CHAPTER 7. ESTIMATING THE FULL-SCALE HEAT RELEASE RATE OF A CABLE TRAY FIRE

7.1 Objectives

This chapter has the following objectives:

- Describe the numerous functions that electrical cables perform in a nuclear power plant (NPP).
- Explain the factors that determine how a cable will behave in a fire.
- Describe the ways that fires can occur in cable tray installations.
- Discuss the various types of combustion reactions.
- Explain the processes that electrical failures can initiate in a cable tray.

7.2 Introduction

Fires in grouped electrical cable trays pose distinct fire hazards in power generating facilities. In the past, cable tray installations have caused fires that resulted in serious damage to NPPs. In fact, during the 1950s and early 1960s, NPPs in the United States experienced several fires with serious losses propagated by electrical cables. A 1966 NFPA fire hazard study (Hedland, 1966) described 24 such fires, the most serious of which occurred at the Peach Bottom Atomic Power Station operated by Philadelphia Electric Company. The most important aspect of the NAPA study, however, is that it pointed out (probably for the first time) that *grouped cables can spread flame much faster than individual cables*.

The 1975 fire at the Browns Ferry Nuclear Power Plant (BFNP) operated by the Tennessee Valley Authority (TVA) demonstrated the vulnerability of electric cables installed in an NPP when exposed to elevated temperatures as a result of a fire. In response to the Browns Ferry incident, the NRC's Executive Director for Operations (EDO) established a special review group to identify lessons that can be learned from the event and to make recommendations for the future treatment of cable trays and cable fires (NUREG-0050). After the BFNP fire, the NRC conducted a series of operating plant inspections and thorough reviews of NPP fire protection programs. On the basis of this information, the NRC issued new fire protection requirements in 10 CFR 50.48 and Appendix R to 10 CFR Part 50. The new regulations imposed a minimum set of fire protection program and post-fire safe-shutdown (FSSD) requirements. (See Appendix A for more on electrical cables.)

Electrical cables perform numerous functions in an NPP:

- power cables that supply electricity to motors, transformers, and heaters
- lighting cables that supply electricity to normal lighting fixtures and fluorescent lighting ballasts
- control cables that connect plant equipment such as motor-operated valves (MOVs) and motor starters to remote initiating devices (e.g., switches, relays, and contacts)
- instrumentation cables that transmit low-voltage signals between input devices (e.g., readout panels)
- communication cables (telephone lines)
- heat tracing cables.

The primary cables of concern for FSSD of the reactor are typically power, control, and instrumentation cables. The function of a given cable dictates its acceptable operating parameters. These parameters are important because what constitutes acceptable performance of one type of cable at elevated fire temperatures may not be acceptable performance for another (e.g., a cable that demonstrates acceptable performance for power applications at a certain elevated fire temperature may not be acceptable for instrumentation applications at the same temperature).

Power cables are the least susceptible to fire-induced failure. Control cables are more susceptible to such failure than power cables but typically less susceptible than instrument cables, which are often the most easily affected by elevated temperatures and the first to suffer fire-induced failures.

7.3 Cable Tray Fire Burning Mode Classification

Electrical cables constitute a serious fire hazard for NPPs because the combustible polymeric insulation and jacket material are present in large quantities. This large fuel load can cause NPP fires to burn for extended periods. To compound the problem, the combustion of a fully developed cable fire may be incomplete because of the presence of smoke; whereas general building fires on ground level usually burn in the presence of clear air, because smoke escapes through windows and doors before descending to the fuel.

The behavior of cables in a fire depends on a number of factors, including their constituent materials and construction, as well as their location and installation geometry. The component material and the construction of the cable are very important, as is the nature of the given fire. For example, polymer-insulated cables are regarded as fire hazards because all organic materials will burn under most fire conditions and will liberate heat and toxic gases (such as carbon monoxide.) Depending on their location and means of installation, cables can contribute to a fire in a number of ways. For example, burning cables can propagate flames from one area to another or they can add to the amount of fuel available for combustion and can liberate smoke containing toxic and corrosive gases. Similarly, the grouped cables could pose a more serious threat in situations where they run through open spaces connecting different parts of an NPP. In these situations, the cables could propagate and spread the fire between compartments. Thus, the hazards associated with burning cables must be considered in the context of the surroundings. Sometimes, cables comprise a very small proportion of the combustible material; in other situations, they can be the major contribution.

Cable tray fires can occur from various sources. The scenarios of concern include (1) a fire within a cable tray (regardless of how it is initiated) and (2) as exposure fire (i.e., a fire that originates outside of the cable tray and subsequently ignites the cable tray). It is common practice to consider only self-ignited cable fires to occur in power cable trays since they carry enough electrical energy for ignition. Control and instrumentation cables typically do not carry enough electrical energy for self ignition.

To determine the behavior of a given type of cable, they are subject to a variety of standard small- and large scale tests. As stated in NUREG/CR-2431, “Burn Mode Analysis of Horizontal Cable Tray Fires,” February 1982, the cable fire growth tests performed to date have demonstrated different burn modes in horizontal and vertical configurations. The results of horizontal and vertical cable tray tests showed that jacket or insulation material may melt (thermoplastic) or form a considerable char (thermoset). The insight gained from the various cable tray fire tests indicate different types of combustion reactions.

- In pyrolysis, flaming was uniform over the outer surface of the cable bundle and throughout the cable bundle. The cable region involved in the fire grew steadily for the duration of the test.
- With smoldering and/or melting, the jacket and/or insulation material melted and coalesced into a large mass, and flaming occurred principally on the outer surface of the fused mass. Fire involvement depended upon the shape and position of the fused mass within the cable tray.
- With deep-seated combustion, the jacket and/or insulation material formed considerable char, and flaming occurred principally on the outer surface of the cable bundle. Flaming was neither continuous nor uniform, but rather occurred as sporadic bursts of fire. After the surface flaming subsided, a glowing cable region slowly progressed along the cables with sporadic flaming issuing from the region. The deep-seated fire, as a subclass of smoldering combustion, is defined as having a fuel interior temperature between the fuel vapor and surface auto-ignition temperatures of the fuel and a fuel surface temperature below the upper or surface auto-ignition temperature.
- Interior combustion resulted in uniform flaming over the outer surface and throughout the cable bundle. The cable region involved in the fire grew steadily and continuously, and the surface fire slowly progressed along the cable with sporadic flaming.

7.4 Cable Tray Heat Release Rate

As stated above, cable insulation and jacket material dominates the combustible fuel loading in most NPP areas. Most of this material is found on cables that are routed in extensive cable tray arrays. Review of the literature on cable tray fires indicates that there are no reliable correlations for the rate of heat release from a full-scale fire. The most systematic studies available are those from Tewarson, et al. (1979), and Sumitra (1982). A useful engineering analysis and basic correlation of their data has been prepared by Lee, 1985, who showed that the peak full-scale HRR can be predicted according to the bench-scale HRR measurements. Lee’s correlation for the HRR from measured data is based on the following equation:

$$\dot{Q}_{fs} = 0.45 \ \dot{Q}''_{bs} \ A_f \qquad (7\text{-}1)$$

Where:

$\dot{Q}_{fs}$ = full-scale HRR (kW)

$\dot{Q}''_{bs}$ = bench-scale HRR (kW/m^2)

A_f = exposed cable tray area actively pyrolyzing (m^2)

The bench-scale HRR $(\dot{Q}''_{bs})$, is the peak value measured under the heat flux condition of 60 kW/m^2. The pyrolysis or burning area, A_f, can vary with time as a cable fire spreads. For screening purposes, this area can be estimated assuming area of the fuel involved in fire.

The bench-scale HRR data for a number of cable types measured by Tewarson, et al., and Sumitra, are tabulated in Table 7-1. Note that polyethylene/polyvinylchloride (PE/PVC) cables were the most flammable of all cables tested.

Table 7-1. Bench-Scale HRR of a Cable Tray Fire

Cable Sample	**Bench-Scale HRR per Unit Area $\dot{Q}''_{bs}$ (kW/m^2)**
ld PE	1,071
PE/PVC	589
XPE/FRXPE	475
XPE/Neoprene	354
PE, PP/Cl.S.PE	345
XPE/Neoprene	302
FRXPE/Cl.S.PE	258
PE, Nylon/PVC, Nylon	231
XPE/Cl.S.PE	204
Silicone, glass braid, asbestos	182
XPE/XPE	178
PE, PP/Cl.S.PE	177
Silicone, glass braid	128
Teflon	98
Cl.S. - Chlorosulfonated; FRXPE - Fire Retardant Crosslinked Polyethylene; PE - Polyethylene; PP - Polypropylene; PVC - Polyvinylchloride; XPE - Crosslinked Polyethylene	

Typically, the IEEE-383-qualified cables are thermoset material, while the unqualified cables are constructed of thermoplastic material. Table 7-2 lists commonly found cables.

Table 7-2. Thermoplastic vs. Thermoset Cables

Thermoplastic Cable Construction

Allied Chemical's Halar (ethylene copolymer with chlorotrifluoroethylene)
DuPont's PFA (perflouroalkoxy branched polymers)
Dynamit Nobel's Dyflor (polyvinylidene fluoride)
Ethylenetetrafluoroethylene (ETFE) (known as Tefzel$^{\circledR}$)
Fluorinated polyethylene-polypropylene (FEP) (known as Teflon$^{\circledR}$)
Low and high polyethylene (PE)
Nylon, chlorinated polyethylene (CPE)
Polyvinyl chloride (PVC)
Polyvinyl fluoride (PVF) (known as Tedlar$^{\circledR}$)
Polyurethane, polypropylene (PPE)
Polytetrafluoroethylene (PTFE) (known as Teflon$^{\circledR}$)
Teflon, and fluorinated polymers such as DuPont's TFE copolymers with ethylene (known as Tefzel$^{\circledR}$)

Thermoset Cable Construction

Crosslinked polyethylene (XLPE)
Crosslinked polyolefin (XLPO)
Chloroprene rubber (CR)
DuPont's Hypalon (Chlorosulphonated polyethylene)
Ethylvinyl acetate (EVA)
Ethylene propylene rubber (EPR)
Nitrile or rubber butadiene nitrite (NBR)
Styrene butadiene rubber (SBR)
Polybutadiene, neoprene, and silicone rubber

7.5 Cable Failure Criteria (Critical Temperature and Critical Heat Flux)

Electrical failure can initiate several fire-related processes, such as melting, pyrolysis, gasification, ignition, and combustion of cable. The lower the heat flux requirement to ignite the electrical cables, the greater the fire hazard is in terms of ignition and flame spread.

A quantitative FHA requires a damage threshold for cables exposed to fires. Electrical cables are typically the primary target for most analyses. The two general types of electrical cables that are anticipated in an NPP are qualified and unqualified. These terms respectively refer to cables that pass or fail the fire test defined in the IEEE-383 standard promulgated by the Institute of Electrical and Electronic Engineers (IEEE). See Appendix A, Section A.5.8, for a discussion of cable damage threshold exposure heat-flux.

7.6 Assumptions and Limitations

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

(1) This correlation is based on the data obtained from flaming fire of cable samples.

(2) A complex cable tray configuration may be present in many NPPs. For very complex cable tray arrays, the above correlation would give a less accurate approximation for the HRR.

(3) The equation should be used to calculate the HRR for any type of cable.

7.7 Required Input for Spreadsheet Calculations

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

(1) cable type (material)

(2) exposed cable tray burning area (ft^2)

7.8 Cautions

(1) Use (07_Cable_HRR_Calculations.xls) spreadsheet on the CD-ROM for calculation.

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

7.9 Summary

There is currently no direct HRR data available on the burning of full-scale or intermediate-scale cable tray arrays. Available mass loss data, measured in a series of intermediate-scale fires, was used to estimate HRR. The resulting HRR, in turn, was used to develop a predicted method for full-scale fire behavior based on the bench-scale HRR data for cables.

Estimating the HRR, $\dot{Q}_{fs}$, of cables involves the following steps:

(1) Determine the bench-scale HRR, $\dot{Q}''_{bs}$.
(2) Calculate the exposed cable tray area, A_f.

7.10 References

“Fire-Induced Vulnerability Evaluation (FIVE) Methodology,” EPRI TR-100370, Electric Power Research Institute, Palo Alto, California, 1992.

Hedlund, C.F., “Grouped Combustible Wire and Cables,” *Fire Journal*, Volume 60, pp. 5–8, March 1966.

Lee, B.T., “Heat Release Rate Characteristics of Some Combustibles Fuel Sources in Nuclear Power Plants,” NBSIR 85-3195, U.S. Department of Commerce, National Bureau of Standards (NBS), Washington, DC, July 1985.

NUREG-0050, “Recommendations Related to Browns Ferry Fire,” Report by Special Review Group, U.S. Nuclear Regulatory Commission, Washington, DC, February 1976.

NUREG/CR-2431, “Burn Mode Analysis of Horizontal Cable Tray Fires,” U.S. Nuclear Regulatory Commission, Washington, DC, February 1982.

Sumitra, P.S., “Categorization of Cable Flammability. Part I, Intermediate-Scale Fire Tests of Cable Tray Installations,” Interim Report NP-1881, EPRI Research Project 1165-1, Factory Mutual Research Corporation, Norwood Massachusetts, 1982.

Tewarson, A., J.L. Lee, and R.F. Pion, “Categorization of Cable Flammability, Part I, Experimental Evaluation of Flammability Parameters of Cables Using Laboratory-Scale Apparatus,” EPRI Project RP1165-1, Factory Mutual Research Corporation, Norwood, Massachusetts, 1979.

7.11 Additional Readings

Babrauskas, V., “Burning Rates,” Section 3, Chapter 3-1, *SFPE Handbook of Fire Protection Engineering,* 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

Babrauskas, V., “Free-Burning Fires,” *Fire Safety Journal*, Volume 11, page 33–51, 1986.

7.12 Problems

Example Problem 7.12-1

Problem Statement

A 32-gallon trash can exposure fire source is located 2 m (6.5 ft) beneath a horizontal cable tray. It is assumed that the trash fire ignites an area of approximately 2 m^2 (21 ft^2) of the cable tray. The cables in the tray are IEEE-383 unqualified and made of PE/PVC insulation material. Compute the full-scale HRR of the PE/PVC cable insulation. The bench-scale HRR of PE/PVC is 589 kW/m^2.

Solution

Purpose:

(1) Calculate the full-scale HRR of the PE/PVC insulation material.

Assumptions:

(1) Lee's correlation is valid for this fire scenario.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 07_Cable_HRR Calculations.xls

FDT^s Input Parameters:

-Exposure Cable Tray Burning Area (A_f) = 21 ft^2

-Select Material: **PE/PVC** (the one with a bench-scale HRR of 589 kW/m^2)

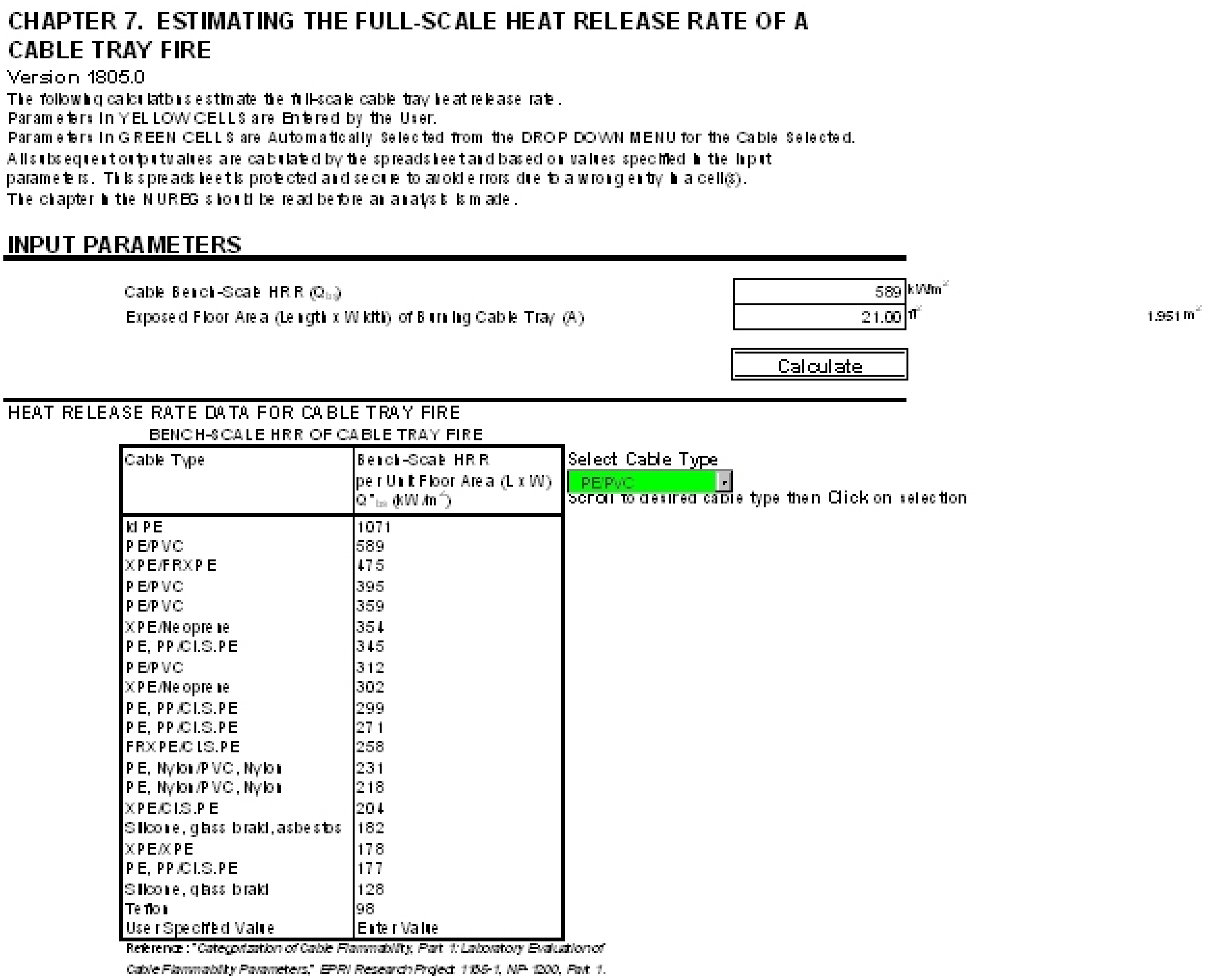
Results*

Cable Insulation	Full Scale HRR $(\dot{Q}_{fs})$ kW (Btu/sec)
PE/PVC	517 (490)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 07_Cable_HRR Calculations.xls



CHAPTER 7. ESTIMATING THE FULL-SCALE HEAT RELEASE RATE OF A CABLE TRAY FIRE

Version 1805.0

The following calculations estimate the full-scale cable tray heat release rate.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Cable 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

Cable Bench-Scale HRR (Q_{bs})	589	kW/m^2	
Exposed Floor Area (Length x Width) of Burning Cable Tray (A)	21.00	ft^2	1.951 m^2

