CHAPTER 14. ESTIMATING PRESSURE RISE ATTRIBUTABLE TO A FIRE IN A CLOSED COMPARTMENT

14.1 Objectives

This chapter has the following objectives:

- Discuss some systems of pressure measurement.
- Explain how to calculate pressure rise.
- Define relevant terms, including pressure rise.

14.2 Introduction

In a closed compartment or a compartment with small leakages, the release of heat from the combustion process could cause compartment pressure to rise as a result of the volumetric expansion of gases. It is this pressure rise that drives the mass flow out, and prevents mass flow into the compartment. In Chapter 2, we referred to this as the first stage of the fire.

When thermal energy rapidly accumulates in the form of hot gases, and the compartment has small openings to the surroundings, this pressure rise is very rapid and any hydrostatic pressure differences with height are negligible. For example, an addition of 100 kW to a 60-m^3 (2,119-ft^3) enclosure with an opening of 0.01 m^2 (0.10 ft^2) will cause a steady-state pressure rise of ≈1,000 Pa (0.14 psi) in several seconds. The hydrostatic pressure difference decreases at a rate of 10 Pa (0.0014 psi) per meter as the height increases. In this case, we see that the difference is negligible and the vent flow is determined by the pressure rise caused by the volumetric expansion of gases. Figure 14-1 illustrates the overpressure-time profile in an enclosure.

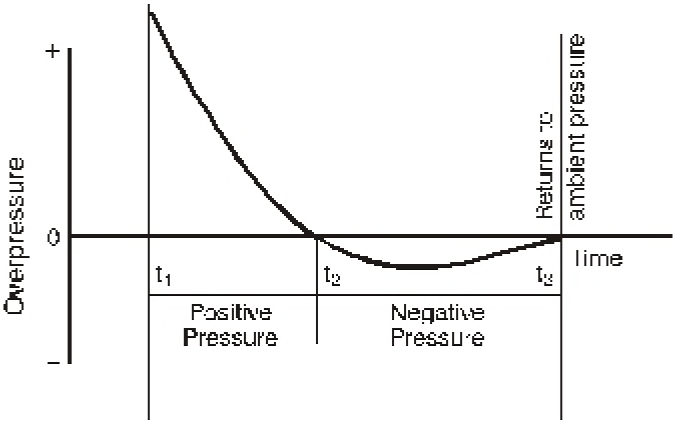


Figure 14-1 Overpressure Generated at a Fixed Location

Failure of a compartment due to pressure rise from a fire would be extremely rare. The vast majority of compartments have some form of leakage. Pressure rise (and buoyancy) are important to recognize in fire dynamic analysis because the increase in pressure can cause smoke and other products of combustion to be transported into adjoining compartments.

14.3 Definition of Pressure

Pressure can be defined as the amount of force brought to bear on some unit area of an object. When we press our thumb down on a table, we are applying force on the table. The harder we press, the greater the force, and the greater the pressure we apply to the table's surface.

Similarly, the air in the sky above us presses down on our bodies and all objects around us with a pressure of approximately 14.7 pounds per square inch (psi) of surface area. This pressure, which is essentially the average air pressure at sea level, is also known as one standard atmosphere. A pressure of two atmospheres *generally* means that a pressure of 29.4 psi is present, or two times the standard atmospheric pressure of 14.7 psi.

We emphasize the word "generally" because pressure also has absolute and relative scales of measurement. The 14.7 psi of atmospheric pressure at sea level is an absolute measurement, which is more properly presented in units of pounds per square inch-absolute, or psia for short. Zero psia refers to a complete absence of pressure, such as one might find in the perfect vacuum of outer space. By contrast, the most common relative scale of measurement, which is primarily used only in the United States, presents numerical values in terms of gauge pressure, where a reading of zero matches an absolute pressure of one standard atmosphere. In this system, an absolute pressure of 15.7 psia would be expressed as 1.0 pound per square inch-gauge, or 1.0 psig for short. Thus, two atmospheres of absolute pressure would be equivalent to one atmosphere gauge pressure (*Handbook of Chemical Hazard Analysis Procedures*).

Among the other systems of pressure measurement that are of an absolute nature, the most common include the following examples:

- Millimeters of mercury (mm Hg): 760 mm Hg equal one standard atmosphere.
- Inches of mercury (in. Hg): 29.9 in. Hg equal one standard atmosphere.
- Pascals (Pa) or Newton per square meter (N/m^2): 101,325 Pa or 101,325 N/m^2 equal one standard atmosphere.
- Bars: 1.01325 bars equal one standard atmosphere.
- Inches of water (in. H_2O): 407.6 in. H_2O equal one standard atmosphere.

Inches of water and inches of mercury are not commonly used in the scientific community, with the exception that meteorologists have traditionally reported current atmospheric pressures in inches of mercury. Nonetheless, it is beneficial to know of their existence.

14.4 Pressure Rise Calculations

As previously discussed, the combustion process raises the temperature of a gaseous system. This increase in temperature, in turn, causes a pressure rise attributable to expansion of the gases. According to the ideal gas law, when heat is added to an ideal gas in a fixed volume, the pressure must rise in response to the temperature. In a building fire situation, the resulting pressure and the rate of pressure rise are often kept very small by gas leaks through openings in the walls of the buildings (such as cracks around windows and doors). However, situations may arise where the enclosure can be considered to be well sealed, such as certain compartments on ships.

According to Karlsson and Quintiere (1999), the maximum pressure difference inside a compartment as a result of expansion of gases is given by the following expression:

$$\frac{P - P_a}{P_a} = \frac{\dot{Q}t}{V\rho_a c_v T_a} \tag{14-1}$$

Where:

P = compartment pressure attributable to combustion (atm)
P_a = initial atmospheric pressure (atm)
$\dot{Q}$ = heat release rate of the fire (kW)
t = time (sec)
V = compartment volume (m^3)
$_a$ = ambient air density (kg/m^3)
c_v = specific heat of air at constant volume (kJ/kg-K)
[values of c_v range from 0.71 to 0.85 kJ/kg-K]
T_a = ambient air temperature (K)

14.5 Assumptions and Limitations

The method discussed in this chapter is subject to several assumptions and limitations:

(1) The energy release rate is constant.

(2) The mass loss rate of the fuel is neglected in the conversion of mass.

(3) The specific heat does not change with temperature.

(4) The hydrostatic pressure difference over the height of the compartment is ignored and assumed to be negligible compared to the dynamic pressure.

14.6 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) compartment width (ft)

(2) compartment length (ft)

(3) compartment height (ft)

(4) fire heat release rate (ft)

(5) time after ignition (s)

14.7 Cautions

(1) Use (14_Compartment_Over_Pressure_Calculations.xls) spreadsheet on the CD-ROM for calculations.

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

14.8 Summary

According to the ideal gas law, when heat is added to an ideal gas in a fixed volume, the pressure must rise in response to the temperature. In a building fire situation, the resulting pressure and the rate of pressure rise are often kept small by gas leaks through openings in the walls of the buildings (such as through penetrations and cracks around windows/doors). However, situations may arise where the enclosure can be considered to be well sealed. It is important to recognize the increase in pressure within the fire compartment will cause products of combustion to also be transported into adjacent spaces.

The purpose of this chapter is to provide simple analytical method for calculating the dynamic pressure build-up in a closed compartment. We then use the results to show that the rapid pressure rise. This result can be used to justify the so-called “constant pressure assumption,” which is typically used when examining a “leaky” compartment fire.

14.9 References

Handbook of Chemical Hazard Analysis Procedures, Federal Emergency Management Agency (FEMA), US Department of Transportation (DOT), and U.S. Environmental Protection Agency (EPA).

Karlsson, B., and J.G. Quintiere, *Enclosure Fire Dynamics*, Chapter 8, “Conservation Equations and Smoke Filling,” CRC Press LLC, New York, pp. 181–225, 1999.

14.10 Problems

Example Problem 14-10.1

Problem Statement

A closed compartment in a facility pump room has dimensions 10 ft wide x 12 ft long x 10 ft high (w_c x l_c x h_c). A fire starts with a constant HRR of $\dot{Q}$ = 100 kW. Estimate the pressure rise attributable to the expansion of gases after 10 seconds.

Solution

Purpose:

(1) Estimate the pressure rise in the compartment 10 seconds after ignition.

Assumptions:

(1) The energy release rate is constant.
(2) The mass rate of the fuel is neglected in the conversion of mass.
(3) The specific heat is constant with temperature.
(4) The hydrostatic pressure difference over the height of the compartment is negligible compared to the dynamic pressure.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 14_Compartment_Over_Pressure_Calculations.xls

FDT^s Input Parameters:

-Compartment Width (w_c) = 10 ft
-Compartment Length (l_c) = 12 ft
-Compartment Height (h_c) = 10 ft
-Fire Heat Release Rate $(\dot{Q})$ = 100 kW
-Time After Ignition (t) = 10 sec

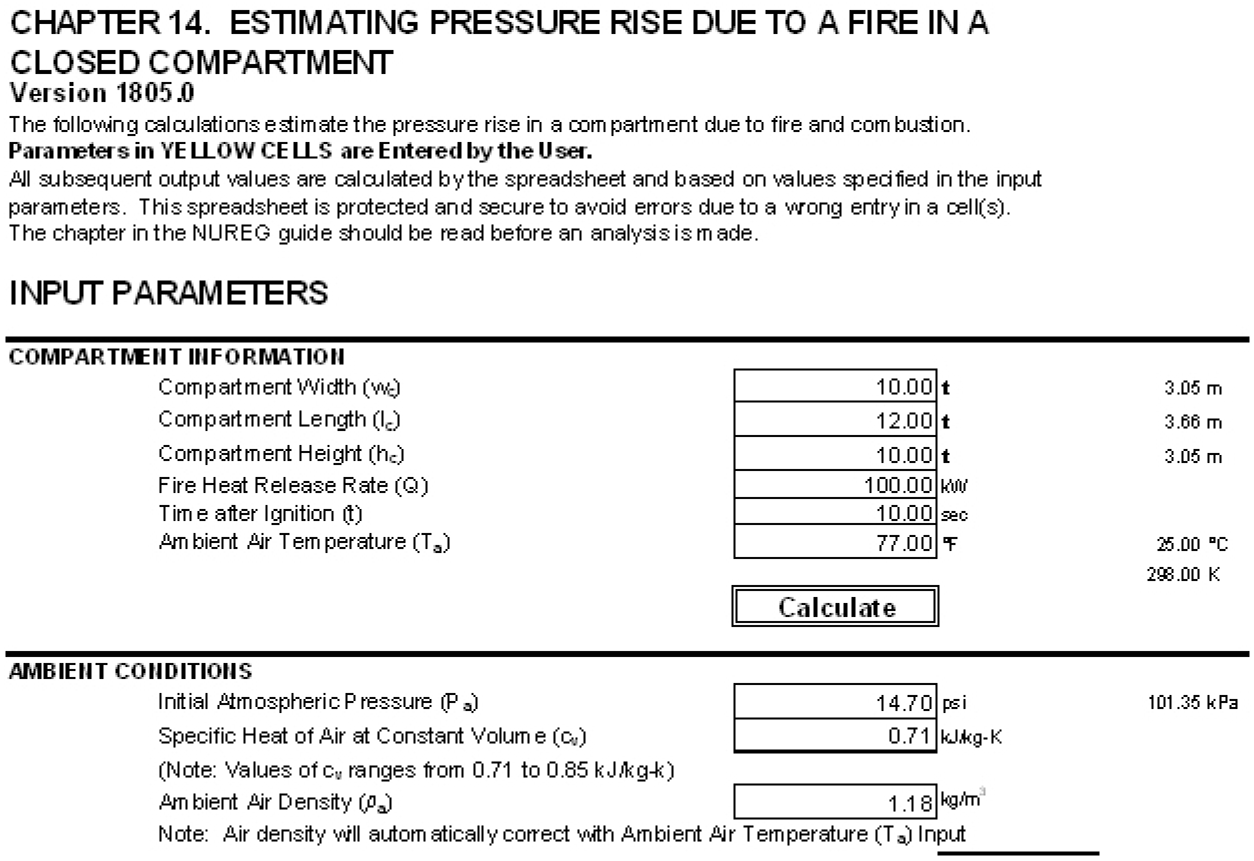
Results*

Pressure Rise	11.90 kPa (1.73 psi)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 14_Compartment_Over_Pressure_Calculations.xls



CHAPTER 14. ESTIMATING PRESSURE RISE DUE TO A FIRE IN A CLOSED COMPARTMENT

Version 1805.0

The following calculations estimate the pressure rise in a compartment due to fire and combustion.

Parameters in YELLOW CELLS are Entered by the User.

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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	10.00	t	3.05 m
Compartment Length (l_c)	12.00	t	3.66 m
Compartment Height (h_c)	10.00	t	3.05 m
Fire Heat Release Rate (Q)	100.00	kW	
Time after Ignition (t)	10.00	sec	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K

Calculate

AMBIENT CONDITIONS

Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa
Specific Heat of Air at Constant Volume (c_v)	0.71	kJ/kg-K	

(Note: Values of c_v ranges from 0.71 to 0.85 kJ/kg-k)

Ambient Air Density (ρ_a)	1.18	kg/m^3

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

METHOD OF KARLSSON AND QUINTIERE

Reference: *Karlsson and Quintiere, Enclosure Fire Dynamics, 1999, Page 102.*

$(P - P_a) / P_a = Q\,t / (V\,\rho_a\,c_v\,T_a)$

Where
P = compartment pressure due to fire and combustion (kPa)
P_a = initial atmospheric pressure (kPa)
Q = heat release rate of the fire (kW)
t = time after ignition (sec)
V = compartment volume (m^3)
ρ_a = ambient density (kg/m^3)
c_v = specific heat of air at constant volume (kJ/kg-K)
T_a = ambient air temperature (K)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where
V = volume of the compartment (m^3)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)

V = 33.98 m^3 1200 ft^3

Pressure Rise in Compartment

$(P - P_a) / P_a = Q\,t / (V\,\rho_a\,c_v\,T_a)$

$(P-P_a)/P_a$ = 0.117 atm

Multiplying by the atmospheric pressure (P_a) = 101 kPa

Gives a pressure difference = 11.90 kPa 1.73 psi Answer

This example shows that in a very short time the pressure in a closed compartment rises to quite large value.

Most buildings have leaks of some sort. The above example indicates that even though a fire compartment may be closed, the pressure is very rapid and would presumably lead to sufficient leaks to prevent further pressure rise from occurring. We will use this conclusion when dealing with pressure rises in enclosures with small leaks.

NOTE

The above calculations are based on principles developed in the Enclosure Fire Dynamics. 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 14.10-2

Problem Statement

A facility has a sealed compartment (assume zero leakage) with a blowout panel that is designed to fail at two atmospheres. The compartment is 20 ft wide x 25 ft long x 10 ft high. A fire is assumed with a constant heat release rate of 255 kW.

At what time (sec) does the blowout panel fail?

Solution

Purpose:

(1) Estimate the time after ignition the pressure reaches 2 atm (202.5 kPa).

Assumptions:

(1) The energy release rate is constant.
(2) The mass rate of the fuel is neglected in the conversion of mass.
(3) The specific heat is constant with temperature.
(4) The hydrostatic pressure difference over the height of the compartment is negligible compared to the dynamic pressure.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 14_Compartment_Over_Pressure_Calculations.xls

FDT^s Input Parameters:

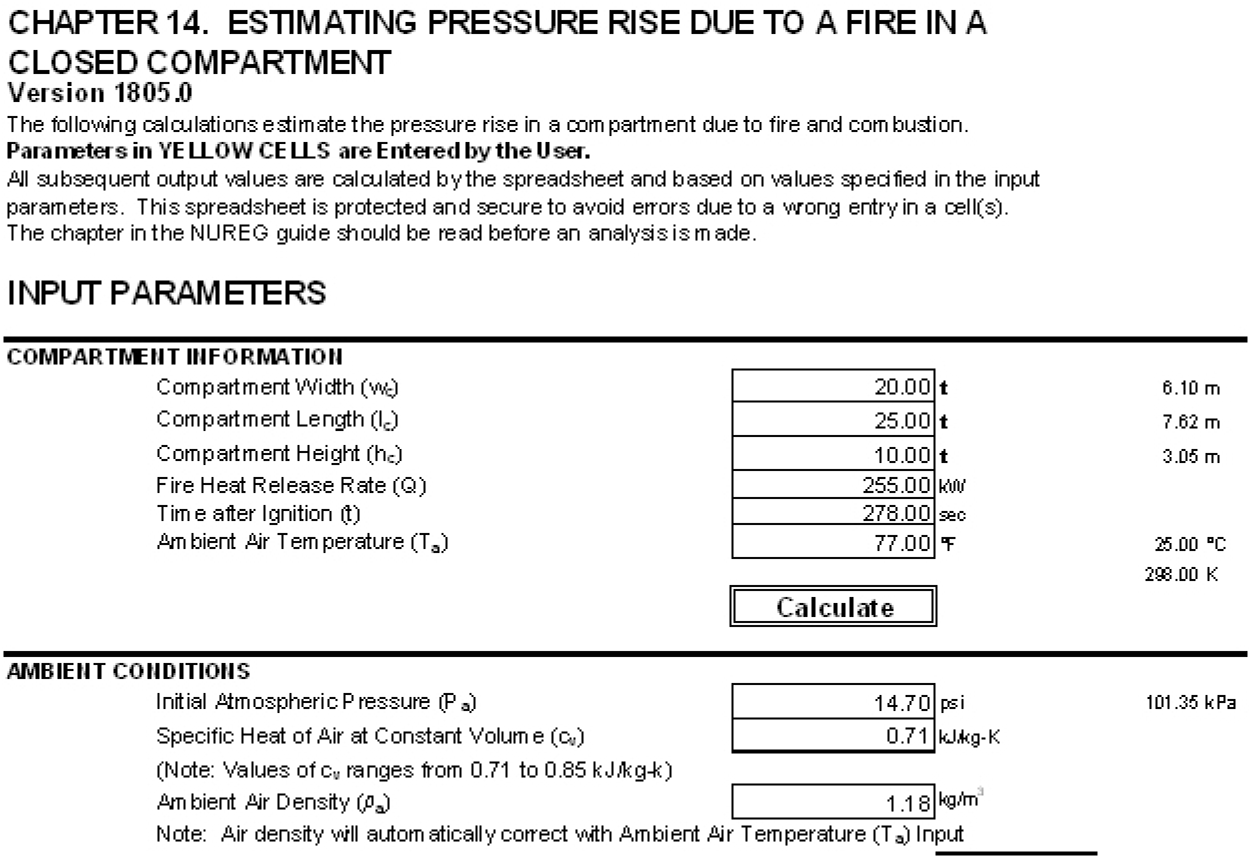
-Compartment Width (w_c) = 20 ft
-Compartment Length (l_c) = 25 ft
-Compartment Height (h_c) = 10 ft
-Fire Heat Release Rate $(\dot{Q})$ = 255 kW
-Time After Ignition (t) = varies until output is 202.5 kPa

Results*

Time after ignition	278 sec

*see spreadsheet on next page

Spreadsheet Calculations
FDT^s: 14_Compartment_Over_Pressure_Calculations.xls



CHAPTER 14. ESTIMATING PRESSURE RISE DUE TO A FIRE IN A CLOSED COMPARTMENT

Version 1805.0

The following calculations estimate the pressure rise in a compartment due to fire and combustion.
Parameters in YELLOW CELLS are Entered by the User.
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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	t	6.10 m
Compartment Length (l_c)	25.00	t	7.62 m
Compartment Height (h_c)	10.00	t	3.05 m
Fire Heat Release Rate (Q)	255.00	kW	
Time after Ignition (t)	278.00	sec	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K

Calculate

AMBIENT CONDITIONS

Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa
Specific Heat of Air at Constant Volume (c_v)	0.71	kJ/kg-K	

(Note: Values of c_v ranges from 0.71 to 0.85 kJ/kg-k)

Ambient Air Density (ρ_a)	1.18	kg/m^3

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

METHOD OF KARLSSON AND QUINTIERE

Reference: *Karlsson and Quintiere, Enclosure Fire Dynamics, 1999, Page 192*.

$(P - P_a) / P_a = Q\,t / (V\,\rho_a\,c_v\,T_a)$

Where P = compartment pressure due to fire and combustion (kPa)
P_a = initial atmospheric pressure (kPa)
Q = heat release rate of the fire (kW)
t = time after ignition (sec)
V = compartment volume (m^3)
ρ_a = ambient density (kg/m^3)
c_v = specific heat of air at constant volume (kJ/kg-K)
T_a = ambient air temperature (K)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where V = volume of the compartment (m^3)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)

V = 141.58 m^3 5000 ft^3

Pressure Rise in Compartment

$(P - P_a) / P_a = Q\,t / (V\,\rho_a\,c_v\,T_a)$

$(P-P_a)/P_a$ = 1.998 atm

Multiplying by the atmospheric pressure (P_a) = 101 kPa

Gives a pressure difference = 202.48 kPa 29.37 psi **Answer**

This example shows that in a very short time the pressure in a closed compartment rises to quite large value.

Most buildings have leaks of some sort. The above example indicates that even though a fire compartment may be closed, the pressure is very rapid and would presumably lead to sufficient leaks to prevent further pressure rise from occurring. We will use this conclusion when dealing with pressure rises in enclosures with small leaks.

NOTE

The above calculations are based on principles developed in the Enclosure Fire Dynamics. 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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CHAPTER 15. ESTIMATING THE PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

15.1 Objectives

This chapter has the following objectives:

- Define the nature and implications of an explosion.
- Explain the various causes, hazards, and effects of explosions.
- Explain how to calculate the energy released by an explosion.
- Explain how to calculate the pressure increase attributable to an explosion.

15.2 Introduction

In its most widely accepted sense, the term “explosion” means a bursting associated with a loud, sharp noise and an expanding pressure front, varying from a supersonic shock wave to a relatively mild wind. The term has also been extended to encompass chemical or physical/chemical events that produce explosions.

An explosion is defined as a sudden and violent release of high-pressure gages into the environment. The primary keyword in this definition is “rapid.” The release must be sufficiently fast so that energy contained in the high-pressure gas dissipates in a shock wave. The second key word is “high pressure,” which signifies that, at the instant of release, the gas pressure is above the pressure of the surroundings. Note that the basic definition is independent of the source or mechanism by which the high-pressure gas is produced (Senscal, 1997).

Despite this commonly accepted definition, the literature includes many other interrelations of the concept of an explosion:

- A rapid release of high-pressure gases into the environment (Cruice, 1991).
- A sudden conversion of potential energy (chemical or mechanical) into kinetic energy in the form of rapidly expanding gases (NFPA, 921).
- A physical reaction characterized by four elements: high-pressure gas; confinement or restriction of the pressure; rapid production or release of that pressure; and change or charge to the confining (restricting) structure, container, or vessel caused by the pressure release. The generation and violent escape of gases are the primary criteria of an explosion (NFPA 921).
- The noise or bang attributable to the sudden release of a strong pressure wave or blast wave, which relates to the basic meaning of the word, “sudden outburst” (Bodhurtha, 1980).
- An exothermic chemical process that when occurring at constant volume, gives rise to a sudden and significant pressure rise (Vervalin, 1985).

- In general scientific terms, an explosion is said to have occurred in the atmosphere if energy is released over a sufficiently small time and in a sufficiently small volume so as to generate a pressure wave of finite amplitude traveling away from the source (Baker et al., 1983). This energy may have originally been stored in the system in a variety of forms; these include nuclear, chemical, electrical, or pressure energy, for example. However, the release is not considered to be explosive unless it is rapid enough and concentrated enough to produce a pressure wave that one can hear. Even though many explosions damage their surroundings, it is not necessary that external damage be produced by the explosion. All that is necessary is that the explosion is capable of being heard.

While these definitions differ, they share the following characteristics of an explosion:

- release of high pressure gases
- rapid expansion of gases
- formation of a pressure wave or blast wave of sufficient intensity to be heard

The last of these characteristic is often favored by explosion investigators. The ability to be heard enables investigations to define whether an incident was an explosion, based on what happened and what the results were.

Explosions are often characterized by their primary means of generation (physical or chemical); this categorization includes the following types of explosions:

- Physical explosions are those caused when the high-pressure gas is generated only by mechanical means without any chemical change, as in the following types of explosions:
    - external heating of a tank resulting in increased internal pressure and resultant failure of the tank
    - sudden release of super-heated liquid which flash-evaporates, causing a rapid explosion
- Chemical explosions are those when the high-pressure gas is generated only by chemical reactions without any physical or chemical interaction, as in the following:
    - Combustion explosions are caused by rapid oxidation of combustion material, which results in an explosion of gases that triggers a pressure wave. Combustion explosions include the following types:
        - dust explosions
        - gas explosions
        - natural gas explosions
        - backdraft explosions
        - mists
    - Thermal explosions are a special class of chemical explosions where the heat released by the reaction of two or more chemical compounds results in a more rapid reaction rate that eventually results in an explosion. These types of explosions are a great concern in chemical processes.
    - Condensed phase explosions are those caused by rapid reactions of chemical components in the solid or liquid phase. This type of chemical explosion includes those resulting from high explosives or propellants (solid and liquid) used for missile fuel.

- Nuclear explosions are associated with the fission or fusion of matter.
- Detonations and deflagrations are often distinguished by the speed or rate of propagation of the combustion wave through the material. In a detonation, the flame or combustion wave propagates through the reactants at supersonic speeds on the order of 2,000 m/sec (6,562 ft/sec). By contrast, the rate of propagation in a deflagration is below the speed of sound in air at 20 °C (68 °F), which is approximately 330 m/sec (1,082 ft/sec). The fact that detonations propagate at supersonic speeds implies the existence of a shock wave, which is the reason that the reactions propagate so rapidly. (The shock wave compresses reactants, causing the reaction to occur faster.) The practical distinction between detonations and deflagrations also relates to the amount of damage caused. Specifically, the pressure attained during a detonation can be up to 20 atmospheres (284 psi). By contrast, the overpressure caused by the pressure in a typical deflagration wave is on the order of 1 atmosphere (14.70 psi) for C_2H_2 in air.

15.3 Explosion Hazard

The hazards associated with deflagration include catastrophic equipment failure, ejection of flame and unburned product (possibly hazardous in its own right) into the surroundings, possible secondary explosions leading to catastrophic facility damage, and personal injury. The following elements must exist *simultaneously* in order for a deflagration to occur:

- a flammable mixture consisting of a fuel and oxygen, usually from air, or other oxidant
- a means of ignition
- an enclosure

The term “flammable mixture” denotes that the fuel and oxygen components are intimately mixed and are each present at a concentration that falls within a flammable composition boundary characteristic of each system of fuel, oxygen, and inert material (inert gas or solid). Ignition of a flammable mixture occurs when a point source of sufficient energy achieves a temperature above the ignition temperature of the mixture. All incandescent sparks (e.g., mechanical, electrical, electrostatic) have sufficient temperature to cause ignition, but may lack sufficient energy to heat a minimal propagating mass to its ignition temperature. A hot process surface may have a temperature below that required for prompt ignition, but may have a large energy content. Dust deposits on such surfaces can be subjected to accelerated self-heating and eventual ignition.

Should ignition of a flammable mixture occur within an enclosure, regardless whether of the enclosure has ventilation points, the internal pressure will increase as necessary, to satisfy the non-steady-state material balance equation. The time needed to achieve the maximum deflagration pressure depends on size of the enclosure and the characteristics of the fuel, but generally can extend up to a few hundred milliseconds. Some venting of the expanding combustion gases occurs through normal process openings, but these are usually too small to prevent the development of destructive pressures.

15.4 Explosive Range

A certain quantity—neither too little nor too much—of flammable gas mixed with a certain quantity of air allows a mixture to become explosive and propagate the explosion flame. The lower and upper boundaries of this “explosive range” are known as the lower explosion limit (LEL) and the upper explosion limit (UEL), respectively[1]. When the quantity of flammable gas and/or air is either below or above these boundaries, the mixture is not explosive and will not propagate the explosion flame. At the LEL or UEL, the mixture will burn when ignited, causing an insignificant flame propagation. Between the two boundaries, there is a point at which flame propagation reaches its maximum.

15.5 Backdraft Explosion

Fires in oxygen-starved environments result in unburned fuel, “fuel vapor,” which is a complex mixture of combustion gases, vapors, and aerosols suspended in the smoke. If the gas layer is hot enough (i.e., at its ignition temperature) it may immediately ignite when the fuel-rich smoke layer mixes with air (thereby receiving adequate oxygen) when the smoke-filled compartment or building is vented.

By contrast, when the gas layer is relatively cool, particularly in a severely oxygen-restricted fire, the fuel vapor may not immediately ignite when the compartment or building is vented. Rather, in such instances the ignition of the fuel vapor may be delayed until fresh air is introduced, mixes, with the vapor, and makes its way back to the fire source. When this occurs, the flame itself becomes the ignition source, and the ignition delay results from the time required to mix the fuel-rich smoke layer with oxygen-rich fresh air. This phenomenon, known as a “backdraft explosion,” has the characteristics of a premixed fuel/air deflagration.

15.6 Smoke Explosion

It is also possible for a smoldering fire to produce sufficient unburned fuel and carbon monoxide to form a premixed combustible atmosphere. If the smoldering fire raises the temperature to the autoignition temperature of the mixture, the smoke/gas cloud will deflagrate causing a “smoke explosion.” Such explosions have been observed in smoldering fires involving polyurethane foams.

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[1] The terms “upper flammability limit” (UFL) and “lower flammability limit” (LFL) are also used to describe the flammable range of gases. For our purposes, they are synonymous with UEL and LEL respectively.

15.7 Unconfined and Confined Explosions

Explosions that occur in open air, known as “unconfined explosions,” are fundamentally different — and require different countermeasures — than “confined explosions,” which occur within some sort of containment. Confined explosions often occur in a process vessel or pipework, but may also occur in buildings. The explosion of a flammable mixture in a process vessel or pipework may be a detonation or a deflagration. The overpressure in a confined explosion is attributable to the expansion of the hot gases and may be exacerbated by the release of gases through an explosion vent (even a door or window) when the resulting turbulence produces a second pressure peak, as illustrated in Figure 15-1 (Harris, 1983).

