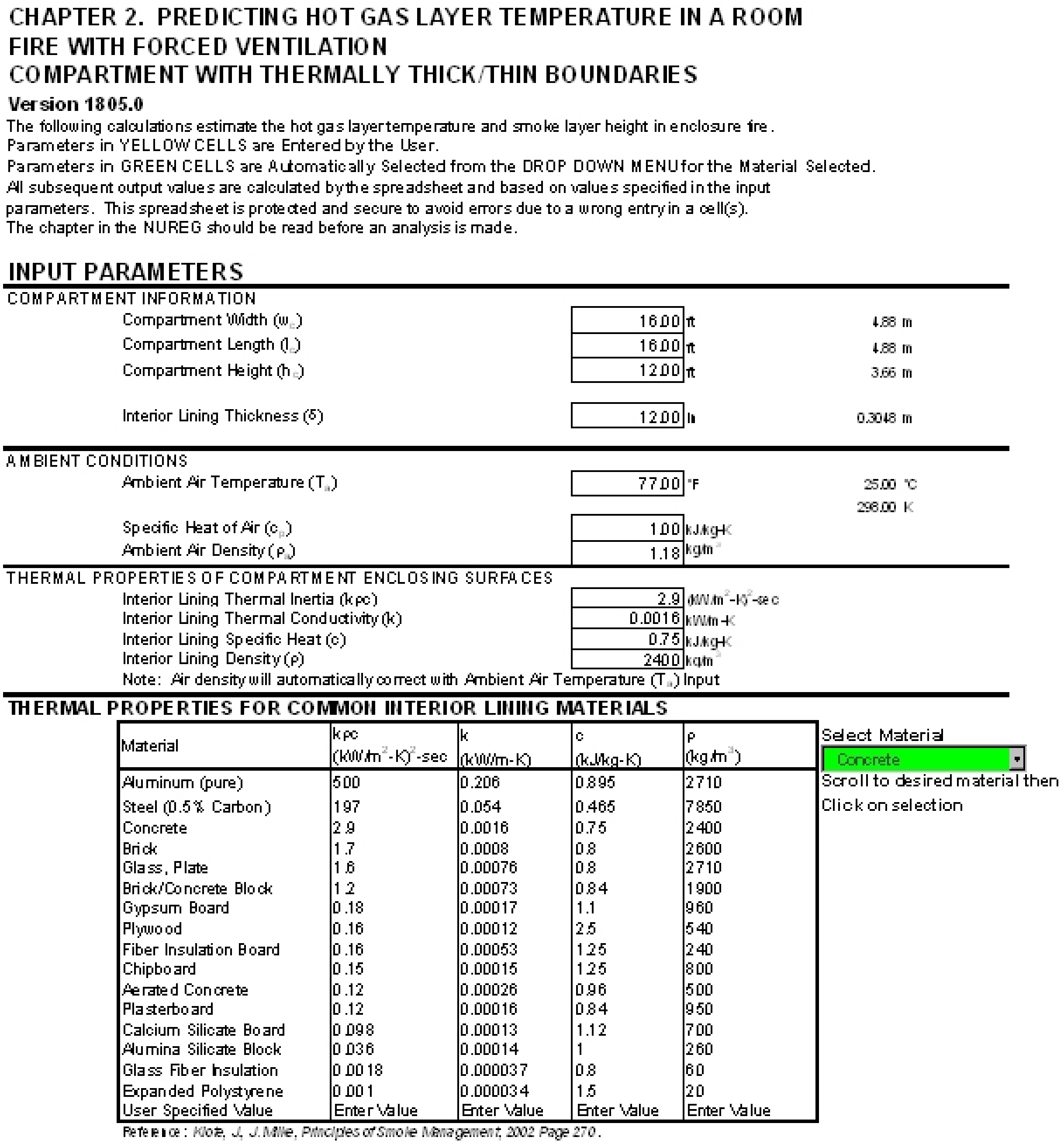
| Boundary Material | Hot Layer Gas Temperature ($T_g$) °C (°F) | |
|---|---|---|
| | Method of Foote, Pagni & Alvares (FPA) | Method of Deal & Beyler |
| Concrete | 142 (288) | 87 (190) |
| Gypsum Board | 218 (426) | 223 (452) |

*see spreadsheets on next page at t = 2 min.

**Spreadsheet Calculations**

(a) Boundary Material: Concrete

FDT$^s$: 02.2_Temperature_FV.xls



## CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION
## COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

**Version 1805.0**

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

### INPUT PARAMETERS

COMPARTMENT INFORMATION

| | | | | |
|---|---|---|---|---|
| Compartment Width ($w_c$) | 16.00 | ft | 4.88 | m |
| Compartment Length ($l_c$) | 16.00 | ft | 4.88 | m |
| Compartment Height ($h_c$) | 12.00 | ft | 3.66 | m |
| Interior Lining Thickness ($\delta$) | 12.00 | in | 0.3048 | m |

AMBIENT CONDITIONS

| | | | | |
|---|---|---|---|---|
| Ambient Air Temperature ($T_a$) | 77.00 | °F | 25.00 | °C |
| | | | 298.00 | K |
| Specific Heat of Air ($c_p$) | 1.00 | kJ/kg-K | | |
| Ambient Air Density ($\rho_a$) | 1.18 | kg/m$^3$ | | |

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

| | | |
|---|---|---|
| Interior Lining Thermal Inertia ($k\rho c$) | 2.9 | (kW/m$^2$-K)$^2$-sec |
| Interior Lining Thermal Conductivity ($k$) | 0.0016 | kW/m-K |
| Interior Lining Specific Heat ($c$) | 0.75 | kJ/kg-K |
| Interior Lining Density ($\rho$) | 2400 | kg/m$^3$ |

Note: Air density will automatically correct with Ambient Air Temperature ($T_a$) Input

### THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

| Material | $k\rho c$ (kW/m$^2$-K)$^2$-sec | $k$ (kW/m-K) | $c$ (kJ/kg-K) | $\rho$ (kg/m$^3$) |
|---|---|---|---|---|
| Aluminum (pure) | 500 | 0.206 | 0.895 | 2710 |
| Steel (0.5% Carbon) | 197 | 0.054 | 0.465 | 7850 |
| Concrete | 2.9 | 0.0016 | 0.75 | 2400 |
| Brick | 1.7 | 0.0008 | 0.8 | 2600 |
| Glass, Plate | 1.6 | 0.00076 | 0.8 | 2710 |
| Brick/Concrete Block | 1.2 | 0.00073 | 0.84 | 1900 |
| Gypsum Board | 0.18 | 0.00017 | 1.1 | 960 |
| Plywood | 0.16 | 0.00012 | 2.5 | 540 |
| Fiber Insulation Board | 0.16 | 0.00053 | 1.25 | 240 |
| Chipboard | 0.15 | 0.00015 | 1.25 | 800 |
| Aerated Concrete | 0.12 | 0.00026 | 0.96 | 500 |
| Plasterboard | 0.12 | 0.00016 | 0.84 | 950 |
| Calcium Silicate Board | 0.098 | 0.00013 | 1.12 | 700 |
| Alumina Silicate Block | 0.036 | 0.00014 | 1 | 260 |
| Glass Fiber Insulation | 0.0018 | 0.000037 | 0.8 | 60 |
| Expanded Polystyrene | 0.001 | 0.000034 | 1.5 | 20 |
| User Specified Value | Enter Value | Enter Value | Enter Value | Enter Value |

Select Material
Concrete ▾
Scroll to desired material then Click on selection

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

COMPARTMENT MASS VENTILATION FLOW RATE

| | | | |
|---|---|---|---|
| Forced Ventilation Flow Rate (m) | 1000.00 | cfm | 0.472 $m^3/sec$<br>0.559 kg/sec |

FIRE SPECIFICATIONS

| | | |
|---|---|---|
| Fire Heat Release Rate (Q) | 500.00 | kW |

Calculate

## METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/m c_p T_a)^{0.72}(h_k A_T/m c_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

$T_a$ = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

$c_p$ = specific heat of air (kJ/kg-K)

$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)

$A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where $t_p$ = thermal penetration time (sec)

$\rho$ = interior construction density ($kg/m^3$)

$c_p$ = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

$\delta$ = interior construction thickness (m)

$t_p$ = 26128.98 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or $(k/\delta)$ for $t > t_p$

Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where $A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

$w_c$ = compartment width (m)

$l_c$ = compartment length (m)

$h_c$ = compartment height (m)

$A_0$ = area of ventilation opening ($m^2$)

$A_T$ = 118.92 $m^2$

Compartment Hot Gas Layer Temperature With Forced Ventilation

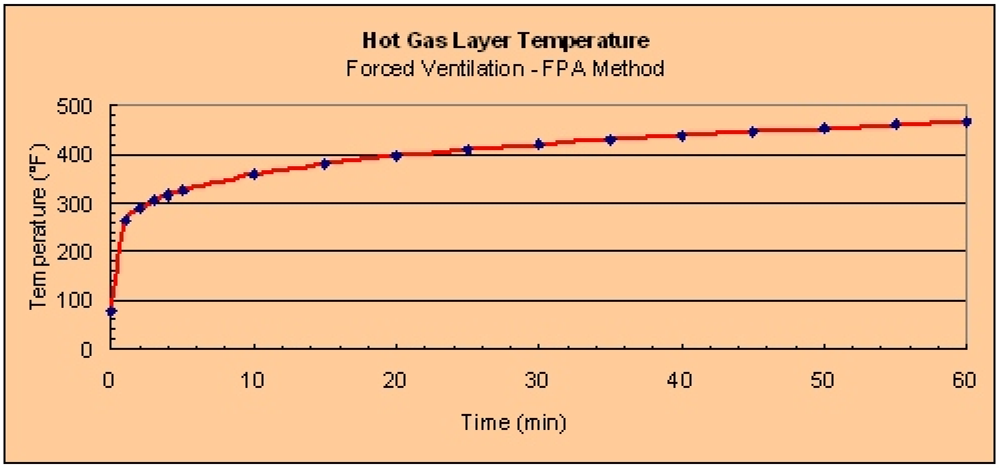
$\Delta T_g/T_a = 0.63(Q/m c_p T_o)^{0.72}(h_k A_T/m c_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