Calculate

HEAT RELEASE RATE DATA FOR CABLE TRAY FIRE

BENCH-SCALE HRR OF CABLE TRAY FIRE

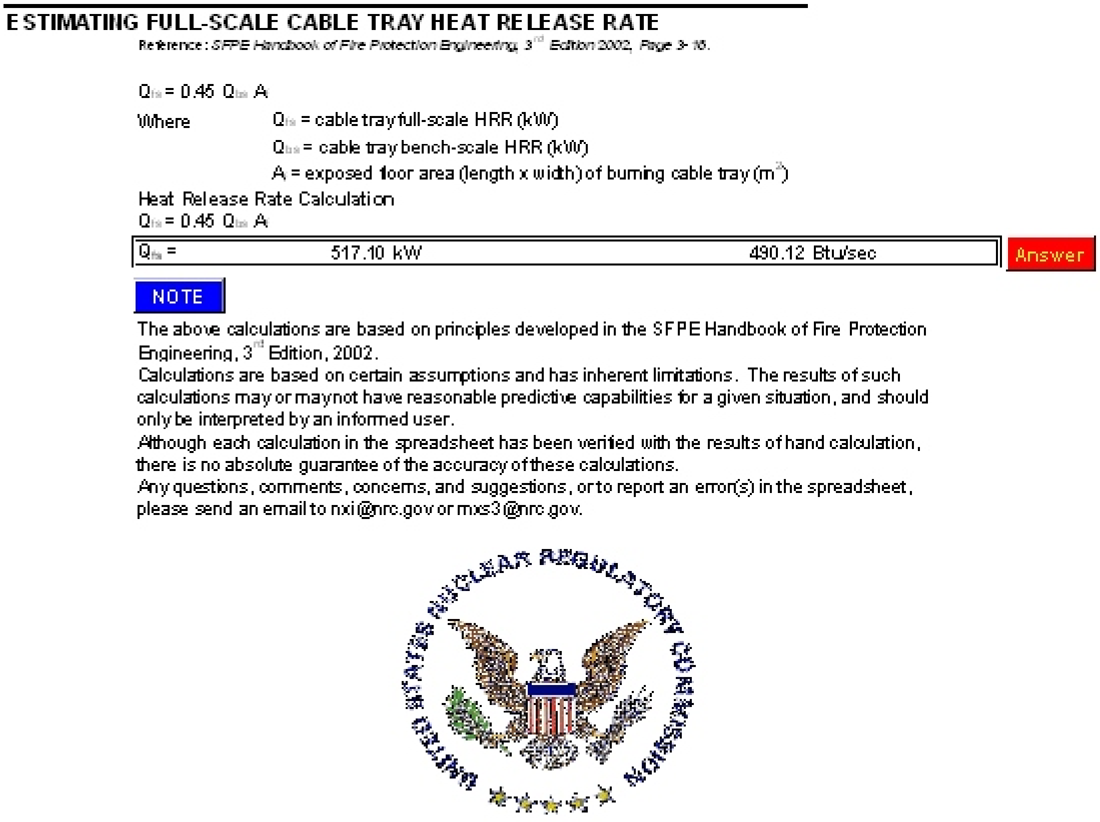
Cable Type	Bench-Scale HRR per Unit Floor Area (L x W) $\dot{Q}''_{bs}$ (kW/m^2)
XLPE	1071
PE/PVC	589
XPE/FRXPE	475
PE/PVC	395
PE/PVC	359
XPE/Neoprene	354
PE, PP/Cl.S.PE	345
PE/PVC	312
XPE/Neoprene	302
PE, PP/Cl.S.PE	299
PE, PP/Cl.S.PE	271
FRXPE/Cl.S.PE	258
PE, Nylon/PVC, Nylon	231
PE, Nylon/PVC, Nylon	218
XPE/Cl.S.PE	204
Silicone, glass braid, asbestos	182
XPE/XPE	178
PE, PP/Cl.S.PE	177
Silicone, glass braid	128
Teflon	98
User Specified Value	Enter Value

Reference: *"Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.*

Select Cable Type

PE/PVC

Scroll to desired cable type then Click on selection



ESTIMATING FULL-SCALE CABLE TRAY HEAT RELEASE RATE

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition 2002, Page 3-16.

$Q_{fs} = 0.45\ Q_{bs}\ A$

Where
Q_{fs} = cable tray full-scale HRR (kW)
Q_{bs} = cable tray bench-scale HRR (kW)
A = exposed floor area (length x width) of burning cable tray (m^2)

Heat Release Rate Calculation

$Q_{fs} = 0.45\ Q_{bs}\ A$

Q_{fs} =	517.10 kW	490.12 Btu/sec

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 has 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 7.12-2

Problem Statement

A 1.5-ft-high stack of untreated wood pallets (exposure fire source) from a recent plant modification ignites and is located 1.5 m (5 ft) beneath a horizontal cable tray. It is assumed that the wood pallets ignite an area of approximately 4 m^2 (43 ft^2) of the cable tray. The cables in the tray are IEEE-383 qualified and made of PE insulation material. Compute the full-scale HRR of PE cable insulation. The bench-scale HRR of PE material is 1,071 kW/m^2.

Solution

Purpose:

(1) Calculate the full-scale HRR of the PE insulation material.

Assumptions:

(1) Lee's correlation is valid for this fire scenario.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 07_Cable_HRR Calculations.xls

FDT^s Input Parameters:

-Exposure Cable Tray Burning Area (A_f) = 43 ft^2

-Select Material: **Id PE**

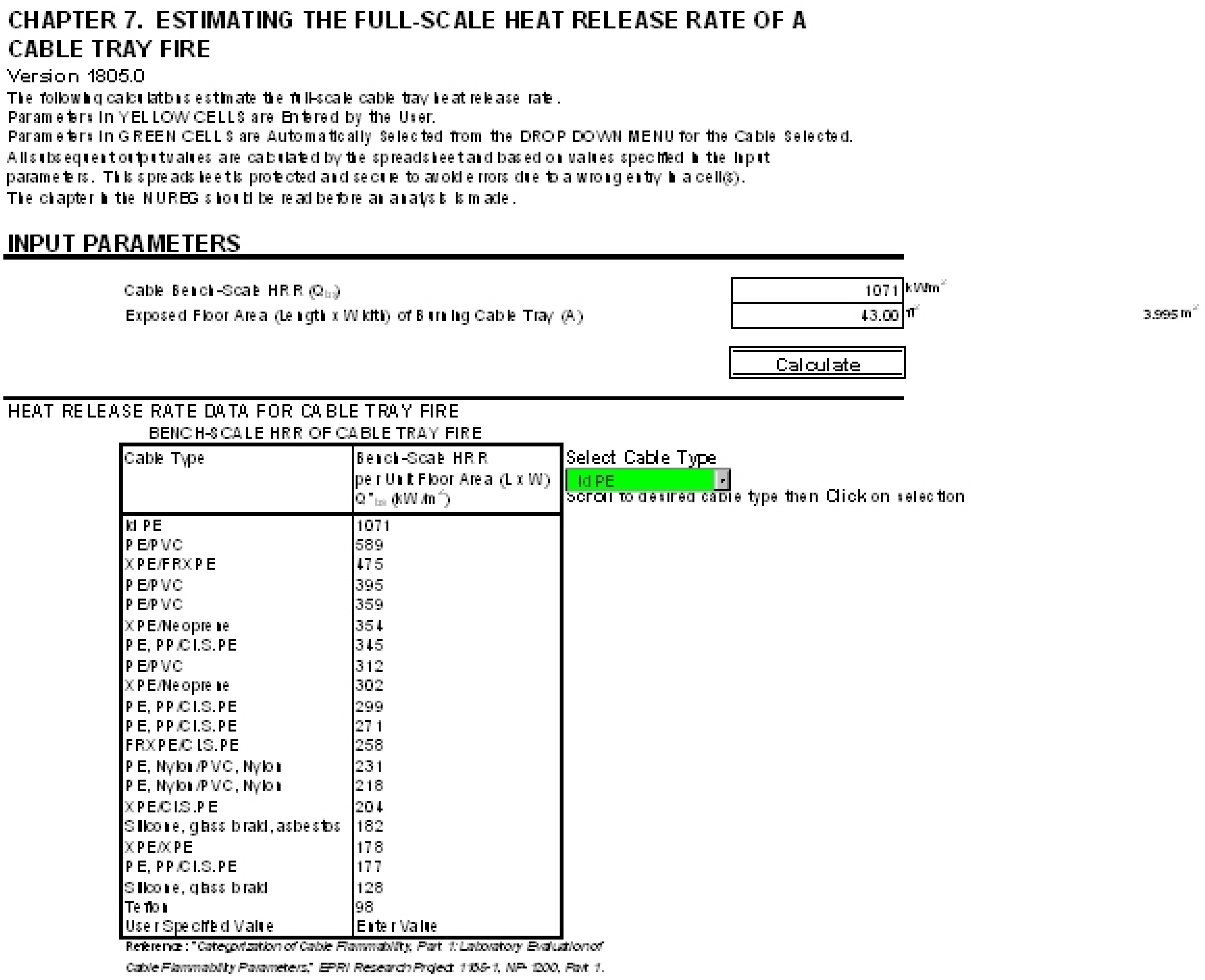
Results*

Cable Insulation	Full Scale HRR $(\dot{Q})$ kW (Btu/sec)
Id PE	1,925 (1,825)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 07_Cable_HRR Calculations.xls



CHAPTER 7. ESTIMATING THE FULL-SCALE HEAT RELEASE RATE OF A CABLE TRAY FIRE

Version 1805.0

The following calculations estimate the full-scale cable tray heat release rate.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Cable 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

Cable Bench-Scale HRR (Q_{bs})	1071	kW/m^2	
Exposed Floor Area (Length x Width) of Burning Cable Tray (A)	43.00	ft^2	3.995 m^2

HEAT RELEASE RATE DATA FOR CABLE TRAY FIRE

BENCH-SCALE HRR OF CABLE TRAY FIRE

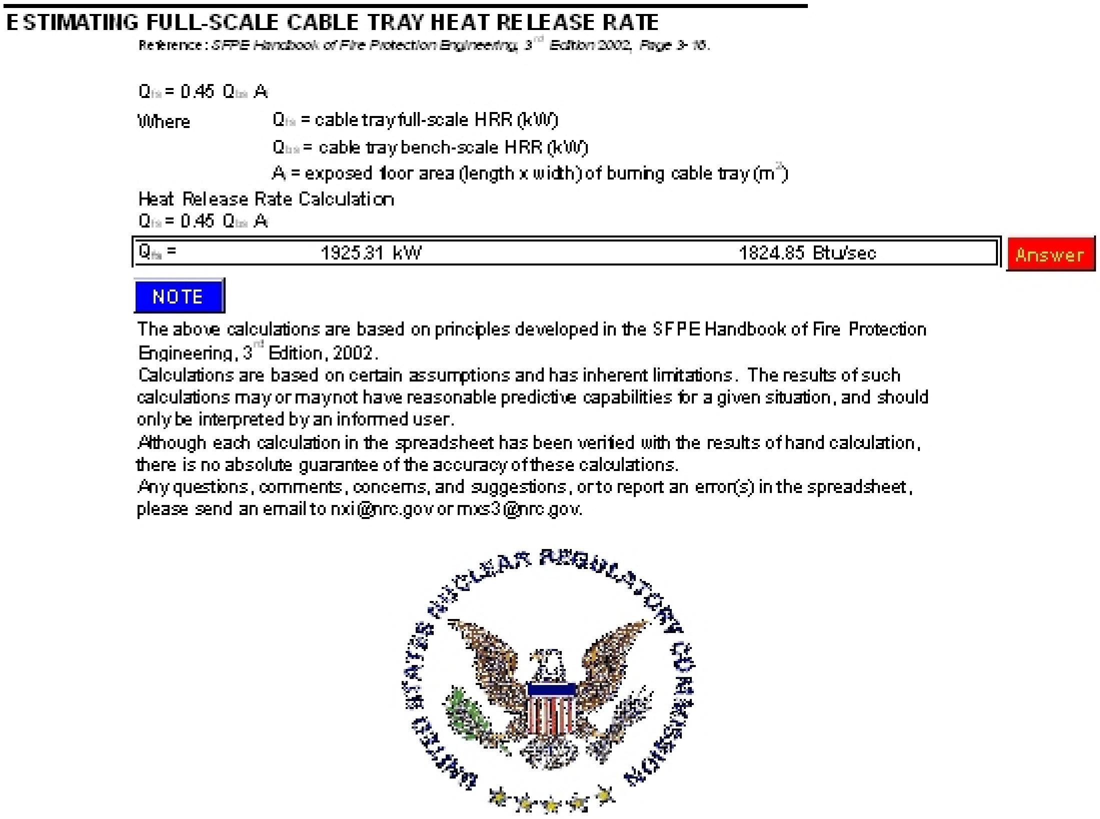
Cable Type	Bench-Scale HRR per Unit Floor Area (L x W) Q''_{bs} (kW/m^2)
Id PE	1071
PE/PVC	589
XPE/FRXPE	475
PE/PVC	395
PE/PVC	359
XPE/Neoprene	354
PE, PP/CI.S.PE	345
PE/PVC	312
XPE/Neoprene	302
PE, PP/CI.S.PE	299
PE, PP/CI.S.PE	271
FRXPE/CLS.PE	258
PE, Nylon/PVC, Nylon	231
PE, Nylon/PVC, Nylon	218
XPE/CI.S.PE	204
Silicone, glass braid, asbestos	182
XPE/XPE	178
PE, PP/CI.S.PE	177
Silicone, glass braid	128
Teflon	98
User Specified Value	Enter Value

Select Cable Type

Id PE

Scroll to desired cable type then Click on selection

Reference: *"Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.*



ESTIMATING FULL-SCALE CABLE TRAY HEAT RELEASE RATE

Reference : SFPE Handbook of Fire Protection Engineering, 3rd Edition 2002, Page 3-16.

$Q_{fs} = 0.45\ Q_{bs}\ A$

Where Q_{fs} = cable tray full-scale HRR (kW)

Q_{bs} = cable tray bench-scale HRR (kW)

A = exposed floor area (length x width) of burning cable tray (m^2)

Heat Release Rate Calculation

$Q_{fs} = 0.45\ Q_{bs}\ A$

Q_{fs} =	1925.31 kW	1824.85 Btu/sec	Answer

NOTE

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

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Example Problem 7.12-3

Problem Statement

A 3.5 ft diameter flammable liquid (lubricating oil) pool fire arises from a breach in an auxiliary cooling water pump oil tank. The pool fire is located on the floor, 3 m (10 ft) beneath a horizontal cable tray. It is assumed that the pool fire ignites an area of approximately 1 m^2 (10.8 ft^2) of the cable tray. The cables in the tray are IEEE-383 unqualified and made of XPE/FRXPE insulation material. Compute the full scale HRR of XPE/FRXPE cable insulation. The bench-scale HRR of XPE/FRXPE is 475 kW/m^2.

Solution

Purpose:

(1) Calculate the full-scale HRR of the XPE/FRXPE insulation material.

Assumptions:

(1) Lee's correlation is valid for this fire scenario.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 07_Cable_HRR Calculations.xls

FDT^s Input Parameters:

-Exposure Cable Tray Burning Area (A_f) = 10.8 ft^2
-Select Material: **XPE/FRXPE**

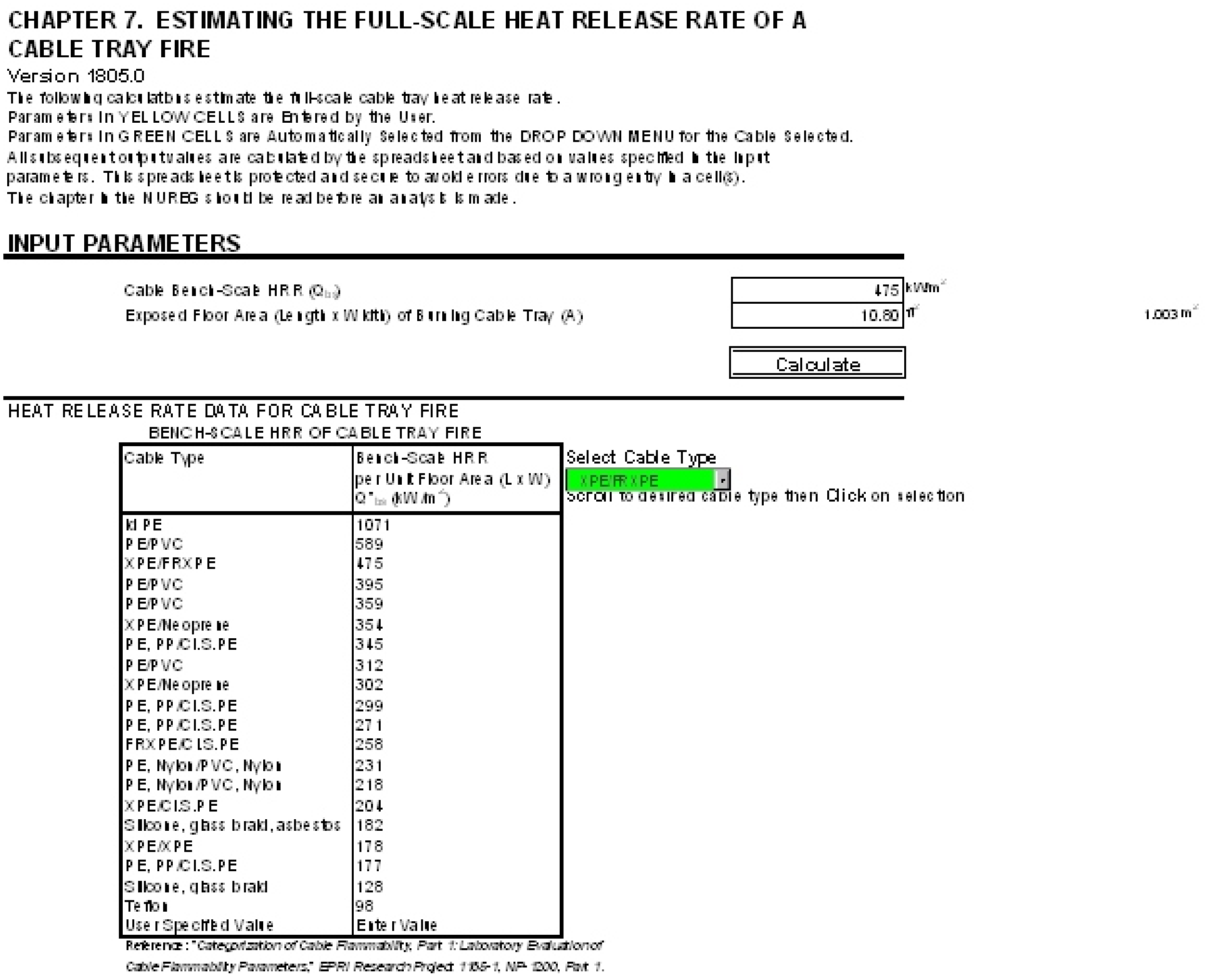
Results*

Cable Insulation	Full Scale HRR $(\dot{Q}_{b})$ kW (Btu/sec)
XPE/FRXPE	214 (203)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 07_Cable_HRR Calculations.xls



CHAPTER 7. ESTIMATING THE FULL-SCALE HEAT RELEASE RATE OF A CABLE TRAY FIRE

Version 1805.0

The following calculations estimate the full-scale cable tray heat release rate.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Cable 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