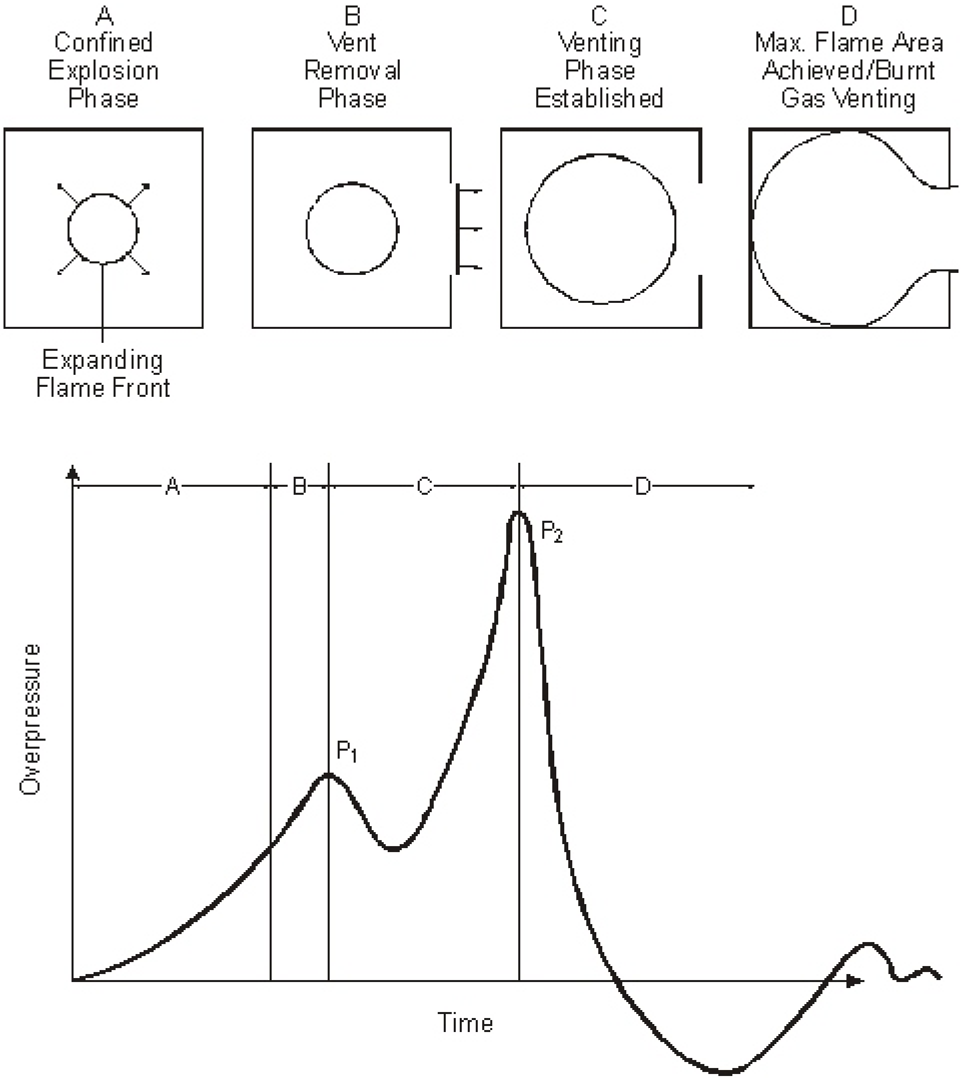


Figure 15-1 Pressure Peaks of an Explosion Inside a Building

Confined explosion usually will not cause an accidental release of gas in any quantity directly into the atmosphere. Rather, such explosions usually release gases within some form of such as compartment or building of an industrial plant. If a flammable mixture forms and is ignited under these contained conditions, a confined gas explosion will occur. Moreover, if a gas is accidentally released into the air, mixes with air and is ignited, the flame front travels through the mixture, propagating in a spherical geometry whenever possible rather than remaining stationary, as illustrated in Figure 15-2.

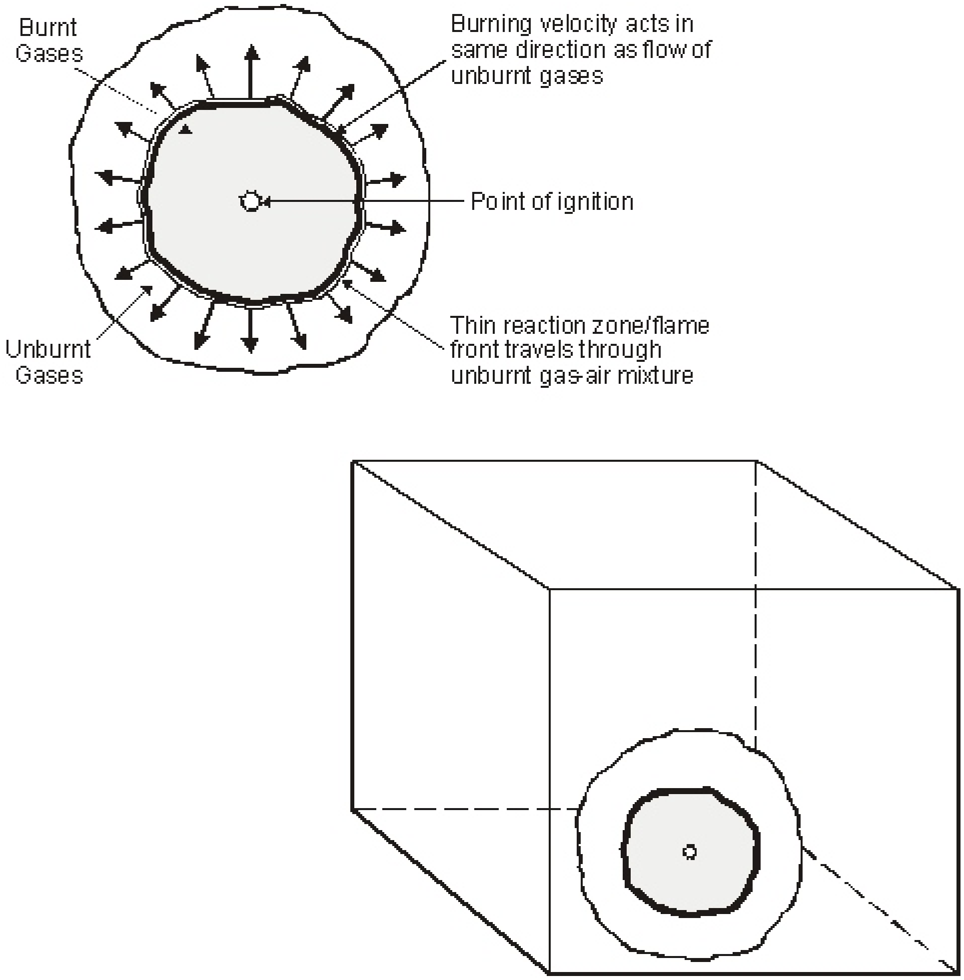


Figure 15-2 Propagation of Explosion Flame

15.8 Estimating the Effects of Explosions

When a firecracker or a stick of dynamite explodes, the violence and speed of the reactions taking place produce what is referred to as either a shock wave or a blast wave. Technically speaking, there is a difference between these two terms, but we will treat them rather interchangeably here. Either type of wave can be thought of as a thin shell of highly compressed air and/or hot gases that expands rapidly in all directions from the point at which the explosion is initiated. Such waves can move at velocities exceeding the speed of sound in air, and, therefore, are capable of producing sonic "booms," much like those associated with supersonic aircraft. This is how significant explosions produce a loud "bang."

The damage caused by a shock or blast wave striking an object or a person is a complex function of many factors, and it is well beyond the scope of this chapter to describe all of the complex interactions involved. Instead, we will simply refer to the wave as a rapidly expanding shell of compressed gases. We can then measure the strength of the wave in units of pressure (psi), and we can relate the effects of peak overpressure within the wave (i.e., the maximum pressure in the wave in excess of normal atmospheric pressure) to the level of property or personal injury that is likely to result.

Table 15-1 lists damage effects on people and property, which might be expected to result from explosions characterized by various peak overpressures (Clancey, 1972). It is important to note that peak overpressures in a shock or blast wave are highest near the source of the explosion and decrease rapidly with distance from the explosion site. Additionally, it must be noted that the extent of damage incurred is heavily influenced by the location of the blast relative to nearby reflecting surfaces.

Table 15-1. Estimated Damage Attributable to Explosive Overpressure
(Clancey, 1972)

Overpressure* (psig)	**Expected Damage**
0.03	Occasional breaking of large windows that are already under strain.
0.04	Glass failure caused by loud noises (143 dB) or sonic booms.
0.10	Breaking of small windows under strain.
0.15	Typical glass failure.
0.40	Some damage to house ceilings; 10% window glass breakage.
0.40	Limited minor structural damage.
0.50–1.0	Windows usually shattered; some damage to window frames.
0.7	Minor damage to house structures.
1.0	Houses made uninhabitable by partial demolition.
1.0–2.0	Failure and buckling of corrugated metal panels; housing wood panels are blown in.
1.0–8.0	Slight to serious injuries (e.g., skin lacerations from flying glass and other missiles).

Table 15-1. Estimated Damage Attributable to Explosive Overpressure (Clancey, 1972)

Overpressure* (psig)	**Expected Damage**
1.3	Slight distortion of the steel frames of clad buildings.
2.0	Partial collapse of walls and roofs of houses.
2.0–3.0	Shattering of non-reinforced concrete or cinder block walls.
2.3	Lower limit of serious structural damage.
2.4–12.2	Up to 90% eardrum rupture among exposed populations.
2.5	50% destruction of home brickwork.
3.0	Distortion of steel frame buildings; may pull away from their foundations.
3.0–4.0	Ruin of frameless steel panel buildings.
4.0	Rupture of cladding of light industrial buildings.
5.0	Snappy of wood utility poles.
5.0–7.0	Nearly complete destruction of houses.
7.0	Overturning of loaded train cars.
7.0-8.0	Shearing of flexure causes failure of 8–12-inch thick non-reinforced brick.
9.0	Demolition of loaded train cars.
10.0	Probable total destruction of building.
0.10	Up to 99% fatalities among exposed populations as a result of direct blast effects.

* These are the peak pressures formed (in excess of normal atmospheric pressure) by blast and shock waves. For SI units, 1 psi = 6.894757 kPa.

As shown in Table 15-1, an explosion may give rise to (1) blast damage, (2) thermal effects, (3) missile damage, (4) ground shock, (5) cratering, and (6) personal injury. Not all of these effects arise from every explosion. For example, an aerial blast may not cause a crater.

In addition to the personal injuries and property damage caused by direct exposure to peak overpressures, the blast wave also has the potential to cause indirect, secondary effects:

- Damage may result from missiles, fragments, and environmental debris set in motion by the explosion or by the heat generated.
- Damage may result from forcible movement of exposed people and their subsequent impact with ground surfaces, walls, or other stationary objects.

Many of the data on the effects of explosions come from studies of industrial and military explosives, but an increasing amount of information is becoming available from the investigation of process plant explosions.

15.8.1 Estimating Explosive Energy Release in a Confined Explosion

One typical explosion in an enclosure is caused by flammable gas leaking, which mixes with air in the enclosure and subsequently ignites to cause an explosion.

The energy released by expansion of compressed gas upon rupture of a pressurized enclosure may be estimated using the following equation (Zalosh, 1995):

$$E = \alpha \Delta H_C m_F \quad (15\text{-}1)$$

Where:

E = explosive energy released (kJ)
= yield (i.e., the fraction of available combustion energy participating in blast wave generation)
H_c = theoretical net heat of combustion (kJ/kg)
m_F = mass of flammable vapor release (kg)

The yield, , is typically in the range of 1 percent (0.01) for unconfined mass releases, to 100 percent (1.0) for confined vapor releases (Zalosh, 1995). Table 15-2 presents the theoretical net heat of combustion for flammable gases.

Table 15-2. Heat of Combustion, Ignition Temperature, and Adiabatic Flame Temperature* of Flammable Gases

Flammable Gas	**Heat of Combustion H_c (kJ/kg)**	**Ignition Temperature T_{ig} °C (°F)**	**Adiabatic Flame Temperature T_{ad} °C (°F)**
Acetylene	48,220	755 (1,391)	2,637(4,779)
Carbon monoxide (commercial)	10,100	765 (409)	2,387 (4,329)
Ethane	47,490	945 (1,733)	1,129 (2,064)
Ethylene	47,170	875 (1,607)	2,289 (4,152)
Hydrogen	130,800	670 (1,238)	2,252 (4,085)
Methane	50,030	1190 (2,174)	1,173 (2,143)
n-Butane	45,720	1025 (1,877)	1,339 (2,442)
n-Heptane	44,560	-	1,419 (2,586)
n-Octane	44,440	-	1,359 (2,478)
n-Pentane	44,980	-	1,291 (2,356)
Propane	46,360	1,010 (1,850)	1,281 (2,338)
Propylene	45,790	1,060 (1,940)	2,232 (4,050)

*Adiabatic flame temperature of lower limiting fuel/air mixture.

15.8.2 TNT Mass Equivalent Calculations

One of the most common methods used to estimate the effects of an explosion is to relate the exploding fuel to trinitrotoluene (TNT). This method converts the energy contained in the flammable cloud into an equivalent mass of TNT, primarily because blast effects of TNT have been extensively studied as a function of TNT weight and distance from the source. Hence, we can infer the blast effects of an explosion by relating an explosion to an "equivalent" explosion of TNT. To do so, we relate a given fuel type and quantity to an equivalent TNT charge weight, as follows (Zalosh, 1995):

$$W_{TNT} = \frac{E}{4500} \qquad (15\text{-}2)$$

Where:

W_{TNT} = weight of TNT (kg)

E = explosive energy released (kJ)

15.8.3 Blast Effects

Blast effects can also be related to the equivalent weight of TNT using by the relationship between the distance from the source, the charge weight, and the overpressure caused by the blast wave, including the reflected shock wave. Figure 15-3 (Zalosh, 1995) gives the relationship between overpressure and "scaled distance" (D_{sc}) (in English and metric units). Scaled distance is the distance at which the overpressure is calculated divided by the cube root of the TNT charge weight.

$$D_{SC} = \frac{D}{W_{TNT}^{\frac{1}{3}}} \qquad (15\text{-}3)$$

Where:

D_{sc} = scaled distance $[m/(kg)^{1/3}]$
D = distance at which the overpressure is calculated (m)
W_{TNT} = weight of TNT (kg)

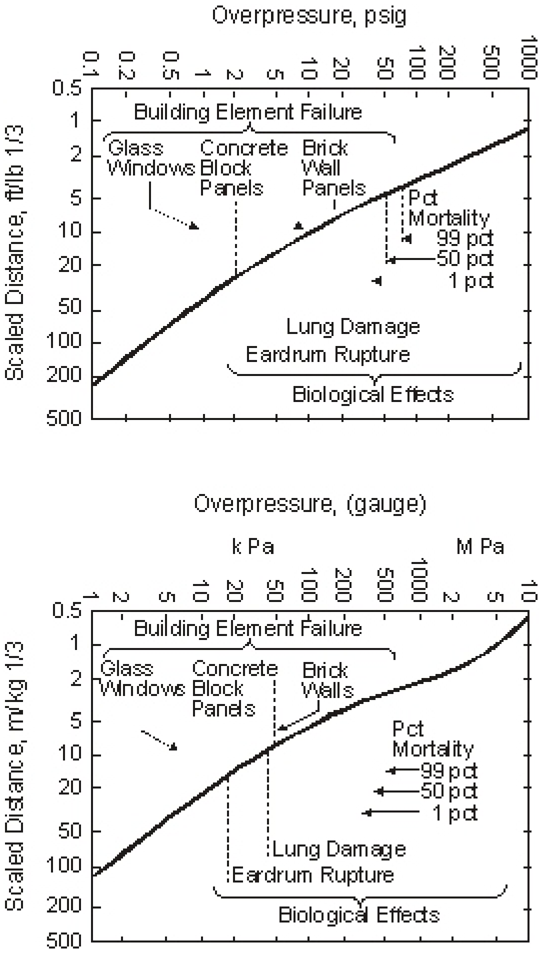


Figure 15-3 Ideal Blast Wave Overpressure vs. Scaled Distance
(Zalosh, 1995, © SFPE. With permission.)

15.9 Effects of Pressure on Humans and the Environments

Human beings are capable of withstanding relatively high dynamic pressures and considerably higher static pressures. When people are fatally injured as a result of blast waves, it is usually because of falling objects, rather than the pressure associated with the blast wave. Table 15-3 summarizes the pressure effects of blast waves on humans (Fischer et al., 1995), which also depend on the impulse of the blast wave. With the exception of smoke gas explosions, fires seldom reach pressures as high as those listed in Table 15-3. A maximum pressure of 8 bar is produced if a premixed gas-air mixture is ignited inside a building. Outside a building, similar explosion produce pressures of the same order of magnitude if the release results in an unconfined vapor cloud explosion (UVCE). Even higher pressures result if the release causes a detonation both inside and outside a building. However, detonations are very rare.

Usually, it is difficult to predict the pressures produced. In addition, the consequences for humans depend to a significant degree on whether something nearby can strike people in the vicinity of the explosion. Consequently, it is generally not worth the effort to find better values for pressure effects on humans. Similarly, pressure effects are usually limited to a small area, and the effect of pressure on the environment is seldom discussed.

Table 15-3. Pressure Effects on Humans

Pressure (kPa)	**Effect**
35 kPa	Limit for eardrum rupture
70 kPa	Limit for lung damage
100 kPa	50-percent eardrum rupture
180 kPa	1-percent mortality
210 kPa	10-percent mortality
260 kPa	50-percent mortality
300 kPa	90-percent mortality
350 kPa	99-percent mortality

15.10 Effects of Pressure on Components

Existing literature provides only limited data on the effects of pressure on components (such as machines); however, it appears that components are usually unaffected by pressure if they are solid and more sensitive to pressure variations if they contain cavities. When it comes to building elements such as windows, walls, and doors, the literature does provide acceptable data. Table 15-4 lists typical failure pressures of such elements (Harris, 1983).

Table 15-4. Typical Failure Pressures of Some Building Elements

Element	**Typical Failure Pressure (kPa)**
Glass windows	2–7
Room doors	2–3
Light partition walls	2–5
50-mm-thick breeze block walls	4–5
Unrestrained brick walls	7–15

15.11 Estimating the Pressure Increase Attributable to a Confined Explosion

The combustion process raises the temperature of a gaseous system and that, in turn, increases the pressure of the system by expanding the gases. The "ideal gas law" quantifies the effects, as follows:

$$P_1T_1 = P_2T_2 \qquad (15\text{-}4)$$

Where P_1T_1 and P_2T_2 represent the pressure and temperature at state 1 and state 2, respectively, in a constant volume system.

The pressure increase caused by the expansion of the gases is determined by the following equation:

$$P_2 = P_1 \frac{T_1}{T_2} \qquad (15\text{-}5)$$

Assuming that the entire confining enclosure is filled with a gas/air mixture, the maximum pressure inside the enclosure at the end of combustion (P_{max}) is given by the following equation:

$$\frac{P_{max}}{P_{amb}} = \frac{T_{ad}}{T_{amb}} \qquad (15\text{-}6)$$

and

$$P_{max} = \left(\frac{T_{ad}}{T_{amb}} \right) P_{amb} \qquad (15\text{-}7)$$

Where:

P_{max} = maximum pressure at end of combustion (kPa)
P_{amb} = initial ambient atmospheric pressure prior to ignition (kPa)
T_{ad} = adiabatic flame temperature of burned gas (K)
T_{amb} = initial ambient temperature gas/air mixture (K)

Remember that absolute temperature (K or R) must be used in these equations. The adiabatic flame temperature of the burned gas should be approximately the values shown for the given flammable gas(es) in Table 15-2.

15.12 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations:

(1) The method assumes point source blast wave energy correlation (i.e., TNT equivalent energy).

(2) The ideal point source blast wave correlations cannot be valid within or near the flammable vapor cloud.

(3) Flammable gases and vapors are mixed with air (or some other oxidant) in proportions between the lower and upper flammable limits.

(4) It is important to recognize that practical applications of flammability/exposibility data for explosion hazard evaluation should account for nonuniform or stratified vapor-air mixtures.

15.13 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) fuel type (material)

(2) mass of flammable vapor (lb)

(3) ambient temperature (°F)

(4) ambient pressure (psi)

15.14 Cautions

(1) Use (15_Explosion_Calculations.xls) spreadsheet on the CD-ROM for pressure increase and explosive energy release calculations associated with explosions.

(2) Make sure to enter the input parameters in the correct units.

15.15 Summary

This chapter discusses methods of calculating the pressure increase and explosive energy release associated with explosions. Within that content, an explosion is defined as a sudden and violent release of high-pressure gases into the environment. The violence of the explosion depends on the rate at which the energy of the high-pressure gases is released. The energy stored in a car tire, for example, is capable of causing an explosive burst, but it can also be dissipated by gradual release. In general, an explosion can release any of the basic types of energy, including (1) physical energy (2) chemical energy.

Physical energy may take such forms as pressure energy in gases, strain energy in metals, or electrical energy. Examples of the violent release of physical energy include the explosion of a vessel as a result of high gas pressure and the sudden rupture of a vessel as a result of brittle fracture. Another physical form is thermal energy, which generally play an important role in creating the conditions for an explosion, rather than as a source of energy for the explosion itself. In particular, superheating a liquid under pressure causes flashing of the liquid if it is let down to atmospheric pressure.

Chemical energy is derived from a chemical reaction. Examples of the violent release of chemical energy are explosions of a vessel as a result of the combustion of flammable gas. Chemical explosions are either (1) uniform explosions or (2) propagating explosions. An explosion in a vessel tends to be a uniform explosion, while an explosion in a long pipe produces a propagating explosion.

15.16 References

Baker, W.E., et al., *Explosion Hazards and Evaluation*, Amsterdam Elservier Science Publishing Company, 1983.

Bodhurtha, F.T., *Industrial Explosion Prevention and Protection*, McGraw-Hill Book Company, New York, 1980.

Clancey, V.J., “Diagnostic Features of Explosion Damage,” Sixth International Meeting of Forensic Science, Edinburgh, England, 1972.

Cruice, W.J., “Explosions,” Section 1, Chapter 5, *NFPA Fire Protection Handbook*, 17th Edition, National Fire Protection Association, Quincy, Massachusetts, 1991.

Fischer, S., et al., *“Vådautsläpp av brandfarliga och giftiga gaser och vätskor”* (in Swedish), FOA-D-95-00099-4.9-SE, Försvarets Forskningsanstalt Stockholm, 1995.

Harris , R.J., *The Investigation and Control of Gas Explosions in Building and Heating Plant*, British Gas, 1983.

NFPA 921, “Fire and Explosion Investigations,” 1992 Edition, National Fire Protection Association, Quincy, Massachusetts.

Senecal, J.A., “Explosion Prevention and Protection,” Section 4, Chapter 14, *NFPA Fire Protection Handbook*, 18th Edition, National Fire Protection Association, Quincy, Massachusetts, 1997.

Vervalin, C.H., Editor, *Fire Protection Manual for Hydrocarbon Processing Plants*, Volume 1, 3rd Edition, Gulf Publishing Company, Houston, Taxes, 1985.

Zalosh, R.G., “Explosion Protection,” Section 3, Chapter 16, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

15.17 Additional Readings

Fardis, M.N., A. Nacar, and M.A. Delichatsios, “R/C Containment Safety Under Hydrogen Detonation,” *Journal of Structural Engineering*, Volume 109, pp. 2511–2527, 1983.

Handbook of Chemical Hazard Analysis Procedures, Federal Emergency Management Agency (FEMA), U.S. Department of Transportation (DOT), and U.S. Environmental Protection Agency (EPA).

Lees, F.P., *Loss Prevention in the Process Industries, Hazard Identification, Assessment and Control*, Volume, 1, Butterworths-Heinnemann, London and Boston, 1980.

15.18 Problems

Example Problem 15.18-1

Problem Statement
In an NPP, a liquid propane gas (LPG)-driven forklift is used to un load materials from an upcoming outage. Mechanical failure could result in the release of LPG in the area. The maximum fuel capacity of the forklift is 10 gallons. Calculate pressure rise, energy released by expanding LPG, and equivalent TNT charge weight. Assume that the mass of the vapor released is 48 lb.

Solution

Purpose:
(1) Estimate pressure rise, energy released, and TNT equivalent.

Assumptions:
(1) The atmospheric pressure is 14.7 psi.
(2) Ambient air temperature is 77 °F.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 15_Explosion_Calculations.xls

FDT^s Input Parameters:
-Select Fuel Type = Propane
-Percent yield = 100%
-Mass of flammable vapor release = 48 lb

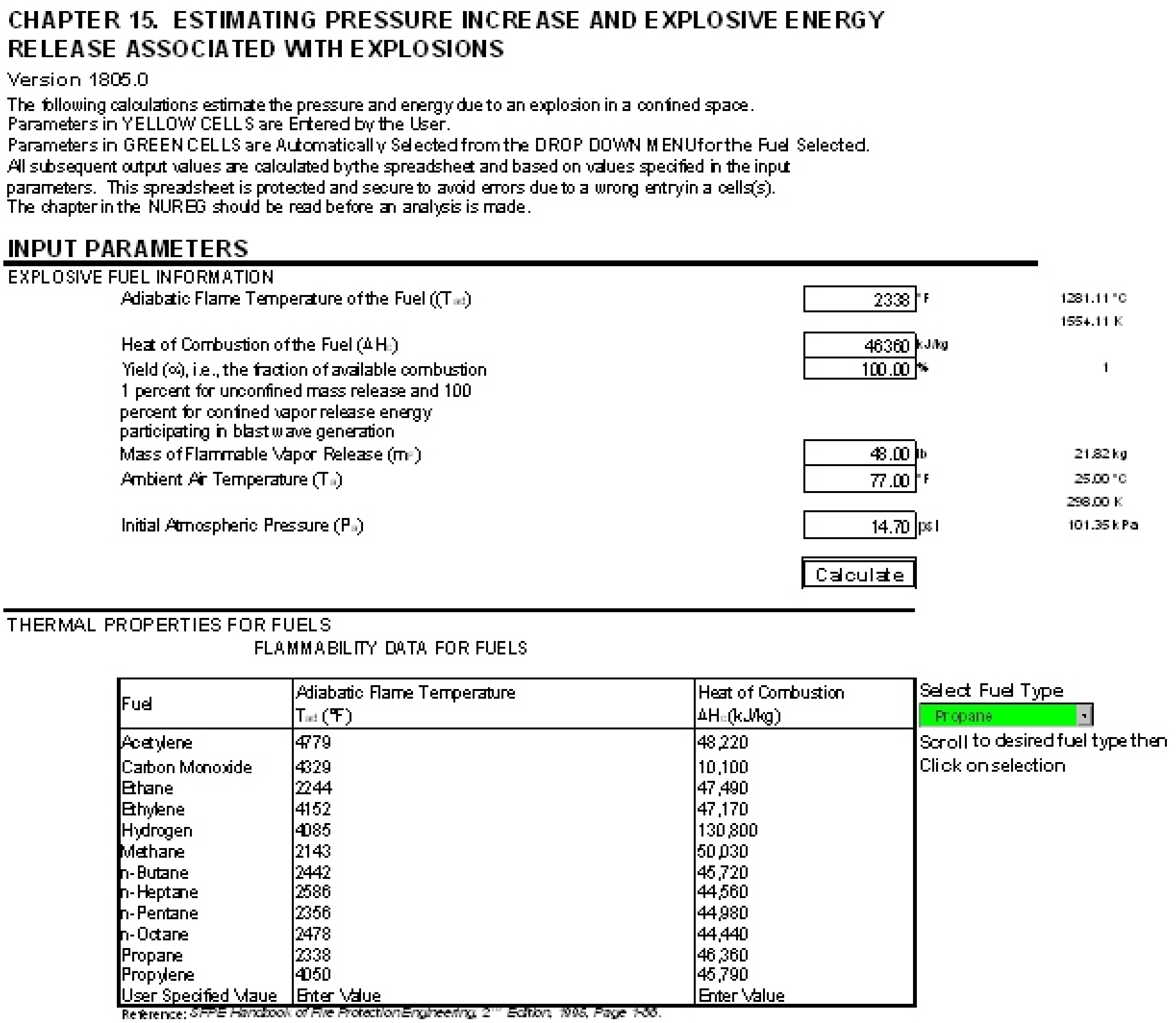
Results*

Pressure Rise	528.6 kPa (76.7 psi)
Energy Released	1,011,491 kJ (957,983 Btu)
Equivalent TNT	225 kg (496 lb)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 15_Explosion_Calculations.xls



CHAPTER 15. ESTIMATING PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

Version 1805.0

The following calculations estimate the pressure and energy due to an explosion in a confined space.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel 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 cells(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

EXPLOSIVE FUEL INFORMATION

Adiabatic Flame Temperature of the Fuel ((T_{ad})	2338	°F	1281.11 °C 1554.11 K
Heat of Combustion of the Fuel (ΔH_c)	46360	kJ/kg	
Yield (∝), i.e., the fraction of available combustion 1 percent for unconfined mass release and 100 percent for confined vapor release energy participating in blast wave generation	100.00	%	1
Mass of Flammable Vapor Release (m_F)	48.00	lb	21.82 kg
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa

THERMAL PROPERTIES FOR FUELS

FLAMMABILITY DATA FOR FUELS

Fuel	Adiabatic Flame Temperature T_{ad} (°F)	Heat of Combustion ΔH_c (kJ/kg)
Acetylene	4779	48,220
Carbon Monoxide	4329	10,100
Ethane	2244	47,490
Ethylene	4152	47,170
Hydrogen	4085	130,800
Methane	2143	50,030
n-Butane	2442	45,720
n-Heptane	2586	44,560
n-Pentane	2356	44,980
n-Octane	2478	44,440
Propane	2338	46,360
Propylene	4050	45,790
User Specified Vlaue	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 1-88.*

Select Fuel Type

Scroll to desired fuel type then Click on selection

METHOD OF ZALOSH

Reference: *SFPE Handbook of Fire Protection Engineering*, 2^{nd} *Edition*, *1995, Page 3-312.*

Pressure Rise from an Confined Explosion

$(P_{max})/P_a = (T_{ad}/T_a)$

Where P_{max} = maximum pressure developed at completion of combustion (kPa)

P_a = initial atmospheric pressure (kPa)

T_{ad} = adiabatic flame temperature (K)

T_a = ambient temperature (K)

$P_{max} = (T_{ad}/T_a)\ P_a$

P_{max} =	528.57 kPa	76.66 psi	**Answer**

Blast Wave Energy Calculation

$E = \alpha\ \Delta H_c\ m_F$

Where E = blast wave energy (kJ) [E is the Trinitrotoluene (TNT) equivalent energy]

α = yield (α is the fraction of available combustion energy participating in blast wave generation)

ΔH_c = heat of combustion (kJ/kg)

m_F = mass of flammable vapor release (kg)

E =	1011490.91 kJ	957983.04 Btu	**Answer**

TNT Mass Equivalent Calculation

$W_{TNT} = E/4500$

Where W_{TNT} = weight of TNT (kg)

E = explosive energy release (kJ)

W_{TNT} =	224.78 kg	495.55 lb	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2^{nd} Edition, 1995.

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.

UNITED STATES NUCLEAR REGULATORY COMMISSION

Example Problem 15.18-2

Problem Statement

An investigator is performing a review of an accident at a facility. The report states that a pipe fitter accidently left his acetylene “B” tank on which leaked its contents and caused the explosion. Assuming the tank was full (40 ft^3 of gas at atmospheric pressure), how large could the explosion have been?

Solution

Purpose:
(1) Estimate energy released, and TNT equivalent.