**Results**

| Time After Ignition (t) |  | $h_k$ (kW/m$^2$-K) | $\Delta T_g/T_0$ | $\Delta T_g$ (K) | $T_g$ (K) | $T_g$ (°C) | $T_g$ (°F) |
|---|---|---|---|---|---|---|---|
| (min) | (sec) |  |  |  |  |  |  |
| 0 | 0 | - | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.22 | 0.35 | 103.76 | 401.76 | 128.76 | 263.77 |
| 2 | 120 | 0.16 | 0.39 | 117.55 | 415.55 | 142.55 | 288.59 |
| 3 | 180 | 0.13 | 0.42 | 126.45 | 424.45 | 151.45 | 304.61 |
| 4 | 240 | 0.11 | 0.45 | 133.17 | 431.17 | 158.17 | 316.71 |
| 5 | 300 | 0.10 | 0.47 | 138.63 | 436.63 | 163.63 | 326.54 |
| 10 | 600 | 0.07 | 0.53 | 157.05 | 455.05 | 182.05 | 359.70 |
| 15 | 900 | 0.06 | 0.57 | 168.94 | 466.94 | 193.94 | 381.10 |
| 20 | 1200 | 0.05 | 0.60 | 177.92 | 475.92 | 202.92 | 397.26 |
| 25 | 1500 | 0.04 | 0.62 | 185.21 | 483.21 | 210.21 | 410.39 |
| 30 | 1800 | 0.04 | 0.64 | 191.39 | 489.39 | 216.39 | 421.51 |
| 35 | 2100 | 0.04 | 0.66 | 196.78 | 494.78 | 221.78 | 431.20 |
| 40 | 2400 | 0.03 | 0.68 | 201.57 | 499.57 | 226.57 | 439.82 |
| 45 | 2700 | 0.03 | 0.69 | 205.88 | 503.88 | 230.88 | 447.59 |
| 50 | 3000 | 0.03 | 0.70 | 209.83 | 507.83 | 234.83 | 454.69 |
| 55 | 3300 | 0.03 | 0.72 | 213.46 | 511.46 | 238.46 | 461.22 |
| 60 | 3600 | 0.03 | 0.73 | 216.83 | 514.83 | 241.83 | 467.29 |



## METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k = 0.4\sqrt{(k\rho c / t)}$ for $t < t_p$

Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

$\delta$ = thickness of interior lining (m)

$h_k$ = 0.088 $kW/m^2$-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

$A_T$ = 118.92 $m^2$

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\ c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

$T_a$ = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

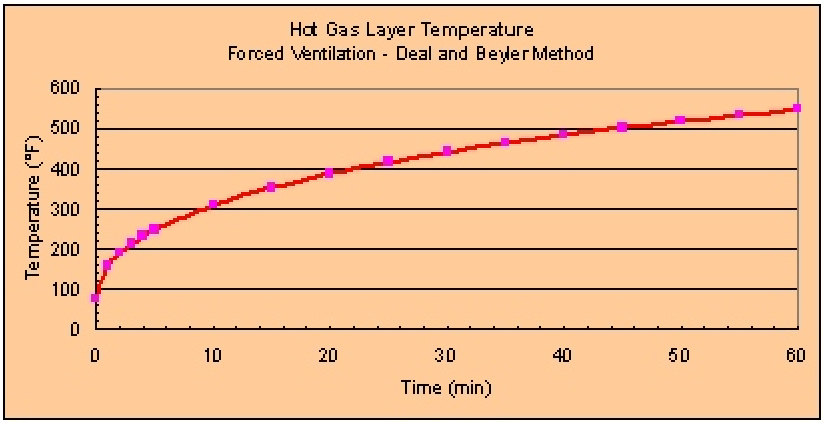
$c_p$ = specific heat of air (kJ/Kg-K)

$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)

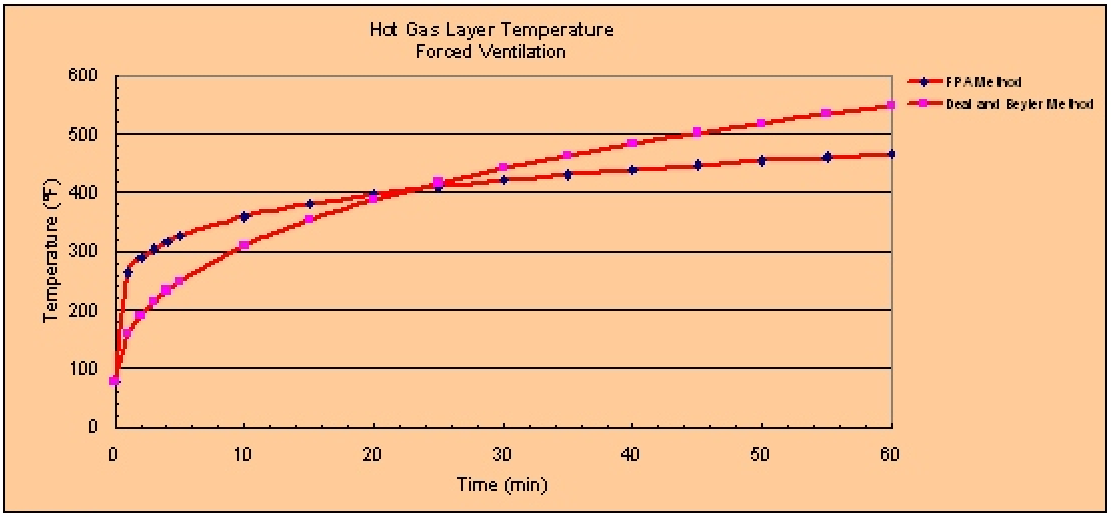
$A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

**Results**

| Time After Ignition (t) | | $h_k$ | $\Delta T_g$ | $T_g$ | $T_g$ | $T_g$ |
|---|---|---|---|---|---|---|
| (min) | (sec) | ($kW/m^2$-K) | (K) | (K) | (°C) | (°F) |
| 0 | 0 | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.09 | 45.39 | 343.39 | 70.39 | 158.70 |
| 2 | 120 | 0.06 | 62.87 | 360.87 | 87.87 | 190.16 |
| 3 | 180 | 0.05 | 75.80 | 373.80 | 100.80 | 213.43 |
| 4 | 240 | 0.04 | 86.39 | 384.39 | 111.39 | 232.50 |
| 5 | 300 | 0.04 | 95.50 | 393.50 | 120.50 | 248.90 |
| 10 | 600 | 0.03 | 129.33 | 427.33 | 154.33 | 309.80 |
| 15 | 900 | 0.02 | 153.41 | 451.41 | 178.41 | 353.15 |
| 20 | 1200 | 0.02 | 172.57 | 470.57 | 197.57 | 387.62 |
| 25 | 1500 | 0.02 | 188.64 | 486.64 | 213.64 | 416.55 |
| 30 | 1800 | 0.02 | 202.57 | 500.57 | 227.57 | 441.62 |
| 35 | 2100 | 0.01 | 214.90 | 512.90 | 239.90 | 463.82 |
| 40 | 2400 | 0.01 | 225.99 | 523.99 | 250.99 | 483.78 |
| 45 | 2700 | 0.01 | 236.08 | 534.08 | 261.08 | 501.94 |
| 50 | 3000 | 0.01 | 245.34 | 543.34 | 270.34 | 518.62 |
| 55 | 3300 | 0.01 | 253.92 | 551.92 | 278.92 | 534.06 |
| 60 | 3600 | 0.01 | 261.90 | 559.90 | 286.90 | 548.43 |



**Summary of Result:**



**NOTE**

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Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
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Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