Cable Bench-Scale HRR (Q_{bs}) 475 kW/m^2

Exposed Floor Area (Length x Width) of Burning Cable Tray (A) 10.80 ft^2 1.003 m^2

HEAT RELEASE RATE DATA FOR CABLE TRAY FIRE

BENCH-SCALE HRR OF CABLE TRAY FIRE

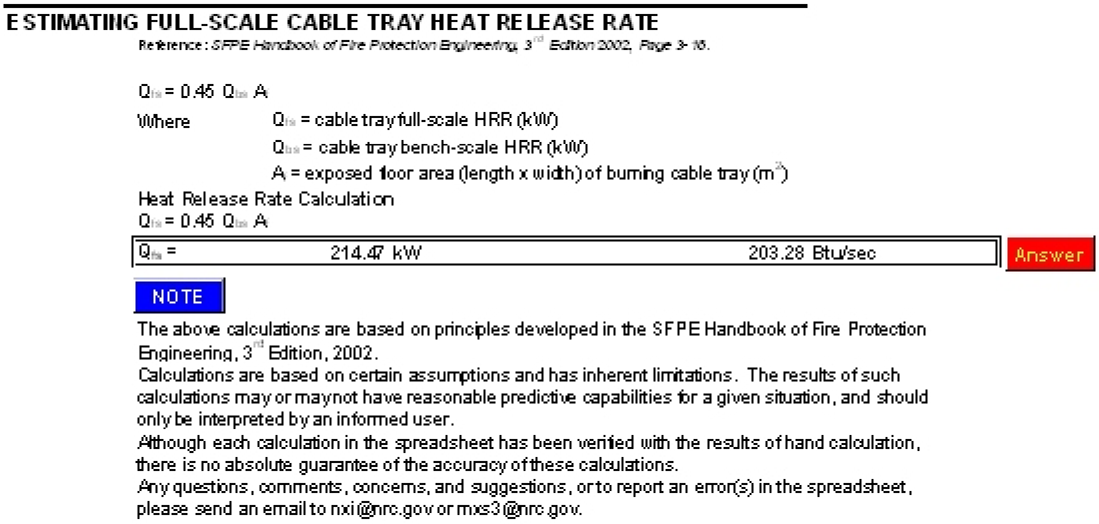
Cable Type	Bench-Scale HRR per Unit Floor Area (L x W) $\dot{Q}''_{bs}$ (kW/m^2)
NPE	1071
PE/PVC	589
XPE/FRXPE	475
PE/PVC	395
PE/PVC	359
XPE/Neoprene	354
PE, PP/Cl.S.PE	345
PE/PVC	312
XPE/Neoprene	302
PE, PP/Cl.S.PE	299
PE, PP/Cl.S.PE	271
FRXPE/Cl.S.PE	258
PE, Nylon/PVC, Nylon	231
PE, Nylon/PVC, Nylon	218
XPE/Cl.S.PE	204
Silicone, glass braid, asbestos	182
XPE/XPE	178
PE, PP/Cl.S.PE	177
Silicone, glass braid	128
Teflon	98
User Specified Value	Enter Value

Select Cable Type

XPE/FRXPE

Scroll to desired cable type then Click on selection

Reference: *"Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.*



ESTIMATING FULL-SCALE CABLE TRAY HEAT RELEASE RATE

Reference : SFPE Handbook of Fire Protection Engineering, 3rd Edition 2002, Page 3-16.

$Q_{fs} = 0.45\ Q_{bs}\ A$

Where Q_{fs} = cable tray full-scale HRR (kW)

Q_{bs} = cable tray bench-scale HRR (kW)

A = exposed floor area (length x width) of burning cable tray (m^2)

Heat Release Rate Calculation

$Q_{fs} = 0.45\ Q_{bs}\ A$

Q_{fs} =	214.47 kW	203.28 Btu/sec	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 has 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.

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CHAPTER 8. ESTIMATING BURNING DURATION OF SOLID COMBUSTIBLES

8.1 Objectives

This chapter has the following objectives:

- Introduce factors that influence the fire duration of solid combustibles.
- Explain how to estimate fire durations for various solid combustibles.
- Approximate first order estimates of burning durations.

8.2 Introduction

The burning duration can be thought of as the time between ignition and the decay phase of a fire. The burning duration (fire) for a given compartment size and ventilation condition is driven by the fuel load. Fuel loading, given in terms of kg (fuel)/m^2 or lb (fuel)/ft^2 is based on the amount of combustibles per unit floor area has been traditionally used to approximate the fire duration. Higher fuel loads typically mean longer durations assuming a fire burning at a constant HRR consumes fuel mass at a constant rate. Given the mass of material being burned per second and the amount of material available to be consumed, it is possible to calculate a first order estimate for the total burning duration of a fuel. Note that for ventilation-controlled fires, higher fuel loads have no effect on compartment temperature, with the exception that the fire duration increases the gas temperature.

8.3 Burning Duration of Solid Combustibles

Fire duration of solid combustibles is an approximation of the potential destructive impact of the burnout[1] of all of the available fuel in a compartment or enclosure with at least one ventilation opening. The intensity and duration of a fully developed fire depend upon the amount of combustibles available, their burning rates, and the air available to support their combustion. Fire intensity is lower when the walls and ceiling absorb significant amounts of energy, rather than acting primarily as insulation or radiation barriers. The possibility that the fire barriers can fail is important to keep in mind. Long after the fully developed fire begins to decay, the fire barriers are still being challenged. However, as in many real fire situations, this threat is usually mitigated by automatic and/or manual fire suppression activities.

---

[1] Burnout as used in this discussion, is when all the available combustibles are consumed. It should be remembered that in most fires, the combustion will be incomplete.

The burning duration of solid combustibles can be estimated if the HRR and total energy contained in the fuel are known. The burning duration can be estimated from the following equation (Buchanan, 2001):

$$\dot{Q} = \frac{E}{t_{solid}} \qquad (8\text{-}1)$$

Where:

$\dot{Q}$ = heat release rate of the fire (kW)
E = total energy contained in the fuel (kJ)
t_{solid} = burning duration of solid fuel (sec)

The maximum possible energy that can be released when fuel burns is the energy contained in the fuel, E, given by the following equation:

$$E = m_{fuel} \Delta H_c \qquad (8\text{-}2)$$

Where:

m_{fuel} = mass of fuel (kW)
H_c = heat of combustion (kJ/kg)

Therefore, Equation (8-1) can be expressed as follows:

$$t_{Solid} = \frac{m_{Fuel} \Delta H_c}{\dot{Q}'' A_{Fuel}} \qquad (8\text{-}3)$$

Where:

t_{Soild} = burning duration (sec)
m_{Fuel} = mass of solid fuel (kg)
H_c = effective heat of combustion (kJ/kg)
$\dot{Q}''$ = heat release rate per unit floor area (kW/m^2)
A_{Fuel} = exposed floor area (length x width) of fuel (m^2)

The exposed fuel surface area (length x width) of fuel (m^2) can be calculated as follows:

$$A_{Fuel} = L x W \qquad (8\text{-}4)$$

Where:

A_{Fuel} = fuel surface area (m^2)
W = fuel exposed width (m)
L = fuel exposed length (m)

Table 8-1 lists the thermal properties of solid combustible materials.

Table 8-1. Thermal Properties of Common Solid Combustible Materials
(Tewarson, 1995, © SFPE. With permission.)

Materials	**HRR per Unit Floor Area** $\dot{Q}''$ **(kW/m^2)**	**Heat of Combustion** H_c **(kJkg)**
PE/PVC	589	24,000
XPE/FRXPE	475	28,300
XPE/Neoprene	354	10,300
PE, Nylon/PVC, Nylon	231	9,200
Teflon	98	3,200
Douglas fir plywood	124	13,000–15,000
Fire-retardant treated plywood	81	13,500
Particle board, 19 mm thick	1,900	17,500
Nylon 6/6	1,313	32,000
Polymethlmethacrylate (PMMA)	665	26,000
Polypropylene (PP)	1,509	43,200
Polystyrene (PS)	1,101	42,000
Polyethylene (PE)	1,408	46,500
Polycarbonate	420	24,400
Polyurethene	710	45,000
Polyvinyl Chloride (PVC) Flexible	237	15,700
Strene-butadiene Copolymers (SBR)	163	44,000
Ethylene Propylene Dien Rubber	956	28,800
Empty Cartons 15 ft high	1700	12,700
Wood pallets, stacked 1.5 ft high	1,420	13,000–15,000
Wood pallets, stacked 5 ft high	3,970	13,000–15,000
Wood pallets, stacked 10 ft high	6,800	13,000–15,000

8.4 Assumptions and Limitations

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

(1) Combustion is incomplete (leaving some residual fuel) and takes place entirely within the confines of the compartment.

(2) Virtually all of the potential energy in the fuel is released in the involved compartment.

8.5 Required Input for Spreadsheet Calculations

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

(1) fuel type (material)

(2) mass of solid fuel (lb)

(3) exposed fuel surface area (ft^2)

8.6 Cautions

(1) Use (08_Burning_Duration_Soild.xls) spreadsheet on the CD-ROM for calculation.

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

8.7 Summary

Estimating the burning duration of solid combustibles involves the following steps:

(1) Determine the mass of fuel.

(2) Calculate the surface area of combustible solid.

(3) Calculate the burning duration using HRR per unit floor area and fuel heat of combustion.

8.8 References

Buchanan, A.H., “Structural Design for Fire Safety,” John Wiley & Sons, Limited, 2001, p. 38.

Karlsson, B., and J.G. Quintiere, *Enclosure Fire Dynamics*, Chapter 3, “Energy Release Rates,” CRC Press LLC, New York, pp. 25–46, 1999.

Tewarson, A., “Generation of Heat and Chemical Compounds in Fires,” Section 3, Chapter 5, *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 2002.

8.9 Problems

Example Problem 8.9-1

Problem Statement

A horizontal power cable fails as a result of self-initiated fire and burn in a compartment. Compute the burning duration of a cable tray with an exposed surface area of 1 ft^2 filled with 10 lb of non-IEEE-383-qualified PE/PVC cables. The heat release per unit floor area of PE/PVC is 589 kW/m^2, and the heat of combustion is 24,000 kJ/kg.

Solution

Purpose:

(1) Calculate the burning duration of the cable material (PE/PVC).

Assumptions:

(1) Combustion is incomplete and takes place entirely within the confines of the compartment.

(2) Virtually all of the potential energy in the fuel is released in the involved compartment.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 08_Burning_Duration Solid.xls

FDT^s Input Parameters:

-Mass of Solid Fuel (m_{solid}) = 10 lb
-Exposure Fuel Surface Area (A_{fuel}) = 1 ft^2
-Select Material: **PE/ PVC**

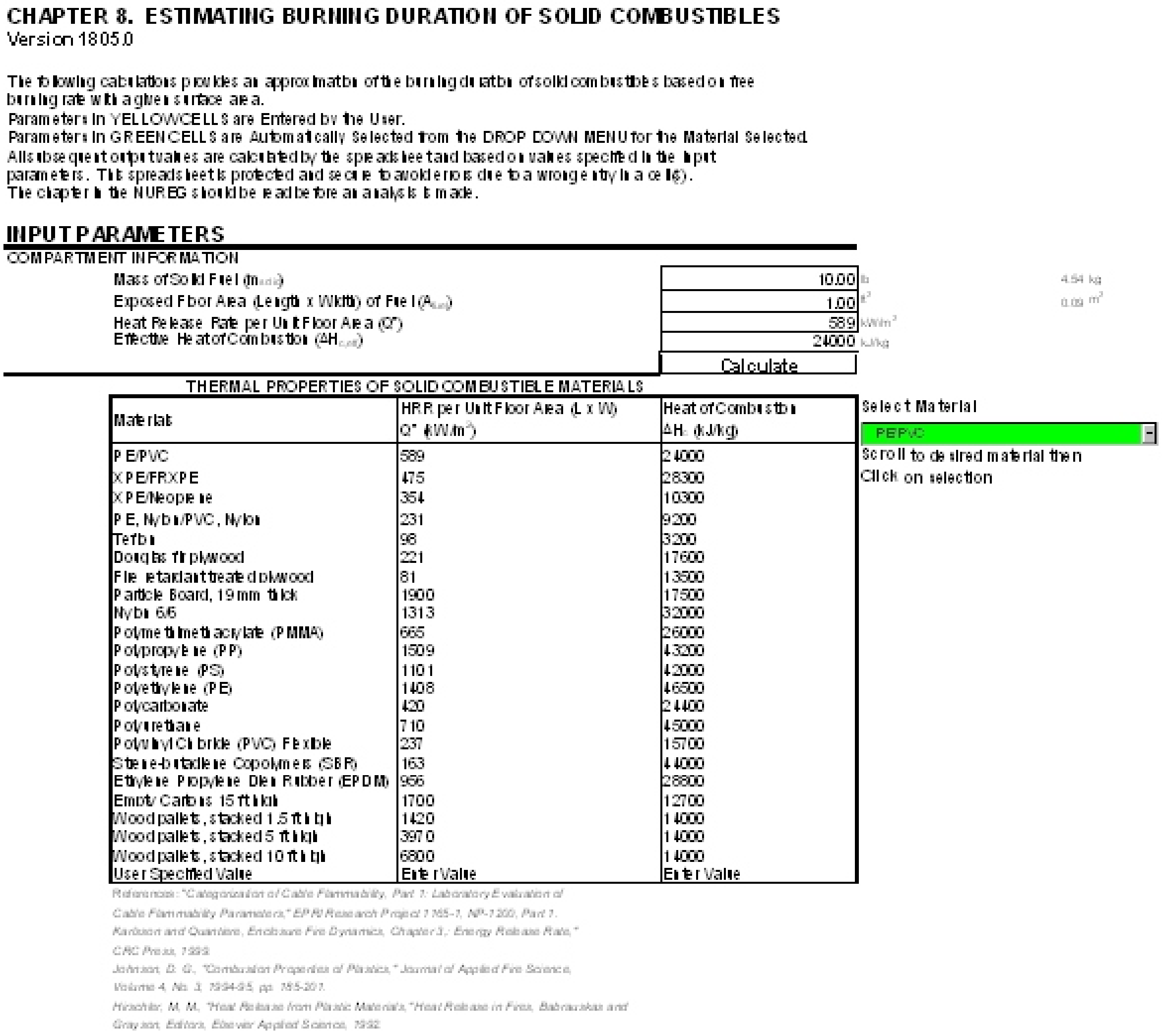
Results*

Material	Burning Duration (t_{solid}) (min.)
PE/PVC	33

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 08_Burning_Duration Solid.xls



CHAPTER 8. ESTIMATING BURNING DURATION OF SOLID COMBUSTIBLES

Version 1805.0

The following calculations provides an approximation of the burning duration of solid combustibles based on free burning rate with a given surface area.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Mass of Solid Fuel (m_{solid})	10.00	lb	4.54 kg
Exposed Floor Area (Length x Width) of Fuel (A_{fuel})	1.00	ft^2	0.09 m^2
Heat Release Rate per Unit Floor Area (Q'')	589	kW/m^2	
Effective Heat of Combustion ($\Delta H_{c,eff}$)	24000	kJ/kg	

THERMAL PROPERTIES OF SOLID COMBUSTIBLE MATERIALS

Materials	HRR per Unit Floor Area (L x W) Q'' (kW/m^2)	Heat of Combustion ΔH_c (kJ/kg)
PE/PVC	589	24000
XPE/FRXPE	475	28300
XPE/Neoprene	354	10300
PE, Nylon/PVC, Nylon	231	9200
Teflon	98	3200
Douglas fir plywood	221	17600
Fire retardant treated plywood	81	13500
Particle Board, 19 mm thick	1900	17500
Nylon 6/6	1313	32000
Polymethylmethacrylate (PMMA)	665	26000
Polypropylene (PP)	1509	43200
Polystyrene (PS)	1101	42000
Polyethylene (PE)	1408	46500
Polycarbonate	420	24400
Polyurethane	710	45000
Polyvinyl Chloride (PVC) Flexible	237	15700
Styrene-butadiene Copolymers (SBR)	163	44000
Ethylene Propylene Dien Rubber (EPDM)	956	28800
Empty Cartons 15 ft high	1700	12700
Wood pallets, stacked 1.5 ft high	1420	14000
Wood pallets, stacked 5 ft high	3970	14000
Wood pallets, stacked 10 ft high	6800	14000
User Specified Value	Enter Value	Enter Value

Select Material

Scroll to desired material then Click on selection

References: "Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.
Karlsson and Quintiere, Enclosure Fire Dynamics, Chapter 3,: Energy Release Rate," CRC Press, 1999.
Johnson, D. G., "Combustion Properties of Plastics," Journal of Applied Fire Science, Volume 4, No. 3, 1994-95, pp. 185-201.
Hirschler, M. M., "Heat Release from Plastic Materials," Heat Release in Fires, Babrauskas and Grayson, Editors, Elsevier Applied Science, 1992.

BURNING DURATION OF SOLID COMBUSTIBLES

Reference: *Buchanan, A.H., "Structural Design for Fire Safety," 2001, Page 38.*

The burning duration of a solid fuel can be calculated if the total energy contained in the fuel and HRR are known.

The burning duration is given by:

$Q = E / t_{solid}$

or

$t_{solid} = (E) / (Q'' A_{Fuel})$

Where t_{solid} = burning duration of solid combustible (sec)
$E = m_{Fuel} \Delta H_c$ = total energy contained in the fuel (kJ)
Q = heat releare rate of fire (kW)
Q'' = heat release rate per unit floor area of fuel (kW/m^2)
A_{Fuel} = exposed floor area (length x width) of fuel (m^2)

$t_{solid} = (m_{Fuel} \Delta H_c) / (Q'' A_{Fuel})$

Where m_{Fuel} = mass of solid fuel (kg)
ΔH_c = fuel effective heat of combustion (kJ/kg)

$t_{solid} = (m_{solid} \Delta H_c) / (Q'' A_{solid})$

t_{solid} =	1989.44 sec	33.16 minutes	Answer

NOTE

The above calculations are based on principles developed in the Structural Design for Fire Safety, 2001.
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 8.9-2

Problem Statement

A horizontal cable tray filled with non-IEEE-383 qualified XPE/FRXPE cables are ignited as a result of overhead welding and burn in a compartment 20 ft wide x 20 ft deep x 10 ft high. The cable tray has a nominal width of 2 ft and a linear length of 24 ft (i.e., exposed surface area of 48 ft^2). Compute the burning duration of XPE/FRXPE cables assuming the mass of cables is 50 lb. The heat release per unit area of XPE/FRXPE is 475 kW/m^2 and heat of combustion is 28,300 kJ/kg.

Solution

Purpose:
(1) Calculate the burning duration of the cable material (XPE/FRXPE).