Assumptions:
(1) The atmospheric pressure is 14.7 psi.
(2) Ambient air temperature is 77 °F.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 15_Explosion_Calculations.xls

FDT^s Input Parameters:
-Select Fuel Type = Acetylene
-Percent yield = 100%
-Mass of vapor release = volume x density (from manufacture’s Web site)
40 ft^3 x .0677 lb/ft^3 = 2.7 lb

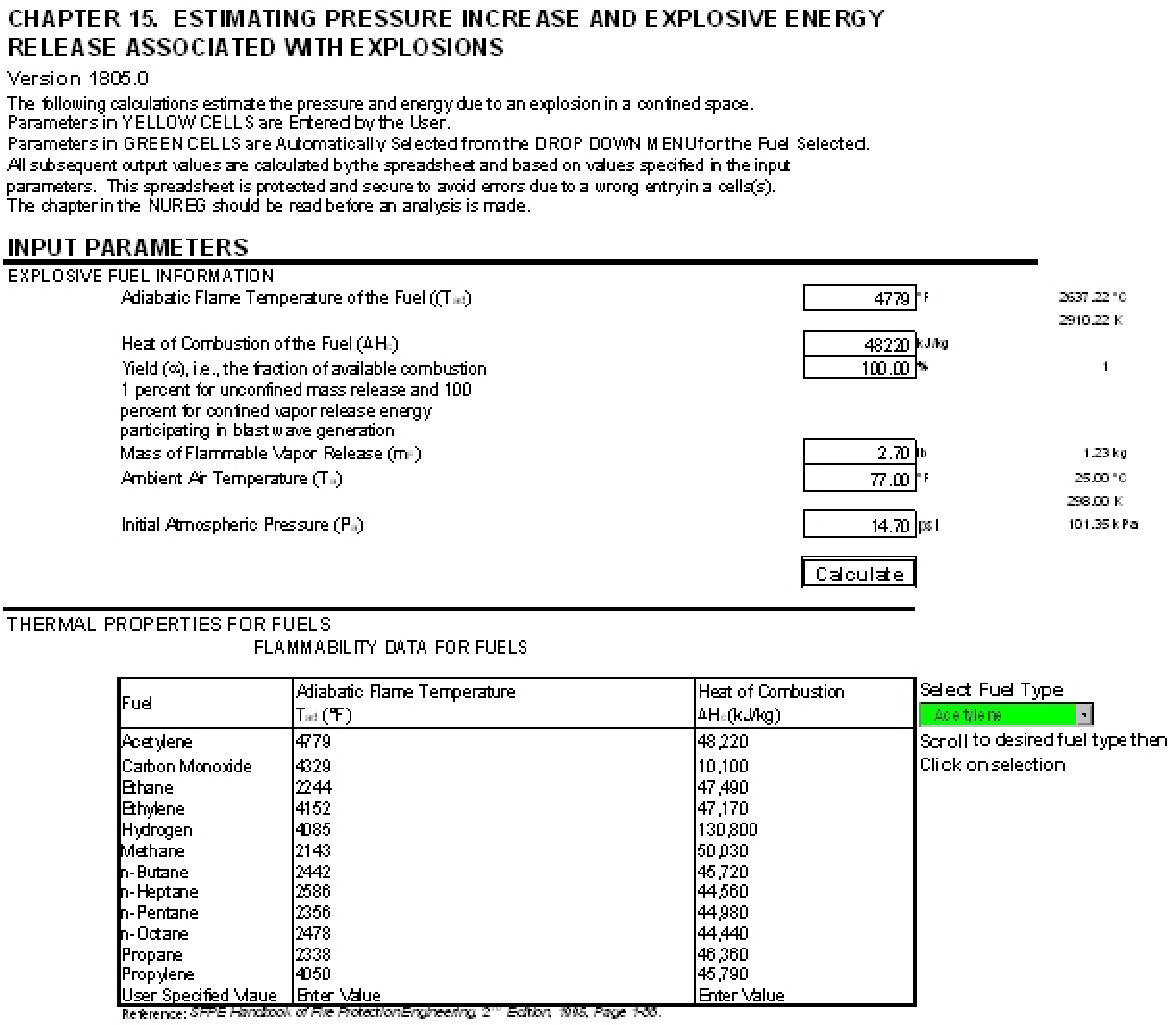
Results*

Energy Released	59,179 kJ (56,049 Btu)
Equivalent TNT	13.2 kg (29.0 lb)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 15_Explosion_Calculations.xls



CHAPTER 15. ESTIMATING PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

Version 1805.0

The following calculations estimate the pressure and energy due to an explosion in a confined space.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel 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

EXPLOSIVE FUEL INFORMATION

Adiabatic Flame Temperature of the Fuel ((T$_{ad}$)	4779	°F	2637.22 °C 2910.22 K
Heat of Combustion of the Fuel (ΔH$_c$)	48220	kJ/kg	
Yield (α), i.e., the fraction of available combustion 1 percent for unconfined mass release and 100 percent for confined vapor release energy participating in blast wave generation	100.00	%	1
Mass of Flammable Vapor Release (m$_F$)	2.70	lb	1.23 kg
Ambient Air Temperature (T$_a$)	77.00	°F	25.00 °C 298.00 K
Initial Atmospheric Pressure (P$_a$)	14.70	psi	101.35 kPa

Calculate

THERMAL PROPERTIES FOR FUELS

FLAMMABILITY DATA FOR FUELS

Fuel	Adiabatic Flame Temperature T$_{ad}$ (°F)	Heat of Combustion ΔH$_c$ (kJ/kg)
Acetylene	4779	48,220
Carbon Monoxide	4329	10,100
Ethane	2244	47,490
Ethylene	4152	47,170
Hydrogen	4085	130,800
Methane	2143	50,030
n-Butane	2442	45,720
n-Heptane	2586	44,560
n-Pentane	2356	44,980
n-Octane	2478	44,440
Propane	2338	46,360
Propylene	4050	45,790
User Specified Viaue	Enter Value	Enter Value

Select Fuel Type

Acetylene

Scroll to desired fuel type then Click on selection

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 1-88.*

METHOD OF ZALOSH

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-312.*

Pressure Rise from an Confined Explosion

$(P_{max})/P_a = (T_{ad}/T_a)$

Where P_{max} = maximum pressure developed at completion of combustion (kPa)

P_a = initial atmospheric pressure (kPa)

T_{ad} = adiabatic flame temperature (K)

T_a = ambient temperature (K)

$P_{max} = (T_{ad}/T_a)\ P_a$

P_{max} = 989.80 kPa 143.56 psi **Answer**

Blast Wave Energy Calculation

$E = \alpha\ \Delta H_c\ m_F$

Where E = blast wave energy (kJ) [E is the Trinitrotoluene (TNT) equivalent energy]

α = yield (α is the fraction of available combustion energy participating in blast wave generation)

ΔH_c = heat of combustion (kJ/kg)

m_F = mass of flammable vapor release (kg)

E = 59179.09 kJ 56048.52 Btu **Answer**

TNT Mass Equivalent Calculation

$W_{TNT} = E/4500$

Where W_{TNT} = weight of TNT (kg)

E = explosive energy release (kJ)

W_{TNT} = 13.15 kg 28.99 lb **Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.

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 15.18-3

Problem Statement
Which has a larger TNT mass equivalent: 10 lb (mass vapor) of acetylene or 5 lb (mass vapor) of hydrogen?

Solution

Purpose:
(1) Estimate TNT equivalent.

Assumptions:
(1) The atmospheric pressure is 14.7 psi.
(2) Ambient air temperature is 77 °F.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 15_Explosion_Calculations.xls

FDT^s Input Parameters:
-Select Fuel Type = Acetylene
-Percent yield = 100%
-Mass of flammable vapor release = 10 lb
-Select Fuel Type = Hydrogen
-Percent yield = 100%
-Mass of flammable vapor release = 5 lb

Results*

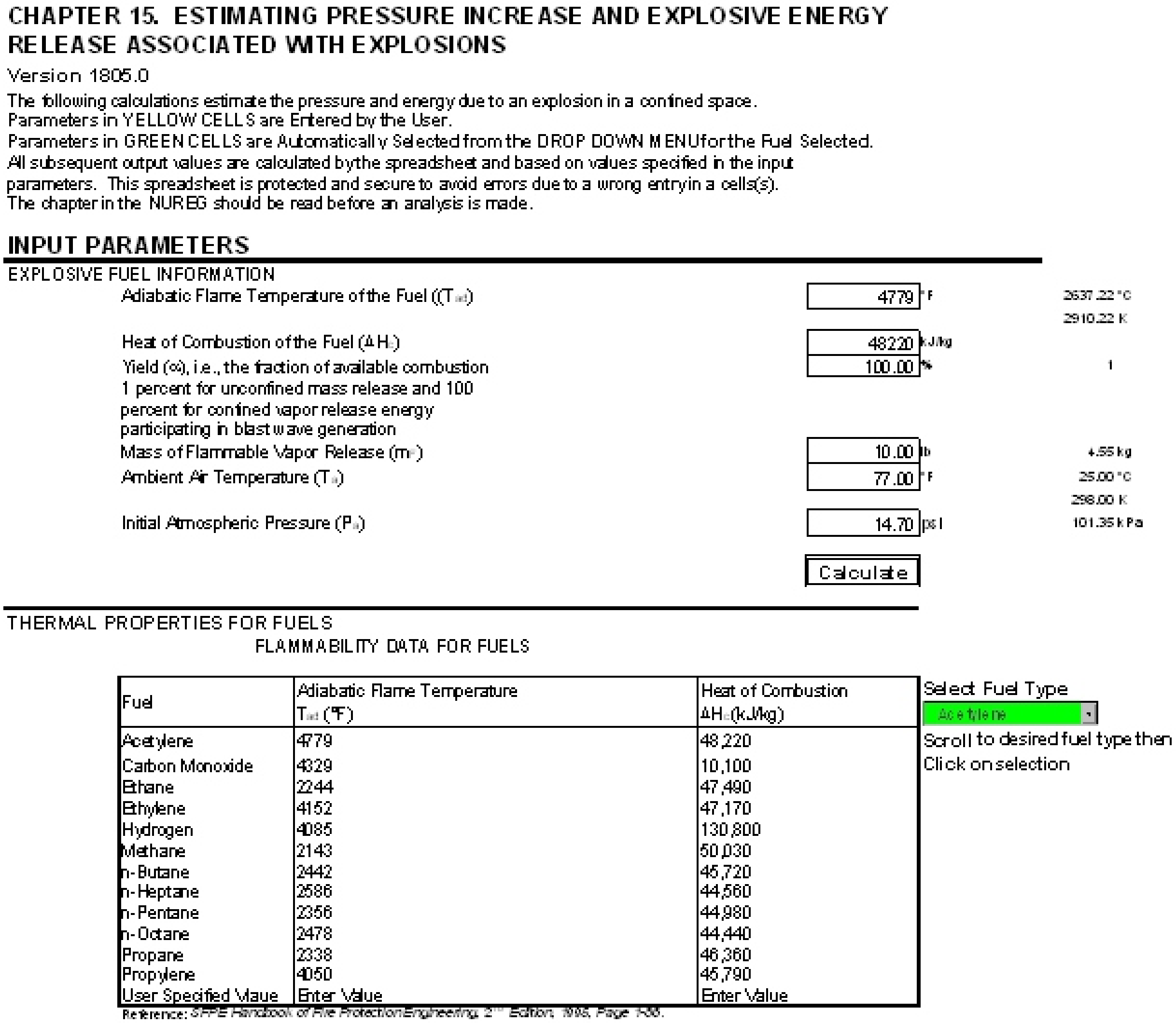
	Acetylene	Hydrogen
Equivalent TNT	48.7 kg (107 lb)	66.0 kg (146 lb)

*see spreadsheet on next page

Therefore, 5 lb of hydrogen produces more explosive force than 10 lb of acetylene.

Spreadsheet Calculations

(a) FDT^s: 15_Explosion_Calculations.xls (Acetylene)



CHAPTER 15. ESTIMATING PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

Version 1805.0

The following calculations estimate the pressure and energy due to an explosion in a confined space.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

EXPLOSIVE FUEL INFORMATION

Adiabatic Flame Temperature of the Fuel ((T_{ad})	4779	°F	2637.22 °C 2910.22 K
Heat of Combustion of the Fuel (ΔH_c)	48220	kJ/kg	
Yield (α), i.e., the fraction of available combustion 1 percent for unconfined mass release and 100 percent for confined vapor release energy participating in blast wave generation	100.00	%	1
Mass of Flammable Vapor Release (m_F)	10.00	lb	4.55 kg
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa

THERMAL PROPERTIES FOR FUELS

FLAMMABILITY DATA FOR FUELS

Fuel	Adiabatic Flame Temperature T_{ad} (°F)	Heat of Combustion ΔH_c (kJ/kg)
Acetylene	4779	48,220
Carbon Monoxide	4329	10,100
Ethane	2244	47,490
Ethylene	4152	47,170
Hydrogen	4085	130,800
Methane	2143	50,030
n-Butane	2442	45,720
n-Heptane	2586	44,560
n-Pentane	2356	44,980
n-Octane	2478	44,440
Propane	2338	46,360
Propylene	4050	45,790
User Specified Viaue	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 2^{nd} Edition, 1995, Page 1-88.*

Select Fuel Type

Scroll to desired fuel type then Click on selection

METHOD OF ZALOSH

Reference: SFPE Handbook of Fire Protection Engineering, 2^{nd} Edition, 1995, Page 3-312.

Pressure Rise from an Confined Explosion

$(P_{max})/P_a = (T_{ad}/T_a)$

Where P_{max} = maximum pressure developed at completion of combustion (kPa)

P_a = initial atmospheric pressure (kPa)

T_{ad} = adiabatic flame temperature (K)

T_a = ambient temperature (K)

$P_{max} = (T_{ad}/T_a)\ P_a$

P_{max} = 989.80 kPa 143.56 psi **Answer**

Blast Wave Energy Calculation

$E = \alpha\ \Delta H_c\ m_F$

Where E = blast wave energy (kJ) [E is the Trinitrotoluene (TNT) equivalent energy]

α = yield (α is the fraction of available combustion energy participating in blast wave generation)

ΔH_c = heat of combustion (kJ/kg)

m_F = mass of flammable vapor release (kg)

E = 219181.82 kJ 207587.10 Btu **Answer**

TNT Mass Equivalent Calculation

$W_{TNT} = E/4500$

Where W_{TNT} = weight of TNT (kg)

E = explosive energy release (kJ)

W_{TNT} = 48.71 kg 107.38 lb **Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2^{nd} Edition, 1995.

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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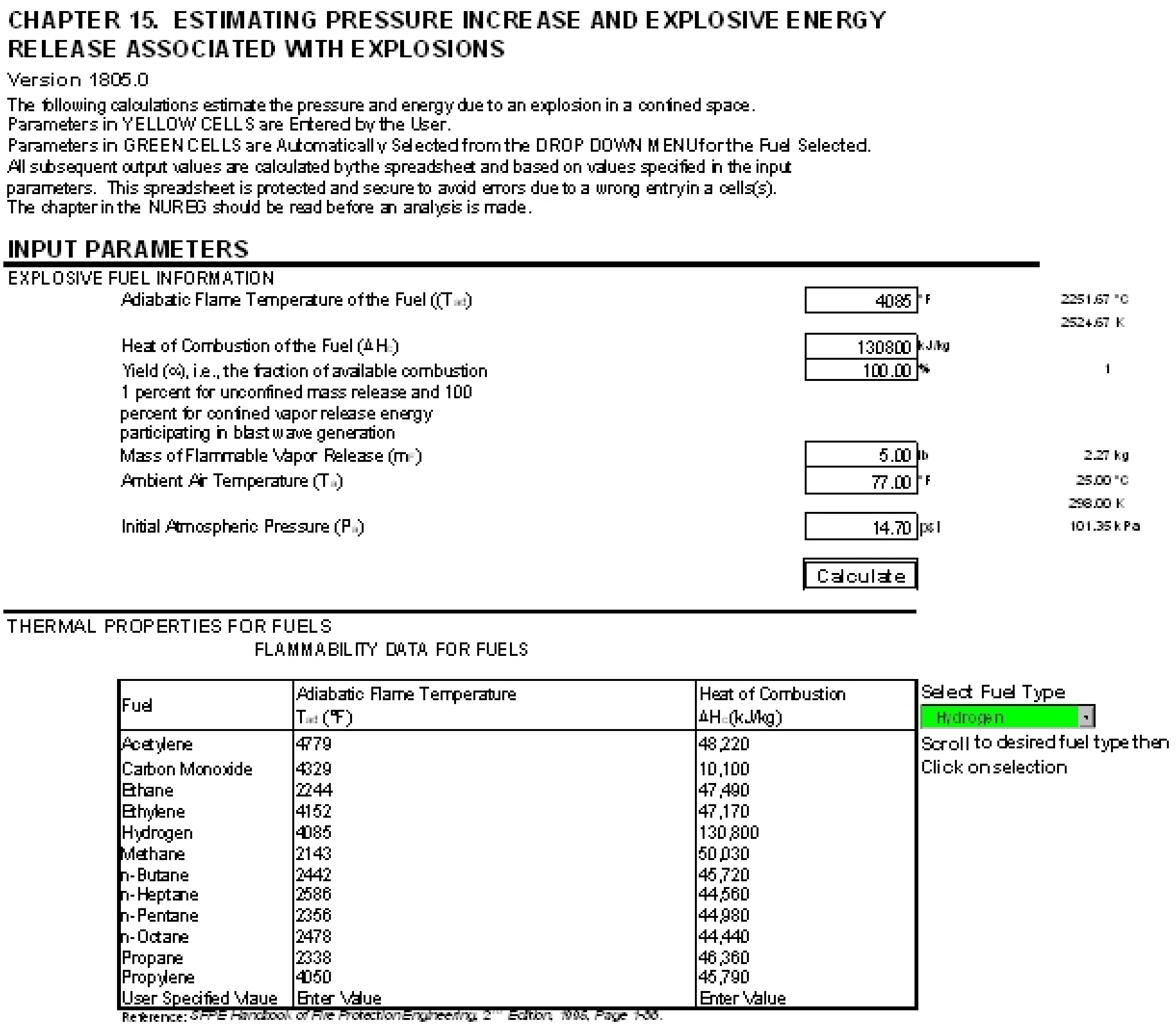
(B) FDT^s: 15_Explosion_Calculations.xls (Hydrogen)



CHAPTER 15. ESTIMATING PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

Version 1805.0

The following calculations estimate the pressure and energy due to an explosion in a confined space.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel 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 cells(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

EXPLOSIVE FUEL INFORMATION

Adiabatic Flame Temperature of the Fuel ((T_{ad}))	4085	°F	2251.67 °C 2524.67 K
Heat of Combustion of the Fuel (ΔH_c)	130800	kJ/kg	
Yield (α), i.e., the fraction of available combustion 1 percent for unconfined mass release and 100 percent for confined vapor release energy participating in blast wave generation	100.00	%	1
Mass of Flammable Vapor Release (m_F)	5.00	lb	2.27 kg
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa

Calculate

THERMAL PROPERTIES FOR FUELS

FLAMMABILITY DATA FOR FUELS

Fuel	Adiabatic Flame Temperature T_{ad} (°F)	Heat of Combustion ΔH_c (kJ/kg)
Acetylene	4779	48,220
Carbon Monoxide	4329	10,100
Ethane	2244	47,490
Ethylene	4152	47,170
Hydrogen	4085	130,800
Methane	2143	50,030
n-Butane	2442	45,720
n-Heptane	2586	44,560
n-Pentane	2356	44,980
n-Octane	2478	44,440
Propane	2338	46,360
Propylene	4050	45,790
User Specified Vlaue	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 2^{nd} Edition, 1995, Page 1-88.*

Select Fuel Type

Hydrogen

Scroll to desired fuel type then Click on selection

METHOD OF ZALOSH

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-312.*

Pressure Rise from an Confined Explosion

$(P_{max})/P_a = (T_{ad}/T_a)$

Where P_{max} = maximum pressure developed at completion of combustion (kPa)

P_a = initial atmospheric pressure (kPa)

T_{ad} = adiabatic flame temperature (K)

T_a = ambient temperature (K)

$P_{max} = (T_{ad}/T_a)\ P_a$

P_{max} =	858.67 kPa	124.54 psi	**Answer**

Blast Wave Energy Calculation

$E = \alpha\ \Delta H_c\ m_F$

Where E = blast wave energy (kJ) [E is the Trinitrotoluene (TNT) equivalent energy]

α = yield (α is the fraction of available combustion energy participating in blast wave generation)

ΔH_c = heat of combustion (kJ/kg)

m_F = mass of flammable vapor release (kg)

E =	297272.73 kJ	281547.00 Btu	**Answer**

TNT Mass Equivalent Calculation

$W_{TNT} = E/4500$

Where W_{TNT} = weight of TNT (kg)

E = explosive energy release (kJ)

W_{TNT} =	66.06 kg	145.64 lb	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.

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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CHAPTER 16. CALCULATING THE RATE OF HYDROGEN GAS GENERATION IN BATTERY ROOMS

16.1 Objectives

This chapter has the following objectives:

- Explain how hydrogen gas is generated in a battery room.
- Describe the conditions under which hydrogen gas will ignite.
- Describe possible ignition sources in a battery room.
- Explain methods of controlling the combustion of hydrogen gas.
- Describe how to estimate hydrogen gas generation rates.

16.2 Introduction

Battery rooms in nuclear power plants (NPPs) represent a potential problem area because of the generation of hydrogen gas. An NPP is typically equipped with large banks of 250-V dc and 125-V dc battery systems (NUREG/CR-2726). The 250-V dc system consists of two banks of 120 lead-calcium (lead-acid) storage cells, and the 125-V dc system typically contains four banks of 60 cells. Each bank is mounted in two rows of battery racks and located in its own battery room.

During operation, as the batteries change chemical energy to electrical energy, the sulfuric acid content of the electrolyte becomes depleted. Therefore, the batteries must be recharged if they are to be used continuously. This is done by connecting a dc charging source that enables current to flow through the battery in the direction opposite of its normal flow, thereby driving the acid back into the electrolyte. However, the byproducts of this charging process, or electrolysis, can present a safety issue. As a cell becomes nearly charged, the charging current becomes greater than that necessary to force the remaining amount of sulfuric acid back into the electrolyte. This results in ionization of the water in the electrolyte liberates hydrogen gas at the positive plate. The maximum rate of formation is 0.42×10^{-3} m^3 (0.42 liter) of hydrogen and 0.21×10^{-3} m^3 (0.21 liter) of oxygen per ampere-hour overcharge at standard temperature and pressure. The gas mixture is explosive when the hydrogen concentration in air exceeds 4.1-percent by volume.

Although the release of this gas is undesirable, the process is necessary to develop a full charge in the cell. Consequently, NPPs must take precautions to prevent explosions from ignition of the flammable gas mixture of hydrogen and oxygen formed during overcharging of lead-acid cells. NPPs employ several methods to reduce the risk associated with high hydrogen concentrations. Regardless of the method used, proper implementation requires an accurate measurement of the hydrogen concentration. A variety of hydrogen detectors are available for use in NPPs. A standard practice is to set hydrogen detection devices to activate at 2.0–2.5-percent by volume of the lower explosive limit (LEL).

16.3 Combustion of Hydrogen Gas

Hydrogen gas has an extremely wide flammability range and the highest burning velocity of any gas. Its ignition temperature is reasonably high [500 °C (932 °F)], but its ignition energy is very low. Because hydrogen contains no carbon, it burns with a nonluminous flame, which is often invisible in daylight. At ordinary temperatures, hydrogen is very light, weighing only about $^1/_{15}$ as much as air.

Combustion of hydrogen according to the reaction—

$$2H_2 + O_2 \text{ ---------->} \; 2H_2O + \text{Energy (heat)}$$

results in a release of about 57.8 kcal/g-mole (5.2×10^4 Btu/lb-mole) of hydrogen burned (NUREG/CR-6042). For a flammable gas mixture, the flammability limits are defined as the limiting concentrations of fuel, at a given temperature and pressure, in which a flame can propagate indefinitely. Limits for upward propagation of flames are wider than those for downward propagation. Limits for horizontal propagation are between those for upward and downward propagation.

The lower flammability limit (LFL) is the minimum concentration of hydrogen required to propagate a flame, while the upper flammability limit (UFL) is the maximum concentration. At the LFL, the hydrogen is in short supply and the oxygen (air) is present in excess. At the UFL for hydrogen in air, the oxygen (air) is in short supply, about 5-percent oxygen by volume. In air at standard temperature and pressure (25 °C, 1 atm), and 100-percent relative humidity, the LFL for hydrogen combustion is 4.1-percent hydrogen concentration by volume. Table 16-1 indicates the approximate hydrogen concentrations required for combustibility in air (NUREG/CR-6042).

Table 16-1. Hydrogen Flammability Limits in Air at Room Temperature

Possible Reaction	**Lower Flammability Limit Volume Percent of Hydrogen**	**Upper Flammability Limit Volume Percent of Hydrogen**
Upward propagation	4.1	74
Horizontal propagation	6.0	74
Downward propagation	9.0	74

Figure 16-1 shows the flammability limits of hydrogen with the addition of excess carbon dioxide and nitrogen (diluents). Note that with 75-percent additional nitrogen, the atmosphere is inert. This corresponds to 5-percent oxygen at the limit of the flammable region, a value very close to that of the UFL for hydrogen air combustion. Similarly, the atmosphere is inert when the carbon dioxide concentration is 60-percent or above, corresponding to 8-percent oxygen or less. The larger specific heat of carbon dioxide reduces the flame temperature and flame velocity; hence, carbon dioxide suppresses flammability more than nitrogen. By contrast, it requires about 60-percent steam to inert a hydrogen-air-steam mixture. Figure 16-2 indicates the regions of flammability of hydrogen-air-steam mixtures (Shapiro and Moffette, 1957).

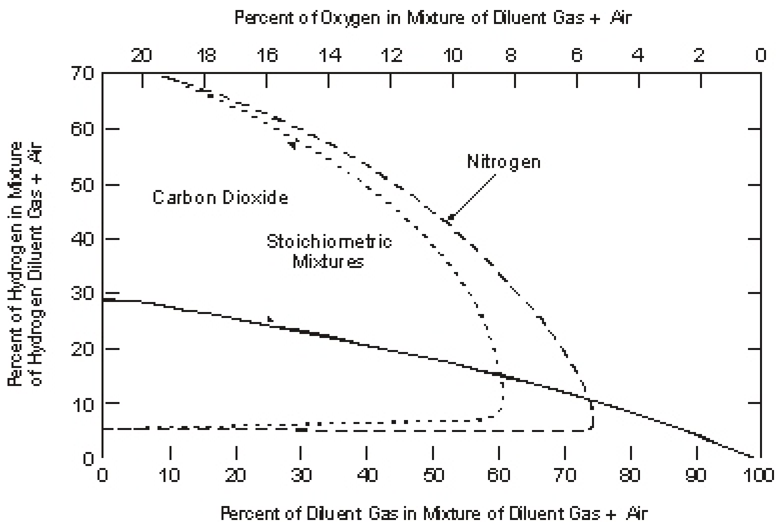


Figure 16-1 Flammability Limits of Hydrogen in Air Diluted with Carbon Dioxide and Nitrogen (Shapiro and Moffette, 1957)

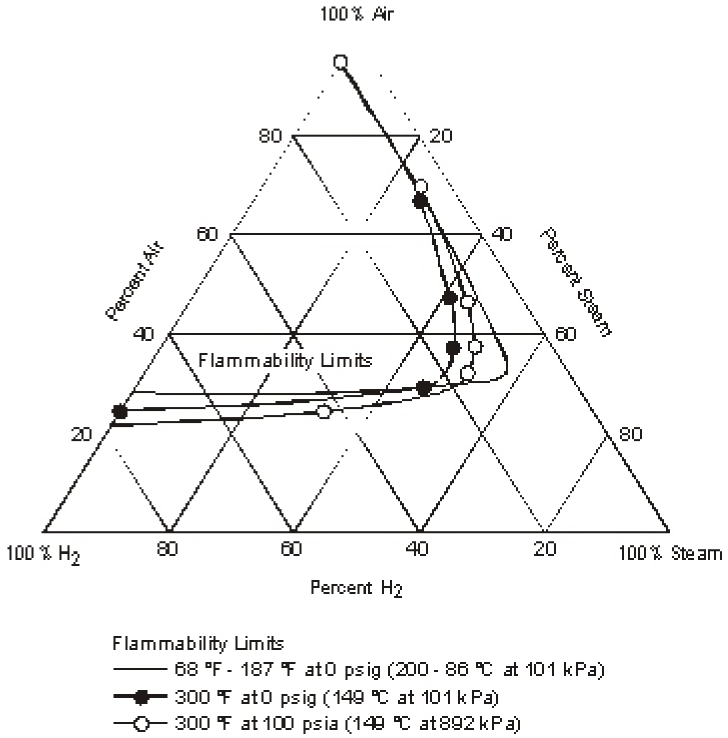


Figure 16-2 Flammability Limits of Hydrogen in Air-Steam Mixtures (Shapiro and Moffette, 1957)

16.4 Ignition of Hydrogen Gas

Accidental ignition of hydrogen could be caused by several sources in a structure if the hydrogen concentration in air were to reach sufficient levels. Ignition of dry hydrogen-air mixtures, particularly when the mixtures are well within the flammability limits, can occur with a very small input of energy (Shapiro and Moffette, 1957). Common sources of ignition are sparks from electrical equipment and the discharge of small static electric charges. In fact, the minimum energy required from a spark for ignition of a quiescent hydrogen air mixture is on the order of 10^{-4} J (10^{-7} Btu)—a very weak spark. Figure 16-3 (Drell and Belles, 1958) shows the ignition energy required as a function of hydrogen concentration. For a flammable mixture, the required ignition energy increases as the hydrogen concentration approaches the flammability limits. The addition of a diluent, such as steam, substantially increases the required ignition energy.

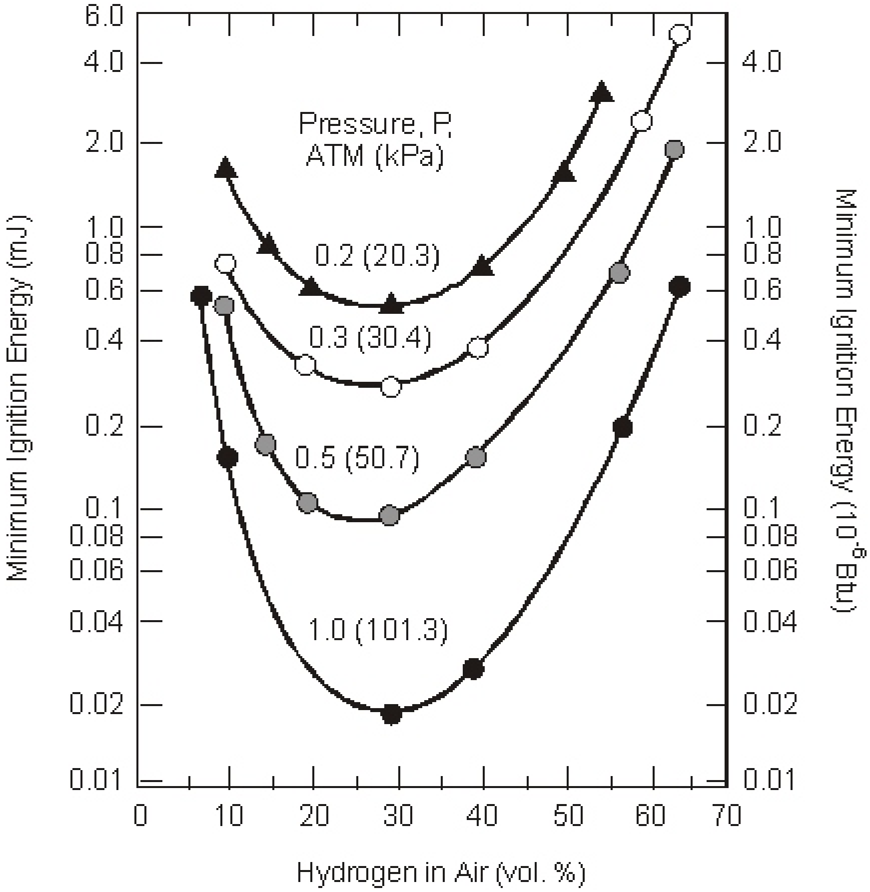


Figure 16-3 Spark Ignition Energies for Dry Hydrogen-Air Mixtures
(Drell and Belles, 1958)

16.4.1 Battery as an Ignition Source

Given the discussion in the previous section, it is relatively easy to accept the fact that a battery can act as an ignition source for the hydrogen-air mixture that results from its own charging process. Since all functional vented batteries generate a stoichiometric mixture of hydrogen and oxygen gases during overcharging and expel them normally from the cell into the battery container, a potential always exists that these gases may explode. Normally, the battery case does not contain any ignition sources, but several abnormal possibilities do exist. One is the internal short-circuiting of a relatively dry cell in overcharging, resulting in an explosion inside the cell with a subsequent ejection of flames into the battery case. A second and more likely source of ignition may exist at an improperly maintained cell terminal, as a result of the high temperatures generated during high-rate discharge. A third source of ignition may occur at the site of stray leakage currents.