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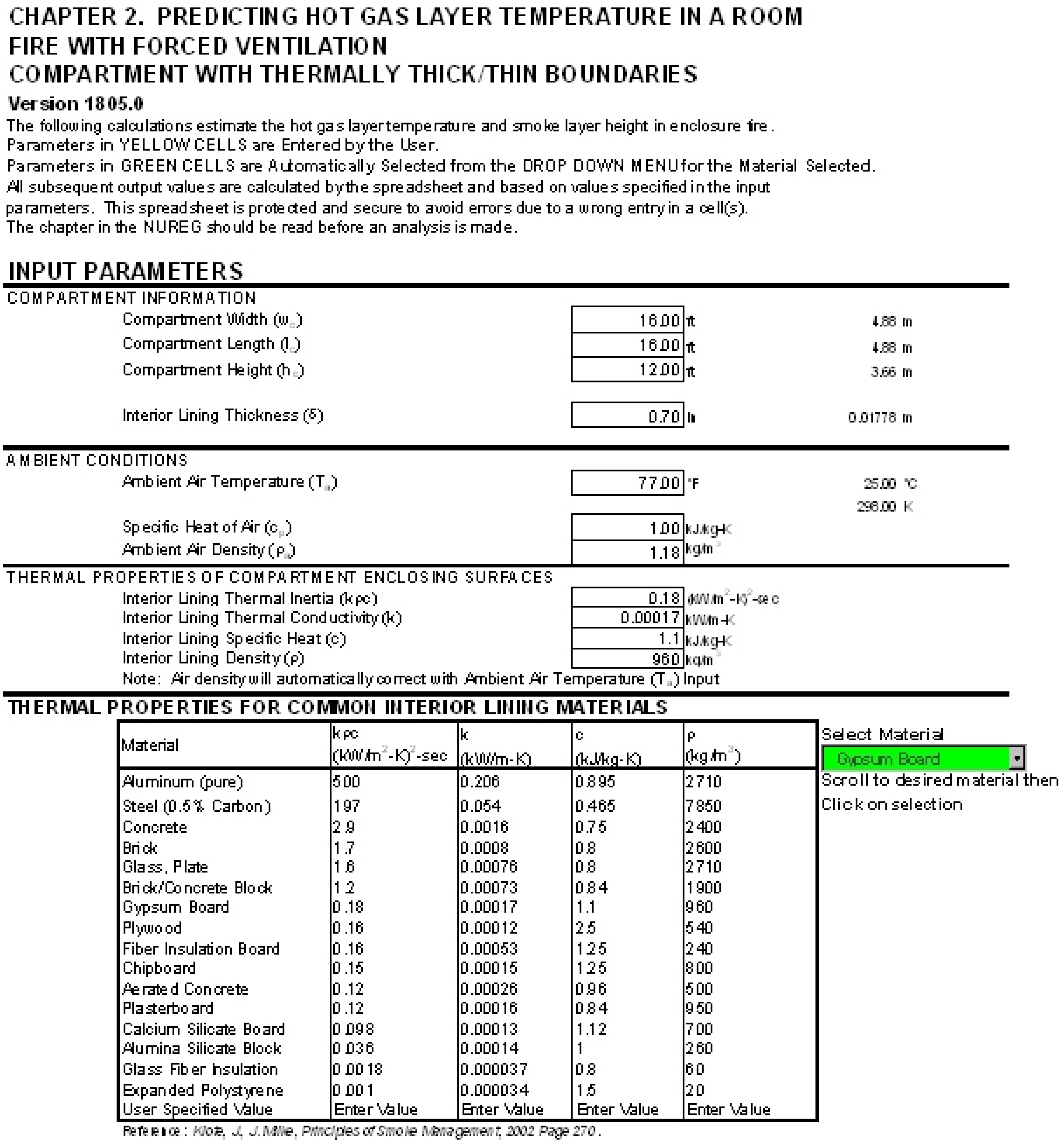
(b) Boundary Material: Gypsum Board
FDT$^s$: 02.2_Temperature_FV.xls



## CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION
## COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

**Version 1805.0**

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

### INPUT PARAMETERS

COMPARTMENT INFORMATION

| | | | |
|---|---|---|---|
| Compartment Width ($w_c$) | 16.00 | ft | 4.88 m |
| Compartment Length ($l_c$) | 16.00 | ft | 4.88 m |
| Compartment Height ($h_c$) | 12.00 | ft | 3.66 m |
| Interior Lining Thickness ($\delta$) | 0.70 | in | 0.01778 m |

AMBIENT CONDITIONS

| | | | |
|---|---|---|---|
| Ambient Air Temperature ($T_a$) | 77.00 | °F | 25.00 °C<br>298.00 K |
| Specific Heat of Air ($c_p$) | 1.00 | kJ/kg-K | |
| Ambient Air Density ($\rho_a$) | 1.18 | kg/m$^3$ | |

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

| | | |
|---|---|---|
| Interior Lining Thermal Inertia ($k\rho c$) | 0.18 | (kW/m$^2$-K)$^2$-sec |
| Interior Lining Thermal Conductivity ($k$) | 0.00017 | kW/m-K |
| Interior Lining Specific Heat ($c$) | 1.1 | kJ/kg-K |
| Interior Lining Density ($\rho$) | 960 | kg/m$^3$ |

Note: Air density will automatically correct with Ambient Air Temperature ($T_a$) Input

**THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS**

| Material | $k\rho c$ (kW/m$^2$-K)$^2$-sec | $k$ (kW/m-K) | $c$ (kJ/kg-K) | $\rho$ (kg/m$^3$) |
|---|---|---|---|---|
| Aluminum (pure) | 500 | 0.206 | 0.895 | 2710 |
| Steel (0.5% Carbon) | 197 | 0.054 | 0.465 | 7850 |
| Concrete | 2.9 | 0.0016 | 0.75 | 2400 |
| Brick | 1.7 | 0.0008 | 0.8 | 2600 |
| Glass, Plate | 1.6 | 0.00076 | 0.8 | 2710 |
| Brick/Concrete Block | 1.2 | 0.00073 | 0.84 | 1900 |
| Gypsum Board | 0.18 | 0.00017 | 1.1 | 960 |
| Plywood | 0.16 | 0.00012 | 2.5 | 540 |
| Fiber Insulation Board | 0.16 | 0.00053 | 1.25 | 240 |
| Chipboard | 0.15 | 0.00015 | 1.25 | 800 |
| Aerated Concrete | 0.12 | 0.00026 | 0.96 | 500 |
| Plasterboard | 0.12 | 0.00016 | 0.84 | 950 |
| Calcium Silicate Board | 0.098 | 0.00013 | 1.12 | 700 |
| Alumina Silicate Block | 0.036 | 0.00014 | 1 | 260 |
| Glass Fiber Insulation | 0.0018 | 0.000037 | 0.8 | 60 |
| Expanded Polystyrene | 0.001 | 0.000034 | 1.5 | 20 |
| User Specified Value | Enter Value | Enter Value | Enter Value | Enter Value |

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

Select Material

🟩 Gypsum Board

Scroll to desired material then Click on selection

|  |  |  |  |
|---|---|---|---|
| COMPARTMENT MASS VENTILATION FLOW RATE |  |  |  |
| Forced Ventilation Flow Rate (m) | 1000.00 | cfm | 0.472 $m^3/sec$<br>0.559 kg/sec |
| FIRE SPECIFICATIONS |  |  |  |
| Fire Heat Release Rate (Q) | 500.00 | kW |  |
|  | Calculate |  |  |

## METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/m c_p T_a)^{0.72}(h_k A_T/m c_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

$T_a$ = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

$c_p$ = specific heat of air (kJ/kg-K)

$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)

$A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where $t_p$ = thermal penetration time (sec)

$\rho$ = interior construction density ($kg/m^3$)

$c_p$ = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

$\delta$ = interior construction thickness (m)

$t_p$ = 490.93 sec

Heat Transfer Coefficient Calculation

$h_k$ = v(kρc/t) for $t < t_p$ or (k/δ) for $t > t_p$

Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)

kρc = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where $A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

$w_c$ = compartment width (m)

$l_c$ = compartment length (m)

$h_c$ = compartment height (m)

$A_v$ = area of ventilation opening ($m^2$)

$A_T$ = 118.92 $m^2$

Compartment Hot Gas Layer Temperature With Forced Ventilation

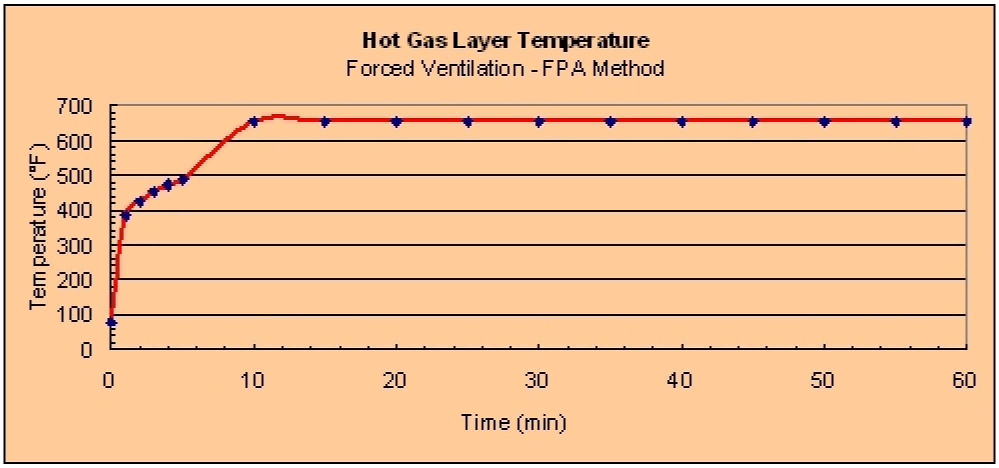
$\Delta T_g/T_a = 0.63(Q/m c_p T_o)^{0.72}(h_k A_T/m c_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

**Results**

| Time After Ignition (t) | | $h_k$ | $\Delta T_g/T_0$ | $\Delta T_g$ | $T_g$ | $T_g$ | $T_g$ |
|---|---|---|---|---|---|---|---|
| (min) | (sec) | (kW/m$^2$-K) | | (K) | (K) | (°C) | (°F) |
| 0 | 0 | - | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.05 | 0.57 | 171.13 | 469.13 | 196.13 | 385.04 |
| 2 | 120 | 0.04 | 0.65 | 193.87 | 491.87 | 218.87 | 425.97 |
| 3 | 180 | 0.03 | 0.70 | 208.55 | 506.55 | 233.55 | 452.39 |
| 4 | 240 | 0.03 | 0.74 | 219.63 | 517.63 | 244.63 | 472.34 |
| 5 | 300 | 0.02 | 0.77 | 228.64 | 526.64 | 253.64 | 488.54 |
| 10 | 600 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 15 | 900 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 20 | 1200 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 25 | 1500 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 30 | 1800 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 35 | 2100 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 40 | 2400 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 45 | 2700 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 50 | 3000 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 55 | 3300 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |
| 60 | 3600 | 0.01 | 1.08 | 320.79 | 618.79 | 345.79 | 654.43 |



## METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k =$ $0.4\sqrt{(k\rho c / t)}$ for $t < t_p$

Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

$\delta$ = thickness of interior lining (m)

$h_k =$ 0.022 $kW/m^2$-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

$A_T =$ 118.92 $m^2$

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\ c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

$T_a$ = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

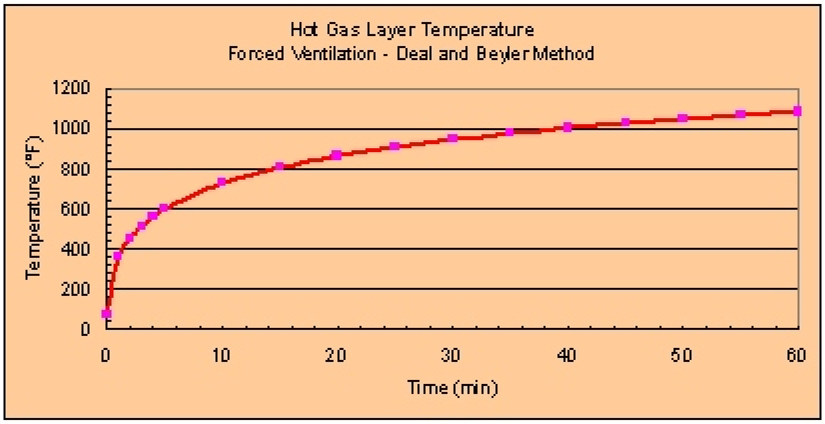
$c_p$ = specific heat of air (kJ/Kg-K)

$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)

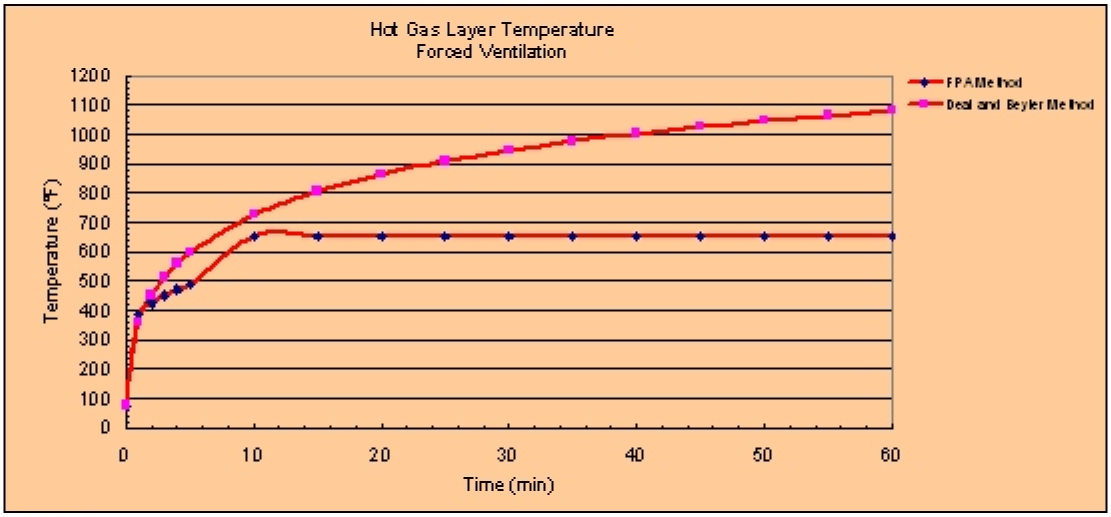
$A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

**Results**

| Time After Ignition (t) | | $h_k$ | $\Delta T_g$ | $T_g$ | $T_g$ | $T_g$ |
|---|---|---|---|---|---|---|
| (min) | (sec) | ($kW/m^2$-K) | (K) | (K) | (°C) | (°F) |
| 0 | 0 | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.02 | 158.01 | 456.01 | 183.01 | 361.42 |
| 2 | 120 | 0.02 | 208.22 | 506.22 | 233.22 | 451.80 |
| 3 | 180 | 0.01 | 242.34 | 540.34 | 267.34 | 513.21 |
| 4 | 240 | 0.01 | 268.57 | 566.57 | 293.57 | 560.43 |
| 5 | 300 | 0.01 | 289.99 | 587.99 | 314.99 | 598.99 |
| 10 | 600 | 0.01 | 361.55 | 659.55 | 386.55 | 727.79 |
| 15 | 900 | 0.01 | 405.93 | 703.93 | 430.93 | 807.67 |
| 20 | 1200 | 0.00 | 437.97 | 735.97 | 462.97 | 865.35 |
| 25 | 1500 | 0.00 | 462.91 | 760.91 | 487.91 | 910.24 |
| 30 | 1800 | 0.00 | 483.22 | 781.22 | 508.22 | 946.80 |
| 35 | 2100 | 0.00 | 500.28 | 798.28 | 525.28 | 977.51 |
| 40 | 2400 | 0.00 | 514.94 | 812.94 | 539.94 | 1003.89 |
| 45 | 2700 | 0.00 | 527.74 | 825.74 | 552.74 | 1026.94 |
| 50 | 3000 | 0.00 | 539.08 | 837.08 | 564.08 | 1047.35 |
| 55 | 3300 | 0.00 | 549.24 | 847.24 | 574.24 | 1065.63 |
| 60 | 3600 | 0.00 | 558.41 | 856.41 | 583.41 | 1082.14 |



Summary of Result:



**NOTE**

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

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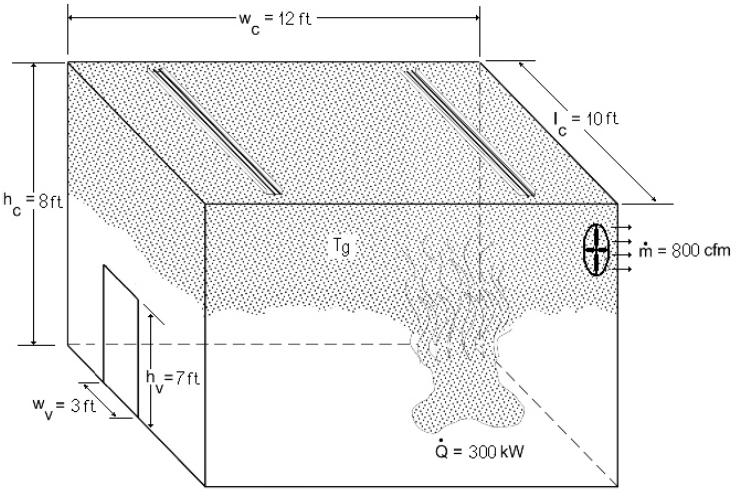
### Example Problem 2.16.2-2

**Problem Statement**

Consider a compartment that is 12 ft wide x 10 ft long x 8 ft high ($w_c$ x $l_c$ x $h_c$) with a vent opening that is 3 ft wide x 7 ft tall ($w_v$ x $h_v$). The compartment boundaries are made of 0.5 ft thick gypsum board. The forced ventilation rate is 800 cfm (exhaust). Calculate the hot gas layer temperature in the compartment for a fire size of 300 kW at 2 minutes.



Example Problem 2-5: Compartment with Forced Ventilation

**Solution**

Purpose:

(1) Determine the hot gas layer temperature in the compartment ($T_g$) at t = 2 min after ignition.

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)
(2) Simple rectangular geometry: no beam pockets
(3) One-dimensional heat flow through the compartment boundaries
(4) Constant Heat Release Rate (HRR)
(5) The fire is located at the center of the compartment or away from the walls
(6) The bottom of the vent is at the floor level
(7) The compartment is open to the outside at the inlet (pressure = 1 atm)

Spreadsheet ($FDT^s$) Information:

Use the following $FDT^s$:

(a) 02.2_Temperature_FV.xls

**Note:** Since gypsum board thickness is more than 1 inch, it is required to use correlations for thermally thick materials. Also, the spreadsheet has two different methods to calculate the hot gas layer temperature. Both methods are presented for comparison.

$FDT^s$ Input Parameters:

- Compartment Width ($w_c$) = 12 ft
- Compartment Length ($l_c$) = 10 ft
- Compartment Height ($h_c$) = 8 ft
- Interior Lining Thickness ($\delta$) = 6 in
- Ambient Air Temperature ($T_a$) = 77 °F
- Specific Heat of Air ($c_p$)= 1 kJ/kg-K
- Material: Select **Gypsum Board** on the $FDT^s$
- Compartment Mass Ventilation Rate $(\dot{m})$ = 800 cfm
- Fire Heat Release Rate $(\dot{Q})$ = 300 kW