Assumptions:
(1) Combustion is incomplete and takes place entirely within the confines of the compartment.
(2) Virtually all of the heat energy in the fuel is released in the involved compartment.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 08_Burning_Duration Solid.xls

FDT^s Input Parameters:
-Mass of Solid Fuel (m_{solid}) = 50 lb
-Exposure Fuel Surface Area (A_{fuel}) = 48 ft^2
-Select Material: **XPE/FRXPE**

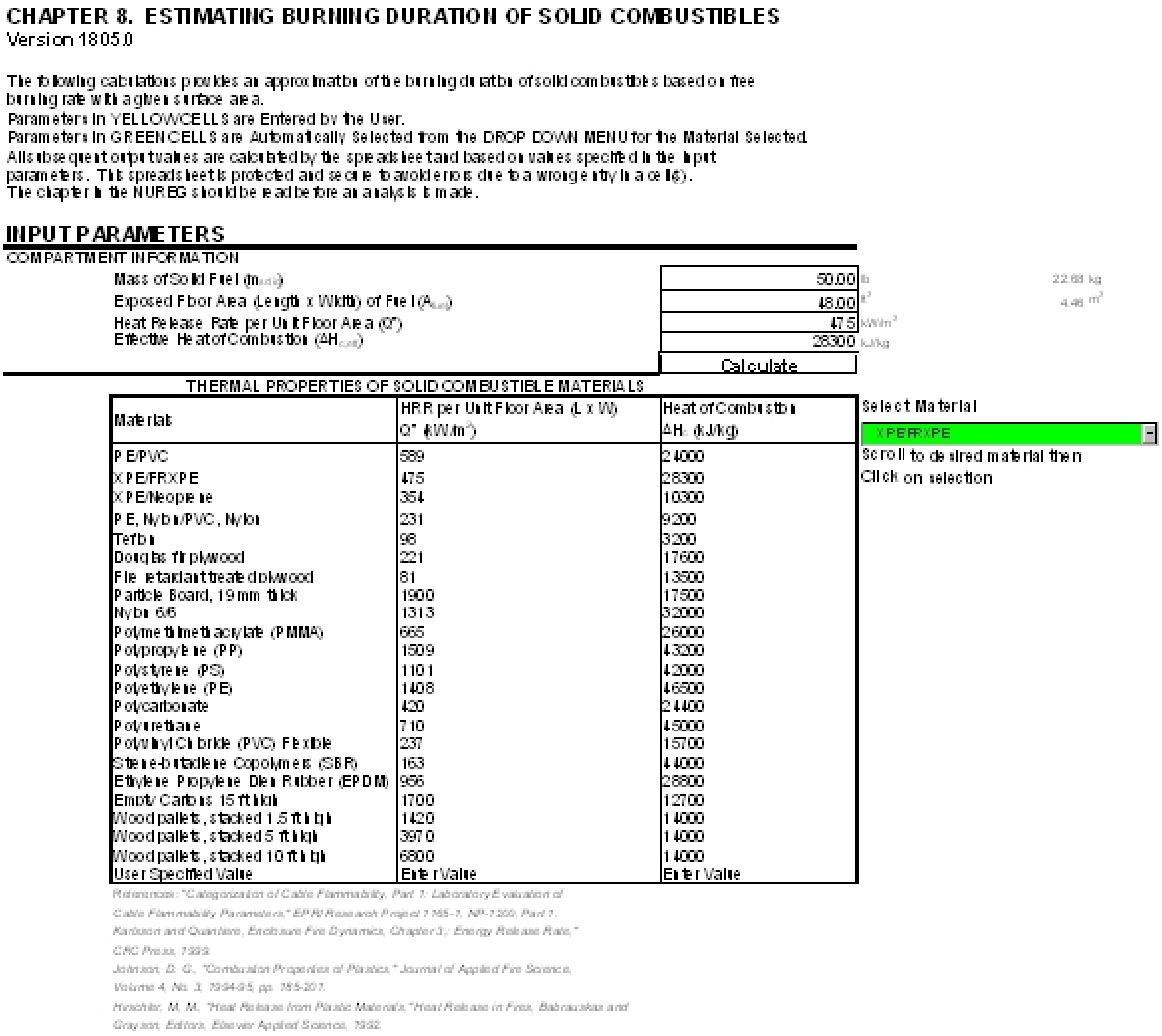
Results*

Material	Burning Duration (t_{solid}) (min.)
XPE/FRXPE	5

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 08_Burning_Duration Solid.xls



CHAPTER 8. ESTIMATING BURNING DURATION OF SOLID COMBUSTIBLES

Version 1805.0

The following calculations provides an approximation of the burning duration of solid combustibles based on free burning rate with a given surface area.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Mass of Solid Fuel (m_{solid})	50.00	lb	22.68	kg
Exposed Floor Area (Length x Width) of Fuel (A_{fuel})	48.00	ft^2	4.46	m^2
Heat Release Rate per Unit Floor Area (Q")	475	kW/m^2		
Effective Heat of Combustion ($\Delta H_{c,eff}$)	28300	kJ/kg		

Calculate

THERMAL PROPERTIES OF SOLID COMBUSTIBLE MATERIALS

Materials	HRR per Unit Floor Area (L x W) Q" (kW/m^2)	Heat of Combustion ΔH_c (kJ/kg)
PE/PVC	589	24000
XPE/FRXPE	475	28300
XPE/Neoprene	354	10300
PE, Nylon/PVC, Nylon	231	9200
Teflon	98	3200
Douglas fir plywood	221	17600
Fire retardant treated plywood	81	13500
Particle Board, 19 mm thick	1900	17500
Nylon 6/6	1313	32000
Polymethylmethacrylate (PMMA)	665	26000
Polypropylene (PP)	1509	43200
Polystyrene (PS)	1101	42000
Polyethylene (PE)	1408	46500
Polycarbonate	420	24400
Polyurethane	710	45000
Polyvinyl Chloride (PVC) Flexible	237	15700
Styrene-butadiene Copolymers (SBR)	163	44000
Ethylene Propylene Dien Rubber (EPDM)	956	28800
Empty Cartons 15 ft high	1700	12700
Wood pallets, stacked 1.5 ft high	1420	14000
Wood pallets, stacked 5 ft high	3970	14000
Wood pallets, stacked 10 ft high	6800	14000
User Specified Value	Enter Value	Enter Value

Select Material

🟩 XPE/FRXPE

Scroll to desired material then Click on selection

References: "Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.
Karlsson and Quintiere, Enclosure Fire Dynamics, Chapter 3,: Energy Release Rate," CRC Press, 1999.
Johnson, D. G., "Combustion Properties of Plastics," Journal of Applied Fire Science, Volume 4, No. 3, 1994-95, pp. 185-201.
Hirschler, M. M., "Heat Release from Plastic Materials," Heat Release in Fires, Babrauskas and Grayson, Editors, Elsevier Applied Science, 1992.

BURNING DURATION OF SOLID COMBUSTIBLES

Reference: *Buchanan, A.H., "Structural Design for Fire Safety," 2001, Page 38.*

The burning duration of a solid fuel can be calculated if the total energy contained in the fuel and HRR are known.

The burning duration is given by:

$Q = E / t_{solid}$

or

$t_{solid} = (E) / (Q'' A_{Fuel})$

Where t_{solid} = burning duration of solid combustible (sec)
$E = m_{Fuel}\, \Delta H_c$ = total energy contained in the fuel (kJ)
Q = heat releare rate of fire (kW)
Q'' = heat release rate per unit floor area of fuel (kW/m^2)
A_{Fuel} = exposed floor area (length x width) of fuel (m^2)

$t_{solid} = (m_{Fuel}\, \Delta H_c) / (Q''\, A_{Fuel})$

Where m_{Fuel} = mass of solid fuel (kg)
ΔH_c = fuel effective heat of combustion (kJ/kg)

$t_{solid} = (m_{solid}\, \Delta H_c) / (Q''\, A_{solid})$

t_{solid} =	303.01 sec	5.05 minutes	Answer

NOTE

The above calculations are based on principles developed in the Structural Design for Fire Safety, 2001.
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 8.9-3

Problem Statement

A fire involving a 1.5-ft-high stack of wood pallets is located in a compartment 40 ft wide x 40 ft deep x 10 ft high. The mass of the wood pallets is 30 lb. Compute the burning duration of the wood pallet fire in the compartment. The exposed surface area of the wood pallets is 4 ft x 4 ft or 16 ft^2.

Solution

Purpose:

(1) Calculate the burning duration of the stack of wood pallets.

Assumptions:

(1) Combustion is incomplete and takes place entirely within the confines of the compartment.

(2) Virtually all of the heat energy in the fuel is released in the involved compartment.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 08_Burning_Duration Solid.xls

FDT^s Input Parameters:
-Mass of Solid Fuel (m_{solid}) = 30 lb
-Exposure Fuel Surface Area (A_{fuel}) = 16 ft^2
-Select Material: **Wood pallet, stacked 1.5 ft high**

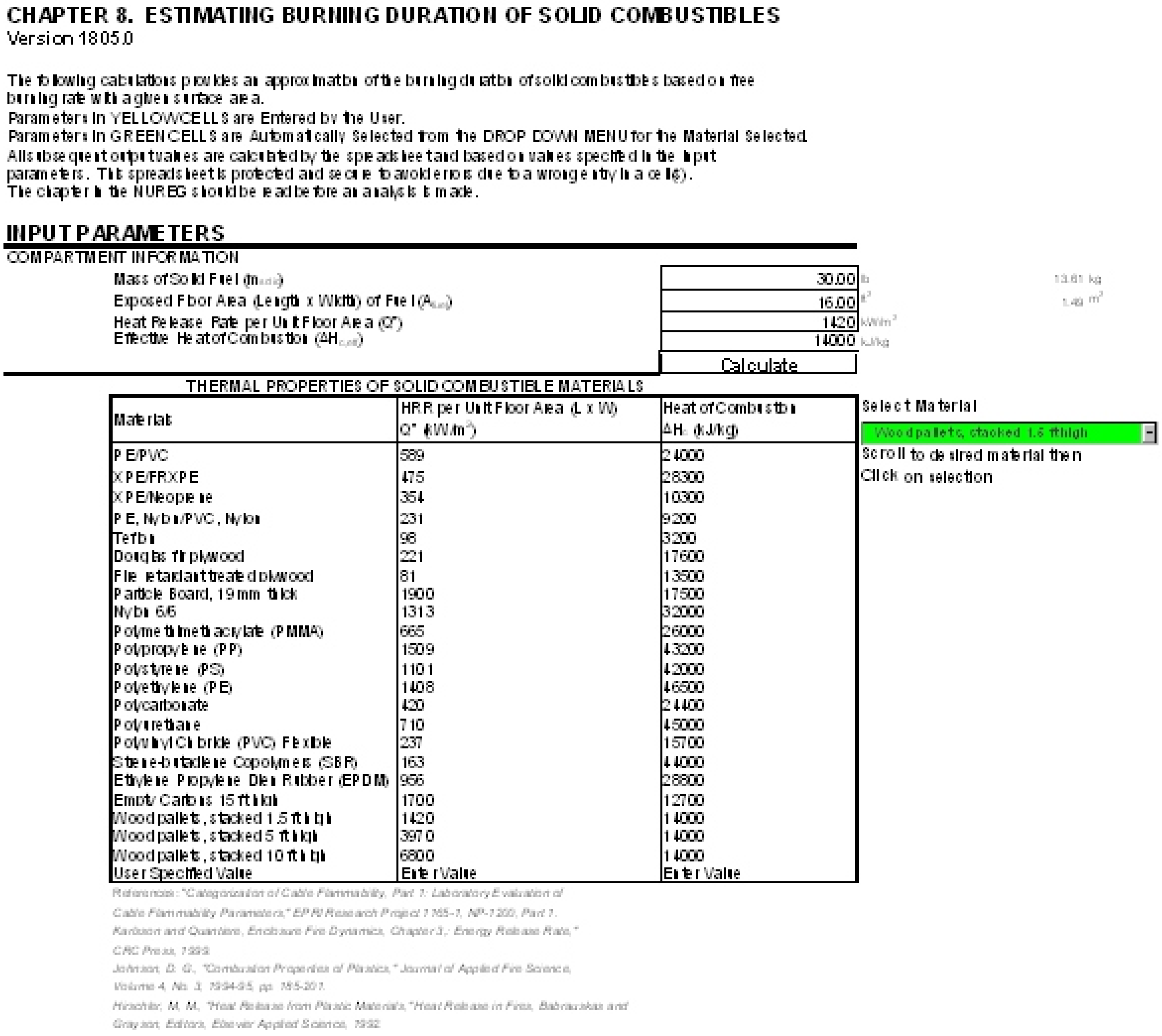
Results*

Material	Burning Duration (t_{solid}) (min.)
Wood pallet, stacked 1.5 ft high	1.5

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 08_Burning_Duration Solid.xls



CHAPTER 8. ESTIMATING BURNING DURATION OF SOLID COMBUSTIBLES

Version 1805.0

The following calculations provides an approximation of the burning duration of solid combustibles based on free burning rate with a given surface area.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Mass of Solid Fuel (m_{solid})	30.00	lb	13.61 kg
Exposed Floor Area (Length x Width) of Fuel (A_{fuel})	16.00	ft^2	1.49 m^2
Heat Release Rate per Unit Floor Area (Q")	1420	kW/m^2	
Effective Heat of Combustion ($\Delta H_{c,eff}$)	14000	kJ/kg	

Calculate

THERMAL PROPERTIES OF SOLID COMBUSTIBLE MATERIALS

Materials	HRR per Unit Floor Area (L x W) Q" (kW/m^2)	Heat of Combustion ΔH$_c$ (kJ/kg)
PE/PVC	589	24000
XPE/FRXPE	475	28300
XPE/Neoprene	354	10300
PE, Nylon/PVC, Nylon	231	9200
Teflon	98	3200
Douglas fir plywood	221	17600
Fire retardant treated plywood	81	13500
Particle Board, 19 mm thick	1900	17500
Nylon 6/6	1313	32000
Polymethylmethacrylate (PMMA)	665	26000
Polypropylene (PP)	1509	43200
Polystyrene (PS)	1101	42000
Polyethylene (PE)	1408	46500
Polycarbonate	420	24400
Polyurethane	710	45000
Polyvinyl Chloride (PVC) Flexible	237	15700
Styrene-butadiene Copolymers (SBR)	163	44000
Ethylene Propylene Diene Rubber (EPDM)	956	28800
Empty Cartons 15 ft high	1700	12700
Wood pallets, stacked 1.5 ft high	1420	14000
Wood pallets, stacked 5 ft high	3970	14000
Wood pallets, stacked 10 ft high	6800	14000
User Specified Value	Enter Value	Enter Value

Select Material

Wood pallets, stacked 1.5 ft high

Scroll to desired material then Click on selection

References: "Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.
Karlsson and Quintiere, Enclosure Fire Dynamics, Chapter 3,: Energy Release Rate,"
CRC Press, 1999.
Johnson, D. G., "Combustion Properties of Plastics," Journal of Applied Fire Science, Volume 4, No. 3, 1994-95, pp. 185-201.
Hirschler, M. M., "Heat Release from Plastic Materials," Heat Release in Fires, Babrauskas and Grayson, Editors, Elsevier Applied Science, 1992.

BURNING DURATION OF SOLID COMBUSTIBLES

Reference: *Buchanan, A.H., "Structural Design for Fire Safety," 2001, Page 38.*

The burning duration of a solid fuel can be calculated if the total energy contained in the fuel and HRR are known.

The burning duration is given by:

$Q = E / t_{solid}$

or

$t_{solid} = (E) / (Q'' A_{Fuel})$

Where t_{solid} = burning duration of solid combustible (sec)

$E = m_{Fuel}\, \Delta H_C$ = total energy contained in the fuel (kJ)

Q = heat releare rate of fire (kW)

Q'' = heat release rate per unit floor area of fuel (kW/m^2)

A_{Fuel} = exposed floor area (length x width) of fuel (m^2)

$t_{solid} = (m_{Fuel}\, \Delta H_C) / (Q'' A_{Fuel})$

Where m_{Fuel} = mass of solid fuel (kg)

ΔH_C = fuel effective heat of combustion (kJ/kg)

$t_{solid} = (m_{solid}\, \Delta H_C) / (Q'' A_{solid})$

t_{solid} =	90.26 sec	1.50 minutes	Answer

NOTE

The above calculations are based on principles developed in the Structural Design for Fire Safety, 2001.
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.
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CHAPTER 9. ESTIMATING THE CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

9.1 Objectives

This chapter has the following objectives:

- Discuss various types of fire plumes.
- Discuss the fire plume that is most common encountered.
- Identify the temperature and flow characteristics of the fire plume.
- Define relevant terms including fire plume, air entrainment, plume temperature, ceiling jet, and virtual origin.

9.2 Introduction

A fire plume is a buoyantly rising column of hot combustion products, along with unburned fuel vapor and admixed air. When fire in a building continues to grow, the plume typically impinges on the ceiling, unless the fire remains very small or the ceiling is very high. The interaction of a plume with a ceiling is discussed in subsequent sections.

Figure 9-1 shows a turbulent column of hot gases rising because of buoyancy differences. The effect of the turbulence will cause rapid mixing of the hot gases with the cooler surrounding air. The addition of cold mass to the rising column decreases its velocity, widens the column, and reduces its temperature. When plume height is large in comparison to the width of the base of the plume, the average midline temperature (relative to ambient temperature) is found to decrease at a rate that is inversely proportional to the height of the plume raised to the $^5/_3$ power. Similarly, the average velocity of the midline is inversely proportional to the height of the plume raised to the ⅓ power. Correlations have been developed to predict the temperature and velocity distribution across a plume at any given height. These correlations are related in terms of the HRR driving the plume.

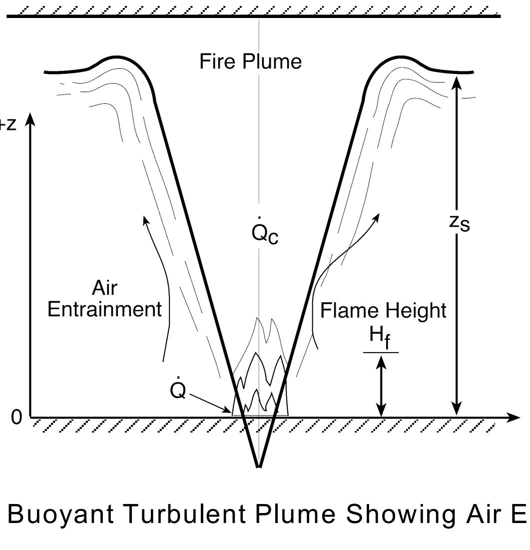


Figure 9-1 A Buoyant Turbulent Plume Showing Air Entrainment

The foregoing discussion refers to a rising column of hot gases, with no combustion taking place. This is applicable to a fire in which the combustion occurs close to the base of the fire plume. However, if combustion continues within the fire plume, the release of heat increases the plume temperature and velocity. The turbulence intensity in a fire plume is high; the velocity fluctuations at the centerline can be up to 30 percent of the average velocity, and the temperature fluctuations can be even greater.

In general, a fire plume contains smoke particles. As surrounding air mixes into the plume, it dilutes the smoke and reduces the temperature. This mixing is called entrainment. In order to predict which environment a given fire will produce, it is necessary to know the rate of entrainment into the plume. Researchers have proposed various correlations to calculate the rate of entrainment in a fire plume, however, the results are not entirely reliable. Small ambient distribution in the air near the plume can also have substantial effects on the entrainment rate. When combustion occurs only in the lower portion of a plume, there is roughly an order of magnitude more entrained air present than the stoichiometric requirement at the plume height above when there is no combustion occurring.

A fire plume can be subdivided into flaming (reacting) and non-flaming (non-reacting) zones. The flaming zone lies just above the fire source and the fuel vapors released by the combustibles burn in this zone. The air required by the reaction is supplied by the entrainment attributable to the upward movement of the reactants. Above the flaming zone where no reaction is taking place in the column of hot products of combustion is defined as the non-flaming zone.