16.4.2 Control of Hydrogen Gas Combustion

An NPP can effectively control a flammable gas-oxidant mixture by reducing the concentration of oxidant or by adding an inert constituent to the mixture. Both processes can be explained most easily by referring to a flammability diagram. Figure 16-4 (NFPA 69, 1997 Edition) for example, shows a typical flammability diagram representing a mixture of combustible gas, an inert gas, (nitrogen), and an oxidant, (oxygen), at a given temperature and pressure. A mixture of air (79-percent N_2 and 21-percent O_2, by volume) and combustible gas is represented by line DABE. A given mixture of combustible gas and air, whether ignitable or not, is specified by some point on this line. Point A indicates the UFL of this mixture, while point B represents its LFL. Point C represents the limiting oxidant concentration to prevent ignition; any mixture containing less oxygen cannot be ignited. Any point within the area bounded by curve FBCAG is in the flammable range and can be ignited. Any mixture of oxygen and combustible gas alone (i.e., without any nitrogen) is represented by the left-hand side of the triangle. Any mixture of nitrogen and combustible gas alone (i.e., no oxygen present) is represented by the right-hand side of the triangle.

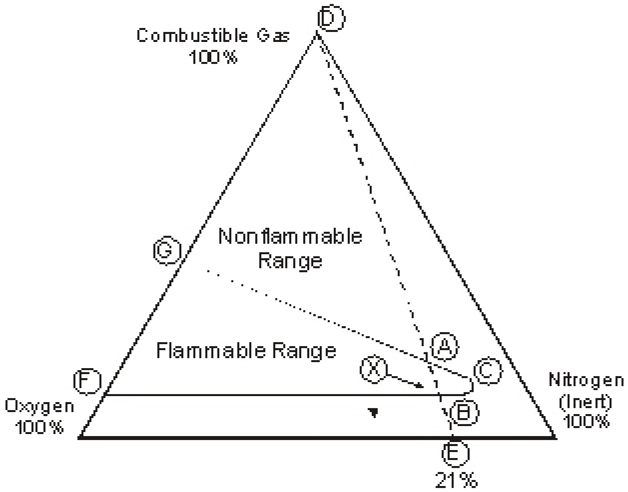


Figure 16-4 Typical Flammability Diagram
(NFPA 69, 1997 Edition, © NFPA. With permission.)

NPPs rely on several simple (but extremely important) methods to prevent hydrogen combustion in battery rooms. First, the rooms are well-ventilated to prevent excessive hydrogen buildup. The battery room ventilation system in NPPs typically limits hydrogen concentration to less than 2 percent of the total volume of the room and maintains a constant temperature of 25 °C (77 °F). The air flow rate is approximately 10 air changes per hour. As an additional precaution, no open flame or smoking is allowed in the proximity of the battery room. Also, any work in the room must be performed with non-sparking tools made of brass, aluminum, or wood (Linden, 1994).

To date, there have been no major accidents involving hydrogen gas in the battery rooms at NPPs (NUREG/CR-2726). However, in other (non-nuclear) industries, there have been instances of hydrogen explosions reported in battery charging areas ranging in size from submarine battery rooms to uninterruptible power supply (UPS) battery rooms where batteries create a real problem during periods of high recharge.

On March 20, 2001, a hydrogen explosion occurred in the UPS/battery room of a large computer data center in Sacramento, California ("Explosion in Rancho Cordova," 2001). The explosion blew a 400+ ft^2 hole in the roof, collapsed numerous walls and ceilings throughout the data center, and significantly damaged a large portion of the 50,000 ft^2 building.

16.5 Fire Protection Code Requirements for Battery Rooms

Regarding battery room fire protection for NPPs, Regulatory Guide (RG) 1.189 states that battery rooms should be separated from each other and other areas of the plant by barriers having a minimum fire rating of 3 hours, inclusive of all penetrations and openings. RG 1.189 also states that ignition sources (such as the DC switchgear room and inverters should not be located in batteries rooms. In addition, RG 1.189 recommends that automatic fire detection should be provided to alarm and annunciate in the control room and alarm locally. Ventilation systems in the battery rooms should also be capable of maintaining the hydrogen gas concentration well below 2 percent. Loss of ventilation should be alarmed in the control room and standpipe, and a hose station and portable fire extinguishers should be readily available outside the room.

Similar to RG 1.189, Section E2.12 of NFPA 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," 2001 Edition recommends that battery rooms should be separated from adjacent areas by fire-rated barriers. It also recommends that battery rooms should be ventilated to limit the concentration of hydrogen gas to 1-percent by volume in accordance with NFPA 69, "Standard on Explosion Prevention Systems." In addition, NFPA 805 requires that direct current switchgear and inverters should not be located in battery rooms. For detailed information, refer to IEEE-484, "Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications."

In similar fashion, Section 8.7 of NFPA 804, "Standard for Fire Protection for Advanced Light Water Reactor Electric Generating Plants," 2001 Edition recommends that battery rooms should be protected against fires and explosion, and that ventilation should be provided to limit the concentration of hydrogen to 2-percent by volume. It also recommends that battery rooms should be separated from other areas of the plant by fire barriers having a 1-hour minimum rating and direct current switchgear and inverters should not be located in battery rooms.

Finally, Section 3-4 of NFPA 801, "Standard for Fire Protection for Facilities Handling Radioactive Materials," 2003 Edition, provides additional guidance for battery rooms, stating that "the facility shall be subdivided into separate fire areas as determined by the fire hazards analysis for the purpose of limiting the spread of fire, protecting personnel, and limiting the consequential damage to the facility. Fire areas shall be separated from each other by barriers with fire resistance commensurate with the potential fire severity. " Specifically, Section A-3-4 of NFPA 801 recommends that battery rooms should be separated by fire barriers having a 3-hour minimum rating. It also recommends that electrical equipment, such as the switchgear and relay rooms should be located in separate fire areas.

NFPA 70E, "Standard for Electrical Safety Requirements for Employee Workshops," 2000 Edition contains additional requirements for vented-type batteries, which require ventilation to limit hydrogen gas concentration exceeding 1-percent by volume. Similar requirements exist for valve-regulated lead-acid (VRLA) storage batteries.

16.6 Method of Calculating the Rate of Hydrogen Generation in Battery Rooms

As previously explained, hydrogen gas is primarily generated in battery rooms as a result of battery overcharge. The generation of hydrogen is particularly important because of its rapid production rate and high flammability. A hydrogen-rich environment could accumulate in a battery room if the ventilation flow through the space is completely stopped or other events allow hydrogen accumulation. The formation of flammable fuel (hydrogen)/oxidant mixtures within a battery room can lead to premixed flame propagation in the form of fire and explosion events, which can cause failure of the structures, ventilation systems, power systems, and monitoring systems. A significant amount of hydrogen gas is liberated only when the battery approaches full charge. The maximum hydrogen evolution rate is 7.56×10^{-6} m^3 (0.000267 ft^3) per minute per charging ampere per cell at 25 °C (77 °F) and 1-atmosphere (Yuasa, Inc., 2000).

The method to calculate the amount of hydrogen produced from batteries in an enclosure is excerpted from the appendix to Section 58.00 of the Yuasa Catalog (2000). This method considers an antimony alloy-type (flat plate, tubular, or Manchex) battery at a point where it is nearing its end of life, or equalizing charge at 2.33 VPC (volts per cell).

The rate of hydrogen generation from a battery can be approximated using the following equation (Yuasa, Inc., 2000):

$$H_{gen} = \frac{F_C}{1000} \; \frac{A_H}{100} \; K \; N \qquad (16\text{-}1)$$

Where:

H_{gen} = hydrogen gas generation, ft^3/min
F_C = float current per 100 A_H (temperature compensated) in milliamperes
A_H = ampere hours (nominal 8 hour)
K = constant - 1 A_H = 0.000267 ft^3
N = number of cells

Table 16-2 summarizes the float current (F_C) demand of fully charged stationary lead-acid cells.

Table 16-2. Float Current Demand for a Stationary Battery

Charge Voltage (VPC)	**Float Current (F_C) milliamperes per 100 AH @ 8-hour rate**		
	Antimony		**Calcium**
	New	**Old**	
2.15	15	60	-
2.17	19	80	4
2.20	26	105	6
2.23	37	150	8
2.25	45	185	11
2.27	60	230	12
2.33	120	450	24
2.37	195	700	38
2.41	300	1,100	58

Note: The above values apply when the electrolyte temperature is 25 °C (77 °F). The values double for every 8 °C (15 °F) of temperature rise. If the temperature drops, the current value is halved for every 8 °C (15 °F) decrease. Antimony ranges indicate current increases attributable to cell aging.

16.7 Method of Calculating Flammable Gas and Vapor Concentration Buildup in Enclosed Spaces

The minimum and maximum concentration of combustible material in a homogeneous mixture with a gaseous oxidizer that will propagate a flame is called flammable limits. Upper and lower flammability limits represent the range of concentrations of fuel in air in which a premixed flame can propagate.

A deflagration is possible if the concentration of a gas rises above its LFL. A detonation can occur if the velocity of a propagation of a combustion zone is greater than the speed of sound in the unreacted medium. For a detonation pressure rises are estimated as 2 to 4 times that of a deflagration. Deflagrations are characterized by slow subsonic propagation of a flame front, and slow but uniform rise in the pressure and temperature of the gas by the heat released from the combustion.

A detonation produces a shock wave driven and sustained by the chemical energy released from the chemical reaction. The shock wave and the reaction propagate together in the unburned gas at a speed which exceeds that of sound in the unburned medium, i.e., of the order of 1,500 to 2,000 m/sec (Fardis et al., 1983). The shock front is characterized by an abrupt increase in pressure, temperature, and density of the gas, and by the net forward movement of the gas particles. Shock reflection produces a large pressure on the wall (e.g., 2 to 4 times the incident pressures for a deflagration), and generates a purely mechanical wave which propagates inward in the already burnt gas until interacts with another wave produced by the reflection elsewhere.

The volume gas or vapor for deflagration is give by the following expression:

$$V_{def} = \frac{V}{LFL} \qquad (16\text{-}2)$$

Where:

V_{def} = volume of gas vapor for deflagration (ft^3)
V = volume of the enclosure (ft^3)
LFL = lower flammability of gas or vapor (percent-volume)

16.8 Method of Calculating Flammable Gas and Vapor Concentration Buildup Time in Enclosed Spaces

NFPA 69, “Standard on Explosion Prevention Systems,” provides a method to calculate the time to buildup of combustible concentration of a flammable gas in enclosed area.

If a constant source of flammable gas is introduced into an enclosed volume, the buildup of flammable gas concentration is given by the following equation:

$$C = \frac{G}{Q}\left(1 - e^{-KN}\right) \qquad (16\text{-}3)$$

Where:

C = gas concentration by volume
G = flammable/combustible gas discharge rate (ft^3/min)
Q = volume of air in enclosure (ft^3/min)
K = mixing efficiency factor (constant)
N = number of theoretical air changes

Equation (16-3) can be rewritten into a more convenient logarithmic form:

$$\ln\left(1 - \frac{CQ}{G}\right) = -KN \qquad (16\text{-}4)$$

In perfect conditions, K = 1.0, Table 16-3 lists mixing efficiency factor (K) for certain conditions.

Table 16-3. Mixing Efficiency for Various Ventilation Arrangements

Method of Supplying	**Efficiency K Values**	
	Single Exhaust Opening	**Multiple Exhaust Opening**
No Positive Supply		
Infiltration through cracks	0.2	0.3
open doors, or windows	0.2	0.4
Forced Air Supply		
Grills and registers	0.3	0.5
Diffusers	0.5	0.7
Perforated ceiling	0.8	0.9

16.9 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations:

(1) Hydrogen gas is primarily generated in battery rooms as a result of battery overcharge.

(2) The generation of hydrogen environment could occur if the ventilation flow through the vapor space is completely stopped or other events allow hydrogen accumulation.

(3) This method assumes that significant amounts of hydrogen gas are liberated only when the battery approaches full charge.

(4) The calculations will produce a first order approximation.

(5) The battery hydrogen generation equation is based on one specific vendor's recommendations.

16.10 Required Input for Spreadsheet Calculations

The user must obtain the following data before attempting a calculation with the spreadsheet:

(1) charge voltage (vpc)

(2) ampere Hours

(3) number of cells

16.11 Cautions

(1) Make sure to input data in the correct units.

(2) Use spreadsheet (16_Battery_Room_Flammable_Gas_Conc.xls) on the CD-ROM for calculations.

16.12 Summary

(1) Adequate ventilation is the most common form of fire prevention/protection in battery rooms. Ventilation must be adequate to prevent hydrogen gas from exceeding a concentration of 2 percent by volume, and to ensure that pockets of trapped hydrogen gas do not develop (particularly at the ceiling).

(2) The exhaust air outlets from the battery room shall be located separately so that a hazardous concentration of the exhausted air cannot enter or be drawn into the fresh air intakes of environmental air handling systems.

(3) Building and fire codes require spill containment systems for battery installations that contain electrolyte.

(4) NPP should maintain an ambient temperature of 23 to 26 °C (72 to 78 °F) in battery rooms.

(5) To extinguish a fire in a battery room containing lead-acid batteries, use CO_2, fire protection foam, or dry chemical extinguishing media. Do not discharge the extinguisher directly onto the battery. The resulting thermal shock may cause cracking of the battery case and/or cover.

(6) In case of fire, the power should be shut off if batteries are on charge. Use a positive-pressure, self-contained breathing apparatus. Remember that water applied to an electrolyte generates heat and causes it to splatter. Wear acid-resistant clothing.

16.13 References

Drell, I.L., and F.E. Belles, “Survey of Hydrogen Combustion Properties,” Technical Note NACA R 1383, National Advisory Committee for Aeronautics (NACA), Washington, DC, 1958.

“Explosion in Rancho Cordova,” Press Release, Sacramento Metropolitan Fire District, March 20, 2001, available at http://www.smfd.ca.gov.

Fardis, M.N., A. Nacar, and M.A. Delichatsios, “R/C Containment Safety Under Hydrogen Detonation,” *Journal of Structural Engineering*, Volume 109, pp. 2511–2527, 1983.

IEEE-484, “Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications,” The Institute of Electrical and Electronics Engineers, New York.

Linden, D., Editor-in-Chief, *Handbook of Batteries*, 2nd Edition, McGraw-Hill, Inc., New York, 1994.

NFPA 69, “Standard on Explosion Prevention Systems,” 1997 Edition, National Fire Protection Association, Quincy, Massachusetts.

NFPA 70E, “Standard for Electrical Safety Requirements for Employee Workplaces,” 2000 Edition,

National Fire Protection Association, Quincy, Massachusetts.

NFPA 801, “Standard for Fire Protection for Facilities Handling Radioactive Materials,” 1998 Edition, National Fire Protection Association, Quincy, Massachusetts.

NFPA 804, “Standard for Fire Protection for Advanced Light Water Reactor Electric Generating Plants,” 2001 Edition, National Fire Protection Association, Quincy, Massachusetts.

NFPA 805, “Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants,” 2001 Edition, National Fire Protection Association, Quincy, Massachusetts.

Nuclear Regulatory Commission (U.S.), NUREG/CR-2726, “Light-Water Reactor Hydrogen Manual.” NRC: Washington, D.C. August 1983.

Nuclear Regulatory Commission (U.S.), NUREG/CR-6042, Rev. 2, “Perspective on Reactor Safety,” NRC Washington, DC, March 2002.

Nuclear Regulatory Commission (U.S.), Regulatory Guide 1.189, “Fire Protection for Operating Nuclear Power Plants,” NRC Washington, DC, April 2001.

Shaprio, Z.M., and T.R. Moffette, “Hydrogen Flammability Data and Application to PWR Loss-of-Coolant Accident,” WAPD-SC-545, Bettis Plant, September 1957.

Yuasa, Inc., *Safety Storage, Installation, Operation, and Maintenance Manual*, Section 58.00, Heritage™ Series, Flooded Lead-Acid Batteries, 2000.

16.14 Problems

Example Problem 16.14-1

Problem Statement

Assume a 60-cell GT-41 (3,730 Ampere-hour) battery near the end of its life, on equalize at 2.33 VPC at an electrolyte temperature of 92 °F (33 °C). Estimate the rate of hydrogen generation (in cubic feet per minute).

Solution

Purpose:

(1) Estimate the rate of hydrogen generation.

Assumptions:

(1) Old Antimony-type battery

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 16_Battery_Room_Flammable_Gas_Conc.xls
(click on Battery_Room_Hydrogen)

FDT^s Input Parameters:

-Ampere Hours = 3730 Ah
-Number of Cells = 60
-Click on Old Antimony type and Select 2.33 VPC

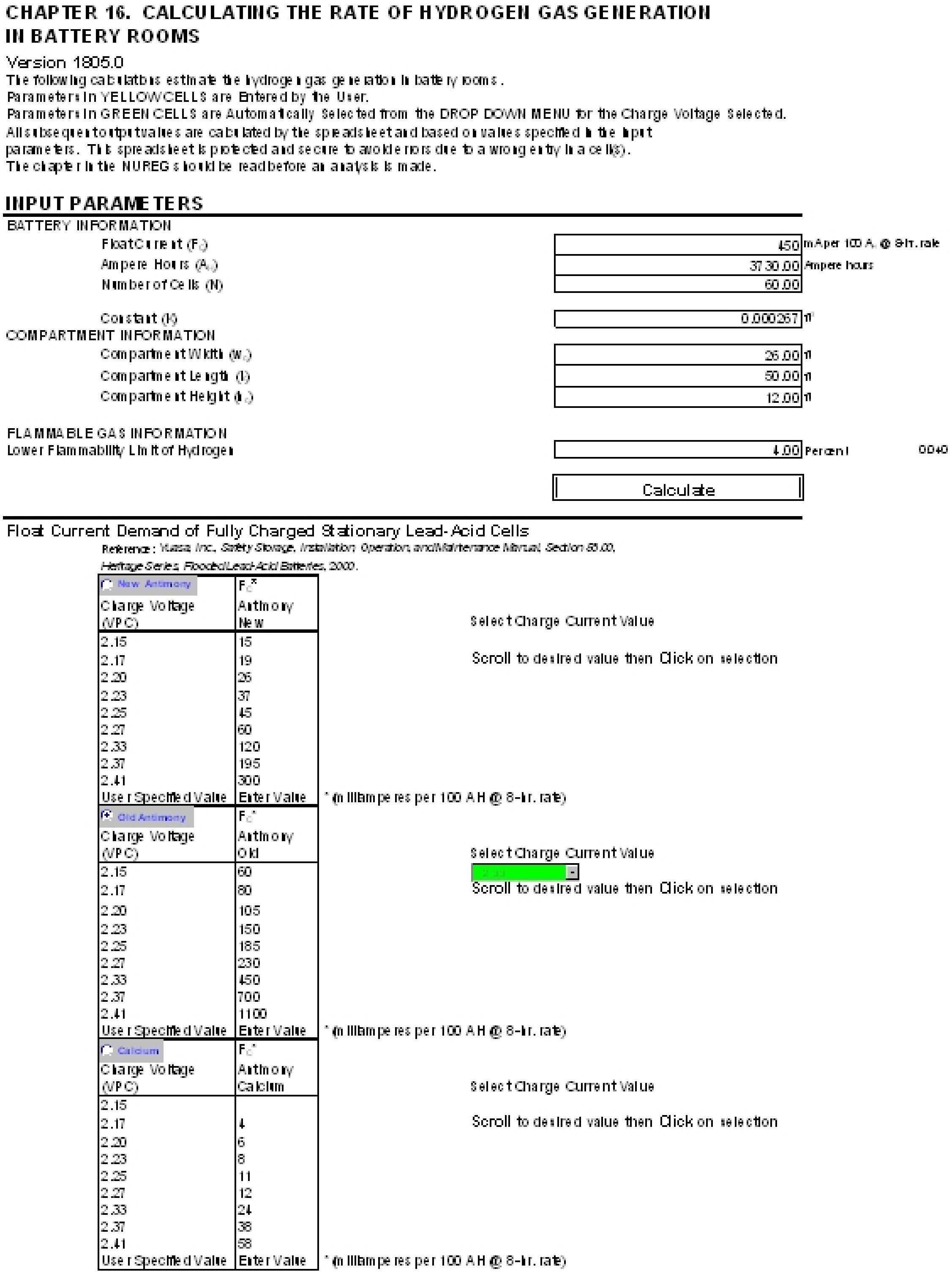
Results*

Generation Rate	0.538 ft^3/m (0.0152 m^3/min)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 16_Battery_Room_Flammable _Gas_Conc.xls (Battery_Room_Hydrogen)



CHAPTER 16. CALCULATING THE RATE OF HYDROGEN GAS GENERATION IN BATTERY ROOMS

Version 1805.0

The following calculations estimate the hydrogen gas generation in battery rooms.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Charge Voltage 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

BATTERY INFORMATION

Float Current (F_c)	450	mA per 100 A. @ 8-hr. rate
Ampere Hours (A_h)	3730.00	Ampere hours
Number of Cells (N)	60.00	
Constant (K)	0.000267	ft^3

COMPARTMENT INFORMATION

Compartment Width (w_c)	26.00	ft
Compartment Length (l_c)	50.00	ft
Compartment Height (h_c)	12.00	ft

FLAMMABLE GAS INFORMATION

Lower Flammability Limit of Hydrogen	4.00	Percent	0.040

Calculate

Float Current Demand of Fully Charged Stationary Lead-Acid Cells

Reference: *Yuasa Inc., Safety Storage, Installation, Operation, and Maintenance Manual, Section 58.00, Heritage Series, Flooded Lead-Acid Batteries, 2000.*

○ New Antimony Charge Voltage (VPC)	F_c* Antimony New
2.15	15
2.17	19
2.20	26
2.23	37
2.25	45
2.27	60
2.33	120
2.37	195
2.41	300
User Specified Value	Enter Value

Select Charge Current Value

Scroll to desired value then Click on selection

* (milliamperes per 100 AH @ 8-hr. rate)

● Old Antimony Charge Voltage (VPC)	F_c* Antimony Old
2.15	60
2.17	80
2.20	105
2.23	150
2.25	185
2.27	230
2.33	450
2.37	700
2.41	1100
User Specified Value	Enter Value

Select Charge Current Value

Scroll to desired value then Click on selection

* (milliamperes per 100 AH @ 8-hr. rate)

○ Calcium Charge Voltage (VPC)	F_c* Antimony Calcium
2.15	
2.17	4
2.20	6
2.23	8
2.25	11
2.27	12
2.33	24
2.37	38
2.41	58
User Specified Value	Enter Value

Select Charge Current Value

Scroll to desired value then Click on selection

* (milliamperes per 100 AH @ 8-hr. rate)

METHOD OF YUSHA, INC.

Reference: *Yuasa, Inc., Safety Storage, Installation, Operation and Maintenance Manual, Section 58.00, Heritage Series, Flooded Lead-Acid Batteries, 2000.*

Estimating Hydrogen Gas Generation Rate

$H_{2(gen)} = F_C/1000 \times A_H/100 \times K \times N$

This equation is based on when electrolyte temperature is 77 °F (25 °C)
For every 15 °F (8 °C) electrolyte temperaturte rise the equation will multiply by 2

Where
$H_{2(gen)}$ = hydrogen gas generation rate (ft^3/min)
F_C = float current (mA per 100 A_H @ 8-hr. rate)
A_H = ampere hours (normal 8 hour)
K = constant - 1 A_H = 0.000267 ft^3
N = number of cells

$H_{2(gen)} = F_C/1000 \times A_H / 100 \times K \times N \times 2$

Since electrolyte temperature is 92 °F (33 °C) the equation is multiply by 2

$H_{2(gen)}$ =	0.538 ft^3/min	0.015230 m^3/min		Answer

Estimating Hydrogen Gas In Compartment Based on Given Flammability Limit

$H_{2(comp)} = V \times FL$

Where
$H_{2(comp)}$ = hydrogen gas in compartment (ft^3)
V = volume of compartment (ft^3)
FL = hydrogen gas flammability limit

Volume of Compartment

$V = w_C \times L_C \times h_C$

Where
V = compartment volume (ft^3)
w_C = compartment Width (ft)
L_C = compartment Length (ft)
h_C = compartment Height (ft)

V = 15600 ft^3

$H_{2(comp)} = V \times FL$

$H_{2(comp)}$ = 624 ft^3

Estimating Time Required to Reach Hydrogen Concentration on Given Flammability Limit

$t_{H2} = H_{2(comp)} / H_{2(gen)}$

Where
t_{H2} = time require to reach on given flammability limit (min)
$H_{2(comp)}$ = hydrogen gas in compartment (ft^3)
$H_{2(gen)}$ = hydrogen gas generation rate (ft^3/min)

t_{H2} =	1160.30 min. or approximately	19 hours	Answer

NOTE

The above calculations are based on method presented in the Yuasa, Inc., Safety Storage, Installation, Operation, and Maintenance Manual, Section 58.00, Heritage Series, Flooded Lead-Acid Batteries, 2000.
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.

UNITED STATES NUCLEAR REGULATORY COMMISSION

Example Problem 16-2

Problem Statement

Consider an enclosure (10ft wide x 10ft long x 10ft high) 1,000 ft^3 (28 m^3) in turbine generator area of a nuclear facility in which hydrogen gas is accumulated. Calculate the concentration of hydrogen gas by volume reaching its LFL of 4 percent.

Solution

Purpose:

(1) Estimate the concentration of hydrogen gas in the compartment at LFL.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 16_Battery_Room_Flammable _Gas_Conc.xls
(click on Flammable_Gas_Buildup)

FDT^s Input Parameters:

-Compartment Width (w_c) = 10 ft
-Compartment Length (l_c) = 10 ft
-Compartment Height (h_c) = 10 ft
-Select Hydrogen

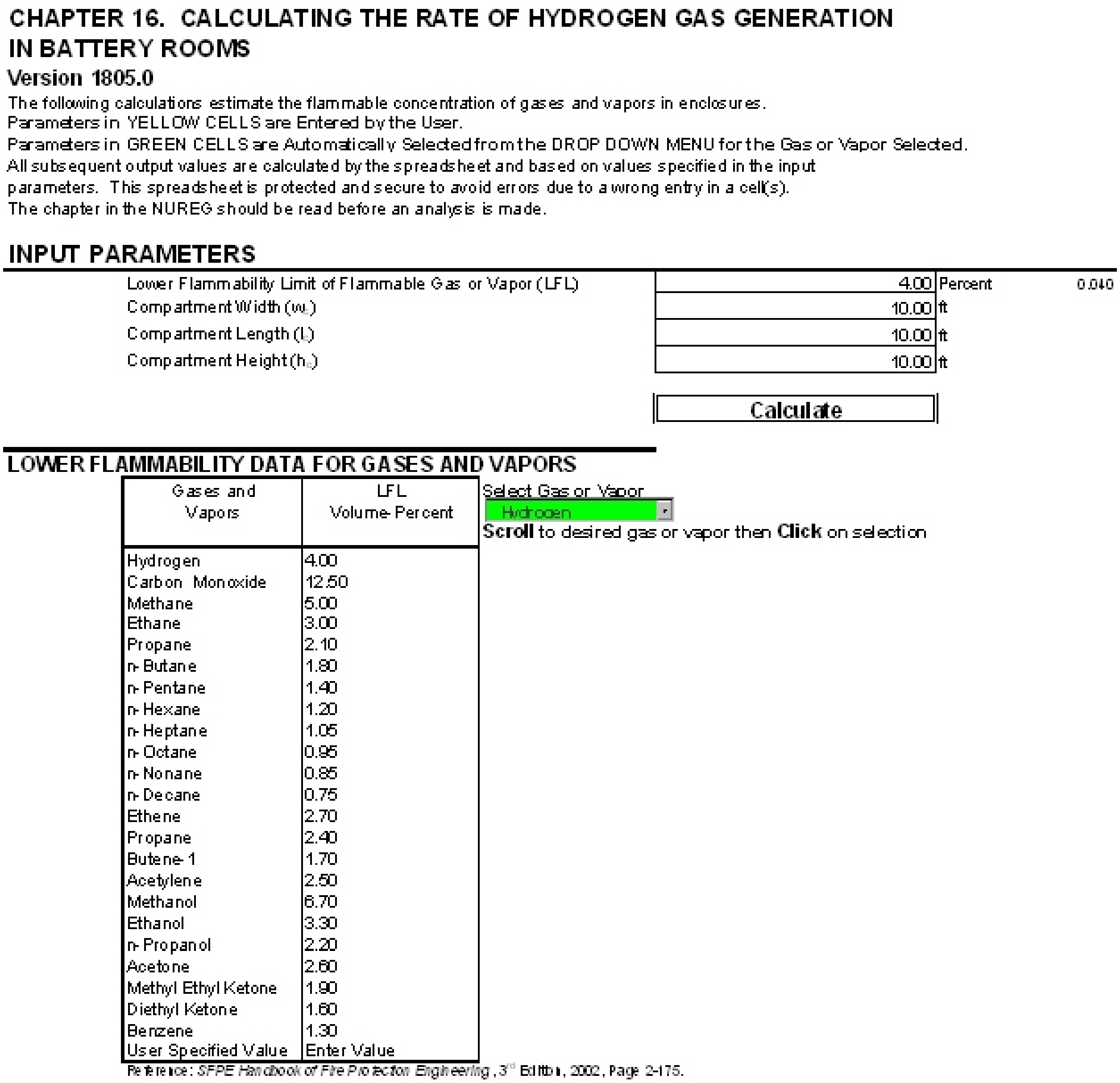
Results*

Volume	40 ft^3 (1.13 m^3)

*see spreadsheet on next page

Therefore, the concentration of hydrogen gas in the 1000 ft^3 compartment is 4% (40/1000).