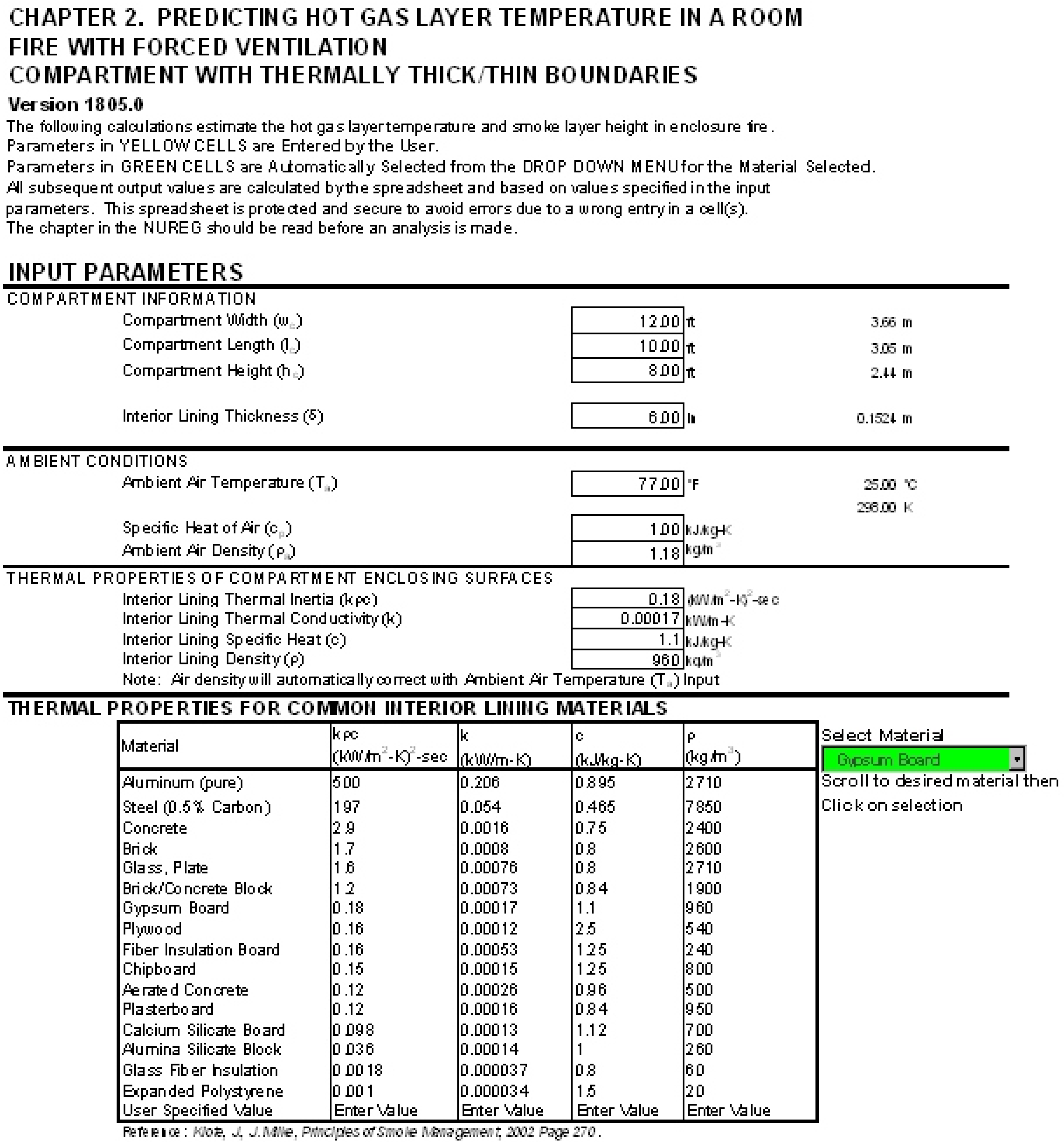
**Results***

| Boundary Material | Hot Layer Gas Temperature ($T_g$) °C (°F) | |
|---|---|---|
| | Method of Foote, Pagni & Alvares (FPA) | Method of Deal & Beyler |
| Gypsum Board | 216 (423) | 256 (493) |

*see spreadsheet on next page at t = 2 min

## Spreadsheet Calculations

FDT$^s$: 02.2_Temperature_FV.xls



# CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION

## COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

**Version 1805.0**

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

## INPUT PARAMETERS

COMPARTMENT INFORMATION

| | | | | |
|---|---|---|---|---|
| Compartment Width ($w_c$) | 12.00 | ft | 3.66 | m |
| Compartment Length ($l_c$) | 10.00 | ft | 3.05 | m |
| Compartment Height ($h_c$) | 8.00 | ft | 2.44 | m |
| Interior Lining Thickness ($\delta$) | 6.00 | in | 0.1524 | m |

AMBIENT CONDITIONS

| | | | | |
|---|---|---|---|---|
| Ambient Air Temperature ($T_a$) | 77.00 | °F | 25.00 | °C |
| | | | 298.00 | K |
| Specific Heat of Air ($c_p$) | 1.00 | kJ/kg-K | | |
| Ambient Air Density ($\rho_a$) | 1.18 | kg/m$^3$ | | |

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

| | | |
|---|---|---|
| Interior Lining Thermal Inertia ($k\rho c$) | 0.18 | (kW/m$^2$-K)$^2$-sec |
| Interior Lining Thermal Conductivity ($k$) | 0.00017 | kW/m-K |
| Interior Lining Specific Heat ($c$) | 1.1 | kJ/kg-K |
| Interior Lining Density ($\rho$) | 960 | kg/m$^3$ |

Note: Air density will automatically correct with Ambient Air Temperature ($T_a$) Input

**THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS**

| Material | $k\rho c$ (kW/m$^2$-K)$^2$-sec | $k$ (kW/m-K) | $c$ (kJ/kg-K) | $\rho$ (kg/m$^3$) |
|---|---|---|---|---|
| Aluminum (pure) | 500 | 0.206 | 0.895 | 2710 |
| Steel (0.5% Carbon) | 197 | 0.054 | 0.465 | 7850 |
| Concrete | 2.9 | 0.0016 | 0.75 | 2400 |
| Brick | 1.7 | 0.0008 | 0.8 | 2600 |
| Glass, Plate | 1.6 | 0.00076 | 0.8 | 2710 |
| Brick/Concrete Block | 1.2 | 0.00073 | 0.84 | 1900 |
| Gypsum Board | 0.18 | 0.00017 | 1.1 | 960 |
| Plywood | 0.16 | 0.00012 | 2.5 | 540 |
| Fiber Insulation Board | 0.16 | 0.00053 | 1.25 | 240 |
| Chipboard | 0.15 | 0.00015 | 1.25 | 800 |
| Aerated Concrete | 0.12 | 0.00026 | 0.96 | 500 |
| Plasterboard | 0.12 | 0.00016 | 0.84 | 950 |
| Calcium Silicate Board | 0.098 | 0.00013 | 1.12 | 700 |
| Alumina Silicate Block | 0.036 | 0.00014 | 1 | 260 |
| Glass Fiber Insulation | 0.0018 | 0.000037 | 0.8 | 60 |
| Expanded Polystyrene | 0.001 | 0.000034 | 1.5 | 20 |
| User Specified Value | Enter Value | Enter Value | Enter Value | Enter Value |

Select Material
Gypsum Board ▾
Scroll to desired material then Click on selection

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

COMPARTMENT MASS VENTILATION FLOW RATE

| | | |
|---|---|---|
| Forced Ventilation Flow Rate (m) | 800.00 cfm | 0.378 $m^3$/sec<br>0.447 kg/sec |

FIRE SPECIFICATIONS

| | |
|---|---|
| Fire Heat Release Rate (Q) | 300.00 kW |

Calculate

## METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/m c_p T_a)^{0.72}(h_k A_T/m c_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

$T_a$ = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

$c_p$ = specific heat of air (kJ/kg-K)

$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)

$A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where $t_p$ = thermal penetration time (sec)

$\rho$ = interior construction density ($kg/m^3$)

$c_p$ = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

$\delta$ = interior construction thickness (m)

$t_p$ = 36068.24 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or $(k/\delta)$ for $t > t_p$

Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where $A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

$w_c$ = compartment width (m)

$l_c$ = compartment length (m)

$h_c$ = compartment height (m)

$A_v$ = area of ventilation opening ($m^2$)

$A_T$ = 55.00 $m^2$

Compartment Hot Gas Layer Temperature With Forced Ventilation

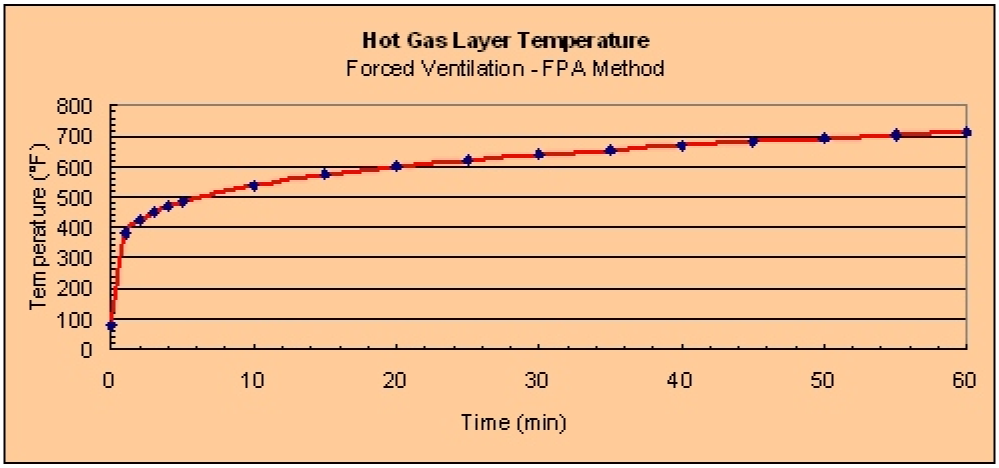
$\Delta T_g/T_a = 0.63(Q/m c_p T_o)^{0.72}(h_k A_T/m c_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