9.3 Fire Plume Characteristics

Fire plumes can be characterized into various groups, depending on the scenario under investigation. This chapter focuses on the point source thermal plume, which is the plume most commonly encountered in fire dynamics applications. The point source thermal plume (or axisymmetric buoyant plume), as described by George, Alpert, and Tamanini (1977) and Alpert and Ward (1984), results when a diffusion flame is formed above the burning fuel. An axis of symmetry is assumed to exist along the vertical centerline of the plume. Another fire plume category, known as the line plume, is caused by a diffusion flame formed above a long and narrow burner that allows air to be entrained from two sides as the hot gases rise. Examples of line fires including flame spread over flammable wall linings, a balcony spill plume, a long sofa, a row of townhouses, and the advancing front of forest fire.

The unconfined axisymmetric plume has no physical barriers to limit vertical movement or restrict air entrainment across the plume boundary. In a confined space the fire plume can be influenced by surrounding surfaces. For example, the area through which air may be entrained is reduced if an item is burning against a wall. Similarly, if the fire plume impinges on a ceiling, it will be deflected horizontally to form a ceiling jet. Impingement on a ceiling also reduces the amount of air entrained by the plume. The most important consequence of plumes interacting with their surroundings is heat transfer to the surfaces involved and the speed at which these surfaces (if combustible) will ignite and contribute to the fire growth process.

The axisymmetric fire plume is conventionally divided into three zones, as shown in Figure 9-2. In the continuous flame zone, the upward velocity is near zero at the base and increases with height. In the intermittent flame zone the velocity is relatively constant, while in the far field zone the velocity decreases with height.

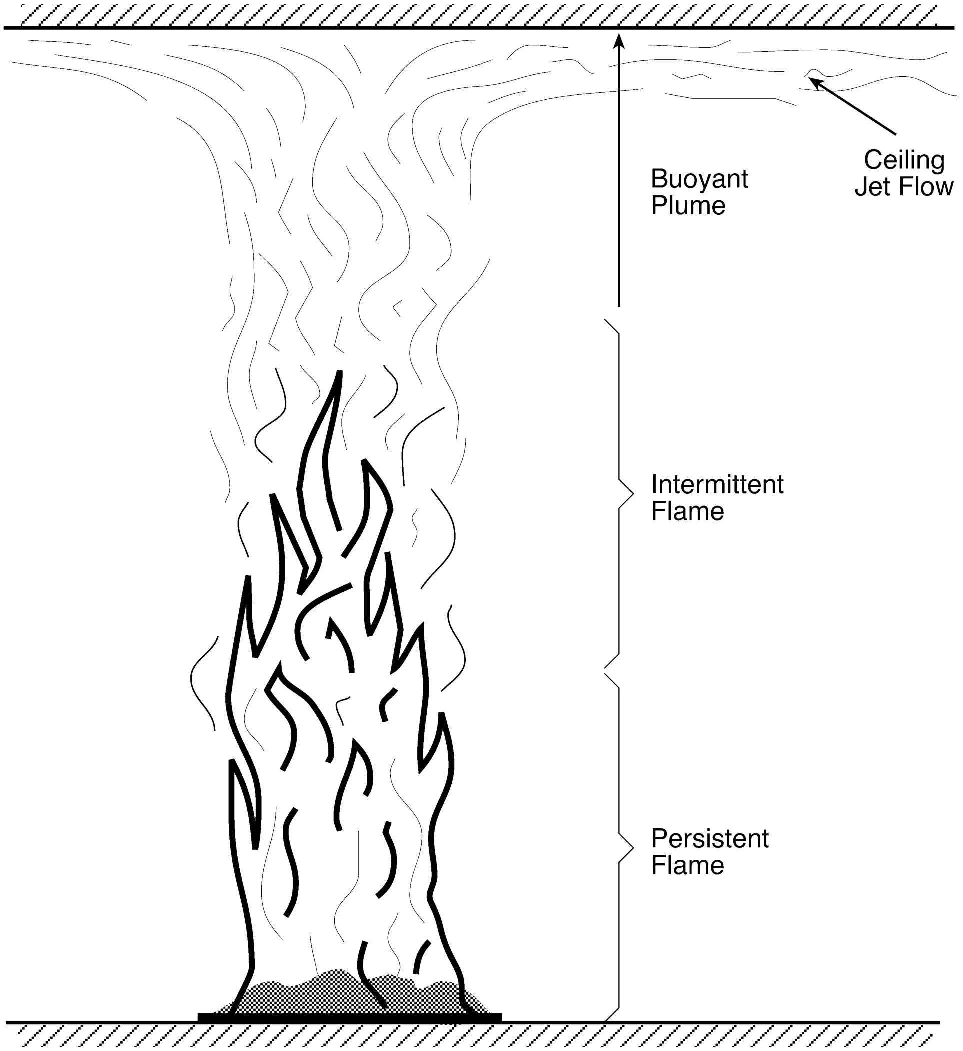


Figure 9-2 Three Zones of the Axisymmetric Buoyant Fire Plume

The quantity of air entrained, along with a resultant decrease in plume temperature and increase in the total mass transported in the plume, are governed by the plume velocity and entrainment coefficient. The entrained flow is proportional to the plume velocity at a particular elevation. This proportional constant is the entrainment coefficient. Hence, the amount of air entrained is related to the plume velocity multiplied by the entrainment coefficient.

Temperature, velocity, and mass flow rates of the fire plume above the flame are critical to the many technical aspects of fire growth in a compartment, including the following examples:

- the rate of formation and descent of the smoke layer
- the temperature and concentration of the hot smoke layer
- the required size of the smoke and heat venting systems
- the actuation time of sprinklers and detectors

9.3.1 Plume Temperature

The peak temperature is found in the plume centerline, and decreases toward the edge of the plume where more ambient air is entrained to cool the plume. The centerline temperature, denoted $T_{p(centerline)}$, varies with height. In the continuous flame region, for example, the centerline temperature is roughly constant and represents the mean flame temperature. By contrast, the temperature decreases sharply above the flames as an increasing amount of ambient air is entrained into the plume. The symbol $T_{p(centerline)}$ describes the increase in centerline plume temperature above the ambient temperature, T_a, as shown in the following equation:

$$\Delta T_{p(centerline)} = T_{p(centerline)} - T_a \qquad (9\text{-}1)$$

Numerous correlations are available to estimate the plume centerline temperature. These correlations relate the temperature as a function of HRR and of height above the source. For example, consider a region of a ceiling jet at radial distance from the fire axis equal to the vertical distance from the fire source to the ceiling. In this region, the maximum velocity in the jet drops to half the value near the fire axis, and the temperature (relative to ambient) drops to about 40 percent of the value near the fire axis. The maximum velocity and temperature exist at a distance below the ceiling equal to about 1-percent of the distance from the fire source to the ceiling. If the walls are much farther away than this, the temperature and velocity of the ceiling jet decay to negligibly low values before the jet encounters the nearest wall. However, if the nearest wall is not far away, a reflection occurs when the jet reaches the wall, and the reflected jet moves back toward the fire axis just under the original jet. Thus, the hot layer under the ceiling becomes thicker.

If the compartment has an opening and fire continues, the hot layer ultimately becomes thick enough to extend below the top of the opening, after which the hot, smoke-laden gases begin to exit from the compartment.

Heskestad (1995) provided a simple correlation for estimating the maximum centerline temperature of a fire plume as a function of ceiling height and HRR:

$$T_{p(centerline)} - T_a = \frac{9.1\left(\frac{T_a}{g c_p^2 \rho_a^2}\right)^{\frac{1}{3}} \dot{Q}_c^{\frac{2}{3}}}{\left(z - z_0\right)^{\frac{5}{3}}} \qquad (9\text{-}2)$$

Where:

$T_{p(centerline)}$ = plume centerline temperature (K)
T_a = ambient air temperature (K)
$\dot{Q}_c$ = convective HRR (kW)
g = acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/Kg-K)
$_a$ = ambient air density (kg/m^3)
z = elevation above the fire source (m)
z_0 = hypothetical virtual origin of the fire (m)

The virtual origin is the equivalent point source height of a finite area fire (Figure 9-3). The location of the virtual origin is needed to calculate the thermal plume temperature for fires that originate in an area heat source. The thermal plume calculations are based on the assumption that the plume originates in a point heat source. Area heat sources include pool fires and burning three-dimensional objects such as cabinets and cable trays. The use of a point heat source model for area sources is accomplished by calculating the thermal plume parameters at the virtual point source elevation, rather than the actual area source elevation.

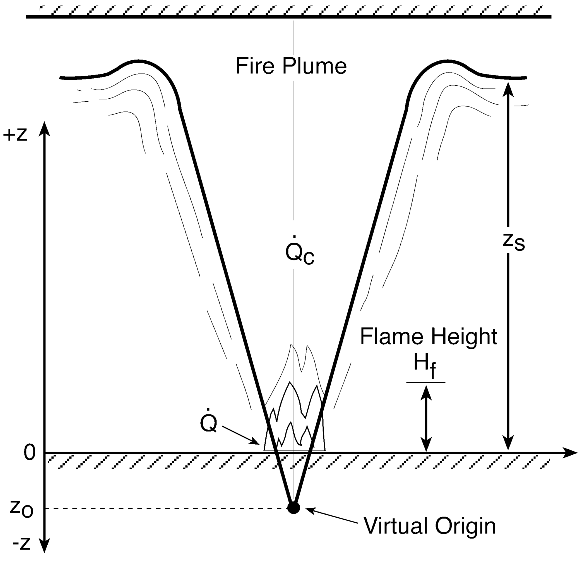


Figure 9-3 Fire Plume with Virtual Origin

The virtual origin, z_0, depends on the diameter of the fire source and the total energy released, as follows:

$$\frac{z_0}{D} = -1.02 + 0.083\frac{\dot{Q}^{\frac{2}{5}}}{D} \qquad (9\text{-}3)$$

Where:

z_0 = virtual origin (m)
D = diameter of fire source (m)
$\dot{Q}$ = total HRR (kW)

For non-circular pools, the effective diameter is defined as the diameter of a circular pool with an area equal to the actual area given by the following equation:

$$D = \sqrt{\frac{4A_f}{\pi}} \qquad (9\text{-}4)$$

Where:

D = diameter of the fire (m)
A_f = fuel spill area or curb area (m^2)

Total HRR $\dot{Q}$ is used when calculating the mean flame height and position of the virtual origin. However, the convective HRR $\dot{Q}_c$ is used when estimating other plume properties, since this is the part of the energy release rate that causes buoyancy. The energy losses attributable to radiation from the flame are typically on the order of 20 to 40 percent of the total HRR $\dot{Q}$. The higher of these values is valid for the sootier and more luminous flames, often from fuels that burn with a low combustion efficiency. The convective HRR is, therefore, often in the range 0.6 $\dot{Q}$ to 0.8 $\dot{Q}$ where $\dot{Q}$ is the total HRR.

9.4 Application for Centerline Fire Plume Correlation

The centerline temperature correlation can be used to predict the temperature increase of the structural elements and subsequent failure of the compartment structure. Also, thermal plume temperature may be used to estimate the temperature of a target located above the plume.

As previously discussed, it is common for a fire plume impinging on a ceiling to make a 90-degree turn and spread out readily under the ceiling, thereby forming a ceiling jet. This ceiling jet is important for two reasons:

(1) Devices to detect the fire, as well as automatic sprinklers, are generally mounted right under the ceiling. Knowledge of the time of arrival and properties of the ceiling jet are crucial to predict when a device will actuate. The actuation of devices, (e.g., sprinklers smoke and thermal detectors) are discussed in Chapters 10, 11, and 12.

(2) The downward thermal radiation from the ceiling jet (including a small fraction from the hot ceiling itself) is a major factor in preheating and igniting combustible items that are not yet involved in the fire. This radiation is very important in determining the rate of fire spread.

9.5 Assumptions and Limitations

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

(1) All heat energy is released at a point.

(2) The correlation was developed for two-dimensional area sources.

(3) If the surrounding air is at an elevated temperature, the temperature difference between the plume and the surrounding environment is small. In this situation, the thermal plume cools less effectively, so Equation 9-2 will underestimate the temperature.

(4) The thermal plume equation is not valid when the momentum forces in a plume are more significant than the buoyant forces, as in a jet fire. If this type of situation is encountered, specialized calculation approaches should be used.

9.6 Required Input for Spreadsheet Calculations

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

(1) heat release rate of the fire (kW)

(2) distance from the top of the fuel to the ceiling (ft)

(3) surface area of the combustible fuel (ft^2)

9.7 Cautions

(1) Use (09_Plume_Temperature_Calculations.xls) spreadsheet in the CD-ROM for calculation.

(2) Make sure to use correct units when entering the input parameters.

9.8 Summary

This chapter discusses fire plume and ceiling jet flow concepts and related fire hazard calculations. The region of hot gas that flows above the flame is called a plume. The plume changes in temperature, velocity, and diameter primarily because surrounding air is entrained (or mixed) into the upward plume flow. This entrained air reduces the plume temperature and increases the width of the plume. The total flow of the gases increases rapidly high above the flame. The plume temperature and combustion product concentrations are highest just above the flame. Moving upward, the temperature decreases because the cooler entrained air from the surrounding environment is mixed with the hot plume gas flow. The concentration of combustion products is also reduced.

Estimating the centerline temperature of a fire plume involves the following steps:

(1) Calculate the diameter of the fire.

(2) Calculate the virtual origin of the fire.

(3) Calculate the convective HRR.

(4) Calculate the plume centerline temperature $T_{p(centerline)}$.

9.9 References

Alpert, R.L., and E.J. Ward, "Evaluation of Unsprinklered Fire Hazard," *Fire Safety Journal*, Volume 7, No. 177, 1984.

Heskestad, G., "Fire Plumes," Section 2, Chapter 2, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

George, W.K., R.L. Alpert and F. Tamanini, "Turbulence Measurements in an Axisymmetric Buoyant Plume," *International Journal of Heat Mass Transfer,* Volume 20*,* pp.1145–1154, 1977.

9.10 Additional Readings

Drysdale, D.D., *An Introduction to Fire Dynamics*, Chapter 4, "Diffusion Flames and Fire Plumes," 2nd Edition, John Wiley and Sons, New York, 1998.

Fire Dynamics, Course Guide, Federal Emergency Management Agency (FEMA), United States Fire Administration (USFA), National Emergency Training Center, Emmitsburg, Maryland, 1995.

Friedman, R., *Principle of Fire Protection Chemistry and Physics*, 3rd Edition, National Fire Protection Association, Quincy, Massachusetts, 1998.

Karlsson, B., and J.G. Quintiere, *Enclosure Fire Dynamics*, Chapter 4, "Fire Plumes and Flame Heights," CRC Press LLC, New York, pp. 181–225, 1999.

Quintiere, J.G., *Principles of Fire Behavior*, Delmar Publishers, Albany, New York, 1997.

9.11 Problems

Example Problem 9.11-1

Problem Statement

A steel beam is located 25 ft above the floor. Calculate the temperature of the beam exposed from a 34.5 ft^2 lube oil pool fire. Assume the HRR of the fire is 5,000 kW.

Solution

Purpose:
(1) Determine the plume centerline temperature for the pool fire scenario.

Assumptions:
(1) All heat is released at a point.
(2) Buoyant forces are more significant than momentum forces.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 09_Plume_Temperature_Calculations.xls

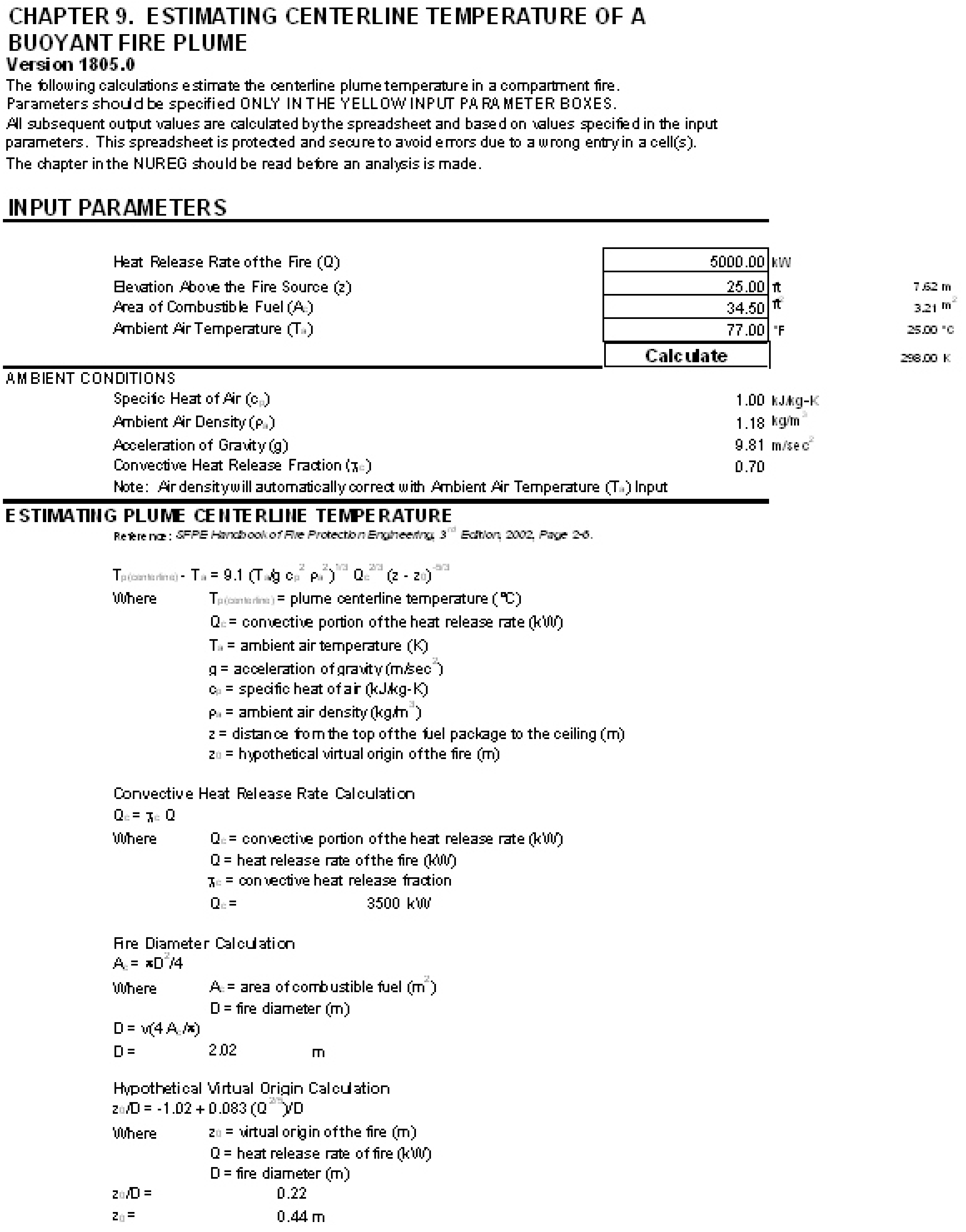
FDT^s Input Parameters:
-Heat Release Rate $(\dot{Q})$ = 5,000 kW
-Distance from the Top of the Fuel to the Ceiling (z) = 25 ft
-Area of Combustible Fuel (A_c) = 34.5 ft^2

Results*

Heat Release Rate $\dot{Q}$ (kW)	Plume Centerline Temperature ($T_{p(centerline)}$) °C (°F)
5,000	244 (471)

*see spreadsheet on next page

Spreadsheet Calculations
FDT^s: 09_Plume_Temperature_Calculations.xls



CHAPTER 9. ESTIMATING CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

Version 1805.0

The following calculations estimate the centerline plume temperature in a compartment fire.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
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

Heat Release Rate of the Fire (Q)	5000.00	kW		
Elevation Above the Fire Source (z)	25.00	ft	7.62	m
Area of Combustible Fuel (A_c)	34.50	ft^2	3.21	m^2
Ambient Air Temperature (T_a)	77.00	°F	25.00	°C
	Calculate		298.00	K

AMBIENT CONDITIONS

Specific Heat of Air (c_p)	1.00	kJ/kg-K
Ambient Air Density (ρ_a)	1.18	kg/m^3
Acceleration of Gravity (g)	9.81	m/sec^2
Convective Heat Release Fraction (χ_c)	0.70	

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

ESTIMATING PLUME CENTERLINE TEMPERATURE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 2-6.