Spreadsheet Calculations
FDT^s: 16_Battery_Room_Flammable _Gas_Conc.xls (Flammable_Gas_Buildup)



CHAPTER 16. CALCULATING THE RATE OF HYDROGEN GAS GENERATION IN BATTERY ROOMS

Version 1805.0

The following calculations estimate the flammable concentration of gases and vapors in enclosures.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Gas or Vapor 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

Lower Flammability Limit of Flammable Gas or Vapor (LFL)	4.00	Percent	0.040
Compartment Width (w_c)	10.00	ft	
Compartment Length (l_c)	10.00	ft	
Compartment Height (h_c)	10.00	ft	

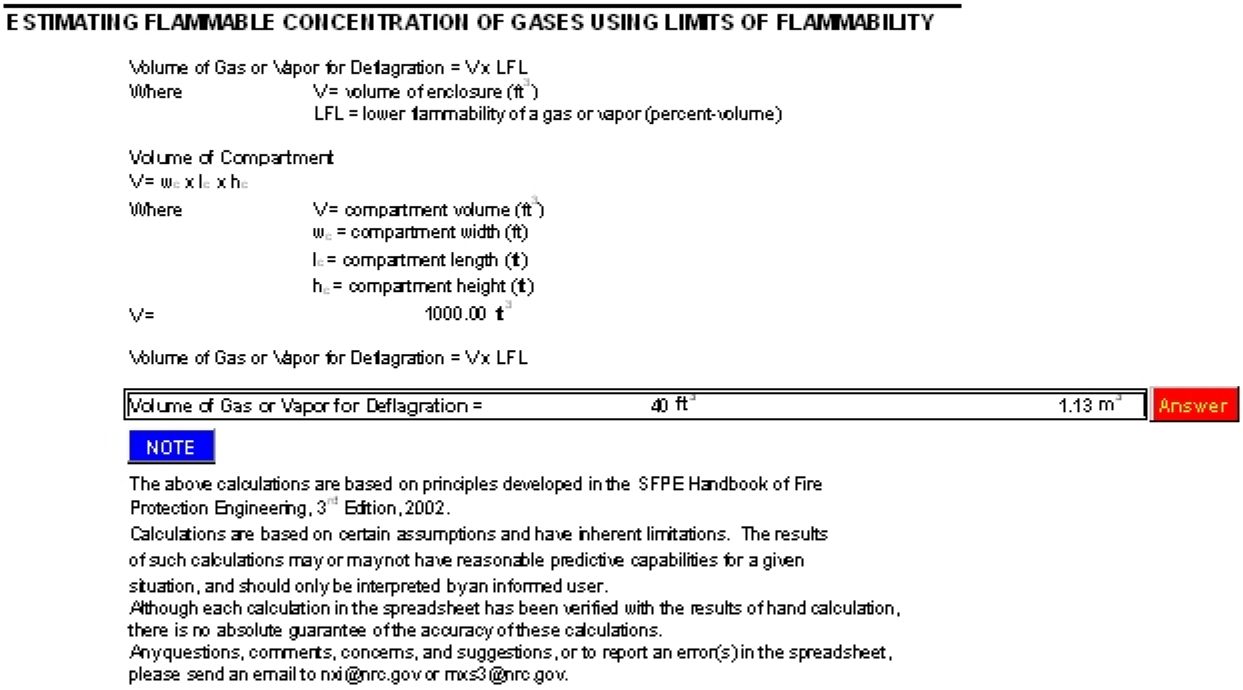
LOWER FLAMMABILITY DATA FOR GASES AND VAPORS

Select Gas or Vapor

Scroll to desired gas or vapor then **Click** on selection

Gases and Vapors	LFL Volume-Percent
Hydrogen	4.00
Carbon Monoxide	12.50
Methane	5.00
Ethane	3.00
Propane	2.10
n-Butane	1.80
n-Pentane	1.40
n-Hexane	1.20
n-Heptane	1.05
n-Octane	0.95
n-Nonane	0.85
n-Decane	0.75
Ethene	2.70
Propane	2.40
Butene-1	1.70
Acetylene	2.50
Methanol	6.70
Ethanol	3.30
n-Propanol	2.20
Acetone	2.60
Methyl Ethyl Ketone	1.90
Diethyl Ketone	1.60
Benzene	1.30
User Specified Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 2-175.



ESTIMATING FLAMMABLE CONCENTRATION OF GASES USING LIMITS OF FLAMMABILITY

Volume of Gas or Vapor for Deflagration = V x LFL

Where V = volume of enclosure (ft^3)
LFL = lower flammability of a gas or vapor (percent-volume)

Volume of Compartment

$V = w_c \times l_c \times h_c$

Where V = compartment volume (ft^3)
w_c = compartment width (ft)
l_c = compartment length (ft)
h_c = compartment height (ft)

V = 1000.00 ft^3

Volume of Gas or Vapor for Deflagration = V x LFL

Volume of Gas or Vapor for Deflagration =	40 ft^3	1.13 m^3	Answer

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.
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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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Example Problem 16-3

Problem Statement

Assume a leak of 100 ft^3/min of a 15-percent hydrogen gas/air mixture in a compartment that is 29 ft wide x 15 ft long x 12 ft high (w_c x l_c x h_c). How long would it take to reach a hydrogen concentration of 2 percent throughout the enclosure, assuming infiltration through multiple compartment cracks?

Solution

Purpose:

(1) Estimate the time until the room reaches 2% hydrogen concentration.

Assumptions:

(1) Infiltration through compartment leaks.
(2) The mass rate of the fuel is neglected in the conversion of mass.
(3) The specific heat is constant with temperature.
(4) The hydrostatic pressure difference over the height oft he compartment is negligible compared to the dynamic pressure.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 16_Battery_Room_Flammable _Gas_Conc.xls
(click on Flammable_Gas_Buildup_Time)

FDT^s Input Parameters:

-Compartment Width (w_c) = 29 ft
-Compartment Length (l_c) = 15 ft
-Compartment Height (h_c) = 12 ft
-Enter 100 ft^2/min as the Leakage Rate
-Enter 15% as Percent of Combustible Gas/Air Mixture
-Enter 2% as Combustible Gas Concentration (C)
-Click on Infiltration Through Cracks and select 0.3 from the drop-down menu

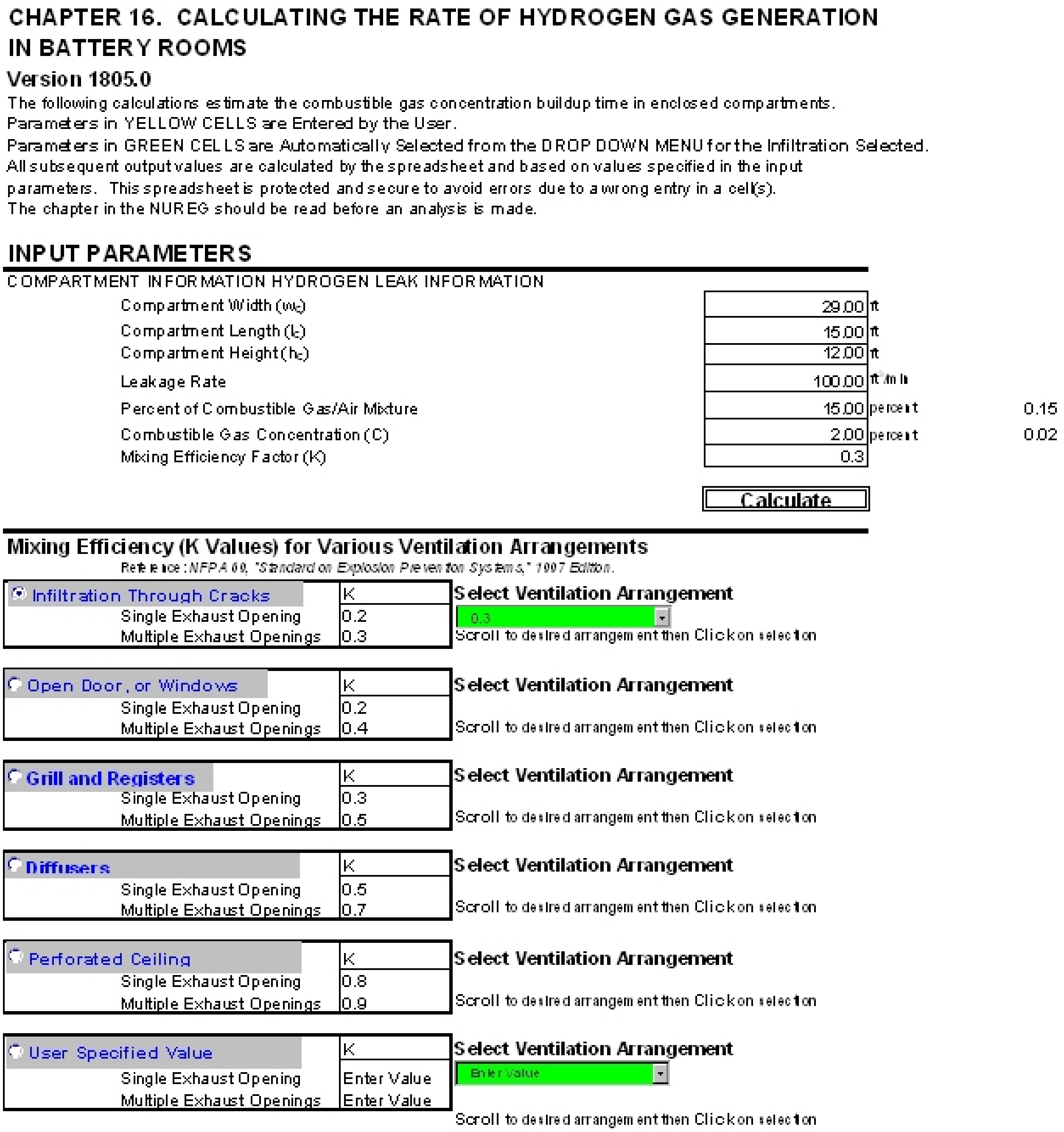
Results*

Time	20.9 minutes

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 16_Battery_Room_Flammable_Gas_Conc.xls (Flammable_Gas_Buildup_Time)



CHAPTER 16. CALCULATING THE RATE OF HYDROGEN GAS GENERATION IN BATTERY ROOMS

Version 1805.0

The following calculations estimate the combustible gas concentration buildup time in enclosed compartments.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Infiltration 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 HYDROGEN LEAK INFORMATION

Compartment Width (w_c)	29.00	ft	
Compartment Length (l_c)	15.00	ft	
Compartment Height (h_c)	12.00	ft	
Leakage Rate	100.00	ft^3/min	
Percent of Combustible Gas/Air Mixture	15.00	percent	0.15
Combustible Gas Concentration (C)	2.00	percent	0.02
Mixing Efficiency Factor (K)	0.3		

Calculate

Mixing Efficiency (K Values) for Various Ventilation Arrangements

Reference: *NFPA 69, "Standard on Explosion Prevention Systems," 1997 Edition.*

● Infiltration Through Cracks	K
Single Exhaust Opening	0.2
Multiple Exhaust Openings	0.3

Select Ventilation Arrangement
0.3
Scroll to desired arrangement then Click on selection

○ Open Door, or Windows	K
Single Exhaust Opening	0.2
Multiple Exhaust Openings	0.4

Select Ventilation Arrangement
Scroll to desired arrangement then Click on selection

○ Grill and Registers	K
Single Exhaust Opening	0.3
Multiple Exhaust Openings	0.5

Select Ventilation Arrangement
Scroll to desired arrangement then Click on selection

○ Diffusers	K
Single Exhaust Opening	0.5
Multiple Exhaust Openings	0.7

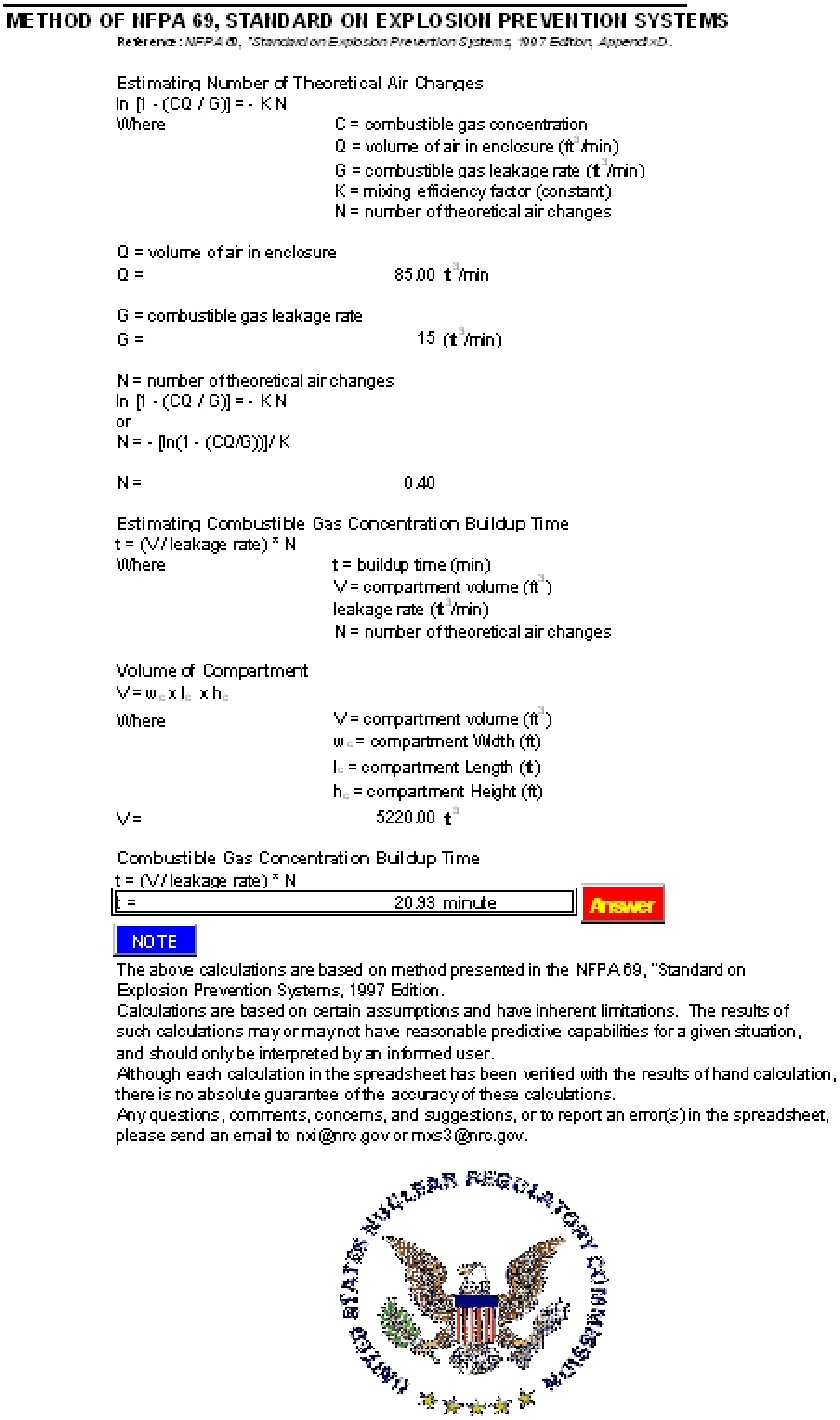
Select Ventilation Arrangement
Scroll to desired arrangement then Click on selection

○ Perforated Ceiling	K
Single Exhaust Opening	0.8
Multiple Exhaust Openings	0.9

Select Ventilation Arrangement
Scroll to desired arrangement then Click on selection

○ User Specified Value	K
Single Exhaust Opening	Enter Value
Multiple Exhaust Openings	Enter Value

Select Ventilation Arrangement
Enter Value
Scroll to desired arrangement then Click on selection



METHOD OF NFPA 69, STANDARD ON EXPLOSION PREVENTION SYSTEMS

Reference: NFPA 69, "Standard on Explosion Prevention Systems, 1997 Edition, Appendix D.

Estimating Number of Theoretical Air Changes

ln [1 - (CQ / G)] = - K N

Where
C = combustible gas concentration
Q = volume of air in enclosure (ft^3/min)
G = combustible gas leakage rate (ft^3/min)
K = mixing efficiency factor (constant)
N = number of theoretical air changes

Q = volume of air in enclosure
Q = 85.00 ft^3/min

G = combustible gas leakage rate
G = 15 (ft^3/min)

N = number of theoretical air changes
ln [1 - (CQ / G)] = - K N
or
N = - [ln(1 - (CQ/G))]/ K

N = 0.40

Estimating Combustible Gas Concentration Buildup Time
t = (V/ leakage rate) * N

Where
t = buildup time (min)
V = compartment volume (ft^3)
leakage rate (ft^3/min)
N = number of theoretical air changes

Volume of Compartment
V = w_c x l_c x h_c

Where
V = compartment volume (ft^3)
w_c = compartment Width (ft)
l_c = compartment Length (ft)
h_c = compartment Height (ft)

V = 5220.00 ft^3

Combustible Gas Concentration Buildup Time
t = (V/ leakage rate) * N
t = 20.93 minute

The above calculations are based on method presented in the NFPA 69, "Standard on Explosion Prevention Systems, 1997 Edition.
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.

CHAPTER 17. CALCULATING THE FIRE RESISTANCE OF STRUCTURAL STEEL MEMBERS

17.1 Objectives

This chapter has the following objectives:

- Describe the testing procedures for fire resistance protection of structural steel members.
- Describe the failure criteria for structural steel members.
- Explain how to calculate the fire resistance (failure time) of protected and unprotected structural steel members.

17.2 Introduction

The fire resistance of structures is important in protecting life and property against the hazards of fires. Building codes regulate the fire resistance of structures in a number of ways, including requirements for fire resistance classifications based on such factors as building size, location, and occupancy. In the United States, fire resistance classifications (fire ratings) of floors, roofs, beams, partitions, walls, and columns are based on the results of the "Standard Test Method for Fire Tests of Building Construction and Materials" as defined in ASTM E119. This standard specifies that test specimens must be "truly representative of the design, material, and workmanship for which classification is desired." Testing laboratories throughout North America use gas burners to heat the furnace in such a manner that the temperature inside the furnace follows the time-temperature curve illustrated in Figure 17-1. Table 17-1 identifies the points on this curve that determine its characteristics.

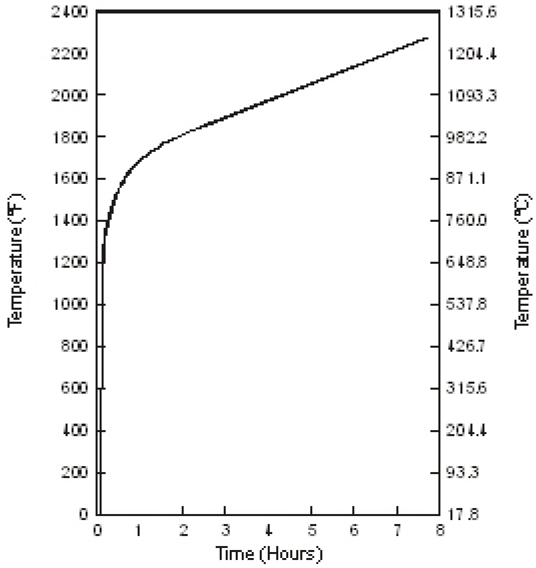


Figure 17-1 Standard Time-Temperature Curve (ASTM E-119)

Table 17-1. Standard Time-Temperature Curve Points

Time	**Temperature °C (°F)**
5 min	38 (100)
10 min	704 (1,300)
30 min	843 (1,550)
1 hr	927 (1,700)
2 hr	1,010 (1,850)
3 hr	1,052 (1,925)
4 hr	1,093 (2,000)
8 hr	1,260 (2,300)

The floors, roofs, beams, partitions, walls, and columns being tested must remain structurally intact and limit heat transmission to the unexposed surfaces. Moreover, for fire barriers such as walls the average temperature increase on the unexposed surfaces cannot exceed 121 °C (250 °F) and cotton waste on the unexposed surface cannot be ignited. Furnace temperature readings are taken as an average of at least eight thermocouples at intervals not exceeding 1 minute during the test period.

A hose stream test is also required for walls and partitions with a rating of at least 1-hour. This test can be conducted immediately after the fire exposure test or, alternatively, it can be conducted on a duplicate sample after exposure to fire for half of the rating period, but not more than 1 hour. If openings develop that permit a projection of water beyond the unexposed surface, the test is considered a failure.

Load-bearing walls or partitions support a portion of the vertical (gravity) loads from a floor or roof. During fire test, such assemblies are not restrained on vertical edges and are loaded to the maximum design load for the test duration. Nonbearing walls or partitions are restrained on all four edges.

If structural steel members supporting floors or roofs are spaced more than 4 feet apart, the maximum temperature at any location cannot exceed 704 °C (1,300 °F) and average temperature cannot exceed 593 °C (1,100 °F) for the following scenarios:

(1) A restrained assembly with up to a 1-hour classification for the full period. For ratings greater than 1 hour, the temperature limitation applies for half the hourly rating, but not less than 1 hour.

(2) An unrestrained assembly cannot exceed the temperature criteria shown above for the full classification or rating period.

If steel structural members are 4 feet or less on center, the average temperature cannot exceed 593 °C (1,100 °F) for the following scenarios:

(1) A restrained assembly with up to a 1-hour classification for the full period. For ratings greater than 1 hour, the temperature limitation applies for half the hourly rating, but not less than 1 hour.

(2) An unrestrained assembly cannot exceed the temperature criteria shown above for the full classification period.

For steel floor or roof units with spans longer than those tested, the average temperature cannot exceed 593 °C (1,100 °F) during the classification period. Floors and roofs are loaded to the maximum design conditions for the classification period.

Columns are loaded to the full design stress and exposed on all four sides to the standard time-temperature curve. The columns must sustain the structural design load for the test period. Where column protections are not required to carry any of the column load (e.g., the fire-resistive covering on a steel column), an alternative column test method uses unloaded columns with the following pass-fail criteria:

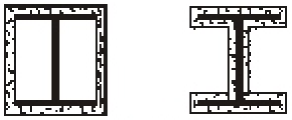
(1) The average temperature increase cannot exceed 538 °C (1,000 °F).

(2) The maximum temperature increase of any thermocouple is 649 °C (1,200 °F).

Individual ratings for loaded beams can be established if the beams are tested as part of a floor assembly; however, the beams must sustain the applied load for the full classification period. The listing is applicable to beams with a weight-to-heated perimeter (W/D) ratio greater than or equal to that of the beam tested. This W/D ratio is the factor that allows the interpolation of coating thicknesses, where W is the weight (lb/ft of length) and D is the heated perimeter (inches) of the structural member.

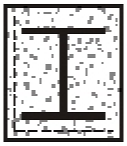
17.3 Fire Resistance of Buildings

Buildings consist of various structural elements that have unique fire resistance ratings and belong to various combustibility groups. The ability of a building to resist collapse during a fire, is called the fire resistance rating. It is characterized by the fire resistance of structural elements such as floor, roof, beams, partitions, fire walls or barriers, bearing walls, and columns. Figure 17-2 illustrates typical methods of protecting structural steel elements from fire. Light protection, using low-density material applied either to the profile of a section or in a box form is the most popular from an economic point of view. Massive protection, particularly concrete encasement, is used in special cases. External protections, referred to as complex protection, include such examples as box protection H-columns with core filling or very thick counter protection. Liquid filling is a special protection method, in which fire resistance is achieved by filling hollow steel members with water. This method is a less common but, an effective way of preventing rapid heating of hollow steel sections. However, a plumbing system is necessary to ensure that the water can flow by convection from member to member and to avoid excessive pressure when the water is heated.

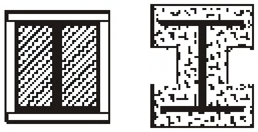


(a) Box Protection (b) Contour Protection

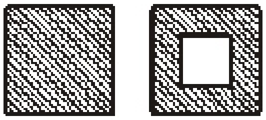
Light Protection



Massive Protection

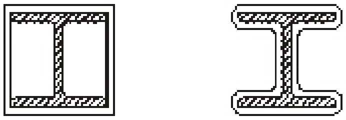


Complex Protection



Liquid-Filling as Fire Protection

Different Fire Resistance



Cross-Section of Columns and Insulation

Figure 17-2 Typical Methods of Protecting Various Structural Steel Elements from Fire

It is important to distinguish between the actual and required fire resistance ratings of a building. The actual rating of a building is determined by the minimum actual fire resistance rating and combustibility group of one of the building's structural elements. The required fire resistance rating of a building is standardized and understood to be the minimum rating that the building has to satisfy given safety requirements. This rating accounts for fire hazards involved in the production processes within the building, the purpose for which the building is intended, the area, the number of stories, and the presence of automatic fire detection and extinguishing systems.

17.4 Fire Resistance of Structural Members

The term fire resistance is used to denote the ability of a building component to resist the thermal insult of a standard rest fire. This rating is usually given in units of time(e.g., 1 hour, 3 hours, etc.). The retention load-bearing capacities by structural members during a fire is very important. Buildings collapse when load-bearing members lose their load-bearing capacity.

The fire resistance of structural members is characterized by their fire resistance ratings, which are defined as the time elapsed from the start of the fire until the time the structure loses its load-bearing or protective capacity. The failure of structural members begins when they are heated to critical temperatures. The fire resistance ratings of structural members are determined either experimentally or by calculations. Experimental methods for determining the fire resistance of structural members have been standardized (e.g., ASTM E119).

17.4.1 Fire Resistance and Temperature Limits of Steel Elements

Steel is a non-combustible material, however, heat effects the material properties and strength of structural steel. For structural elements, the only criterion to be considered is the point where the thermal insult from the fire has weakened the member enough to allow structural collapse of the element.

The fire resistance (or fire endurance) of steel elements varies greatly. The temperature limits for structural steel members are based on the criteria contained in ASTM E119. The maximum single point temperature in a steel beam, column, or girder is 649 °C (1,300 °F) and the allowable average temperature in these members is 530 °C (1,000 °F). During the testing, failure is assumed to occur if either the maximum single point temperature or average temperature is exceeded.

17.4.2 Fire Resistance and Temperature Limits of Reinforced Concrete Elements

The fire resistance or fire endurance of reinforced concrete floors, roofs, and walls is often governed by the criteria for the temperature increase of the unexposed surface, rather than by structural considerations. The ASTM E119 criteria for the temperature rise of the unexposed surface, referred to as heat transmission requirements, limit the increase to an average of 121 °C (250 °F) or a maximum at any one point of 163 °C (325 °F). The purpose of these criteria is to guard against ignition of combustibles on the non-fire side that may be in contact with the fire barrier.

A classical method for estimating the maximum surface temperature reached by reinforced concrete elements is based on of the permanent color changes observed in concrete containing aggregates of siliceous or limestone rock after exposure to high temperatures. Such color changes depend upon the maximum temperature. The surface takes on a pink or red hue when exposed to temperatures of 300–600 °C (572–1,112 °F); dark grey, when exposed temperatures of 600–900 °C (1,112–1,652 °F); brown, when the maximum temperature reached 900–1,200 °C (1,652–2,192 °F); or yellow if the temperature exceeds 1,200 °C (2,192 °F) (Neville, 1975).

Table 17-2 summarizes the ASTM E119 temperature endpoint criteria for structural members. The endpoint temperatures are selected according to conservative estimates of the maximum allowable reduction in load-bearing capacity of the structural member, based on an average reduction in strength attributable to elevated temperatures.

Table 17-2. Temperature Endpoint Criteria for Structural Members (ASTM E119)

Structural Member	**Location**	**Maximum Temperature °C (°F)**
Walls/Partitions (bearing and non-bearings)	Unexposed side	139 (250)
Steel Columns	Average	530 (1,000)
	Single point	649 (1,200)
Floor/Roof Assemblies and Loaded Beams	Unexposed side	139 (250)
	Steel beam (average)	593 (1,100)
	Steel beam (single point)	704 (1,300)
	Pre-stressing steel	426 (800)
	Reinforced steel	593 (1,100)
	Open-web steel joist	593 (1,100)
Steel Beams/Girders (not loaded)	Average	530 (1,000)
	Single point	649 (1,200)

17.5 Failure Criteria for Structural Members

Structural members that are exposed to fire will ultimately fail if the fire is of sufficient duration and intensity. Failure can occur when the member collapses because it can no longer support the design load, or when the deflection is so severe that the member can no longer function in the capacity for it was intended. The failure results from major changes in the mechanical properties of steel, concrete, and other structural materials as they heat up. The ability of a building to remain stable during a fire is equated to the temperature increase in the exposed structural elements. This is based on the fact that the mechanical properties of the structural elements deteriorate as the temperature of the structural materials increases to some critical level. The changes in material properties that are most significant to the performance of structural steel members include the yield strength, modulus of elasticity, and coefficient of thermal expansion. The critical level is generally defined as the temperature at which the yield strength of the material is reduced to the design strength and, therefore, the factor of safety approaches unity.

17.6 Fire Walls and Fire Barrier Walls

NFPA 221, "Standard for Fire Walls and Fire Barrier Walls," contains design and construction requirements for fire walls and fire barriers. The basic difference between the two is that fire walls must remain stable and uncompromised throughout an uncontrolled fire (with sprinklers lacking or assumed to be ineffective), while a fire barrier is intended to help prevent the passage of fire *in conjunction with* other protective measures (such as sprinkler protection).

Fire walls and fire barriers are rated for the number of hours of fire exposure that they can withstand. Table 17-3 summarizes some rules of thumb to estimate the fire resistance ratings for walls based on some common construction materials.

Table 17-3. Typical Fire Resistance of Walls

Material	**Thickness (inches) and Construction Details**	**Fire Resistance (Hours)**
Brick	12, all materials	10
	8, sand and lime	7
	8, clay and shale	5
	8, concrete	6
	4, clay and shale	1¼
	4, concrete, sand, and lime	1½
Hollow partition tile	12, two 6-in. tiles	4
	12, unknown number of cells	3
	8, all tile arrangements	2
Concrete block	16 nominal, 15⅝ actual	4
	12 nominal. 11⅝ actual	3
	8 nominal, 7⅝ actual	1¾

A fire wall is defined as a wall that separates buildings or subdivides buildings and is intended to prevent the spread of fire, by providing fire resistance and structural stability. A fire barrier is a wall that extends to the roof or floor deck above and is intended to restrict the spread of fire by providing fire resistance.

In addition to proper structural design, other design considerations are required to maintain the integrity of the subdividing fire wall or fire barriers, as follows:

- routing of pipes, conduits, and cables to floor level to help prevent the fire wall from being damaged by collapse on either side
- fire-resistant penetration seals at pipes, conduits, cable trays, and HVAC penetrations
- fire doors for personnel or vehicle openings
- fire resistant exterior wing walls at the ends of the fire walls to prevent fire from spreading around its ends
- provision of a parapet, which consists of the fire wall penetrating the roof deck and extending above it

Some fire walls are designed to remain stable after the collapse of a building structure on either side in the event of an uncontrolled fire.

Fire walls must be designed for a minimum uniform lateral load of 5 pounds per square foot (psf) from either direction (applied perpendicular to the face of the wall). Where seismic loading governs, the design load may be considerably higher.

17.7 Fire Resistance Coatings for Structural Steel

Unprotected structural steel loses its strength at high temperatures and, therefore, must be protected from exposure to the heat generated by building fires. This protection, often referred to by the misnomer "fireproofing," insulates the steel from heat. As previously noted, the most common methods of insulating steel are encasement of the member, application of a surface treatment, or installation of a suspended ceiling as part of a floor-ceiling assembly capable of providing fire resistance. Additional methods include sheet steel membrane shields around members and box columns filled with liquid.