**Results**

| Time After Ignition (t) | | $h_k$ (kW/m$^2$-K) | $\Delta T_g/T_0$ | $\Delta T_g$ (K) | $T_g$ (K) | $T_g$ (°C) | $T_g$ (°F) |
|---|---|---|---|---|---|---|---|
| (min) | (sec) | | | | | | |
| 0 | 0 | - | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.05 | 0.57 | 169.45 | 467.45 | 194.45 | 382.01 |
| 2 | 120 | 0.04 | 0.64 | 191.97 | 489.97 | 216.97 | 422.54 |
| 3 | 180 | 0.03 | 0.69 | 206.50 | 504.50 | 231.50 | 448.71 |
| 4 | 240 | 0.03 | 0.73 | 217.48 | 515.48 | 242.48 | 468.46 |
| 5 | 300 | 0.02 | 0.76 | 226.39 | 524.39 | 251.39 | 484.50 |
| 10 | 600 | 0.02 | 0.86 | 256.47 | 554.47 | 281.47 | 538.65 |
| 15 | 900 | 0.01 | 0.93 | 275.89 | 573.89 | 300.89 | 573.61 |
| 20 | 1200 | 0.01 | 0.98 | 290.56 | 588.56 | 315.56 | 600.00 |
| 25 | 1500 | 0.01 | 1.01 | 302.46 | 600.46 | 327.46 | 621.44 |
| 30 | 1800 | 0.01 | 1.05 | 312.56 | 610.56 | 337.56 | 639.60 |
| 35 | 2100 | 0.01 | 1.08 | 321.35 | 619.35 | 346.35 | 655.43 |
| 40 | 2400 | 0.01 | 1.10 | 329.17 | 627.17 | 354.17 | 669.50 |
| 45 | 2700 | 0.01 | 1.13 | 336.22 | 634.22 | 361.22 | 682.20 |
| 50 | 3000 | 0.01 | 1.15 | 342.66 | 640.66 | 367.66 | 693.78 |
| 55 | 3300 | 0.01 | 1.17 | 348.59 | 646.59 | 373.59 | 704.46 |
| 60 | 3600 | 0.01 | 1.19 | 354.09 | 652.09 | 379.09 | 714.36 |



## METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k = 0.4\sqrt{(k\rho c / t)}$ for $t < t_p$

Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec
(a thermal property of material responsible for the rate of temperature rise)
$\delta$ = thickness of interior lining (m)

$h_k$ = 0.022 $kW/m^2$-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

$A_T$ = 55.00 $m^2$

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\ c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

$T_a$ = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

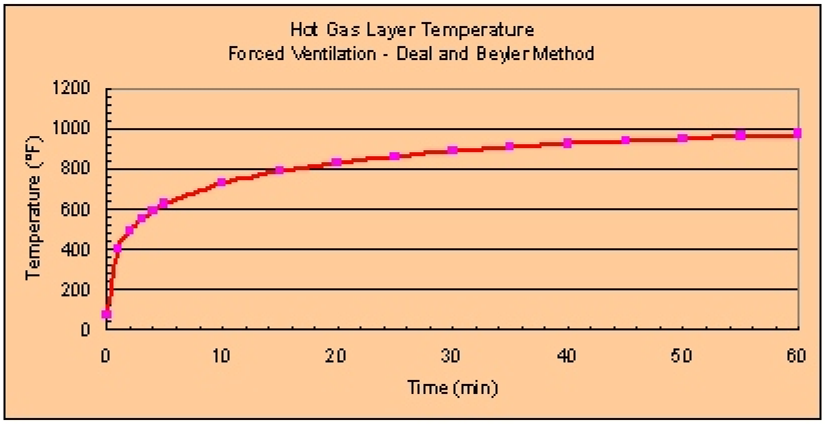
$c_p$ = specific heat of air (kJ/Kg-K)

$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)

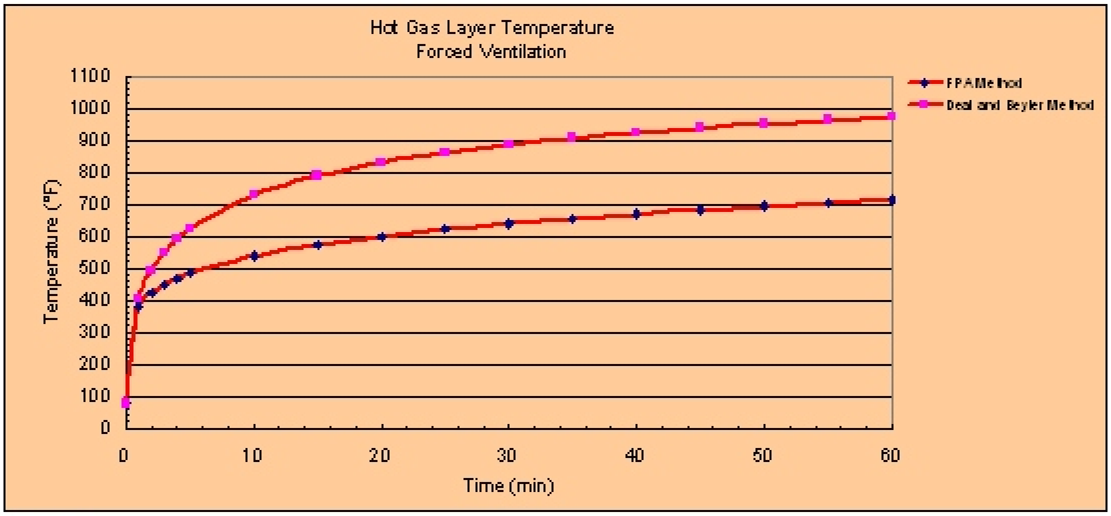
$A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

**Results**

| Time After Ignition (t) | | $h_k$ | $\Delta T_g$ | $T_g$ | $T_g$ | $T_g$ |
|---|---|---|---|---|---|---|
| (min) | (sec) | ($kW/m^2$-K) | (K) | (K) | (°C) | (°F) |
| 0 | 0 | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.02 | 181.58 | 479.58 | 206.58 | 403.84 |
| 2 | 120 | 0.02 | 230.90 | 528.90 | 255.90 | 492.62 |
| 3 | 180 | 0.01 | 262.48 | 560.48 | 287.48 | 549.47 |
| 4 | 240 | 0.01 | 285.79 | 583.79 | 310.79 | 591.42 |
| 5 | 300 | 0.01 | 304.22 | 602.22 | 329.22 | 624.60 |
| 10 | 600 | 0.01 | 362.20 | 660.20 | 387.20 | 728.95 |
| 15 | 900 | 0.01 | 395.59 | 693.59 | 420.59 | 789.06 |
| 20 | 1200 | 0.00 | 418.60 | 716.60 | 443.60 | 830.48 |
| 25 | 1500 | 0.00 | 435.90 | 733.90 | 460.90 | 861.62 |
| 30 | 1800 | 0.00 | 449.62 | 747.62 | 474.62 | 886.31 |
| 35 | 2100 | 0.00 | 460.89 | 758.89 | 485.89 | 906.60 |
| 40 | 2400 | 0.00 | 470.39 | 768.39 | 495.39 | 923.71 |
| 45 | 2700 | 0.00 | 478.57 | 776.57 | 503.57 | 938.43 |
| 50 | 3000 | 0.00 | 485.71 | 783.71 | 510.71 | 951.28 |
| 55 | 3300 | 0.00 | 492.03 | 790.03 | 517.03 | 962.66 |
| 60 | 3600 | 0.00 | 497.68 | 795.68 | 522.68 | 972.82 |



**Summary of Result:**



**NOTE**

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

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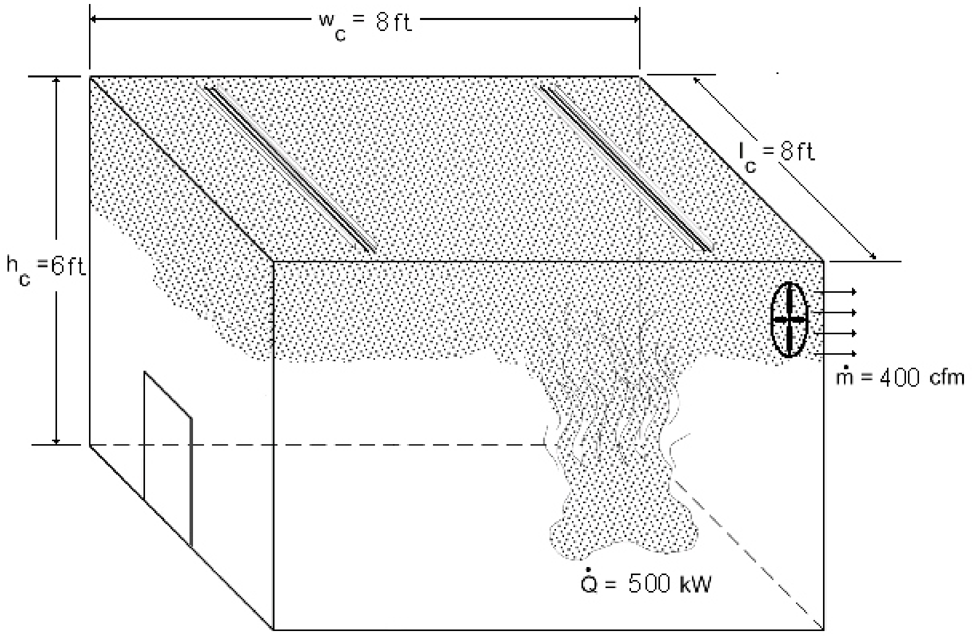
**Problem 2.16.2-3**

**Problem Statement**

Consider a compartment that is 8 ft wide x 8 ft long x 6 ft high ($w_c$ x $l_c$ x $h_c$). The compartment boundaries are made of 0.75 ft thick brick. The forced ventilation rate is 400 cfm (exhaust). Calculate the hot gas layer temperature in the compartment for a fire size of 500 kW at 2 minutes.