$T_{p(centerline)} - T_a = 9.1 (T_a/g\, c_p^2\, \rho_a^2)^{1/3}\, Q_c^{2/3}\, (z - z_0)^{-5/3}$

Where $T_{p(centerline)}$ = plume centerline temperature (°C)
Q_c = convective portion of the heat release rate (kW)
T_a = ambient air temperature (K)
g = acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/kg-K)
ρ_a = ambient air density (kg/m^3)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fire (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\, Q$

Where Q_c = convective portion of the heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release fraction

Q_c = 3500 kW

Fire Diameter Calculation

$A_c = \pi D^2/4$

Where A_c = area of combustible fuel (m^2)
D = fire diameter (m)

$D = \sqrt{(4 A_c/\pi)}$

D = 2.02 m

Hypothetical Virtual Origin Calculation

$z_0/D = -1.02 + 0.083 (Q^{2/5})/D$

Where z_0 = virtual origin of the fire (m)
Q = heat release rate of fire (kW)
D = fire diameter (m)

z_0/D = 0.22
z_0 = 0.44 m

Centerline Plume Temperature Calculation

$T_{p(centerline)} - T_a = 9.1\ (T_a/g\ c_p^2\ \rho_a^2)^{1/3}\ Q_c^{2/3}\ (z - z_0)^{-5/3}$

$T_{p(centerline)} - T_a =$ **218.97**

$T_{p(centerline)} =$ **516.97** K

$T_{p(centerline)} =$	**243.97 °C**	**471.15 °F**	**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.

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 9.11-2

Problem Statement

Estimate the maximum plume temperature at the ceiling of an 8-ft-high room above a 1,000-kW trash fire with an area of 10 ft^2. Assume that the ambient air temperature is 77 °F.

Solution

Purpose:

(1) Determine the maximum plume centerline temperature for the transient combustible fire scenario.

Assumptions:

(1) All heat is released at a point.
(2) Buoyant forces are more significant than momentum forces.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 09_Plume_Temperature_Calculations.xls

FDT^s Input Parameters:
-Heat Release Rate $(\dot{Q})$ = 1000 kW
-Distance from the Top of the Fuel to the Ceiling (z) = 8 ft
-Area of Combustible Fuel (A_c) = 10 ft^2

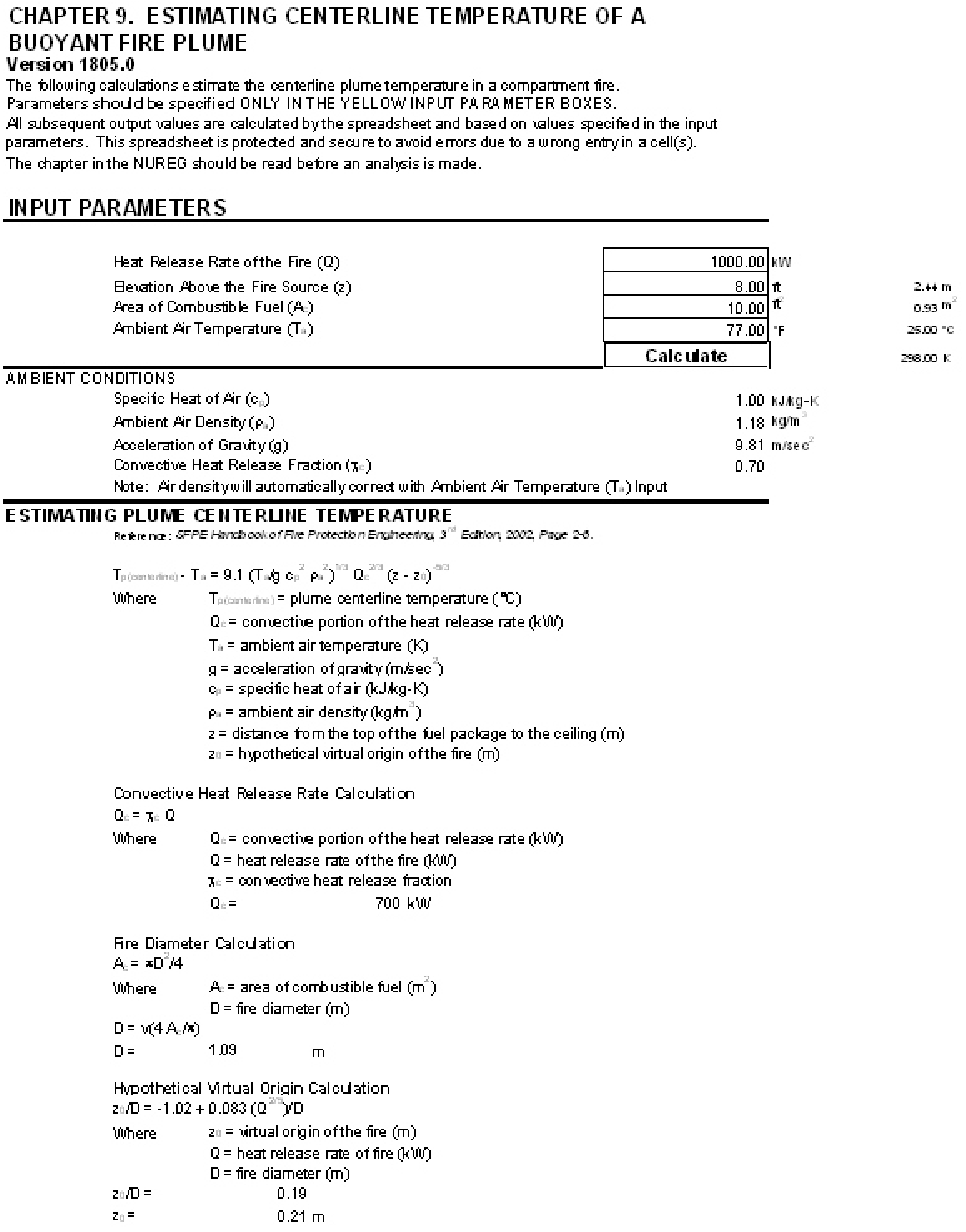
Results*

Heat Release Rate $\dot{Q}$ (kW)	Plume Centerline Temperature ($T_{p(centerline)}$) °C (°F)
1,000	549 (1021)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 09_Plume_Temperature_Calculations.xls



CHAPTER 9. ESTIMATING CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

Version 1805.0

The following calculations estimate the centerline plume temperature in a compartment fire.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
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

Heat Release Rate of the Fire (Q)	1000.00	kW		
Elevation Above the Fire Source (z)	8.00	ft	2.44	m
Area of Combustible Fuel (A_c)	10.00	ft^2	0.93	m^2
Ambient Air Temperature (T_a)	77.00	°F	25.00	°C
	Calculate		298.00	K

AMBIENT CONDITIONS

Specific Heat of Air (c_p)	1.00	kJ/kg-K
Ambient Air Density (ρ_a)	1.18	kg/m^3
Acceleration of Gravity (g)	9.81	m/sec^2
Convective Heat Release Fraction (χ_c)	0.70	

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

ESTIMATING PLUME CENTERLINE TEMPERATURE

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 2-6.*

$$T_{p(centerline)} - T_a = 9.1 \left(T_a/g\, c_p^2\, \rho_a^2\right)^{1/3} Q_c^{2/3} (z - z_0)^{-5/3}$$

Where
$T_{p(centerline)}$ = plume centerline temperature (°C)
Q_c = convective portion of the heat release rate (kW)
T_a = ambient air temperature (K)
g = acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/kg-K)
ρ_a = ambient air density (kg/m^3)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fire (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\, Q$

Where
Q_c = convective portion of the heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release fraction
Q_c = 700 kW

Fire Diameter Calculation

$A_c = \pi D^2/4$

Where
A_c = area of combustible fuel (m^2)
D = fire diameter (m)

$D = \sqrt{(4\, A_c/\pi)}$

D = 1.09 m

Hypothetical Virtual Origin Calculation

$z_0/D = -1.02 + 0.083\, (Q^{2/5})/D$

Where
z_0 = virtual origin of the fire (m)
Q = heat release rate of fire (kW)
D = fire diameter (m)

z_0/D = 0.19
z_0 = 0.21 m

Centerline Plume Temperature Calculation

$T_{p(centerline)} - T_a = 9.1\ (T_a/g\ c_p^2\ \rho_a^2)^{1/3}\ Q_c^{2/3}\ (z - z_0)^{-5/3}$

$T_{p(centerline)} - T_a =$ **524.40**

$T_{p(centerline)} =$ **822.40** K

$T_{p(centerline)}$ =	**549.40** °C	**1020.92** °F	**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.

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.

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CHAPTER 10. ESTIMATING SPRINKLER RESPONSE TIME

10.1 Objectives

This chapter has the following objectives:

- Explain the advantages and disadvantages of sprinklers.
- Identify the four basic types of sprinkler systems.
- Describe the purpose of sprinklers.
- Explain how sprinklers function.

10.2 Introduction

Sprinklers are manufactured in a variety of temperature ratings and orifice sizes. In selecting sprinkler systems, one must carefully consider the potential fire hazard, ceiling configuration, corrosiveness of the environment, susceptibility to damage, etc. Every situation must be thoroughly analyzed to choose the best type of sprinkler system for a given hazard.

Sprinklers produce a cooling effect on the fire when the water from a sprinkler vaporizes to cool the burning materials below their ignition temperature. Sprinklers are designed to control a fire. However, many times the sprinkler system extinguishes the fire because the surrounding materials can no longer heat to their ignition temperature. If the first sprinkler cannot control the fire, a second sprinkler is activated which provides additional cooling. This process continues until the fire is controlled. Sprinklers are reliable thermosensitive devices, they rarely fail, are cost effective, and typically use less water than fire hoses. This helps reduce the amount of equipment damage by applying water directly over the fire. Human response time (i.e., discovery of the fire, travel time by the fire brigade) usually takes much longer than the time required for automatic sprinklers to control a fire while it is still in the early stages. This also reduces the amount of time available for smoke to be produced and damage equipment.

There are four basic types of automatic sprinkler systems. Within these four basic categories, sprinkler systems can be further classified according to the hazard they protect (such as ordinary hazard or in-rack exposure protection), additives to the system (such as antifreeze or foam), or special connection to the system (such as multipurpose piping). Despite these various classifications, sprinkler systems can still be categorized as one of the following four basic types:

- The *automatic wet pipe sprinkler system* is the most prevalent type because it is permanently charged with water, meaning that it is always ready for a fire. When the fusible element of the sprinkler reaches its predetermined temperature, it activates and water flows out of the orifice toward the deflector, causing the water to finely spray on the burning combustibles. An alarm check valve is installed where the water initially enters from the supply source. That valve has fittings to permit the connection of both local and remote location alarms. It also acts as a “check valve,” permitting water to flow only toward the sprinkler. The disadvantage of the wet pipe sprinkler system is that they are not suitable for automatic fire protection in unheated buildings, and should a sprinkler be broken from the piping or a pipe or fitting fail, water will be discharged on to building contents that may be susceptible to water damage.

- The *automatic dry pipe sprinkler system* is similar to the automatic wet pipe system, with the exception that the water in wet pipe system is replaced by compressed air (or nitrogen) and the alarm check valve is replaced by a dry pipe valve. Compressed air holds the dry pipe valve shut, thereby preventing water from entering the system. When a sprinkler activates the air is released, and the water pressure from the supply system opens the dry pipe valve. Water then enters the system, fills the piping, and is discharge by the open sprinkler. The use of a dry pipe sprinkler is subject to many limitations. They should only be used in low-temperature areas because of (1) delay time from releasing the compressed air to water availability and (2) internal pipe corrosion and tuberculation from alternating wet and dry periods.
- The *deluge system* simultaneously discharges water from every open sprinkler on the system. There are no fusible elements in the sprinklers or spray nozzles to hold back the water. The system turns on when a “deluge” valve at the water supply side automatically opens. The system is typically actuated by heat detectors mounted above the open sprinklers. Most deluge systems can also be manually actuated. One disadvantage to this system is water damage can be extensive because of the amount of water that is used with all of the open sprinklers.
- The *pre-action system* is similar to a deluge system with closed heads. Before the water can be released, two conditions must be satisfied. First, the fusible element of the sprinkler must be activated and, second the detector must open the deluge valve. The advantage to this system is that it reduces the amount of accidental discharge to water-sensitive equipment. The disadvantage is that the system is more expensive and complicated than an automatic wet pipe system.

The effectiveness of a sprinkler installation depends on many factors. Some factors are characteristics of the system itself, such as the thermal rating and spacing of the sprinklers, the depth at which the individual sprinklers are mounted below the ceiling, and their pressure and flow characteristics. Other factors are characteristics of the building or compartment in which the system is installed. Compartment characteristics include the height of the ceiling; the area of the compartment; and the presence of openings, joists, or ventilation currents at the ceiling level, which can affect the flow of hot gases. Still other factors depend upon the type of fire load in the compartment, such as the type of combustible and the closeness and height of its stacking, which can affect both the rate of fire development and the ability of the sprinkler system to control the fire.

As previously stated, sprinklers are the most reliable thermosensitive devices, but many factors can cause them to fail, including a lack of available water caused by a closed water supply valve; a broken water supply header; or an empty water tank. A fire pump could also fail to start automatically. If the pump is driven by an electric motor, such pump failures could result from a power failure. If the pump is driven by a diesel engine, pump failures could result from poor maintenance, dead batteries, or a lack of fuel. Other causes of failure could include shutting down for maintenance or repairs, allowing unusual items to enter water mains, corrosion or tuberculation in the sprinkler piping, corroded or painted sprinkler heads, partial sprinklers, combustible overloading, or an inadequate water supply.

Sprinkler technology is changing fast. The installation requirements for the common types of sprinklers are discussed in NFPA 13. Newer sprinklers that are not covered in NFPA 13 must be installed in accordance with their specific listing requirements.

There are three basic installation configurations of sprinklers (upright, pendant, and sidewall) and a number of different variations of the three. Within these three basic types of sprinklers, there are a number of different kinds of sprinklers:

- Spray sprinkler
- Conventional sprinkler
- Fast-response sprinkler
- Residential sprinkler
- Extended coverage sprinkler
- Quick-response sprinkler
- Quick-response extended coverage sprinkler
- Large-drop sprinkler
- Early suppression fast response (ESFR) sprinkler
- Open sprinkler
- Special sprinkler
- Specific application sprinkler
- Flush sprinkler
- Concealed sprinkler
- Recessed sprinkler
- Corrosion-resistant sprinkler
- In-rack sprinkler
- Dry sprinkler

The ESFR sprinkler is one of the newer sprinklers being widely used for high challenge fires. Unlike other sprinklers that are designed only to control fires, the ESFR is designed with a fast response, large water droplet size, and the velocity to extinguish a high-challenge fire. As a result, very strict design and installation requirements must be followed when using an ESFR sprinkler.

The extended coverage sprinkler is another relatively new sprinkler technology. This usually reduces the number of required branch lines, thereby decreasing the cost of the system.

10.3 Operating Principles of Automatic Sprinklers

The two main functions of an automatic sprinkler system are to (1) detect a fire and (2) control it or prevent its growth. Automatic sprinklers are installed to protect property and occupants, give warning of fire existence and control only in burning areas.

The most common sprinklers have either a soldered metallic element or a liquid-filled bulb. The NFPA Handbook, 18th Edition, defines fusible sprinklers as common fusible-style automatic sprinklers that operate when a metal alloy of a predetermined melting point fuses. Various combinations of levers, struts, and links or other soldered members are used to reduce the force acting upon the solder so that the sprinkler is held closed with the smallest practical amount of metal and solder. This minimizes the time of operation by reducing the mass of fusible metal to be heated. The solders used with the automatic sprinklers are alloys of optimum fusibility composed primarily of tin, lead cadmium, and bismuth, which all have sharply defined melting points. Although an individual metal may have a low melting point, an alloy that includes that metal may have a lower melting point. The mixture of two or more metals that gives the lowest possible melting point is called a *eutectic alloy*.

Bulb sprinklers are a second style of operating element. Such sprinklers use a process in which heat causes the liquid in the bulb to expand and shatter the bulb at a predetermined temperature. This releases a seal valve and allows water to be sprayed onto the burning materials by the deflector. The predetermined temperature can be changed by adjusting the type and amount of liquid in the bulb. Bulb sprinklers are the most stable against atmospheric corrosion.

Other styles of thermosensitive operating elements that may be employed to provide automatic discharge include bimetallic discs, fusible alloy pellets, and chemical pellets.

10.3.1 Heat Transfer Characteristics for Heat-Sensitive Elements

Figure 10-1 schematically illustrates the fundamental heat transfer characteristics for the heat-sensitive element of the sprinkler. Conduction from the heated gas, convection from the heated gas, and radiation from the fire combine to transfer heat to the fusible element. Heat is always transferred away from the element by conduction to its supporting structure. Heat-sensitive elements are generally not perfectly insulated from other components of the sprinkler. The link mechanism holds the sprinkler closed and finite thermal resistance permits heat flow from the element. The quantity versus time history for the difference between the in-flow and out-flow of heat determines the time for the element to reach its operating temperature.

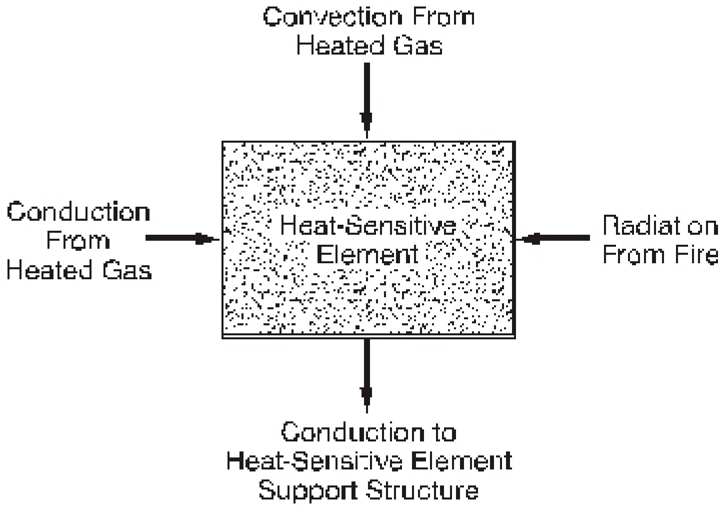

Figure 10-1 Heat Transfer Characteristics of the Heat-Sensitive Element of a Sprinkler

10.3.2 Sprinkler Dynamics

Figure 10-2 shows how the mechanical force exists in a solder-type link-and-lever-style automatic sprinkler. The construction shown is diagrammatic and does not represent any particular sprinkler. This figure is reproduced from the NFPA Handbook, 18th Edition (Isman, 1997).