Encasement of structural steel members has been a common and satisfactory method of insulating steel to increase its fire resistance. In floor systems composed of reinforced concrete slabs supported by structural steel beams, the encasement can be placed within the floor. Figure 17-3 illustrates this old encasement technique. The major disadvantages of this procedure are the increased weight and cost, which are attributable to increased framework, concrete, and structural support. To reduce the weight and cost of encasement, surface treatment utilizing lath and plaster or gypsum board, or any of a variety of spray-on coatings have been developed, as shown in Figure 17-4. Sprayed-on mineral fiber coatings are widely used to protect structural steel. If applied correctly, such coatings provide excellent protection; however, the coating can easily be knocked off the member during construction or plant modification. Consequently, sprayed-on mineral coatings are suspect with regard to their effectiveness over long-term use.

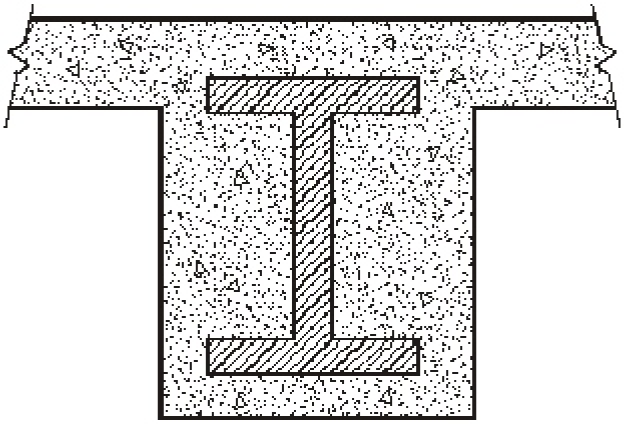
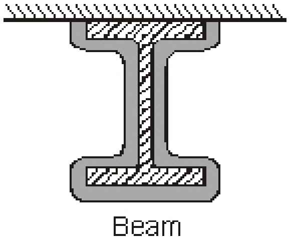
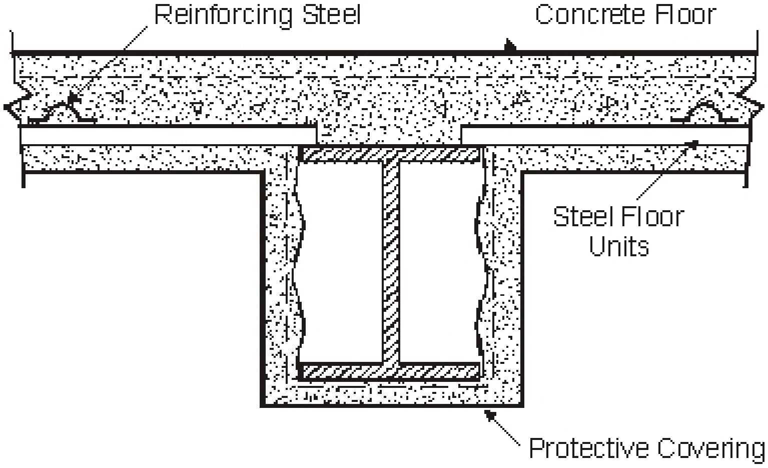


Figure 17-3 Encasement of a Steel Beam by Monolithic Casting of Concrete Around the Beam



Spray-on Fire Proofing



Furred Steel Beams with Non-combustible Protection

Figure 17-4 Spray-On Mineral Fiber and Noncombustible Protective Coatings

Cementitious materials also have been used as sprayed-on coatings, despite the fact that they can spall during a fire and have experienced adhesion problems in actual use. Thus, effective application, complete coverage, and long-term maintenance are attributes that must be evaluated in considering the use of sprayed-on coatings.

The latest advancements have been made with intumescent paints and coatings. These coatings swell to many times their installed thickness when heated to form an insulation barrier which increases the fire endurance of the structural steel. They are primarily used for non-exposed steel subject to elevated temperatures, because prolonged exposure to flame can destroy the char coating.

17.8 Calculating Fire Resistance or Endurance

The traditional approach to structural fire protection is to specify the fire resistance or fire endurance ratings for construction classifications identified in the building codes. The individual fire resistance or endurance ratings are established by subjecting various structural members and assemblies to the standard fire test (ASTM E119 or NFPA 251, "Standard Methods of Tests of Fire Endurance of Building Construction and Materials").[1]

During the past three decades, a substantial amount of research has conducted to develop and validate computer models of the mechanical and thermal properties of structural members, as well as compartment fire behavior, heat transfer, and structural performance at elevated temperatures. These studies have resulted in more realistic predictions of structural behavior in fires than was possible with the traditional code and standard fire test procedures of the past.

As a result, several empirically derived correlations are available to calculate the fire resistance of steel columns, beams, and trusses. The correlations are based on curve-fitting techniques using data gathered by performing the standard test numerous times on variations of a standard assembly. In some cases, a best-fit line has been drawn for the data point; in other cases, lines have been drawn conservatively to estimate the fire resistance by connecting the two lowest points. Numerical methods are also available to estimate the temperature increase in steel structural elements. The equations in these methods are derived from simplified heat transfer approaches.

Compared to the traditional test approaches, modern calculation methods offer the advantages of economy and better predictability. These calculation methods calculate either (1) the fire resistance or endurance that would have been obtained in the standard fire test or (2) structural or thermal performance in an actual building fire compartment.

17.8.1 Equivalent Fire Resistance of Structural Steel

Fire testing of the structural steel has been ongoing for many years and has yielded substantial data and experience. The procedures described in the following subsections reflect the methods for calculating equivalent fire resistance. It should be noted that many of these calculation methods are obtained from test data. Consequently, one should be cautious when applying these methods to materials that have not been used in the tests that form the basis for the calculation methods. For example, the data for structural steel are based on testing of A7 and A36 structural steel, which have different mechanical properties at both normal and elevated temperatures than the high-strength steels that have become popular in recent years. Consequently, when we use the term structural steel for fire resistance calculations in this section, we mean A7 and A36 steels.

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[1] ASTM E119 and NFPA 251 utilize virtually identical testing methods.

17.8.2 Steel Column (Unprotected)

In general, unprotected steel columns of small cross-sectional area have a fire resistance of not more than 10–20 minutes (ASCE, 1992). However, heavier columns are capable of much better fire performance. Figure 17-2 illustrates typical sections of unprotected structural steel columns. Based on theoretical and experimental studies, the following formulae have been developed for calculating the fire resistance of unprotected steel columns (Milke, 1995):

$$R = 10.3\left(\frac{W}{D}\right)^{0.7} \text{for} \frac{W}{D} < 10 \qquad (17\text{-}1)$$

and

$$R = 8.3\left(\frac{W}{D}\right)^{0.8} \text{for} \frac{W}{D} \geq 10 \qquad (17\text{-}2)$$

Where:

R = fire resistance time (minutes)
W = weight of steel column per linear foot (lb/ft)
D = heated perimeter (in) as shown in Figure 17-5

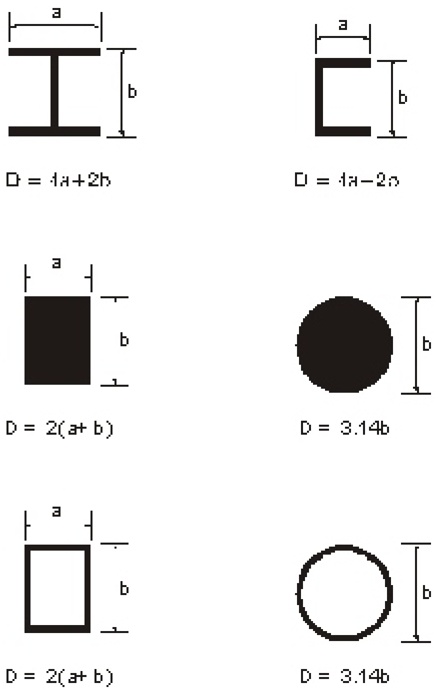


Figure 17-5 Sections of Unprotected Steel Columns

The fire resistance or endurance of structural steel columns can be improved by insulating the members. The next few subsections discuss the fire resistance of steel members protected by various insulation materials.

17.8.3 Steel Column (Protected with Gypsum Wallboard)

A common protective method is to box in steel columns using gypsum wallboard. Based on the accumulated fire-test results, the following empirical equation has been developed to determine resistance or endurance of steel columns protected by gypsum wallboard (Milke, 1995):

$$R = 130\left(\frac{h}{2}\frac{W'}{D}\right)^{0.75} \qquad (17\text{-}3)$$

Where:

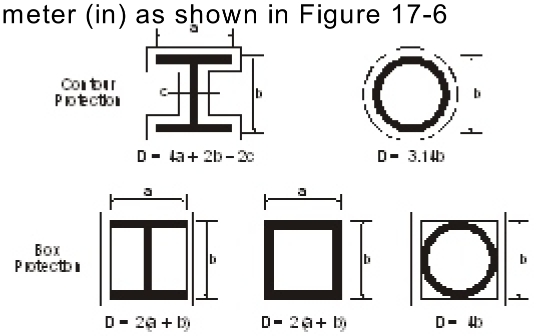
R = fire resistance time (minutes)
h = thickness of protection (in)
W' = weight of steel column and gypsum wallboard protection per foot of length (lb/ft)
D = heated perimeter (in) as shown in Figure 17-6

The following formula can be used to derive the total weight of both the column and its gypsum wallboard protection (W'):

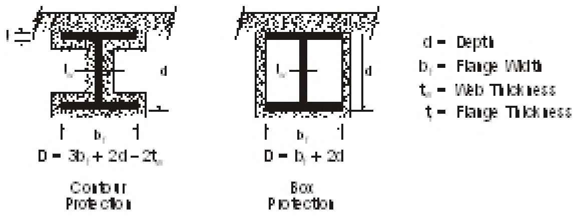
$$W' = W + \frac{50hD}{144} \qquad (17\text{-}4)$$

Where:

W' = weight of steel column and gypsum wallboard protection per foot of length (lb/ft)
W = weight of steel column per linear foot (lb/ft)
h = thickness of protection (in).
D = heated perimeter (in) as shown in Figure 17-6



(a) Heated Perimeters for Columns



(b) Heat Perimeters for Beams

Figure 17-6 Heat Perimeters for Common Column and Beam Shapes

To improve the structural integrity during exposure to fire, gypsum wallboard can be reinforced with inorganic fiber. Such reinforced gypsum wall board is usually classified by the accredited testing laboratories, such as Underwriters Laboratories (UL) in North America.

17.8.4 Steel Column (with Low-Density Protection)

Based on experimental and theoretical studies, the following expression has been derived for the fire resistance of steel sections protected by light (low-density) insulating materials (Milke, 1995):

$$R = \left(C_1 \frac{W}{D} + C_2 \right) h \qquad (17\text{-}5)$$

Where:

R = fire resistance (minutes)
C_1, C_2 = material constants that are known for a specific protecting material
W = weight of steel column per linear foot (lb/ft)
D = heated perimeter (in) as shown in Figure 17-6
h = thickness of protection (in)

As noted above, the material constants $C_1$and C_2 are specific to a given protection material. For cases in which the values of $C_1$and C_2 are not known, conservative assessment of the fire resistance of protected steel columns can be conservatively assessed using the following equations (ASCE, 1992):

For protection material with a density ( ) of 20 < $\leq$ 50 lb/ft^3

$$R = \left(1200 \frac{W}{D\rho} + 30 \right) h \qquad (17\text{-}6)$$

Equation 17-6 applies to protections consisting of chemically stable materials, such as vermiculite, perlite, and sprayed material fiber with various binders, and dense mineral wool.

$$R = \left(1200 \frac{W}{D\rho} + 72 \right) h \qquad (17\text{-}7)$$

Equation 17-7 applies to protections consisting of cement pastes or gypsum, such as cementitious mixtures and plasters.

Where:

R = fire resistance (minutes)
W = weight of steel section per linear foot (lb/ft)
D = heated perimeter (in) shown in Figure 17-6
= density of protected material (lb/ft^3)
h = thickness of protection (in)

For protection material with a density ( ) of 10 ≤   ≤ 20 lb/ft^3

$$R = \left(45\frac{W}{D} + 30\right)h \qquad (17\text{-}8)$$

Equation 17-8 applies to small round and square columns (less than 6 in.) and thick protection (h ≥ 1.5 in.).

$$R = \left(60\frac{W}{D} + 30\right)h \qquad (17\text{-}9)$$

Equation 17-9 applies to any shape, sizes, and thickness of protection.

Where:

R = fire resistance (minutes)
W = weight of steel section per linear foot (lb/ft)
D = heated perimeter (in) as shown in Figure 17-6
  = density of protected material (lb/ft^3)
h = thickness of protection (in)

17.8.5 Steel Column (Protected with Spray-On Materials)

The American Iron and Steel Institute (AISI, 1980) has developed the following formula for two types of spray-on low-density fire protection known as cementitious and mineral fiber insulation:

Cementitious insulation

$$R = \left(69\frac{W}{D} + 31\right)h \qquad (17\text{-}10)$$

Mineral fiber insulation

$$R = \left(63\frac{W}{D} + 42\right)h \qquad (17\text{-}11)$$

Where:

R = fire resistance (minutes)
W = weight of steel column per linear foot (lb/ft)
D = heated perimeter (in) as shown in Figure 17-6
h = thickness of protection (in)

17.8.6 Steel Column (Protected by Concrete)

Concrete encasement is another means of protecting for steel columns. The following empirical formulae have been developed to predict the fire resistance of concrete encased steel columns:

Normal weight concrete protection of uniform thickness on all sides and square shape

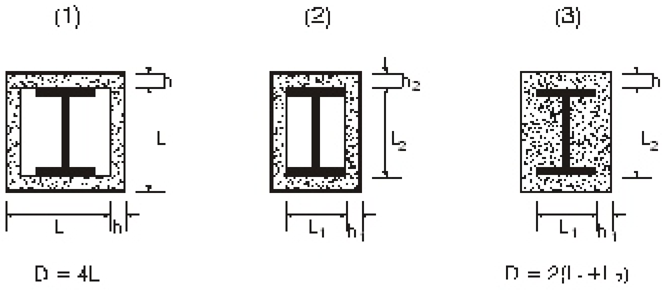
$$R = 11\left(\frac{W}{D}\right)^{0.7} + 19h^{1.6}\left[1 + 94\left(\frac{H}{\rho_c h(L+h)}\right)^{0.8}\right] \qquad (17\text{-}12)$$

Lightweight concrete protection

$$R = 11\left(\frac{W}{D}\right)^{0.7} + 23h^{1.6}\left[1 + 94\left(\frac{H}{\rho_c h(L+h)}\right)^{0.8}\right] \qquad (17\text{-}13)$$

Where:

R = fire resistance time at equilibrium moisture condition, here assumed to be 4-percent of the concrete by volume (minutes)
W = weight of steel column per linear foot (lb/ft)
D = developed heated perimeter of steel columns (in) shown in Figure 17-7
h = thickness of concrete protection (in)
H = thermal capacity of steel section at ambient temperature (0.11W Btu/ft-°F)
$_c$ = density of concrete at ambient temperature (lb/ft^3)
L = interior dimension of one side of square concrete box protection (in) (see note if the box protection is not square).



(1) Square shape protection with a uniform thickness of concrete cover on all sides
(2) Rectangular shape with varying thickness of concrete cover
(3) Encasement having all re-entrant spaces filled with concrete

Figure 17-7 Concrete-Protected Structural Steel Columns

Notes:

(1) If the concrete box protection is not square, or if the concrete cover thickness is not constant, h and L are taken as average values [i.e., $h = ½ (h_1 + h_2)$ and $L = ½ (L_1 + L_2)$.]

(2) If the steel column is completely encased in concrete, with all re-entrant spaces filled, the thermal capacity of the concrete within the re-entrant space may be added to the thermal capacity of the steel column, thereby increasing the value of H as follows:

$$H = 0.11W + \frac{\rho_c}{720}\left(L_1 L_2 - A_s\right) \qquad (17\text{-}14)$$

Where:

H = thermal capacity of steel section at ambient temperature (0.11W Btu/ft-°F)
W = weight of steel column per linear foot (lb/ft)
$_c$ = density of concrete at ambient temperature (lb/ft^3)
L_1 = steel column flange width (in)
L_2 = depth of steel column (in)
A_s = cross-sectional areas of steel column (in^2)

17.8.7 Steel Beams

When a beam is fire tested alone or as a part of a floor or roof assembly, it expands as it is heated. Floor test furnaces encase the specimen in a rigid restraining frame. If the beam is built tightly into the frame, the frame resists its expansion and moments are generated in the beam. The critical temperature of beams is much better understood and has limits of 593 °C (1,100 °F) when the beam is tested as part of an assembly, and 538 °C (1,000 °F) when the beam is tested alone.

W/D concepts can also be applied to assess protection requirements for steel beams in both restrained and unrestrained assemblies. To determine the fire resistance of steel beams protected by low-density protection, we can use the same formulae as for steel columns (Equations 17-5 through 17-11), as shown in Figure 17-6.

In the case of beams, only three sides of the beam are exposed to fire Figure 17-6b. The top of the beam is assumed to be a floor or roof slab, made of a perfectly insulating material. Thus, there is no heat exchange between the floor or roof slab and the steel. Because only three sides of the beam are exposed to heat, the values of the heated perimeter (D) of beams in these formulas are smaller than those of the corresponding column. As a result, the fire resistance of a beam, (i.e., the time to reach a specific failure temperature in the steel) is longer than that for a column. In addition, because the floor or roof on the top of the beam normally absorbs heat transmitted through the beam, which is not taken into account in the formulae the fire resistance calculated using these formulae, are more conservative for beams than for columns.

17.8.7.1 Beam Substitution Correlation for Structural Steel Beams Protected by Spray-On Materials

For beams protected by spray-on protections, the International Committee for the Study and Development of Tubular Structures (ICSDTS) (1976) has developed a scaling formula that enables substitution of one beam for another by varying the thickness of the protection.

Provided the deck is the same and D is calculated only for three-sided exposure, the following beam substitution equation has achieved code acceptance (Milke, 1995, and UL, 1995):

$$h_1 = \left(\frac{\frac{W_2}{D_2} + 0.6}{\frac{W_1}{D_1} + 0.6} \right) h_2 \qquad (17\text{-}15)$$

Where:

h = thickness of spray-applied protection (in)
W = weight of the structural beam per linear foot (lb/ft); see note
D = heated perimeter of the beam (in) as shown in Figure 17-6; see note

Note: h_1, W_1, and D_1 refer to the substitute (unrated) beam and required thickness of fire protection material.

h_2, W_2, and D_2 refer to the beam and fire protection thickness in the approved assembly (rated beam).

Use of above the equation is subject to the following limitations:

- The unrestrained beam in the tested design has a rating of not less than 1-hour.
- The equation is limited to beams with a weight-to-heated-perimeter ratio (W/D) of 0.37 or greater.
- The thickness of the spray-on protection (h_1) cannot be less than 0.95 cm (⅜ inch).

The above equation pertains only to the determination of the protection thickness for a beam in a floor or roof assembly.

17.8.7.2 Column Substitution Correlation for Structural Steel Columns Protected by Spray-On Materials

A scaling substitution correlation has also been developed to calculate the required thickness of spray-on protection for columns (UL, 1995) as follows:

$$h_2 = 1.25h_1\left(\frac{W_1}{D_1}\right)\left(\frac{D_2}{W_2}\right) \qquad (17\text{-}16)$$

Where:

h_1 = thickness of spray-on protection on the approved assembly (rated column), (in)
h_2 = required thickness of spray-on protection on substitute column (in) (smaller wide flange section)
W_1 = weight of the structural column per linear foot for the approved assembly (rated column (lb/ft)
W_2 = weight of the structural column per linear foot for the smaller wide flange section (lb/ft)
D_1 = heated perimeter of the column (in), for the approved assembly (rated column) as shown in Figure 17-6
D_2 = heated perimeter of the column (in) for the smaller wide flange section as shown in Figure 17-6

Use of the above column substitution correlation is subject to following limitations:

- The unrestrained beam in the tested design has a rating of not less than 1-hour.
- The equation is limited to beams with a weight-to-heated-perimeter ratio (W/D) of 0.95 cm (⅜ inch) or greater.
- The thickness of the spray-on protection (h_1) cannot be less than 0.95 cm (⅜ inch).

17.8.8 Numerical Method to Estimate the Temperature Increase in Structural Steel Elements

For structural steel elements, there is a critical temperature at which the steel loses so much strength that it can no longer support its design load. In such cases, calculations of the fire resistance of the steel members can be reduced to calculating the temperature of the steel. North American standards assume that the critical temperature condition is reached when the average temperature in a steel section reaches 538 °C (1,000 °F).

The simple numerical method is based on the principle that the heat entering the steel over the exposed surface area in a small time step, t (sec), is equal to the heat required to raise the temperature of the steel by T_s (°C or °F), assuming that the steel section is a lumped mass at uniform temperature. This numerical method can be further simplified by considering the steel to be a heat sink, with negligible resistance to heat flow; thus, any heat supplied to the steel section is considered to be instantly distributed to give a uniform steel temperature.

17.8.8.1 Unprotected Structural Steel Sections

The following equation calculates the temperature development of an unprotected steel member, using a quasi-stationary approach, iterated for successive time steps of t (sec):

$$\Delta T_s = \frac{F}{V}\frac{1}{\rho_s c_s}\left[h_c\left(T_f - T_s\right)+\sigma\varepsilon\left(T_f^4 - T_s^4\right)\right]\Delta t \qquad (17\text{-}17)$$

Where:
T_s = temperature in the steel member (°F)
F/V = ratio of weight of steel section per linear foot and heated perimeter (m^{-1})
$_s$ = density of steel (kg/m^3)
c_s = specific heat of steel (J/kg-K)
h_c = convective heat transfer coefficient (W/m^2-/K)
= Stefan Boltzmann constant (kW/m^2-K^4)
= flame emissivity
c_s = specific heat of steel (Btu/lb-°F)
T_f = fire temperature (°F)
T_s = steel temperature (°F)
t = time step (sec)

Emissivities for various types of construction are given in Table 17-4 (Buchanan 2001).

Table 17-4. Resultant Emissivity for Different Types of Construction

Type of Construction	**Resultant Emissivity**
Column exposed to fire on all sides	0.7
Column outside facade	0.3
Floor girder with floor slab of concrete (only the underside of the bottom flange being directly exposed to fire)	0.5
Floor girder with floor slab on the top flange girder of I section for which the width-depth ratio is not less than 0.5	0.5
Girder of I section for which the width-depth ratio is less than 0.5	0.7
Box girder and lattice girder	0.7

The fire temperature (T_f) is evaluated at the midpoint of each time step. If the exposure under consideration is that associated with the ASTM E119 test, T_f at any time (t) is obtained from the following expression:

$$T_f = C_1 LOG(0.133t + 1) + T_a \qquad (17\text{-}18)$$

Where:

C_1 = 620 with a fire temperature T_f
T_a = ambient temperature (°F) (Milke, 1995)

The maximum time step (t) can be determined from the following relationship (Molhotra, 1982):

$$\Delta t > 15.9\frac{W}{D} \text{ (English units)} \qquad (17\text{-}19)$$

Table 17-5 shows a spreadsheet for calculating steel temperature using this method (Buchanan, 2001). Kay et al., (1996) have shown that this type of calculation can give a good prediction of steel temperatures in standard fire resistance tests.

Table 17-5. Spreadsheet Calculation for the Temperature of Steel Sections (Buchanan, 2001)

Time	**Steel Temperature (T_s)**	**Fire Temperature (T_f)**	**Difference in Temperature**	**Change in Steel Temperature T_s)**
$t_1 =$ t	Initial steel temperature (T_{s0})	Fire temperature halfway through time step (at t/2)	T_f - T_{s0}	Calculate from Equation (17-17) with values of T_f and T_{s0} from this row
$t_2 = t_1 +$ t	T_s from previous time step + T_s from previous row	Fire temperature halfway through time step (at t_1 + t/2)	T_f - T_s	Calculate from Equation (17-17) with values of T_f and T_s from this row

17.8.8.2 Protected Structural Steel Sections

Protected steel members heat up more slowly than unprotected members because of the applied thermal insulation, which protects the steel from rapid absorption of heat. The calculation method for protected steel members is similar to that for unprotected steel members. However, the equation is slightly different and does not require a heat transfer coefficient because it is assumed that the external surface of the insulation is at the same temperature as the fire gases, while the internal surface of the insulation is at the same temperature as the steel.

The thermal capacity of the insulation material may be neglected if the following inequality is true:

$$c_s \frac{W}{D} > 2c_i \rho_i h \qquad (17\text{-}20)$$

Where:

W/D = ratio of weight of steel section per linear foot and heated perimeter (lb/ft^2)
c_i = specific heat of insulation (Btu/lb-°F)
$_i$ = density of insulation (lb/ft^3)
h = thickness of insulation (in)

If the thermal capacity of the insulation layer is neglected, the temperature rise in the structural steel element can be calculated using the following equation:

$$\Delta T_s = k_i \left(\frac{(T_f - T_s)}{c_s h \frac{W}{D} + \frac{1}{2} c_i \rho_i h^2} \right) \Delta t \qquad (17\text{-}21)$$

Where:

T_s = temperature increase in steel (°F)
k_i = thermal conductivity of insulation material (Btu/ft-hr-°F)
$_i$ = density of insulation (lb/ft^3)
c_i = specific heat of insulation material (Btu/lb-°F)
c_s = specific heat of steel (Btu/lb-°F)
h = thickness of insulation (in)
W/D = ratio of weight of steel section per linear foot and heated perimeter (lb/ft^2)
T_f = fire temperature (°F)
T_s = steel temperature (°F)
t = time step (sec)

If the thermal capacity of the insulating material must be accounted for, as in the case of gypsum and concrete insulating materials, Equation 17-21 can be modified as follows:

$$\Delta T_s = \frac{k_i}{h}\left(\frac{T_f - T_s}{c_s \frac{W}{D} + \frac{1}{2} c_i \rho_i h}\right)\Delta t \qquad (17\text{-}22)$$

The fire temperature (T_f) is evaluated at the midpoint of each time step. If the exposure under consideration is that associated with the ASTM E119 test, T_f at any time (t) is obtained from the following expression:

$$T_f = C_1 \mathrm{LOG}(0.133t + 1) + T_a \qquad (17\text{-}23)$$

Where:

C_1 = 620 with a fire temperature T_f
T_a = ambient temperature (°F) (Milke, 1995)

The maximum time step (t) can be determined from the following relationship (Molhotra, 1982):

$$\Delta t > 15.9\frac{W}{D} \text{ (English units)} \qquad (17\text{-}24)$$

Table 17-6 summarizes the typical thermal properties of various insulation materials.

Table 17-6. Thermal Properties of Insulation Materials (Buchanan, 2001)

Insulation Material	**Density** $_i$ **(lb/ft^3)**	**Thermal Conductivity** k_i **(Btu/ft-hr-°F)**	**Specific Heat** c_i **(Btu/lb-°F)**
Sprays			
Sprayed mineral fiber	19	0.06936	0.2868
Perlite or vermiculite plaster	22	0.06936	0.2868
High-density perlite or vermiculite plaster	35	0.06936	0.2868
Boards			
Fiber-silicate or fiber-calcium silicate	38	0.0867	0.2868
Gypsum plaster	50	0.1156	0.4063
Compressed fiber board			
Mineral wool or fiber silicate	10	0.1156	0.2868

The spreadsheets for calculating steel temperature using this method are based on Table 15-5 (Buchanan, 2001).

17.9 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations:

(1) The heat transfer analysis is one dimensional.
(2) Correlations are based on the analysis of data resulting from performing the standard test numerous times, using curve-fitting techniques to establish the various correlations.
(3) As the structural member heats up, its structural properties can change substantially.
(4) Equation-specific limitations apply (see the various equations throughout this chapter).

17.10 Required Input for Spreadsheet Calculations

The user must obtain the following information to using the spreadsheet:
(1) dimensions of the steel member in question
(2) thermal properties of the applied insulation

17.11 Cautions

(1) Use the appropriate spreadsheet:
(17.1_FR_Beams_Columns_Substitution_Correlation.xls,
17.2_FR_Beams_Columns_Quasi_Steady_State_Spray_Insulated.xls,
17.3_FR_Beams_Columns_Quasi_Steady_State_Board_Insulated.xls,
or 17.4_FR_Beams_Columns_Quasi_Steady_State_Uninsulated.xls)
on the CD-ROM for calculating the fire resistance of structural steel members.
(2) Make sure you are on the correct page of the spreadsheet (for columns or beams).
(3) Make sure to enter all input parameters using the correct units.
(4) Equation (23) is only valid up to 1,000 °F (538 °C) where the carbon steel structural members begin to fail. Predicted temperatures above 1,000 °F (538 °C) are neither accurate nor valid.

17.12 Summary

The fire resistance/endurance of the beams, girders, and columns that comprise the structural frame of the walls, partitions, floor/ceiling assemblies, and roof/ceiling assemblies that serve as barriers to flame movement have been a historical basis for classifying buildings and rating frame and barrier capabilities.

The selection of building materials and the design details of construction have always played an important role in building fire safety. Two of the important structural fire considerations are the ability of the structural frame to avoid collapse and the ability of the barrier to prevent ignition and resulting flame spread into adjacent spaces.

Heat transfer analyses are applied to determine the time period required to heat structural members to a specified critical temperature. The required time period is then defined as the fire resistance/endurance time of the member.

The critical temperature of a structural member can be determined by referring to the temperature endpoint criteria cited in ASTM E119 or by a structural assessment, as discussed in this chapter.

17.13 References

AISI, *Designing Fire Protection for Steel Columns*, 3rd Edition, American Iron and Steel Institute, Washington, DC, 1980.

ASCE Manuals and Reports on Engineering Practice, No. 78, “Structural Fire Protection,” Lie, Editor, American Society of Civil Engineers, New York, 1992.

ASTM E119, “Standard Test Methods for Fire Tests of Building Construction and Materials,” ASTM Fire Test Standard, 5th Edition, American Society of Testing and Materials, West Conshohocken, Pennsylvania, pp. 793–813, 1999.

Buchanan, A.H., *Structural Design for Fire Safety*, John Wiley & Sons Limited, New York, 2001.

International Committee for the Study and Development of Tubular Structure, (ICSDTS), 1976.

Kay, T.R., R.B. Kirby, and R.P. Preston, “Calculation of Heating Rate of an Unprotected Steel Member in a Standard Fire-Resistance Test,” *Fire Safety Journal*, Volume 26, pp. 327–350, 1996.

Milke, J,A., “Analytical Methods for Determining Fire Resistance of Steel Members,” Section 4, Chapter 9, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

Molhotra, H.L., *Design of Fire-Resisting Structures*, Chapman and Hall, 1982.

Neville, A.M., *Properties of Concrete*, Pitman Publishing Limited, 1975.

NFPA 221, “Standard for Fire Walls and Fire Barrier Walls,” 2000 Edition, National Fire Protection Association, Quincy, Massachusetts.

NFPA 251, “Standard Methods of Tests of Fire Endurance of Building Construction and Materials,” 1999 Edition, National Fire Protection Association, Quincy, Massachusetts.

UL Fire Resistance Directory, Volume 1, Underwriters Laboratories, Inc., Northbrook, Illinois, p. 19, 1995.