Example Problem 2-6: Compartment with Forced Ventilation

**Solution**

Purpose:

(1) Determine the hot gas layer temperature in the compartment ($T_g$) at t = 2 min after ignition.

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)
(2) Simple rectangular geometry (no beam pockets)
(3) One-dimensional heat flow through the compartment boundaries
(4) Constant Heat Release Rate (HRR)
(5) The fire is located at the center of the compartment or away from the walls
(6) The bottom of the vent is at the floor level
(7) The compartment is open to the outside at the inlet (pressure = 1 atm)

Spreadsheet ($FDT^s$) Information:

Use the following $FDT^s$:

(a) 02.2_Temperature_FV.xls

**Note:** Since the interior lining material thickness is more than 1 inch, it is required to use correlations for thermally thick materials. Also, the spreadsheet has two different methods to calculate the hot gas layer temperature. We are going to use both methods to compare values.

$FDT^s$ Input Parameters:

- Compartment Width ($w_c$) = 8 ft
- Compartment Length ($l_c$) = 8 ft
- Compartment Height ($h_c$) = 6 ft
- Interior Lining Thickness ($\delta$) = 9 in
- Ambient Air Temperature ($T_a$) = 77 °F
- Specific Heat of Air ($c_p$)= 1 kJ/kg-K
- Material: Select **Brick** on the $FDT^s$
- Compartment Mass Ventilation Rate $(\dot{m})$ = 400 cfm
- Fire Heat Release Rate $(\dot{Q})$ = 500 kW

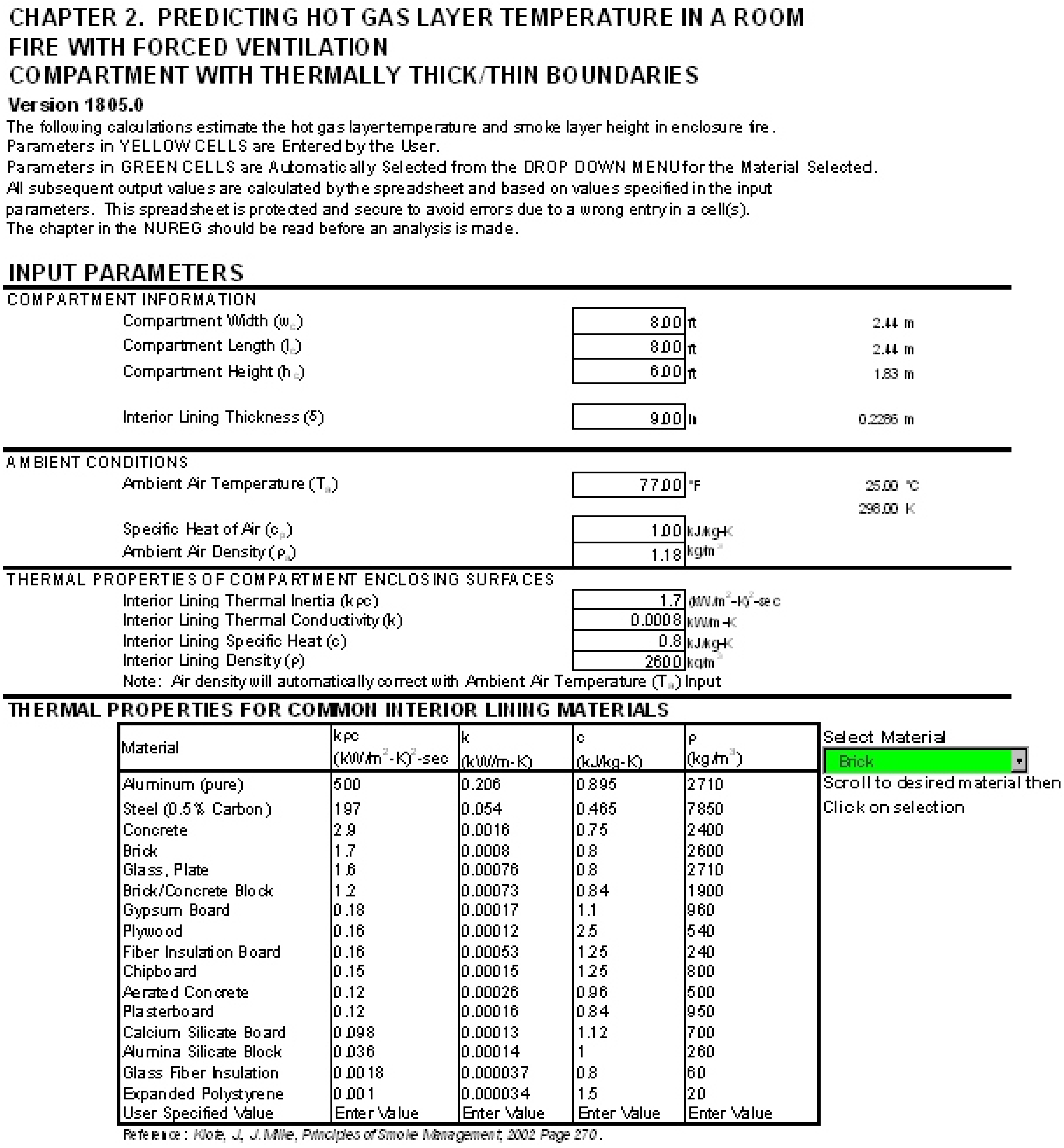
**Results***

| Boundary Material | Hot Layer Gas Temperature ($T_g$) °C (°F) | |
|---|---|---|
| | Method of Foote, Pagni & Alvares (FPA) | Method of Deal & Beyler |
| Brick | 321 (611) | 330 (626) |

*see spreadsheet on next page at t = 2 min.

**Spreadsheet Calculations**

FDT$^s$: 02.2_Temperature_FV.xls



## CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION

## COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

**Version 1805.0**

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input
parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

## INPUT PARAMETERS

COMPARTMENT INFORMATION

| | | | |
|---|---|---|---|
| Compartment Width ($w_c$) | 8.00 | ft | 2.44 m |
| Compartment Length ($l_c$) | 8.00 | ft | 2.44 m |
| Compartment Height ($h_c$) | 6.00 | ft | 1.83 m |
| Interior Lining Thickness ($\delta$) | 9.00 | in | 0.2286 m |

AMBIENT CONDITIONS

| | | | |
|---|---|---|---|
| Ambient Air Temperature ($T_a$) | 77.00 | °F | 25.00 °C<br>298.00 K |
| Specific Heat of Air ($c_p$) | 1.00 | kJ/kg-K | |
| Ambient Air Density ($\rho_a$) | 1.18 | kg/m$^3$ | |

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

| | | |
|---|---|---|
| Interior Lining Thermal Inertia ($k\rho c$) | 1.7 | (kW/m$^2$-K)$^2$-sec |
| Interior Lining Thermal Conductivity ($k$) | 0.0008 | kW/m-K |
| Interior Lining Specific Heat ($c$) | 0.8 | kJ/kg-K |
| Interior Lining Density ($\rho$) | 2600 | kg/m$^3$ |

Note: Air density will automatically correct with Ambient Air Temperature ($T_a$) Input

**THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS**

| Material | $k\rho c$ (kW/m$^2$-K)$^2$-sec | $k$ (kW/m-K) | $c$ (kJ/kg-K) | $\rho$ (kg/m$^3$) |
|---|---|---|---|---|
| Aluminum (pure) | 500 | 0.206 | 0.895 | 2710 |
| Steel (0.5% Carbon) | 197 | 0.054 | 0.465 | 7850 |
| Concrete | 2.9 | 0.0016 | 0.75 | 2400 |
| Brick | 1.7 | 0.0008 | 0.8 | 2600 |
| Glass, Plate | 1.6 | 0.00076 | 0.8 | 2710 |
| Brick/Concrete Block | 1.2 | 0.00073 | 0.84 | 1900 |
| Gypsum Board | 0.18 | 0.00017 | 1.1 | 960 |
| Plywood | 0.16 | 0.00012 | 2.5 | 540 |
| Fiber Insulation Board | 0.16 | 0.00053 | 1.25 | 240 |
| Chipboard | 0.15 | 0.00015 | 1.25 | 800 |
| Aerated Concrete | 0.12 | 0.00026 | 0.96 | 500 |
| Plasterboard | 0.12 | 0.00016 | 0.84 | 950 |
| Calcium Silicate Board | 0.098 | 0.00013 | 1.12 | 700 |
| Alumina Silicate Block | 0.036 | 0.00014 | 1 | 260 |
| Glass Fiber Insulation | 0.0018 | 0.000037 | 0.8 | 60 |
| Expanded Polystyrene | 0.001 | 0.000034 | 1.5 | 20 |
| User Specified Value | Enter Value | Enter Value | Enter Value | Enter Value |

Select Material

Brick

Scroll to desired material then
Click on selection

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

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COMPARTMENT MASS VENTILATION FLOW RATE

Forced Ventilation Flow Rate (m) 400.00 cfm 0.189 $m^3$/sec

0.224 kg/sec

---

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) 500.00 kW

**Calculate**

---

## METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/mc_pT_a)^{0.72}(h_kA_T/mc_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

$T_a$ = ambient air temperature (K)

$Q$ = heat release rate of the fire (kW)

$m$ = compartment mass ventilation flow rate (kg/sec)

$c_p$ = specific heat of air (kJ/kg-K)

$h_k$ = convective heat transfer coefficient (kW/$m^2$-K)

$A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where $t_p$ = thermal penetration time (sec)

$\rho$ = interior construction density (kg/$m^3$)

$c_p$ = interior construction heat capacity (kJ/kg-K)

$k$ = interior construction thermal conductivity (kW/m-K)