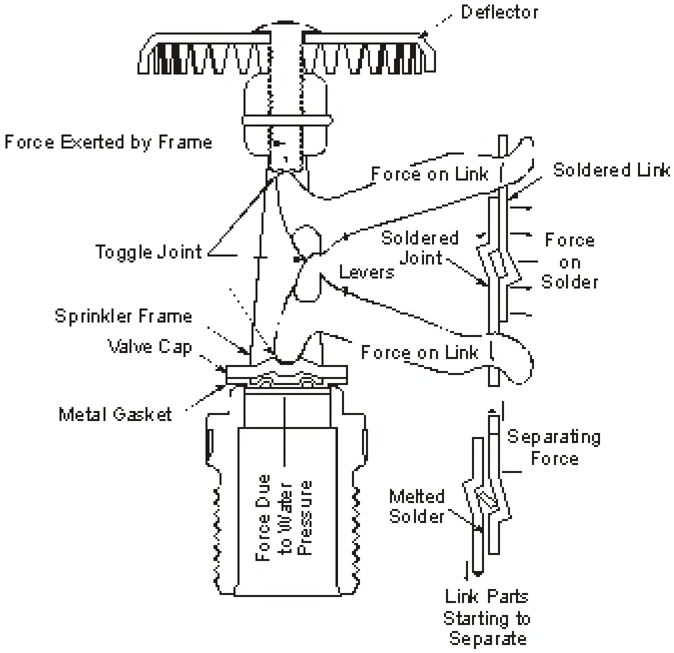

Figure 10-2 Representative Arrangement
of a Solder-Type Link-and-Lever Automatic Sprinkler
(Adapted from NFPA Handbook 18th Edition, 1997 with permission)

The mechanical force normally exerted on the top of the cap or valve is many times that developed by the water pressure below, so that the possibility of leakage, even from water hammer or exceptionally high pressure, is practically eliminated. The mechanical force in a link-and-lever sprinkler is produced by tension in the sprinkler frame, usually created by tightening the screw that holds the deflector down against the toggle joint formed by the levers. This pressure is applied against the valve or cap, but the line of force is not direct. The eccentricity of the loading permits a leveraged reduction of the force, first by the toggle effect of the two levers, and second by the mechanism of the link parts. The force resisted by the solder is made relatively low because solder of the composition needed to give the desired operating temperatures is subject to cold flow under high stress. The sprinkler frame or other parts usually posses a degree of elasticity to provide the energy that produces a positive, sharp release of the operating parts.

To ensure that cold flow will not be a problem, the laboratories that test and list sprinklers use statistical methods to simulate long-term loading of heat-responsive elements. Statistical methods are also employed to ensure that the crush strength of glass bulbs is sufficiently higher than the frame loads that will be applied to the bulbs.

10.3.3 Temperature Ratings of Automatic Sprinklers

Automatic sprinklers have various temperature ratings that are based on the UL standardized test (Operating temperature (bath) test) in which a sprinkler is immersed in a liquid and temperature of the liquid is raised very slowly until the sprinkler operates. In the bath test, an automatic sprinkler operates within a range having a maximum temperature not to excess of either 5 °C (10 °F) or 107 percent of the minimum temperature of the range, whichever is greater. For the purpose of this determination, the marked temperature rating is to be included as one of the values within the range, making a total of eleven values in the range. Water is to be used in bath tests of sprinklers that have operating temperature ratings of 79 °C (175 °F) or lower. Samples having operating temperature ratings of 80–302 °C (176–575 °F) are to be bath-tested in an oil having a flash point exceeding the test temperature (Bryan, 1990).

General sprinkler ratings are given in Table 10-1, based on the NFPA 13, “Standard for Installation of Sprinkler Systems.”

Table 10-1. Temperature Ratings, Classification, and Color Coding of Automatic Sprinklers

Maximum Ceiling Temperature °C (°F)	Temperature Rating °C (°F)	Temperature Classification	Color Code	Glass Bulb Color
38 (100)	57–77 (135–170)	Ordinary	Uncolored or black	Orange or red
66 (150)	79–107 (175–225)	Intermediate	White	Yellow or green
107 (225)	121–149 (250–300)	High	Blue	Blue
149 (300)	163–191 (325–375)	Extra high	Red	Purple
191 (375)	204–246 (400–475)	Very extra high	Green	Black
246 (475)	260–302 (500–575)	Ultra high	Orange	Black
329 (625)	343 (650)	Ultra high	Orange	Black

The temperature rating of each fusible-element-style automatic sprinkler is typically stamped on the soldered link. For bulb sprinklers, the temperature rating must be stamped or cast on some visible part of the sprinkler such as the deflector. Color codes are also used for glass bulbs and frame arms of fusible-element sprinklers. In addition, the recommended maximum room temperature is restricted for both bulbs and fusible-element sprinklers because fusible-element begins to lose its strength somewhat below its actual melting point. Premature operation of a solder sprinkler usually depends on the extent to which the normal room temperature is exceeded, the duration of the excessive temperature, and the load on the operating parts of the sprinkler. While glass bulb sprinklers do not lose strength at temperatures close to their operating temperatures, using them at such temperatures can result in continuous loss and reforming of the air bubble, which creates stresses on the bulb (NFPA Handbook, 18th Edition, 1997). Table 10-2 provides temperature ratings for sprinklers.

Table 10-2. Generic Sprinkler Temperature Rating ($T_{activation}$)

Temperature Classification	**Range of Temperature Ratings °C (°F)**	**Generic Temperature Ratings °C (°F)**
Ordinary	57–77 (135–170)	74 (165)
Intermediate	79–107 (175–225)	100 (212)
High	121–149 (250–300)	135 (275)
Extra high	163–191 (325–375)	177 (350)
Very extra high	204–246 (400–475)	232 (450)
Ultra high	260–302 (500–575)	288 (550)
Ultra high	343 (650)	288 (550)

The concept of a response time index (RTI) was developed by Factory Mutual Research Corporation (FMRC) to be a fundamental measure of thermal sprinkler sensitivity. A sprinkler's RTI is determined in plunge tests with a uniform gas flow of constant temperature and velocity and can be used to predict the sprinkler's activation time in a fire environment. The RTI was developed under the assumption that conductive heat exchange between the sensing element and supportive parts is negligible. The RTI is a function of the time constant, , of the sprinkler which is related to the mass and surface area of the sprinkler thermal element. Faster sprinklers have low RTIs and smaller time constants. Sprinkler thermal elements with low time constants have low ratios of mass to surface area. This is the basis of quick-response sprinklers.

The RTI is defined by the following equation:

$$\mathrm{RTI} = \frac{m_e c_{p(e)}}{h_e A_e}\sqrt{u_{jet}} \qquad (10\text{-}1)$$

Where:

m_e = mass of element (kg)
$c_{p(e)}$ = specific heat of element (kJ/kg-K)
h_e = convective heat transfer coefficient (kW/m^2-K)
A_e = surface area of element (m^2)
u_{jet} = velocity of gas moving past the sprinkler (m/sec)

Table 10-3 provides generic RTIs for sprinklers.

Table 10-3. Generic Sprinkler Response Time Index (RTI)

Common Sprinkler Type	**Generic Response Time Index RTI (m-sec)$^{1/2}$**
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34

NFPA 13 states that “ordinary-temperature-rated sprinklers shall be used throughout the buildings” unless the temperature of the building is other than normal. NFPA 13 goes onto define three cases that would follow in the event of an “abnormal” temperature: These cases are as follows:

(1) “When the maximum ceiling temperatures exceed 38 °C (100 °F), sprinklers with temperatures in accordance with the maximum ceiling temperatures of Table 10-1 shall be used.”

(2) “Intermediate- and high-temperature sprinklers shall be permitted to be used throughout ordinary and extra hazard occupancies.”

(3) Sprinkler should be installed with intermediate-temperature classification if they are “located within 12 in. (305 mm) to one side or 30 in. (762 mm) above an uncovered steam main, heating coil, or radiator; sprinklers under glass or plastic skylights exposed to direct rays of the sun; sprinklers in an unventilated, concealed space, under an uninsulated roof, or in an unventilated attic; or sprinklers in unventilated show windows having high-powered electric lights near the ceiling. Sprinklers within 2.1 m (7 ft) of a low-pressure blow-off valve that discharges free in a large room” should be classified with high-temperature classification. Sprinklers protecting commercial-type cooking equipment and ventilation systems shall be of the high-or extra-high-temperature classification as determined by use of a temperature measuring device.”

10.3.4 Sprinkler Activation

As part of a fire hazard analysis, it is often desirable to estimate both the burning characteristics of selected fuels and their effects in enclosures, as well as when fire protection devices (such as automatic sprinklers or heat and smoke detectors) will activate for specific fire conditions. Equations are available to permit the user to estimate these effects, principally on the basis of experimental correlations.

It has been determined experimentally that convective heat transfer is the most important element in activating sprinklers. Convective heat transfer involves heat transfer through a circulating medium, which, in the case of fire sprinklers, is the room air. The air heated by the fire rises in a plume, entraining other room air as it rises. When the plume hits the ceiling, it generally splits to produce a ceiling gas jet (ceiling jet refers to the relatively rapid gas flow in a shallow layer beneath the ceiling surface, which is driven by the buoyancy of the hot combustion products). The thickness of the ceiling jet flow is approximately 5 to 12-percent of the height of the ceiling above the fire source, with the maximum temperature and velocity occurring 1-percent of the distance from the ceiling to the fire source. The heat sensing elements of the sprinklers within this ceiling jet are then heated by conduction of the heat from the air.

Researchers have developed computer programs to calculate the response time of sprinklers installed below the unconfined ceilings. These programs can determine the time to operation for a user specified fire HRR history. They are convenient to use because they enable the analyst to avoid the tedious repetitive calculations needed to analyze a growing fire. However, an analyst can easily perform these calculations with a scientific hand calculator for steady fires that have a constant HRR. In cases requiring a more detailed analysis of a fire that has important changes in HRR over time, the fire may be represented as a series of steady fires occurring immediately after one another.

For steady-state fires, the time ($t_{activation}$) required to heat the sensing element of a suppression device from room temperature to operation temperature is given by the following equation (Budnick, Evans, and Nelson, 1997):

$$t_{activation} = \frac{RTI}{\sqrt{u_{jet}}} \ln\left(\frac{T_{jet} - T_a}{T_{jet} - T_{activation}}\right) \qquad (10\text{-}2)$$

Where:

$t_{activation}$ = sprinkler head activation time (sec)
RTI = response time index $(m\text{-}sec)^{½}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$T_{activation}$= activation temperature of sprinkler head (°C)

The expressions for estimating the maximum ceiling jet temperature and velocity as a function of ceiling height, radial position, and HRR were developed from analysis of experiments with large-scale fires having HRR from 668 kW to 98,000 kW. The expressions are given for two regions—one where the plume directly strikes the ceiling and the other outside the plume region where a true horizontal flow exists.

The ceiling jet temperature and velocity correlations of a fire plume are given by the following expressions:

$$T_{jet} - T_a = \frac{16.9\ \dot{Q}^{\frac{2}{3}}}{H^{\frac{5}{3}}} \qquad \text{for } \frac{r}{H} \leq 0.18 \qquad (10\text{-}3)$$

$$T_{jet} - T_a = \frac{5.38\ \left(\frac{\dot{Q}}{r}\right)^{\frac{2}{3}}}{H} \qquad \text{for } \frac{r}{H} > 0.18 \qquad (10\text{-}4)$$

$$u_{jet} = 0.96\ \left(\frac{\dot{Q}}{H}\right)^{\frac{1}{3}} \qquad \text{for } \frac{r}{H} \leq 0.15 \qquad (10\text{-}5)$$

$$u_{jet} = \frac{0.195\ \dot{Q}^{\frac{1}{3}}\ H^{\frac{1}{2}}}{r^{\frac{5}{6}}} \qquad \text{for } \frac{r}{H} > 0.15 \qquad (10\text{-}6)$$

Where:

T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$\dot{Q}$ = heat release rate of the fire (kW)
r = radial distance from the plume centerline to the sprinkler head (m)
H = distance from the top of the fuel package to the ceiling level (m)
u_{jet} = ceiling jet velocity (m/sec)

The above correlations are used extensively to calculate the maximum temperature and velocity in the ceiling jet at any distance, r, from the fire axis. Note that the regions for which each expression is valid are given as a function of the ratio of the radial position, r, to the ceiling height, H. Moving away from the centerline of the plume jet, r/H increases. For regions where r/H>0.18, Equation 10-4 is used. Based on the cases where the hot gases have begun to spread under a ceiling located above the fire, Equation 10-3 applies for a small radial distance, r, from the impingement point. (See Figure 10-3.)

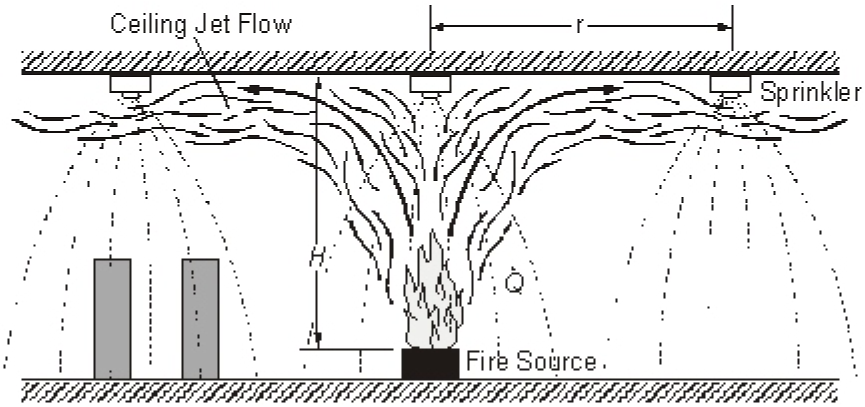

Figure 10-3 Ceiling Jet Flow Beneath an Unconfined Ceiling and Sprinkler Activation

As with the velocities in the ceiling jet flow, u_{jet}, there are two regions, under a ceiling including (1) one close to the impingement point where velocities are nearly constant and (2) another farther away where velocities vary with radial position.

The ceiling jet temperature is important in fire safety because it is generally the region where sprinklers are located; therefore, knowledge of the temperature and velocity of the ceiling jet as a function of position enables us to estimate the sprinklers response time.

The temperature and velocity of a ceiling jet also vary with the depth of the jet. Moving away from the ceiling, the temperature increases to a maximum, then decreases closer to the edge of the jet. This profile is not symmetric as it is with a plume, the maximum occurs along the plume centerline.

With knowledge of plume ceiling jet temperature and velocity, we can estimate the actuation time of a sprinkler, if we also know the spacing and the speed or thermal inertia of the sprinkler. The response of a sprinkler head is given by its RTI.

10.3.5 Sprinkler Spray Interaction with Plume

Once a sprinkler head actuates, water must penetrate the plume to reach the burning fuel surfaces. For this reason, the droplets must have sufficient velocity and size to penetrate through the hot gases flowing in the opposite direction. If a droplet is too small, it will evaporate and/or be moved upward by the plume. For very high-energy release rate fires that grow quickly, it is sometimes necessary to use large drop sprinklers designed to yield droplet sizes and velocities that carry the drops through the plume and flame onto the burning surface.

10.4 Assumptions and Limitations

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

(1) The method assumes the ceiling is unconfined, unobstructed, smooth, flat, and horizontal. The method does not account for effects due to walls or overhead obstructions.

(2) The plume ceiling jet correlations of temperature and velocity assume that the fire source is located away from walls and corners. The primary impact of walls and corners is to reduce the amount of entrained air into the plume. This has the effect of lengthening flames and causing the temperature in a plume to be higher at a given elevation than it would be in the open.

(3) The correlations for estimating the maximum ceiling jet temperature and velocity were developed for steady-state fires and plumes under unconfined ceilings (where the smoke layer does not develop below the ceiling jet during the time of interest).

(4) The plume ceiling jet correlations are valid for unconfined ceilings, as the environment for the outside ceiling jet is uniform in temperature and atmospheric ambient.

(5) All calculations for determining time to operation only consider the convective heating of sensing elements by the hot fire gases. They do not explicitly account for any direct heating by radiation from the flames. The sprinkler is treated as a lumped mass model. The lumped model assumes that thermal gradients are neglected within the thermal element.

(6) This method does not apply to predict response time of sprinklers installed on heat collectors[1] far below the ceiling (in mid air). When sprinklers are too far below the ceiling, most of the heat energy rises past the sprinklers and heat collectors and the sprinklers are not activated. Locating the sprinkler close to the ceiling ensures that the sprinkler will be in the hot gas layer, minimizing activation time and enabling the sprinkler to provide a fully developed water supply pattern to control the fire[2].

10.5 Required Input for Spreadsheet Calculations

The user must obtain the following parameters before using the spreadsheet:
(1) heat release rate of the fire (kW)
(2) activation temperature of the sprinkler (°F)
(3) distance from top of fuel package to the ceiling (ft)
(4) radial distance from the plume centerline to the sprinkler (ft)
(5) ambient air temperature (°F)
(6) sprinkler type

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[1] A flat shield installed above sprinklers.

[2] NRC Information Notice 2002-24, "Potential Problems with Heat Collectors on Fire Protection Sprinklers," July 19, 2002.

10.6 Cautions

(1) Use (10_Detector_Activation_Time.xls) and select the “Sprinkler” spreadsheet on the CD-ROM for estimating sprinkler response time.

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

10.7 Summary

This chapter discusses a method of calculating the response time of sprinkler under an unconfined smooth ceiling in response to steady-state fires. Parameters H and r both relate to the calculation of sprinkler actuation time.

10.8 References

Bryan, J.L., *Automatic Sprinkler and Standpipe Systems*, 2nd Edition, Appendix C, “Operating Temperature (Bath) Test,” p. 505, National Fire Protection Association, Quincy, Massachusetts, 1990.

Budnick, E.K., D.D. Evans, and H.E. Nelson, “Simplified Fire Growth Calculations” Section 11, Chapter 10, *NFPA Fire Protection Handbook*, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1997.

Isman, K.E., “Automatic Sprinklers” Section 6, Chapter 9, *NFPA Fire Protection Handbook*, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1997.

NFPA 13, “Standard for Installation of Sprinkler Systems,” 2002 Edition, National Fire Protection Association, Quincy, Massachusetts.

10. 9 Additional Readings

Alpert, R.L., “Calculation of Response Time of Ceiling-mounted Fire Detectors,” *Fire Technology*, Volume 8, pp. 181–195, 1972.

Alpert, R.L., and E.J. Ward, “Evaluation of Unsprinklered Fire Hazard,” *Fire Safety Journal*, Volume 7, No. 177, 1984.