17.14 Problems

Example Problem 17.14-1

Problem Statement
Calculate the thickness of spray-on fire protection required to provide a 2-hour fire resistance for a W12 x 16 beam to be substituted for a W8 x 18 beam requiring 1.44 in. of protection for the same rating.

Solution

Purpose:

(1) Estimate the spray-on thickness required for the beam substitution.

Assumptions:

(1) The 1.44 in. of spray-on provides the W8 x 18 beam 2 hours of fire resistance.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 17.1_FR_Beams_Columns_Substitution_Correlation.xls
(click on Beam)

FDT^s Input Parameters:

-Known beam insulation thickness
-Select W8 x 18 for Rated Beam
-Select W12 x 16 for Substitute Beam

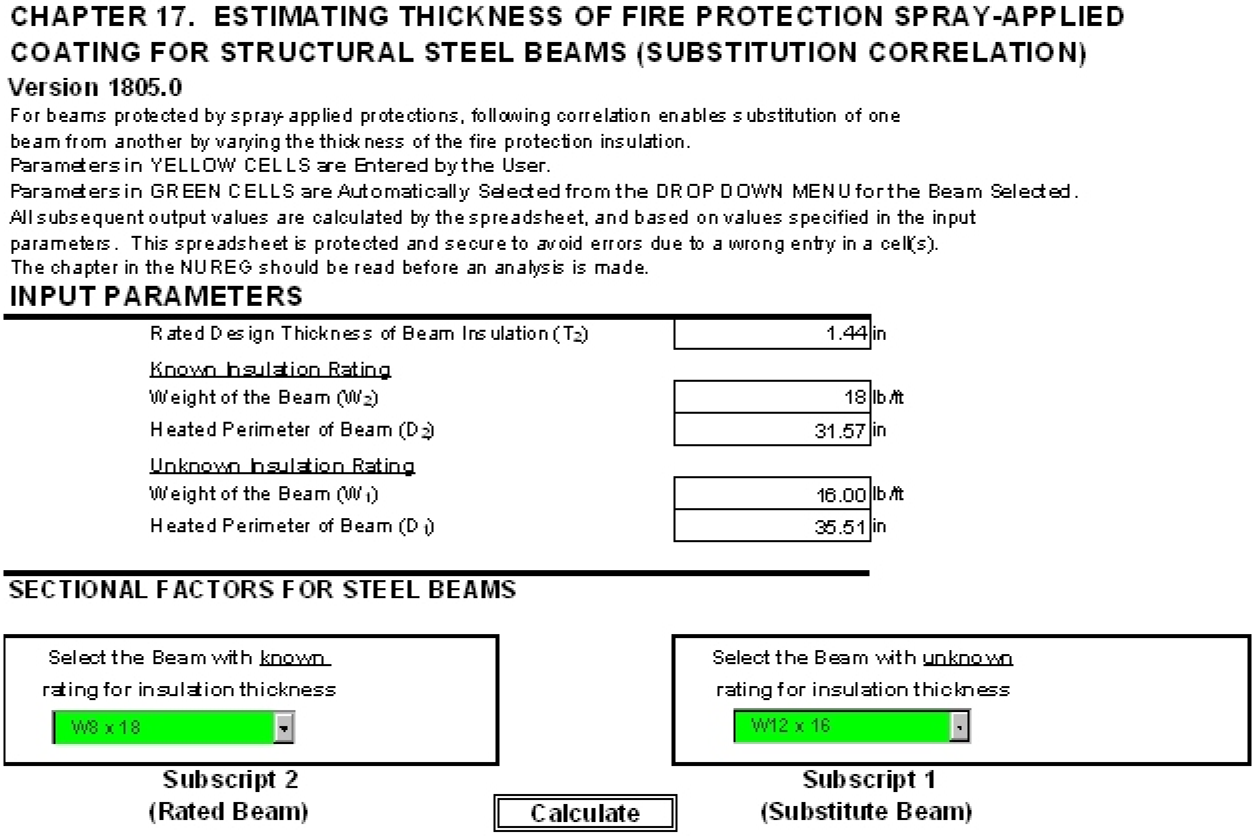
Results*

Substitute Beam Spray on Thickness	1.6 in

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 17.1_FR_Beams_Columns_Substitution_Correlation.xls (Beam)



CHAPTER 17. ESTIMATING THICKNESS OF FIRE PROTECTION SPRAY-APPLIED COATING FOR STRUCTURAL STEEL BEAMS (SUBSTITUTION CORRELATION)

Version 1805.0

For beams protected by spray-applied protections, following correlation enables substitution of one beam from another by varying the thickness of the fire protection insulation.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Beam 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

Rated Design Thickness of Beam Insulation (T_2)	1.44	in
Known Insulation Rating		
Weight of the Beam (W_2)	18	lb/ft
Heated Perimeter of Beam (D_2)	31.57	in
Unknown Insulation Rating		
Weight of the Beam (W_1)	16.00	lb/ft
Heated Perimeter of Beam (D_1)	35.51	in

SECTIONAL FACTORS FOR STEEL BEAMS

Select the Beam with known rating for insulation thickness

W8 x 18

Subscript 2
(Rated Beam)

Select the Beam with unknown rating for insulation thickness

W12 x 16

Subscript 1
(Substitute Beam)

ESTIMATING THICKNESS OF FIRE PROTECTION INSULATION ON UNRATED BEAM

Reference: *UL Fire Resistance Directory, Volume 1, 1995, Page 19.*

$T_1 = ((W_2/D_2 + 0.6)\,T_2)/(W1/D_1 + 0.6)$

Where

T_1 = calculated thickness of fire protection insulation on unrated beam (in)

T_2 = design thickness of insulation on rated beam (in)

W_1 = weight of beam with unknown insulation rating (lb/ft)

W_2 = weight of design rated beam (lb/ft)

D_1 = heated perimeter of unrated beam (in)

D_2 = heated perimeter of the rated beam (in)

Required Equivalent Thickness of Fire Protection Insulation on Unrated Beam

$T_1 = ((W_2/D_2 + 0.6)\,T_2)/(W1/D1 + 0.6)$

T_1 = 1.60 in **Answer**

Beams with a larger W/D ratio can always be substituted for the structural member listed with a specific fire resistive covering without changing the thickness of the covering.

NOTE

The above calculations are based on method developed in the UL Fire Resistance Directory, Volume 1, 1995. 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.

Example Problem 17.14-2

Problem Statement

Use the quasi-steady-state heat transfer approach to determine the fire resistance of a W24 x 76 steel beam protected with 0.5 in. of spray-on mineral fiber material. Sprayed-on mineral fiber has the following thermal properties:

- Thermal Conductivity, k_i = 0.06936 Btu/ft-hr-°F
- Specific Heat, c_i = 0.2868 Btu/lb-°F
- Density, $_i$ =19.0 lb/ft^3

Solution

Purpose:

(1) Estimate the fire resistance of the beam.

Assumptions:

(1) The heat transfer is quasi-steady-state.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 17.2_FR_Beams_Columns_Quasi_Steady_State_Spray_Insulated.xls
(click on Beam)

FDT^s Input Parameters:

-Select W24 x 76 beam
-Enter 0.5 in spray-on thickness
-Select “Sprayed Mineral Fiber” from Insulation Type drop-down menu

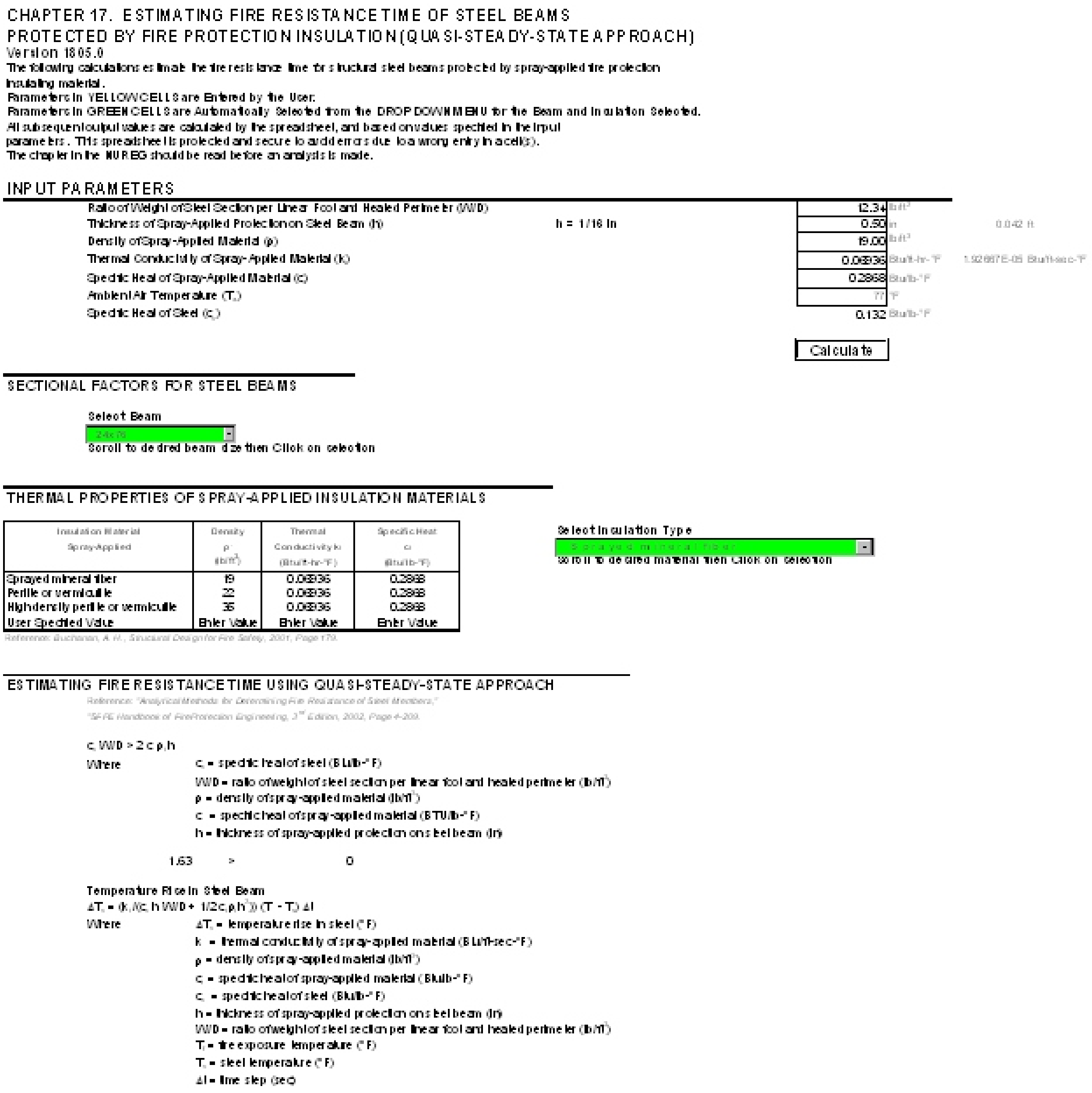
Results*

Fire Resistance	42.5 min

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 17.2_FR_Beams_Columns_Quasi_Steady_State_Spray_Insulated.xls



CHAPTER 17. ESTIMATING FIRE RESISTANCE TIME OF STEEL BEAMS PROTECTED BY FIRE PROTECTION INSULATION (QUASI-STEADY-STATE APPROACH)

Version 1805.0

The following calculations estimate the fire resistance time for structural steel beams protected by spray-applied fire protection insulating material.

Parameters in YELLOW CELLS are Entered by the User.

Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Beam and Insulation 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

Ratio of Weight of Steel Section per Linear Foot and Heated Perimeter (W/D)		12.34	lb/ft²		
Thickness of Spray-Applied Protection on Steel Beam (h)	h = 1/16 in	0.50	in	0.042	ft
Density of Spray-Applied Material (ρ)		19.00	lb/ft³		
Thermal Conductivity of Spray-Applied Material (k)		0.06936	Btu/ft-hr-°F	1.92667E-05	Btu/ft-sec-°F
Specific Heat of Spray-Applied Material (c)		0.2868	Btu/lb-°F		
Ambient Air Temperature (T_a)		77	°F		
Specific Heat of Steel (c_s)		0.132	Btu/lb-°F		

Calculate

SECTIONAL FACTORS FOR STEEL BEAMS

Select Beam

24x76

Scroll to desired beam size then Click on selection

THERMAL PROPERTIES OF SPRAY-APPLIED INSULATION MATERIALS

Insulation Material Spray-Applied	Density ρ (lb/ft³)	Thermal Conductivity k (Btu/ft-hr-°F)	Specific Heat c (Btu/lb-°F)
Sprayed mineral fiber	19	0.06936	0.2868
Perlite or vermiculite	22	0.06936	0.2868
High density perlite or vermiculite	35	0.06936	0.2868
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: Buchanan, A. H., *Structural Design for Fire Safety*, 2001, Page 179.

Select Insulation Type

Sprayed mineral fiber

Scroll to desired material then Click on selection

ESTIMATING FIRE RESISTANCE TIME USING QUASI-STEADY-STATE APPROACH

Reference: "Analytical Methods for Determining Fire Resistance of Steel Members," *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 4-209.

$c_s W/D > 2 c_i \rho_i h$

Where
- c_s = specific heat of steel (Btu/lb-°F)
- W/D = ratio of weight of steel section per linear foot and heated perimeter (lb/ft²)
- ρ_i = density of spray-applied material (lb/ft³)
- c_i = specific heat of spray-applied material (BTU/lb-°F)
- h = thickness of spray-applied protection on steel beam (in)

1.63 > 0

Temperature Rise in Steel Beam

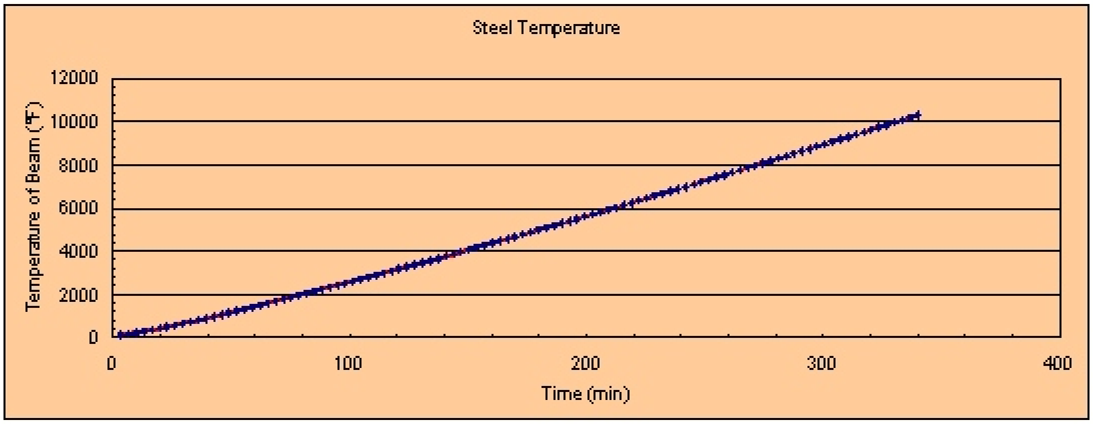
$\Delta T_s = (k_i/(c_s h W/D + 1/2 c_i \rho_i h^2)) (T_f - T_s) \Delta t$

Where
- ΔT_s = temperature rise in steel (°F)
- k_i = thermal conductivity of spray-applied material (Btu/ft-sec-°F)
- ρ_i = density of spray-applied material (lb/ft³)
- c_i = specific heat of spray-applied material (Btu/lb-°F)
- c_s = specific heat of steel (Btu/lb-°F)
- h = thickness of spray-applied protection on steel beam (in)
- W/D = ratio of weight of steel section per linear foot and heated perimeter (lb/ft²)
- T_f = fire exposure temperature (°F)
- T_s = steel temperature (°F)
- Δt = time step (sec)

Results

Time (min)	Time (sec)	ΔT$_s$ (°F)	T$_s$ (°F)	
3.3	196	40	117	
6.5	392	53	170	
9.8	588	60	230	
13.1	785	65	294	
16.3	981	68	362	
19.6	1177	71	433	
22.9	1373	73	506	
26.2	1569	75	581	
29.4	1765	77	658	
32.7	1961	78	737	
36.0	2158	80	817	
39.2	2354	81	898	
42.5	2550	82	980	
45.8	2746	83	1063	Failure of Beam
49.0	2942	84	1148	Failure of Beam
52.3	3138	85	1233	Failure of Beam
55.6	3334	86	1319	Failure of Beam
58.8	3531	87	1406	Failure of Beam
62.1	3727	88	1494	Failure of Beam
65.4	3923	89	1583	Failure of Beam
68.6	4119	89	1672	Failure of Beam
71.9	4315	90	1762	Failure of Beam
75.2	4511	91	1853	Failure of Beam
78.5	4707	91	1944	Failure of Beam
81.7	4904	92	2036	Failure of Beam
85.0	5100	92	2128	Failure of Beam
88.3	5296	93	2221	Failure of Beam
91.5	5492	93	2315	Failure of Beam
94.8	5688	94	2409	Failure of Beam
98.1	5884	94	2503	Failure of Beam
101.3	6080	95	2598	Failure of Beam
104.6	6277	95	2693	Failure of Beam
107.9	6473	96	2789	Failure of Beam
111.1	6669	96	2885	Failure of Beam
114.4	6865	97	2982	Failure of Beam
117.7	7061	97	3079	Failure of Beam
121.0	7257	97	3177	Failure of Beam
124.2	7453	98	3275	Failure of Beam
127.5	7650	98	3373	Failure of Beam
130.8	7846	99	3471	Failure of Beam
134.0	8042	99	3570	Failure of Beam
137.3	8238	99	3670	Failure of Beam
140.6	8434	100	3769	Failure of Beam
143.8	8630	100	3869	Failure of Beam
147.1	8826	100	3969	Failure of Beam
150.4	9023	101	4070	Failure of Beam
153.6	9219	101	4171	Failure of Beam
156.9	9415	101	4272	Failure of Beam
160.2	9611	102	4374	Failure of Beam
163.5	9807	102	4476	Failure of Beam
166.7	10003	102	4578	Failure of Beam
170.0	10199	102	4680	Failure of Beam

Time (min)	Time (sec)	ΔT$_s$ (°F)	T$_s$ (°F)	
173.3	10396	103	4783	Failure of Beam
176.5	10592	103	4886	Failure of Beam
179.8	10788	103	4989	Failure of Beam
183.1	10984	103	5092	Failure of Beam
186.3	11180	104	5196	Failure of Beam
189.6	11376	104	5300	Failure of Beam
192.9	11572	104	5404	Failure of Beam
196.1	11769	104	5508	Failure of Beam
199.4	11965	105	5613	Failure of Beam
202.7	12161	105	5718	Failure of Beam
205.9	12357	105	5823	Failure of Beam
209.2	12553	105	5928	Failure of Beam
212.5	12749	106	6034	Failure of Beam
215.8	12945	106	6139	Failure of Beam
219.0	13142	106	6245	Failure of Beam
222.3	13338	106	6352	Failure of Beam
225.6	13534	106	6458	Failure of Beam
228.8	13730	107	6565	Failure of Beam
232.1	13926	107	6671	Failure of Beam
235.4	14122	107	6778	Failure of Beam
238.6	14318	107	6885	Failure of Beam
241.9	14515	107	6993	Failure of Beam
245.2	14711	108	7101	Failure of Beam
248.4	14907	108	7208	Failure of Beam
251.7	15103	108	7316	Failure of Beam
255.0	15299	108	7424	Failure of Beam
258.3	15495	108	7533	Failure of Beam
261.5	15691	109	7641	Failure of Beam
264.8	15888	109	7750	Failure of Beam
268.1	16084	109	7859	Failure of Beam
271.3	16280	109	7968	Failure of Beam
274.6	16476	109	8077	Failure of Beam
277.9	16672	109	8186	Failure of Beam
281.1	16868	110	8296	Failure of Beam
284.4	17064	110	8406	Failure of Beam
287.7	17261	110	8516	Failure of Beam
290.9	17457	110	8626	Failure of Beam
294.2	17653	110	8736	Failure of Beam
297.5	17849	110	8846	Failure of Beam
300.8	18045	111	8957	Failure of Beam
304.0	18241	111	9067	Failure of Beam
307.3	18437	111	9178	Failure of Beam
310.6	18634	111	9289	Failure of Beam
313.8	18830	111	9400	Failure of Beam
317.1	19026	111	9512	Failure of Beam
320.4	19222	111	9623	Failure of Beam
323.6	19418	112	9734	Failure of Beam
326.9	19614	112	9846	Failure of Beam
330.2	19810	112	9958	Failure of Beam
333.4	20007	112	10070	Failure of Beam
336.7	20203	112	10182	Failure of Beam
340.0	20399	112	10294	Failure of Beam



The Failure Temperature for Steel Beams is Assumed at 1000 °F (538 °C)

NOTE

The above calculations are based on principles developed in the Society of Fire Protection Engineers (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.

UNITED STATES NUCLEAR REGULATORY COMMISSION

CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

18.1 Objectives

This chapter has the following objectives:

- Identify the hazard results of reduced visibility.
- Identify the factors that influence visibility.
- Describe the effects of smoke on nuclear power plants (NPPs).
- Explain how to calculate the visibility through smoke.

18.2 Introduction

As described in Chapter 9, smoke from a fire in a compartment rises in a plume to the ceiling. As the plume rises, air is entrained into it, thereby increasing the volume of smoke and reducing its temperature. The smoke spreads out beneath the ceiling and forms a layer that deepens as the compartment begins to fill with smoke. The production of smoke (smoke particulates) reduces visibility as a result of light absorption and scattering. Visibility through smoke is defined in terms of the furthest distance at which an object can be perceived (distance at which an object is no longer visible). Smoke obscures vision and causes irritation and watering of the eyes. Most notably, the intensity of smoke production has the greatest impact on reduction of visibility in a fire compartment or zone. Reduced visibility and inhaled smoke particles are the most frequent reasons of panic, which disorganizes evacuation and prolongs both rescue and firefighting operations. Moreover, in the consequence of absorption, smoke particles are ideal carriers of toxic gases and intensify the process of absorbing poisonous compounds into the human body.

The lachrymatory (causing or tending to cause tears) effects of smoke and hot gases, such as aldehydes or acids associated with smoke particles, have been shown to be important in interfering with vision. Visibility is generally much better at floor level than at higher levels in a compartment, so the possibility of crawling to safety raises the question of the height at which exit signs should be located. However, if sprinklers operate, their cooling and entrainment effects tend to bring the smoke closer to the floor. Moreover, fog (which may result from the use of sprinklers) will interfere with vision. There is currently no universally accepted position.

18.3 Smoke Obscuration

Unlike temperature, heat flux, or toxic gases, obscured visibility is not, itself, lethal. A hazard results only if the reduced visibility prevents required manual operator action or escape activity. This hazard is crucial, however, and smoke production has, therefore, been regulated longer than any other product of combustion. Evaluations have shown that personnel remote from the source of a fire are particularly at risk from fire effluent in post-flashover fire scenarios (Beitel et al., 1998).

Toxic gases kill largely because people cannot see to find escape routes and because they become disoriented and panic as a result of inhaling irritating gases. A little smoke makes people walk faster, while an increased amount slows the walking speed. Smoke also represents a psychological barrier to an occupant entering a room, often causing people to seek an alternative route and possibly causing the occupant to become trapped in a room without a safe exit (door or window). The same is true for reactor operators who may have to perform specific manual actions in a smoke-filled environment.

18.4 Effect of Smoke on Nuclear Power Plants

Sensitivity studies have shown that prolonged firefighting response times can lead to a noticeable increase in fire risk. Smoke, identified as one of the major contributors to prolonged response times, can also cause misdirected suppression efforts, hamper the ability of main control room (MCR) operators to safely shut down the plant, initiate automatic suppression systems in areas away from the fire, and fail electrical equipment.

Any number of possible fire scenarios could be considered threats to safe NPP operations. For example, a fire in turbine building, cable spreading room (CSR), or the control building can generate toxic combustion products that directly affect the habitability of the MCR or auxiliary shutdown areas. One exception would be a fire in the MCR, itself. The MCR is unique in several ways that significantly reduce the likelihood of a generalized area fire. First, the MCR is continuously manned and, hence, very rapid fire detection and intervention times are expected. This also implies that the transient fuel sources should be very effectively controlled and limited. Second, high-energy electrical equipment is not typically housed in the MCR and, hence, the number of potential high-energy fire sources is limited. Given these factors, the occurrence of a large, generalized fire in the MCR is not considered likely.

18.5 Estimating Visibility Through Smoke — Jin Method

As previously discussed, smoke particles and irritants can reduce visibility and, while loss of visibility is not directly life threatening, it can prevent or delay escape and thus expose people to the risk of being overtaken by fire. Visibility depends on many factors, including the scattering and absorption coefficient of the smoke, size and color of smoke particles, density of smoke, and the eye irritant effect of smoke. Visibility also depends on the illumination in the room, whether an exit sign is light-emitting or light-reflecting, and whether the sign is back- or front-lighted. An individual’s visual acuity and mental state at the time of a fire emergency are other factors.

Most visibility measurements through smoke have relied on test subjects to determine the distance at which an object is no longer visible. However, variations in visual observation of up to 25 to 30 percent can occur with the same observer under the same test conditions but at different times. A correlation between the visibility of test subjects and the optical density of the smoke has been obtained in extensive studies by Jin (1974, 1975, 1978, and 1985) (also reported by Klote and Milke, 2002).

Based on those studies, the relationship between visibility and smoke obscuration is given by the following expression:

$$S = \frac{K}{\alpha_m m_p} \qquad (18\text{-}1)$$

Where:

S = visibility (ft)
K = proportionality constant
$_m$ = specific extinction coefficient (ft^2/lb)
m_p = mass concentration of particulate (lb/ft^3)

The proportionality constant (K) is dependent on the color of the smoke, illumination of the object, intensity of background illumination, and visual acuity of the observer (Klote and Milke, 2002). Table 18-1 provides values of the proportionality constant based on the research of Jin.

Table 18-1. Proportionality Constants for Visibility

Situation	**Proportionality Constant (K)**
Illuminated signs	8
Reflecting signs	3
Building components in reflected light	3

The specific extinction coefficient ($_m$), depends on the size distribution and optical properties of the smoke particulates. Seader and Einhorn (1976) and Seader (1943) obtained values for the specific extinction coefficient ($_m$) from pyrolysis of wood and plastics, as well as from flaming combustion of these same materials. Table 18-2 provides values of $_m$.

Table 18-2. Specific Extinction Coefficient for Visibility

Mode of Combustion	**Specific Extinction Coefficient $_m$ (ft^2/lb)**
Smoldering combustion	21,000
Flaming combustion	37,000

Jin also found that walking speed decreases as smoke density increases; i.e., visibility decreases. It can be expected that a decrease in the visibility of walls and floors would cause subjects to slow down. In thick irritating smoke, tears prevented the subjects from seeing the words on signs and caused them to walk in an irregular manner or along the wall. For low-density smoke, however, the walking speeds in irritating smoke were about the same as those in non-irritating smoke.

The mass concentration of particulate (m_p), is given by the following expression:

$$m_p = \frac{M_p}{V} \qquad (18\text{-}2)$$

Where:

m_p = mass concentration of particulate (lb/ft^3)
M_p = mass of particulates produced (lb)
V = volume of smoke in the space (ft^3)

The smoke particulates produced by a fire primarily consist of soot, and the production of particulates can be estimated as follows:

$$M_p = y_p M_f \qquad (18\text{-}3)$$

Where:

M_p = mass of particulates produced (lb)
y_p = particulate yield
M_f = mass of fuel burned (lb)

Table 18-3 lists values of particulate yield (y_p) for a number of materials from small-scale experiments of turbulent flaming combustion.

Table 18-3. Smoke Particulate Yield (Klote and Milke, 2002)

Material	**Particulate Yield - y_p**
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool (100-percent)	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylmethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118

Table 18-3. Smoke Particulate Yield (Klote and Milke, 2002)

Material	**Particulate Yield - y_p**
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylenetetrafluoroethylene (ETFE; Tefzel™)	0.042
Perfluoroalkoxy (PFA; Teflon™)	0.002
Fluorinated polyethylene-polypropylene (FEP; Teflon™)	0.003
Tetrafluoroethylene (TFE; Teflon™)	0.003

18.6 Assumptions and Limitations

The method discussed in this chapter is subject to several assumptions and limitations:

(1) This method takes into account the irritating and non-irritating effects of smoke.
(2) The correlations are developed for smoldering and flaming combustion.

18.7 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) compartment width (ft)
(2) compartment length (ft)
(3) compartment height (ft)
(4) fuel type (material)
(5) mass of fuel burn (lb)

18.8 Cautions

(1) Use spreadsheet (18_Visibility_Through_Smoke.xls) on the CD-ROM for estimating visibility through smoke.

(2) Make sure to enter the input parameters in the correct units.

18.9 Summary

This chapter describes a method of calculating the visibility through a smoke layer based on experimental correlations and data. The visibility through thin smoke primarily depends on physical obscuration; however, when the smoke is relatively thick, the physiological irritant becomes the dominant factor in impairing visibility. The correlation presented was obtained from laboratory-scale fires; smoke particulate production is expected to vary with the size of the fire and the orientation of the fuel. Equation 18-1 can be used to calculate visibility in such large fires.

18.10 References

Beitel, J.J., C.L. Beyler, L.A. McKenna, and F.W. Williams, "Overview of Smoke Toxicity Testing and Regulations," NRL/MR/6180-98-8128, Naval Research Laboratory, Naval Technology Center for Safety and Survivability Branch, Chemistry Division, Washington, DC, April 15, 1998.

Jin, T., "Visibility Through Fire Smoke, in Main Reports on Production, Movements and Control in Buildings," Japanese Association of Fire Science and Engineering, pp. 100 –153, 1974.

Jin, T., "Visibility Through Fire Smoke," Report of the Fire Research Institute of Japan, 5 (2), pp. 12–18, 1975.

Jin, T., "Visibility Through Fire Smoke," *Journal of Fire and Flammability*, Volume 9, No.2, pp. 135–155, April 1978.

Jin, T. "Irritating Effects of Fire Smoke on Visibility," *Fire Science and Technology*, Volume 5, No. 1, pp. 79–90, 1985.

Klote, J.H., and J.A. Milke, *Principles of Smoke Management*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. (ASHRAE), and Society of Fire Protection Engineers (SFPE), ASHRAE Special Publication, 2002.

Seader, J., and I. Einhorn, "Some Physical, Chemical, Toxicological, and Physiological Aspects of Fire Smokes," National Science Foundation (NSF) Report, Utah University, 1976.

Steiner, A.J., "Method of Fire Hazard Classification of Building Materials," ASTM Bulletin, American Society of Testing and Materials (ASTM), Philadelphia, Pennsylvania, pp. 12–18, March 1943.

18.11 Problems

Example Problem 18.11-1

Problem Statement
A compartment is 30 ft width x 20 ft long x 15 ft high (w_c x l_c x h_c). In the center of the compartment, 1 lb of polypropylene is involved in flaming combustion:

(a) From the center of the compartment, can you see the "Reflecting Exit Sign" at either end of the compartment?

(b) What if you increase the mass of burned fuel (polypropylene) to 2 lbs?

Solution
Purpose:
(1) Determine the visibility of the exit sign.