$\delta$ = interior construction thickness (m)

$t_p$ = 33967.67 sec

Heat Transfer Coefficient Calculation

$h_k = v(k\rho c/t)$ for $t < t_p$ or $(k/\delta)$ for $t > t_p$

Where $h_k$ = heat transfer coefficient (kW/$m^2$-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

$t$ = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where $A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

$w_c$ = compartment width (m)

$l_c$ = compartment length (m)

$h_c$ = compartment height (m)

$A_v$ = area of ventilation opening ($m^2$)

$A_T$ = 29.73 $m^2$

Compartment Hot Gas Layer Temperature With Forced Ventilation

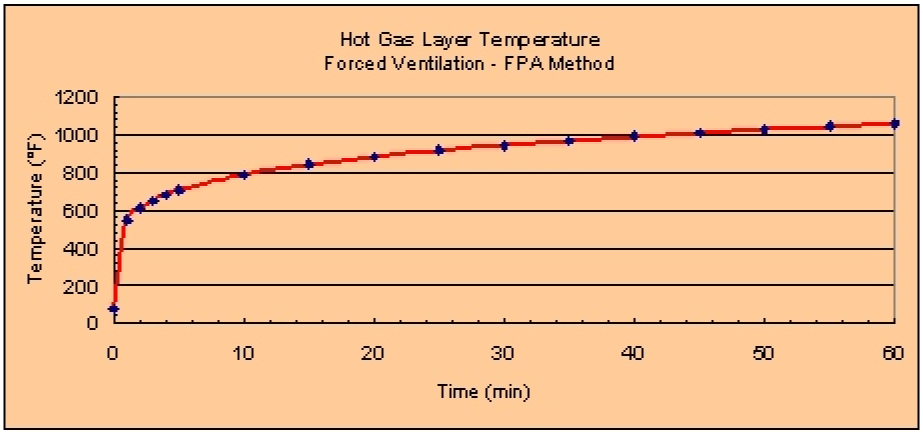
$\Delta T_g/T_a = 0.63(Q/mc_pTo)^{0.72}(h_kA_T/mc_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

| Time After Ignition (t) |  | $h_k$ (kW/m$^2$- K) | $\Delta T_g/T_a$ | $\Delta T_g$ (K) | $T_g$ (K) | $T_g$ (°C) | $T_g$ (°F) |
|---|---|---|---|---|---|---|---|
| (min) | (sec) |  |  |  |  |  |  |
| 0 | 0 | - | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.17 | 0.88 | 261.70 | 559.70 | 286.70 | 548.05 |
| 2 | 120 | 0.12 | 0.99 | 296.47 | 594.47 | 321.47 | 610.65 |
| 3 | 180 | 0.10 | 1.07 | 318.92 | 616.92 | 343.92 | 651.05 |
| 4 | 240 | 0.08 | 1.13 | 335.87 | 633.87 | 360.87 | 681.56 |
| 5 | 300 | 0.08 | 1.17 | 349.63 | 647.63 | 374.63 | 706.34 |
| 10 | 600 | 0.05 | 1.33 | 396.09 | 694.09 | 421.09 | 789.97 |
| 15 | 900 | 0.04 | 1.43 | 426.08 | 724.08 | 451.08 | 843.95 |
| 20 | 1200 | 0.04 | 1.51 | 448.73 | 746.73 | 473.73 | 884.71 |
| 25 | 1500 | 0.03 | 1.57 | 467.12 | 765.12 | 492.12 | 917.81 |
| 30 | 1800 | 0.03 | 1.62 | 482.70 | 780.70 | 507.70 | 945.86 |
| 35 | 2100 | 0.03 | 1.67 | 496.28 | 794.28 | 521.28 | 970.31 |
| 40 | 2400 | 0.03 | 1.71 | 508.36 | 806.36 | 533.36 | 992.04 |
| 45 | 2700 | 0.03 | 1.74 | 519.25 | 817.25 | 544.25 | 1011.65 |
| 50 | 3000 | 0.02 | 1.78 | 529.19 | 827.19 | 554.19 | 1029.54 |
| 55 | 3300 | 0.02 | 1.81 | 538.35 | 836.35 | 563.35 | 1046.02 |
| 60 | 3600 | 0.02 | 1.84 | 546.84 | 844.84 | 571.84 | 1061.32 |



## METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, $3^{rd}$ Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k = 0.4\sqrt{(k\rho c / t)}$ for $t < t_p$

Where $h_k$ = heat transfer coefficient ($kW/m^2$-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

$\delta$ = thickness of interior lining (m)

$h_k$ = 0.067 $kW/m^2$-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

$A_T$ = 29.73 $m^2$

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\ c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

$T_a$ = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

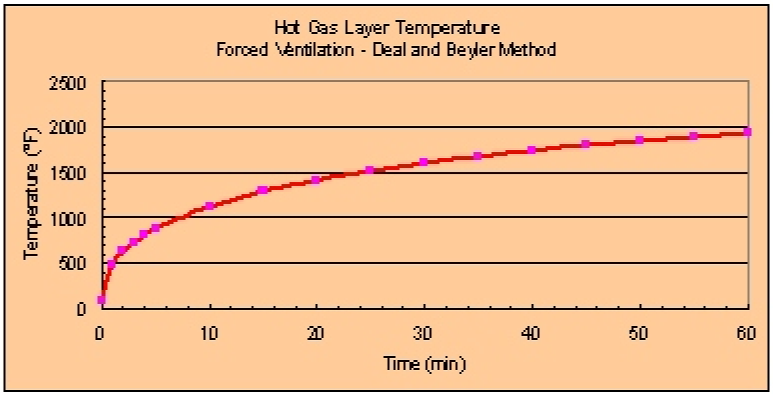
$c_p$ = specific heat of air (kJ/Kg-K)

$h_k$ = convective heat transfer coefficient ($kW/m^2$-K)

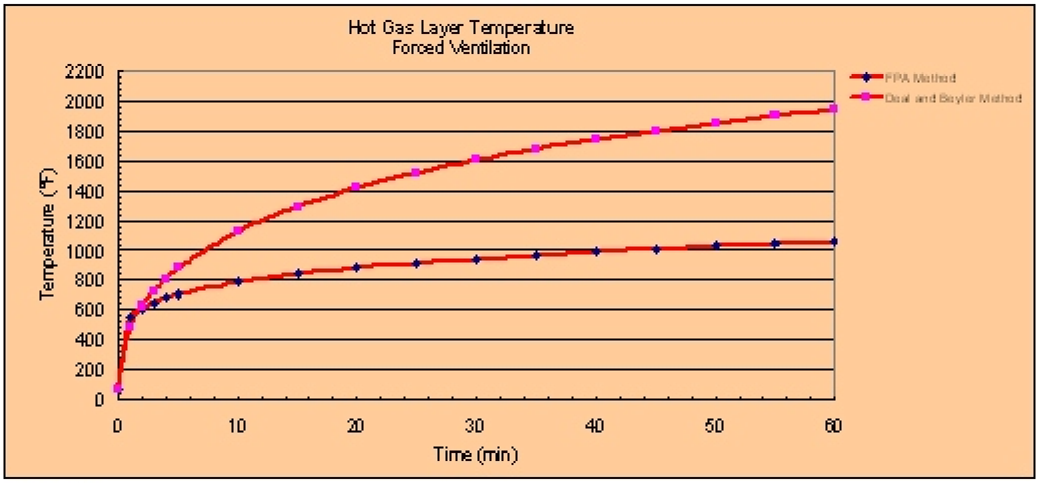
$A_T$ = total area of the compartment enclosing surface boundaries ($m^2$)

**Results**

| Time After Ignition (t) | | $h_k$ | $\Delta T_g$ | $T_g$ | $T_g$ | $T_g$ |
|---|---|---|---|---|---|---|
| (min) | (sec) | ($kW/m^2$-K) | (K) | (K) | (°C) | (°F) |
| 0 | 0 | - | - | 298.00 | 25.00 | 77.00 |
| 1 | 60 | 0.07 | 224.69 | 522.69 | 249.69 | 481.44 |
| 2 | 120 | 0.05 | 305.06 | 603.06 | 330.06 | 626.11 |
| 3 | 180 | 0.04 | 362.51 | 660.51 | 387.51 | 729.52 |
| 4 | 240 | 0.03 | 408.35 | 706.35 | 433.35 | 812.03 |
| 5 | 300 | 0.03 | 446.91 | 744.91 | 471.91 | 881.44 |
| 10 | 600 | 0.02 | 583.70 | 881.70 | 608.70 | 1127.67 |
| 15 | 900 | 0.02 | 675.27 | 973.27 | 700.27 | 1292.48 |
| 20 | 1200 | 0.02 | 744.93 | 1042.93 | 769.93 | 1417.87 |
| 25 | 1500 | 0.01 | 801.34 | 1099.34 | 826.34 | 1519.42 |
| 30 | 1800 | 0.01 | 848.79 | 1146.79 | 873.79 | 1604.83 |
| 35 | 2100 | 0.01 | 889.74 | 1187.74 | 914.74 | 1678.53 |
| 40 | 2400 | 0.01 | 925.74 | 1223.74 | 950.74 | 1743.33 |
| 45 | 2700 | 0.01 | 957.84 | 1255.84 | 982.84 | 1801.11 |
| 50 | 3000 | 0.01 | 986.78 | 1284.78 | 1011.78 | 1853.21 |
| 55 | 3300 | 0.01 | 1013.12 | 1311.12 | 1038.12 | 1900.62 |
| 60 | 3600 | 0.01 | 1037.27 | 1335.27 | 1062.27 | 1944.09 |



**Summary of Result**



**NOTE**

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