Assumptions:
(1) Complete burning within the method specified

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 18_Visibility_Through_Smoke.xls

FDT^s Input Parameters:
-Compartment Width (w_c) = 30 ft
-Compartment Length (l_c) = 20 ft
-Compartment Height (h_c) = 15 ft
-Mass of fuel burn = 1 lb
-Select Polypropylene
-Select Reflecting Signs
-Select Flaming Combustion

Results*

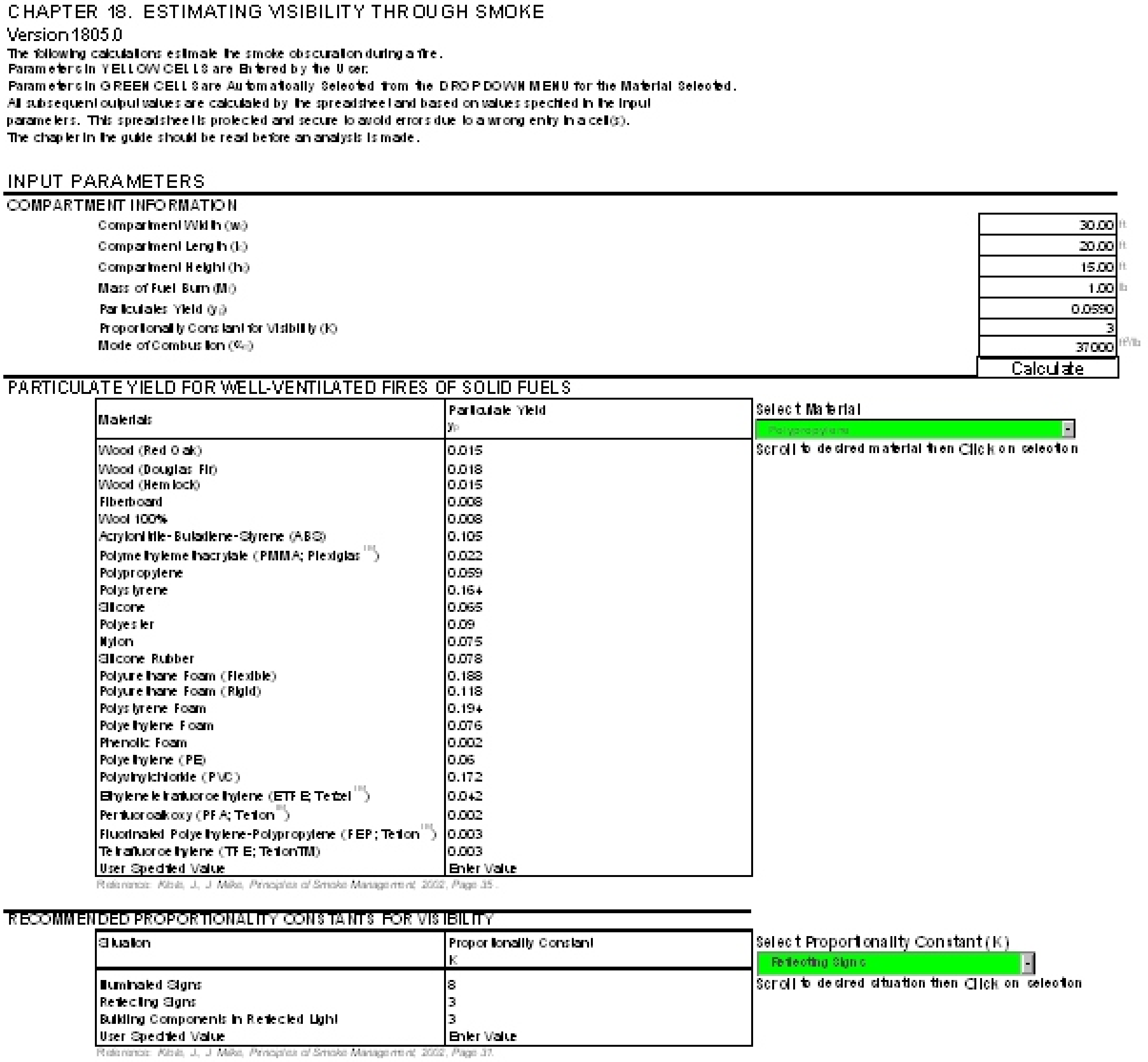
	1 lb of material	**2 lb of material**
Visible Distance	12.37 ft (3.77 m)	6.18 ft (1.88 m)

*see spreadsheet on next page

Therefore, the signs placed at either end of the room (10 feet away) are visible with 1 lb of material burning, but would not be visible if 2 lb of material was burned.

Spreadsheet Calculations

(a) FDT^s: 18_Visibility_Through_Smoke.xls (1 lb polypropylene)



CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

Version 1805.0

The following calculations estimate the smoke obscuration during a 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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w)	30.00	ft
Compartment Length (L)	20.00	ft
Compartment Height (h)	15.00	ft
Mass of Fuel Burn (M)	1.00	lb
Particulates Yield (y_p)	0.0590	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (δ_m)	37000	ft²/lb

Calculate

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylemethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylene tetrafluoroethylene (ETFE; Tefzel™)	0.042
Perfluoroalkoxy (PFA; Teflon™)	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon™)	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 35.

Select Material

Polypropylene

Scroll to desired material then Click on selection

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 37.

Select Proportionality Constant (K)

Reflecting Signs

Scroll to desired situation then Click on selection

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient σ_m (ft^2/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 32.

Select Specific Extinction Coefficient (σ_m)

Flaming Combustion

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 32.

$S = K / \sigma_m\, m_p$

Where S = visibility through smoke (ft)
K = proportionality constant
σ_m = specific extinction coefficient (ft^2/lb)
m_p = mass concentration of particulate (lb/ft^3)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where V = volume of the compartment (ft^3)
w_c = compartment width (ft)
l_c = compartment length (ft)
h_c = compartment height (ft)

$V =$ 9000.00 ft^3

Mass of Particulates Produced (airborne particulate)

$M_p = y_p\, M_f$

Where M_p = mass of particulates produced (lb)
y_p = particulates yield
M_f = mass of fuel consumed (lb)

$M_p = y_p\, M_f$

$M_p =$ 0.060 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where m_p = mass concentration of the particulates (lb/ft^3)
M_p = mass of particulates produced (lb)
V = volume of the compartment (m^3)

$m_p = M_p / V$

$m_p =$ 6.66667E-06 lb/ft^3

Visibility Through Smoke Calculation

$S = K / \sigma_m\, m_p$

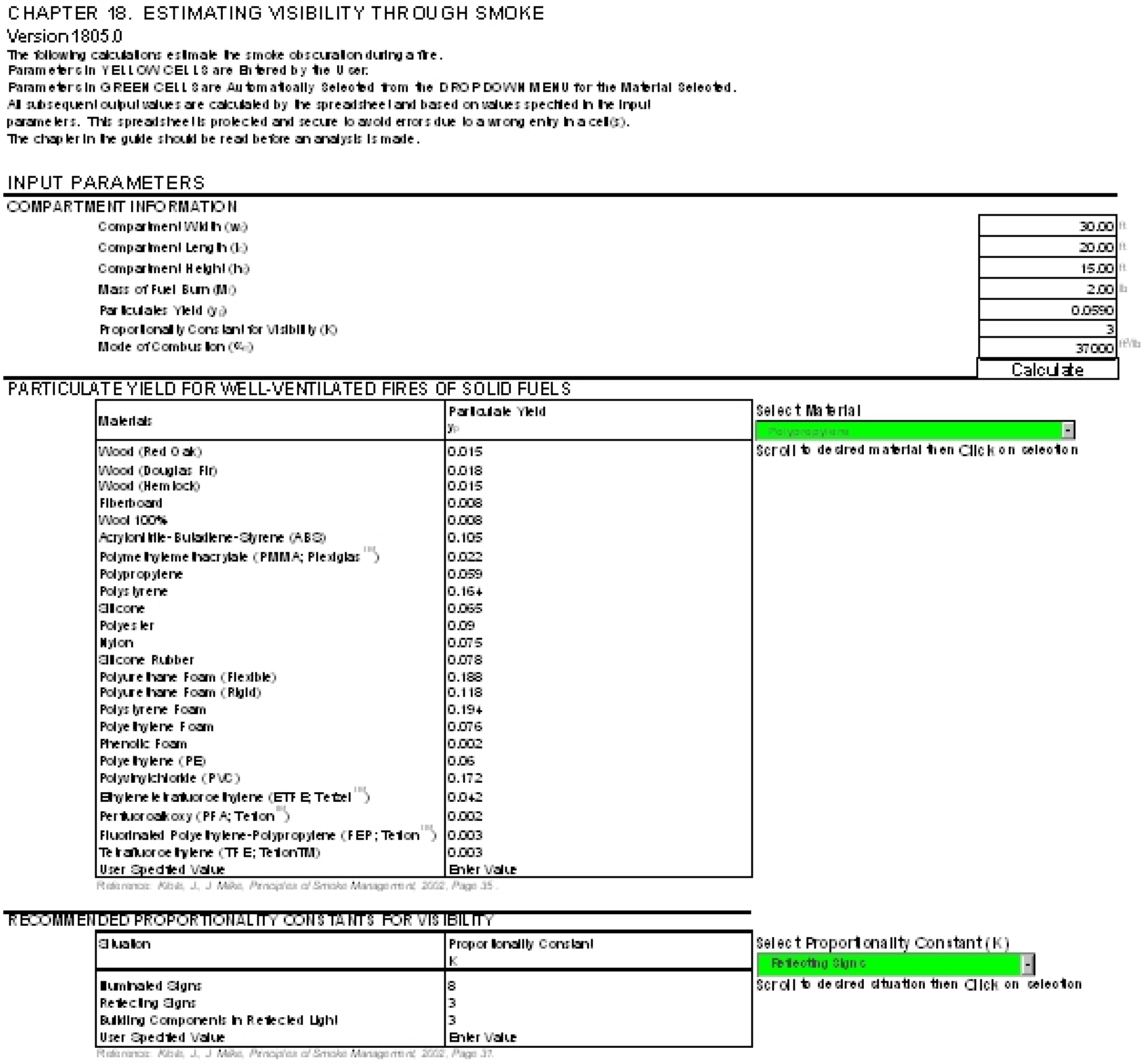
S =	12.37 ft	3.77 m	Answer

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

The above calculations are based on principles developed in the Principles of Smoke Management by Klote and Milke 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.

(b) FDT^s: 18_Visibility_Through_Smoke.xls (2 lb polypropylene)



CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

Version 1805.0

The following calculations estimate the smoke obscuration during a 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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	30.00	ft
Compartment Length (l_c)	20.00	ft
Compartment Height (h_c)	15.00	ft
Mass of Fuel Burn (M_f)	2.00	lb
Particulates Yield (y_p)	0.0590	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (%)	37000	ft²/lb

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylemethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylenetetrafluoroethylene (ETFE; Tefzel™)	0.042
Perfluoroalkoxy (PFA; Teflon™)	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon™)	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 35.

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 37.

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient σ_m (ft²/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

Select Specific Extinction Coefficient (σ_m)

Flaming Combustion

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

$S = K / \sigma_m m_p$

Where
S = visibility through smoke (ft)
K = proportionality constant
σ_m = specific extinction coefficient (ft²/lb)
m_p = mass concentration of particulate (lb/ft³)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where
V = volume of the compartment (ft³)
w_c = compartment width (ft)
l_c = compartment length (ft)
h_c = compartment height (ft)

$V =$ 9000.00 ft³

Mass of Particulates Produced (airborne particulate)

$M_p = y_p M_f$

Where
M_p = mass of particulates produced (lb)
y_p = particulates yield
M_f = mass of fuel consumed (lb)

$M_p = y_p M_f$

$M_p =$ 0.118 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where
m_p = mass concentration of the particulates (lb/ft³)
M_p = mass of particulates produced (lb)
V = volume of the compartment (m³)

$m_p = M_p / V$

$m_p =$ 1.31111E-05 lb/ft³

Visibility Through Smoke Calculation

$S = K / \sigma_m m_p$

$S =$ 6.18 ft 1.88 m **Answer**

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

The above calculations are based on principles developed in the Principles of Smoke Management by Klote and Milke 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.

Example Problem 18.11-2

Problem Statement
A compartment is 10 ft wide x 30 ft long x 12 ft high (w_c x l_c x h_c). What is the minimum amount (lb) of rigid polyurethane foam involved in smoldering combustion necessary to obstruct the visibility for the length of the compartment to a building compartment in reflective light?

Solution

Purpose:

(1) Determine the minimum mass of burning fuel that will obscure the sign.

Assumptions:

(1) Complete burning within the method specified

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 18_Visibility_Through_Smoke.xls

FDT^s Input Parameters:

-Compartment Width (w_c) = 10 ft
-Compartment Length (l_c) = 30 ft
-Compartment Height (h_c) = 12 ft
-Mass of fuel burn = variable
-Select Polyurethane Foam (Rigid)
-Select Reflecting Signs
-Select Smoldering Combustion

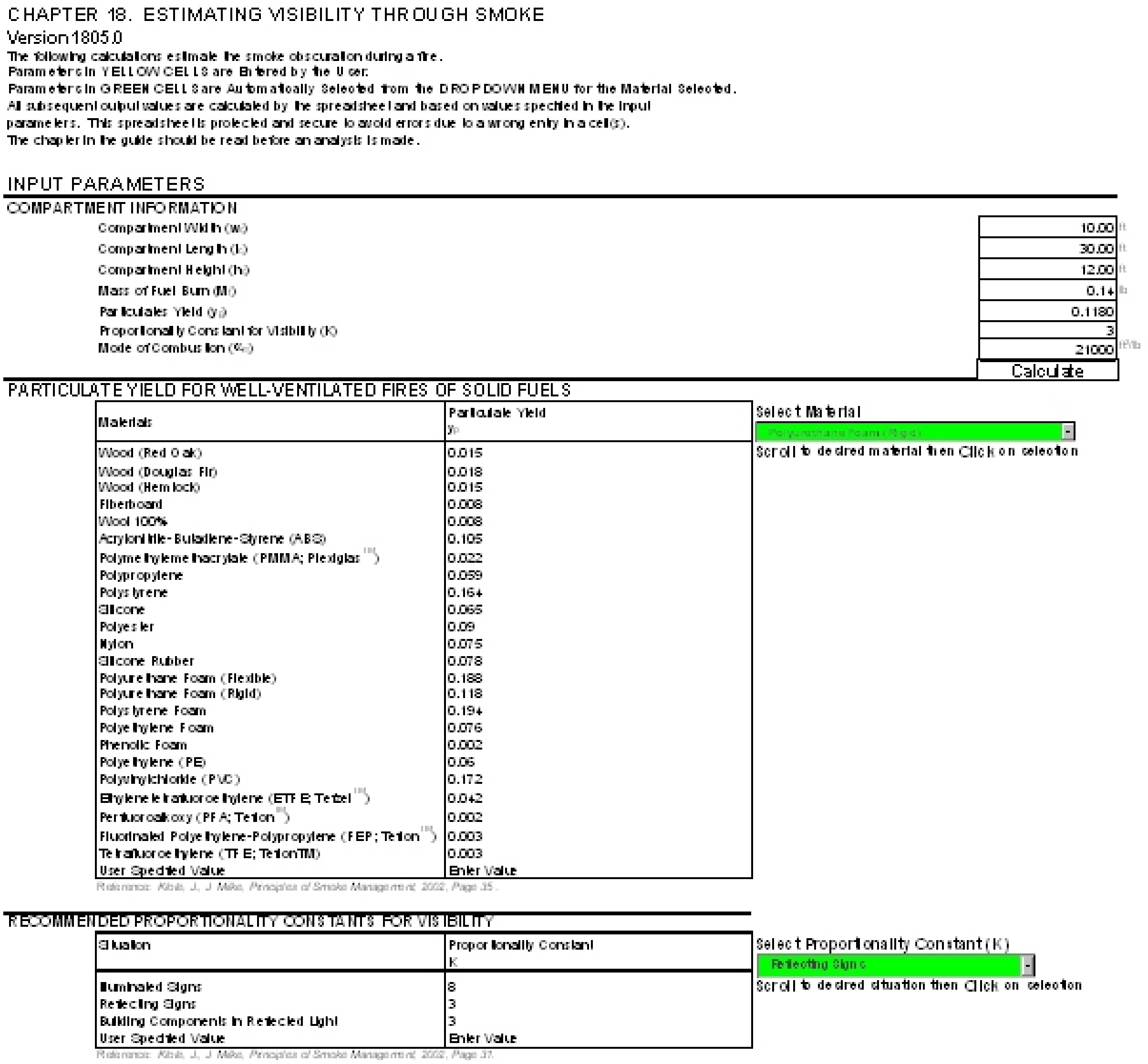
Results*

Visible Distance	Mass of fuel burn
30 ft (9.42 m)	.14 lb (.064 kg)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^{s}: 18_Visibility_Through_Smoke.xls



CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE
Version 1805.0
The following calculations estimate the smoke obscuration during a 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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w)	10.00	ft
Compartment Length (l)	30.00	ft
Compartment Height (h)	12.00	ft
Mass of Fuel Burn (M)	0.14	lb
Particulates Yield (y_s)	0.1180	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (σ_m)	21000	ft²/lb

Calculate

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylemethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylene tetrafluoroethylene (ETFE; Tefzel™)	0.042
Perfluoroalkoxy (PFA; Teflon™)	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon™)	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 35.

Select Material
Polyurethane Foam (Rigid)
Scroll to desired material then Click on selection

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 37.

Select Proportionality Constant (K)
Reflecting Signs
Scroll to desired situation then Click on selection

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient δ_m (ft²/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

Select Specific Extinction Coefficient (δ_m)

Smoldering Combustion ▾

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

$S = K / \delta_m m_p$

Where
S = visibility through smoke (ft)
K = proportionality constant
δ_m = specific extinction coefficient (ft²/lb)
m_p = mass concentration of particulate (lb/ft³)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where
V = volume of the compartment (ft³)
w_c = compartment width (ft)
l_c = compartment length (ft)
h_c = compartment height (ft)

$V =$ 3600.00 ft³

Mass of Particulates Produced (airborne particulate)

$M_p = y_p M_f$

Where
M_p = mass of particulates produced (lb)
y_p = particulates yield
M_f = mass of fuel consumed (lb)

$M_p = y_p M_f$

$M_p =$ 0.01652 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where
m_p = mass concentration of the particulates (lb/ft³)
M_p = mass of particulates produced (lb)
V = volume of the compartment (m³)

$m_p = M_p / V$

$m_p =$ 4.58889E-06 lb/ft³

Visibility Through Smoke Calculation

$S = K / \delta_m m_p$

$S =$	31.13 ft	9.49 m

Answer

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

The above calculations are based on principles developed in the Principles of Smoke Management by Klote and Milke 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.

Example Problem 18.11-3

Problem Statement

An inspector finds 5 lbs of PVC pipe in a compartment 10 ft wide x 30 ft long x 12 ft high (w_c x l_c x h_c):

(a) What is the visibility to a reflecting sign given flaming combustion?

(b) What is the visibility to a reflecting sign given smoldering combustion?

Solution

Purpose:

(1) Determine the visibility under the different burning methods.

Assumptions:

(1) Complete burning within the method specified

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 18_Visibility_Through_Smoke.xls

FDT^s Input Parameters:

-Compartment Width (w_c) = 10 ft
-Compartment Length (l_c) = 30 ft
-Compartment Height (h_c) = 12 ft
-Mass of fuel burn = 5 lbs
-Select PVC
-Select Reflecting Signs
-Select Flaming Combustion (get result)
-Select Smoldering Combustion (get result)

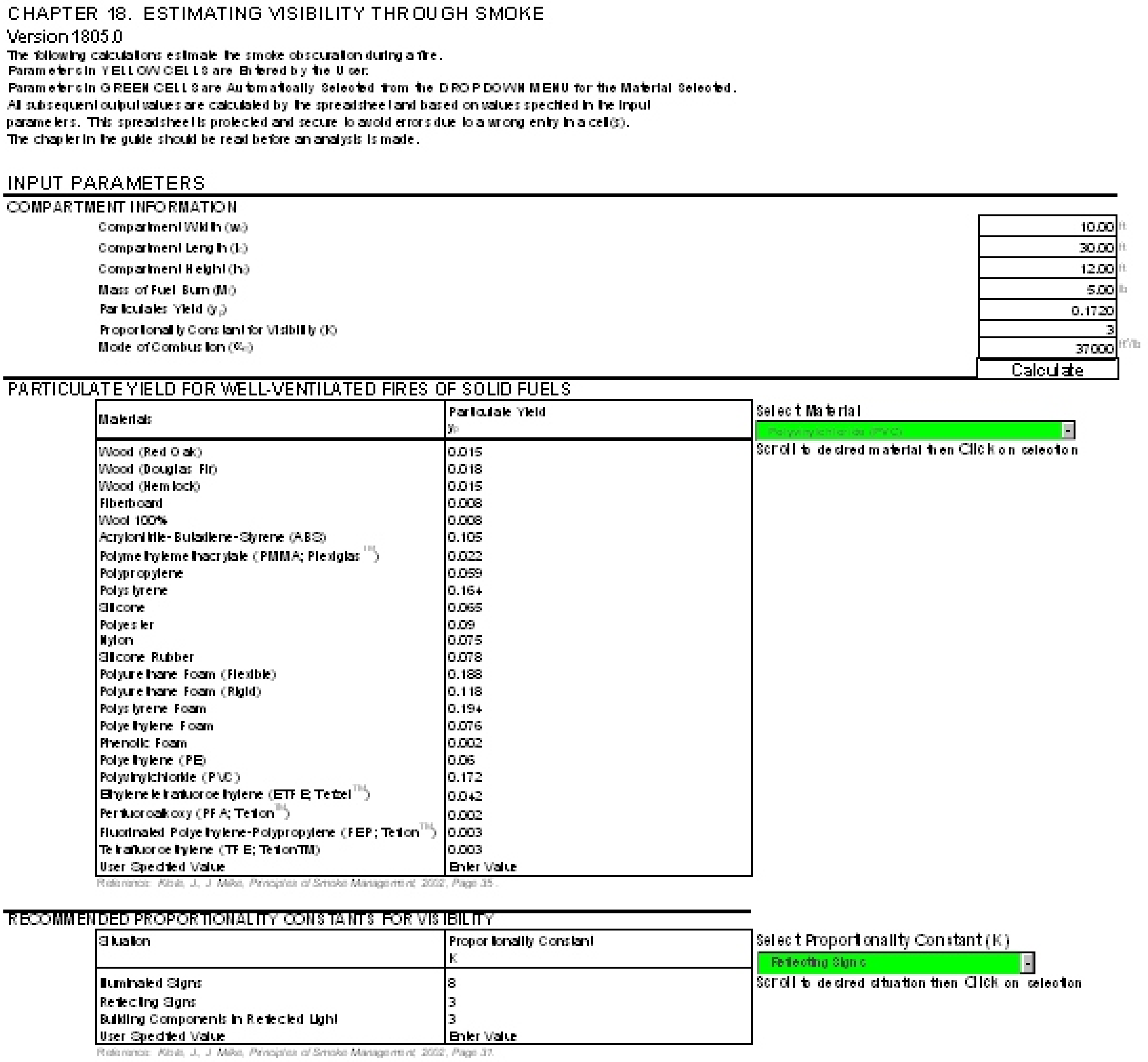
Results*

Burning Method	Visibility
Flaming	.34 ft (0.10 m)
Smoldering	.60 ft (0.18 m)

*see spreadsheet on next page

Spreadsheet Calculations

(a) FDT^s: 18_Visibility_Through_Smoke.xls



CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

Version 1805.0

The following calculations estimate the smoke obscuration during a 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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w)	10.00	ft
Compartment Length (l)	30.00	ft
Compartment Height (h)	12.00	ft
Mass of Fuel Burn (M)	5.00	lb
Particulates Yield (y_p)	0.1720	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (%c)	37000	ft²/lb

Calculate

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylemethacrylate (PMMA; Plexiglas^{TM})	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylene tetrafluoroethylene (ETFE; Tefzel^{TM})	0.042
Perfluoroalkoxy (PFA; Teflon^{TM})	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon^{TM})	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 35.

Select Material

Polyvinylchloride (PVC)

Scroll to desired material then Click on selection

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 37.

Select Proportionality Constant (K)

Reflecting Signs

Scroll to desired situation then Click on selection

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient σ_m (ft^2/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

Select Specific Extinction Coefficient (σ_m)

Flaming Combustion ▾

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

$S = K / \sigma_m m_p$

Where S = visibility through smoke (ft)
K = proportionality constant
σ_m = specific extinction coefficient (ft^2/lb)
m_p = mass concentration of particulate (lb/ft^3)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where V = volume of the compartment (ft^3)
w_c = compartment width (ft)
l_c = compartment length (ft)
h_c = compartment height (ft)

$V =$ 3600.00 ft^3

Mass of Particulates Produced (airborne particulate)

$M_p = y_p M_f$

Where M_p = mass of particulates produced (lb)
y_p = particulates yield
M_f = mass of fuel consumed (lb)

$M_p = y_p M_f$

$M_p =$ 0.86 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where m_p = mass concentration of the particulates (lb/ft^3)
M_p = mass of particulates produced (lb)
V = volume of the compartment (m^3)

$m_p = M_p / V$

$m_p =$ 0.000238889 lb/ft^3

Visibility Through Smoke Calculation

$S = K / \sigma_m m_p$

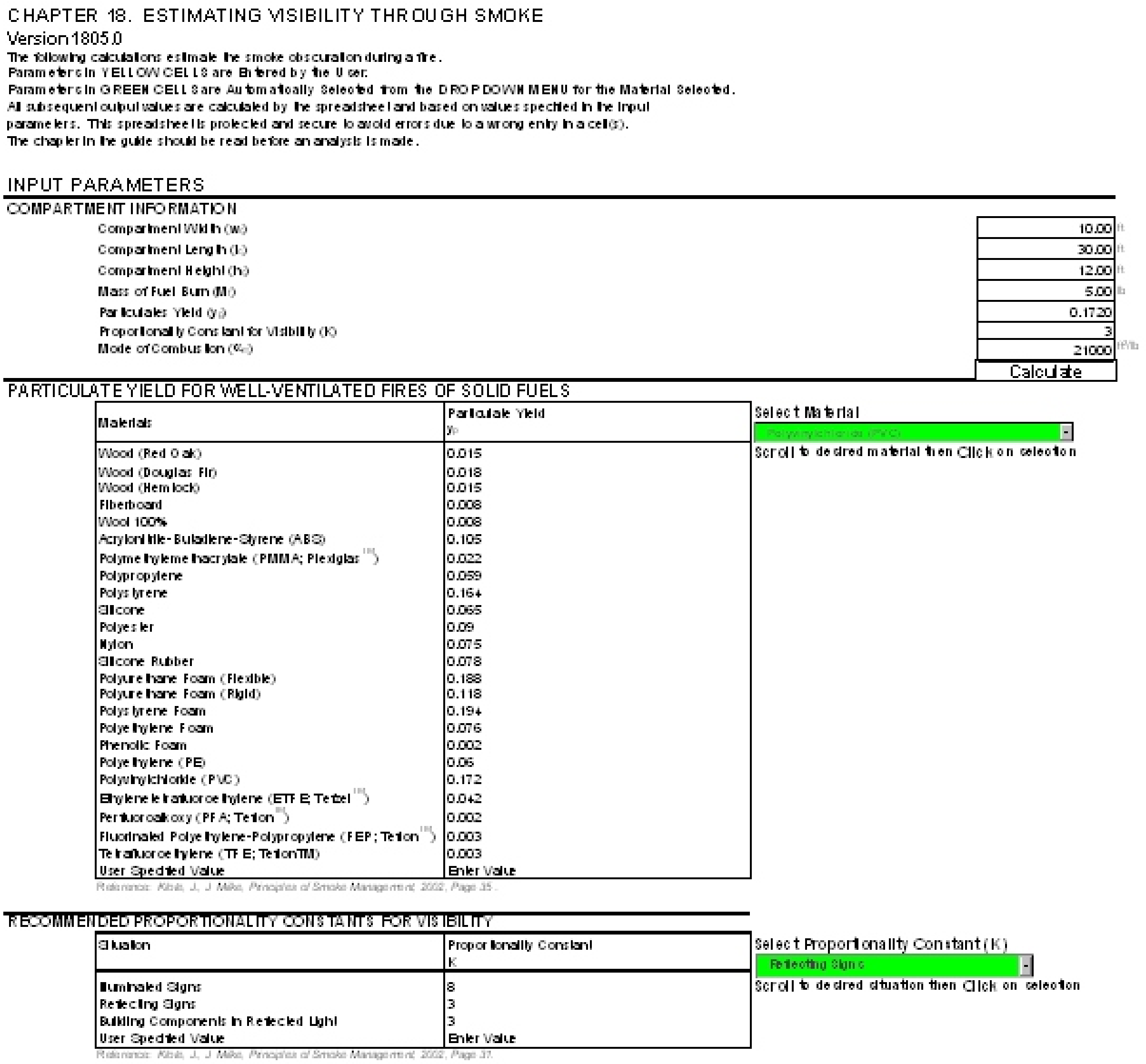
$S =$ 0.34 ft 0.10 m **Answer**

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

The above calculations are based on principles developed in the Principles of Smoke Management by Klote and Milke 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.

(b) FDT^s: 18_Visibility_Through_Smoke.xls



CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

Version 1805.0

The following calculations estimate the smoke obscuration during a 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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	10.00	ft
Compartment Length (l_c)	30.00	ft
Compartment Height (h_c)	12.00	ft
Mass of Fuel Burn (M_f)	5.00	lb
Particulates Yield (y_s)	0.1720	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (δ_m)	21000	ft²/lb

Calculate

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylemethacrylate (PMMA; Plexiglas^{TM})	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylenetetrafluoroethylene (ETFE; Tefzel^{TM})	0.042
Perfluoroalkoxy (PFA; Teflon^{TM})	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon^{TM})	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 35.

Select Material

Polyvinylchloride (PVC)

Scroll to desired material then Click on selection

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 37.

Select Proportionality Constant (K)

Reflecting Signs

Scroll to desired situation then Click on selection

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient α_m (ft²/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

Select Specific Extinction Coefficient (α_m)

Smoldering Combustion

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

$S = K/\alpha_m m_p$

Where
S = visibility through smoke (ft)
K = proportionality constant
α_m = specific extinction coefficient (ft²/lb)
m_p = mass concentration of particulate (lb/ft³)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where
V = volume of the compartment (ft³)
w_c = compartment width (ft)
l_c = compartment length (ft)
h_c = compartment height (ft)

$V =$ 3600.00 ft³

Mass of Particulates Produced (airborne particulate)

$M_p = y_p M_f$

Where
M_p = mass of particulates produced (lb)
y_p = particulates yield
M_f = mass of fuel consumed (lb)

$M_p = y_p M_f$

$M_p =$ 0.86 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where
m_p = mass concentration of the particulates (lb/ft³)
M_p = mass of particulates produced (lb)
V = volume of the compartment (m³)

$m_p = M_p / V$

$m_p =$ 0.000238889 lb/ft³

Visibility Through Smoke Calculation

$S = K/\alpha_m m_p$

$S =$	0.60 ft	0.18 m	Answer

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

The above calculations are based on principles developed in the Principles of Smoke Management by Klote and Milke 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.