Bryan, J.L., *Fire Suppression and Detection Systems*, Macmillan Publishing Company, New York, 1993.

Fire Dynamics Course Guide, Federal Emergency Management Agency (FEMA), United States Fire Administration (USFA), National Emergency Training Center, Emmitsburg, Maryland, 1995.

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

Schifiliti, R.P., B.J. Meacham, and R.P. Custer, “Design of Detection Systems,” Section 4, Chapter 1, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

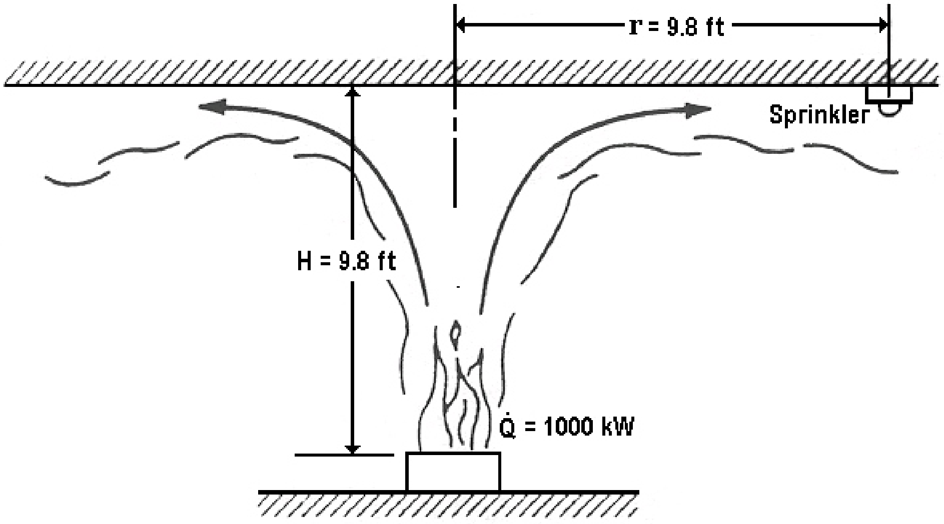
Zalosh, R.G., *Industrial Fire Protection*, John Wiley & Sons Ltd., West Sussex, England, 2003.

10.10 Problems

Example Problem 10.10-1

Problem Statement

A fire with $\dot{Q}$ = 1,000 kW occurs in a space that is protected with sprinklers. Sprinklers are rated at 165 °F (74 °C) [standard response link with RTI = 130 $(\text{m-sec})^{1/2}$] and located 9.8 ft (3 m) on center. The ceiling is 9.8 ft (3.0 m) above the fire. The ambient temperature is 77 °F. Would the sprinklers activate, and if so how long would it take for them to activate?



Solution

Purpose:

(1) Determine if the sprinklers will be activated for the fire scenario.
(2) If the sprinkles are activated, how long would it take for them to activate?

Assumptions:

(1) The fire is located away from walls and corners.
(2) The fire is steady state.
(3) The ceiling is unconfined.
(4) Only convective heat transfer from the hot fire gases is considered.
(5) There is no heavily obstructed overhead.

Spreadsheet (FDT^{s}) Information:

Use the following FDT^{s}:

(a) 10_Detector_Activation_Time.xls (click on *Sprinkler*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 1,000 kW
-Distance from the Top of the Fuel Package to the Ceiling (H) = 9.8 ft
-Radial Distance from the Plume Centerline to the Sprinkler (r) = 9.8 ft
-Ambient Air Temperature (T_a) = 77 °F
-Select Type of Sprinkler = Standard response link
-Select Sprinkler Classification = Ordinary

Note: Ordinary classification has been selected because the rated value for the sprinklers in this problem (165 °F) is within the range of temperature ratings for ordinary sprinklers (135 °F – 170 °F).

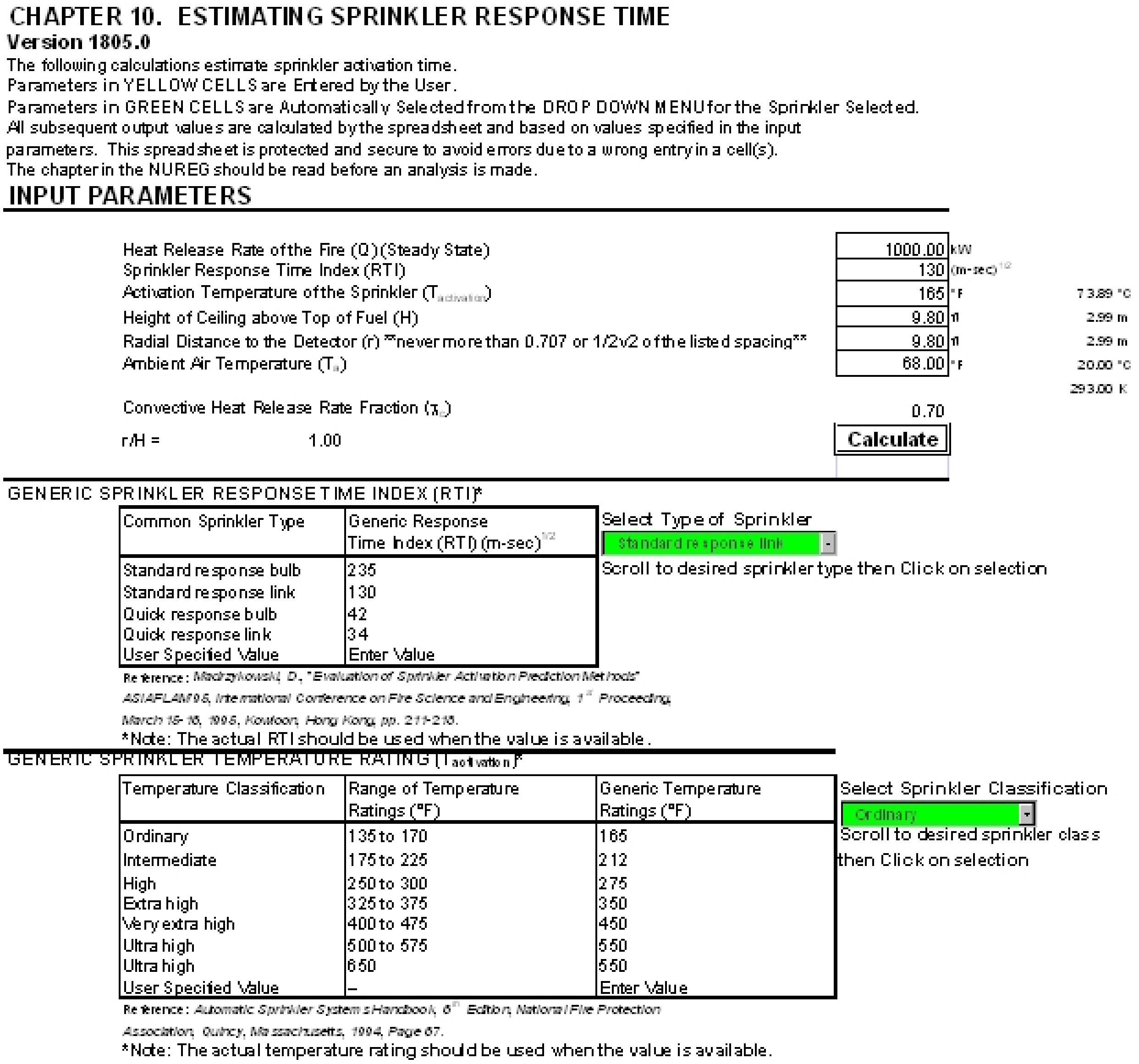
Results*

Sprinkler Type	Sprinkler Activation Time ($t_{activation}$) (min.)
Standard response link	2.9

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 10_Detector_Activation_Time.xls (Sprinkler)



CHAPTER 10. ESTIMATING SPRINKLER RESPONSE TIME

Version 1805.0

The following calculations estimate sprinkler activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Sprinkler 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

Heat Release Rate of the Fire (Q) (Steady State)	1000.00	kW	
Sprinkler Response Time Index (RTI)	130	(m-sec)$^{1/2}$	
Activation Temperature of the Sprinkler ($T_{activation}$)	165	°F	73.89 °C
Height of Ceiling above Top of Fuel (H)	9.80	ft	2.99 m
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	9.80	ft	2.99 m
Ambient Air Temperature (T_a)	68.00	°F	20.00 °C
			293.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		

r/H = 1.00

Calculate

GENERIC SPRINKLER RESPONSE TIME INDEX (RTI)*

Common Sprinkler Type	Generic Response Time Index (RTI) (m-sec)$^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34
User Specified Value	Enter Value

Select Type of Sprinkler
Standard response link
Scroll to desired sprinkler type then Click on selection

Reference: *Madrzykowski, D., "Evaluation of Sprinkler Activation Prediction Methods" ASIAFLAM'95, International Conference on Fire Science and Engineering, 1st Proceeding, March 15-16, 1995, Kowloon, Hong Kong, pp. 211-216.*
*Note: The actual RTI should be used when the value is available.

GENERIC SPRINKLER TEMPERATURE RATING ($T_{activation}$)*

Temperature Classification	Range of Temperature Ratings (°F)	Generic Temperature Ratings (°F)
Ordinary	135 to 170	165
Intermediate	175 to 225	212
High	250 to 300	275
Extra high	325 to 375	350
Very extra high	400 to 475	450
Ultra high	500 to 575	550
Ultra high	650	550
User Specified Value	–	Enter Value

Select Sprinkler Classification
Ordinary
Scroll to desired sprinkler class then Click on selection

Reference: *Automatic Sprinkler Systems Handbook, 6th Edition, National Fire Protection Association, Quincy, Massachusetts, 1994, Page 67.*
*Note: The actual temperature rating should be used when the value is available.

ESTIMATING SPRINKLER RESPONSE TIME

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\,(\ln(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = sprinkler activation response time (sec)
RTI = sprinkler response time index $(m\text{-}sec)^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$T_{activation}$ = activation temperature of sprinkler (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\,(Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18
$T_{jet} - T_a = 5.38\,(Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
Q_c = convective portion of the heat release rate (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the sprinkler (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\,Q$

Where Q_c = convective portion of the heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release rate fraction

Q_c = 700 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.00 r/H > 0.15

$T_{jet} - T_a$ = {5.38 (Qc/r)^2/3}/H
$T_{jet} - T_a$ = 68.46
T_{jet} = 88.46 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\,(Q/H)^{1/3}$ for r/H = 0.15
$u_{jet} = (0.195\,Q^{1/3}\,H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)
Q = heat release rate of the fire (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the sprinkler (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.00 r/H > 0.15

u_{jet} = (0.195 Q^1/3 H^1/2)/r^5/6
u_{jet} = 1.354 m/sec

Sprinkler Activation Time Calculation

$t_{activation} = (RTI/(v\ u_{jet}))\ (\ln\ (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation} =$ 172.85 sec

The sprinkler will respond in approximately	2.88 minutes	**Answer**

NOTE: If $t_{activation}$ = "NUM" Sprinkler does not activate

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003. 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 10.10-2

Problem Statement

If the sprinklers in Problem 10-1 are replaced by sprinklers with a response time index (RTI) of 235 $(\text{m-sec})^{1/2}$, how long would it take for them to activate?

Solution

Purpose:

(1) Determine the activation time for the specified sprinkles under the fire scenario of Problem 10-1.

Assumptions:

(1) The fire is located away from walls and corners.
(2) The fire is steady state.
(3) The ceiling is unconfined.
(4) Only convective heat transfer from the hot fire gases is considered.
(5) There is no heavily obstructed overhead.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (click on *Sprinkler*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 1000 kW
-Distance from the Top of the Fuel Package to the Ceiling (H) = 9.8 ft
-Radial Distance from the Plume Centerline to the Sprinkler (r) = 9.8 ft
-Ambient Air Temperature (T_a) = 77 °F
-Select Type of Sprinkler = Standard response bulb
-Select Sprinkler Classification = Ordinary

Note: The RTI value of 235 $(\text{m-sec})^{1/2}$ corresponds to standard response bulb sprinkler. Ordinary classification has been selected because the rated value for the sprinklers in this problem (165 °F, same as Problem 10-1) is within the range of temperature ratings for ordinary sprinklers (135 °F – 170 °F).

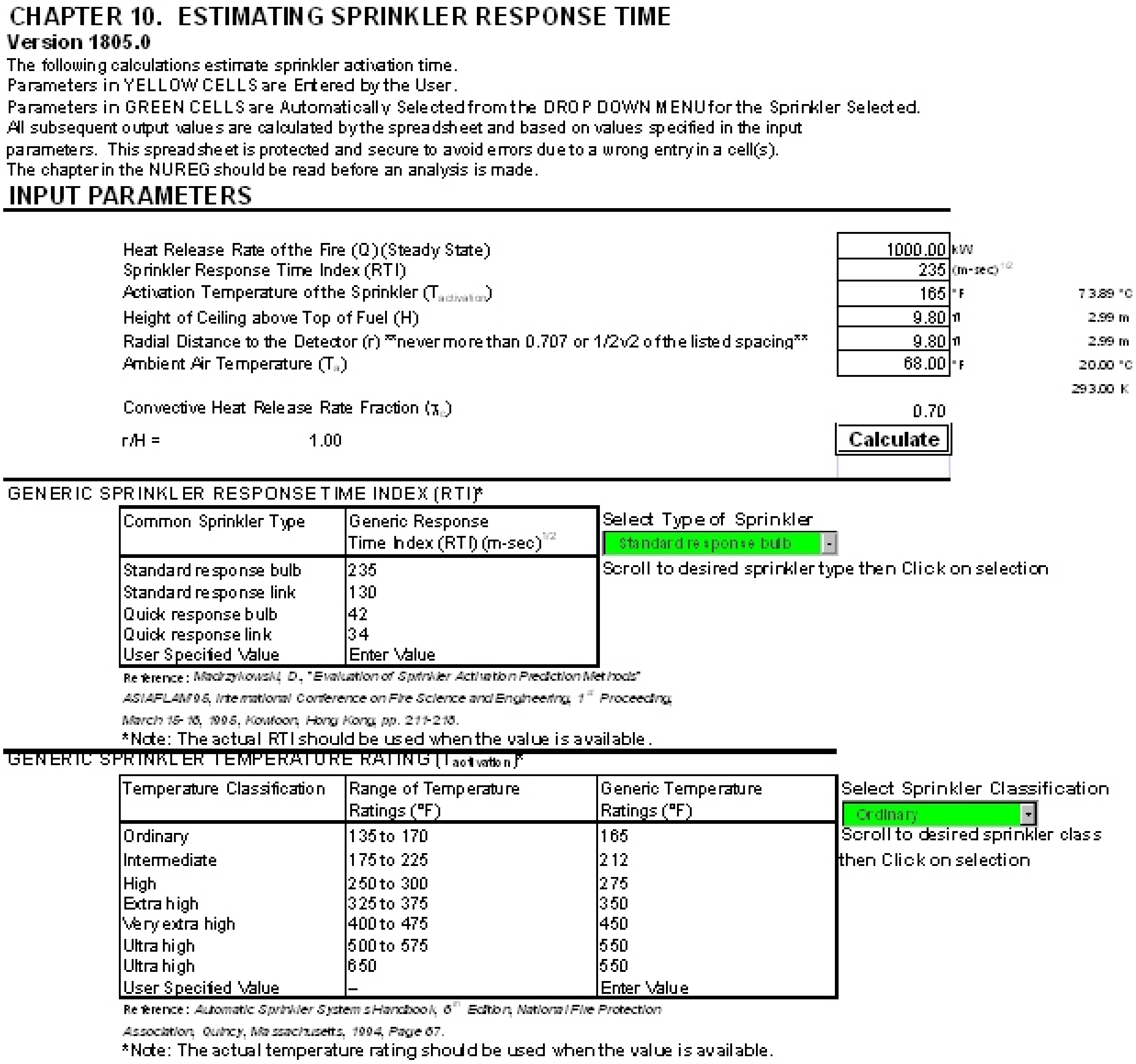
Results*

Sprinkler Type	Sprinkler Activation Time ($t_{activation}$) (min.)
Standard response bulb	5.2

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 10_Detector_Activation_Time.xls (Sprinkler)



CHAPTER 10. ESTIMATING SPRINKLER RESPONSE TIME

Version 1805.0

The following calculations estimate sprinkler activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Sprinkler 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

Heat Release Rate of the Fire (Q) (Steady State)	1000.00	kW	
Sprinkler Response Time Index (RTI)	235	$(m\text{-}sec)^{1/2}$	
Activation Temperature of the Sprinkler ($T_{activation}$)	165	°F	73.89 °C
Height of Ceiling above Top of Fuel (H)	9.80	ft	2.99 m
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	9.80	ft	2.99 m
Ambient Air Temperature (T_a)	68.00	°F	20.00 °C
			293.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		

r/H = 1.00

Calculate

GENERIC SPRINKLER RESPONSE TIME INDEX (RTI)*

Common Sprinkler Type	Generic Response Time Index (RTI) $(m\text{-}sec)^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34
User Specified Value	Enter Value

Select Type of Sprinkler

Standard response bulb

Scroll to desired sprinkler type then Click on selection

Reference: *Madrzykowski, D., "Evaluation of Sprinkler Activation Prediction Methods" ASIAFLAM'95, International Conference on Fire Science and Engineering, 1st Proceeding, March 15-16, 1995, Kowloon, Hong Kong, pp. 211-216.*

*Note: The actual RTI should be used when the value is available.

GENERIC SPRINKLER TEMPERATURE RATING ($T_{activation}$)*

Temperature Classification	Range of Temperature Ratings (°F)	Generic Temperature Ratings (°F)
Ordinary	135 to 170	165
Intermediate	175 to 225	212
High	250 to 300	275
Extra high	325 to 375	350
Very extra high	400 to 475	450
Ultra high	500 to 575	550
Ultra high	650	550
User Specified Value	–	Enter Value

Select Sprinkler Classification

Ordinary

Scroll to desired sprinkler class then Click on selection

Reference: *Automatic Sprinkler Systems Handbook, 6th Edition, National Fire Protection Association, Quincy, Massachusetts, 1994, Page 67.*

*Note: The actual temperature rating should be used when the value is available.

ESTIMATING SPRINKLER RESPONSE TIME

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\ (\ln\ (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = sprinkler activation response time (sec)

RTI = sprinkler response time index (m-sec)$^{1/2}$

u_{jet} = ceiling jet velocity (m/sec)

T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

$T_{activation}$ = activation temperature of sprinkler (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\ (Q_c)^{2/3}/H^{5/3}$ for $r/H = 0.18$

$T_{jet} - T_a = 5.38\ (Q_c/r)^{2/3}/H$ for $r/H > 0.18$

Where T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

Q_c = convective portion of the heat release rate (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the sprinkler (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\ Q$

Where Q_c = convective portion of the heat release rate (kW)

Q = heat release rate of the fire (kW)

χ_c = convective heat release rate fraction

Q_c = 700 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.00 $r/H > 0.15$

$T_{jet} - T_a$ = {5.38 (Qc/r)^2/3}/H

$T_{jet} - T_a$ = 68.46

T_{jet} = 88.46 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\ (Q/H)^{1/3}$ for $r/H = 0.15$

$u_{jet} = (0.195\ Q^{1/3}\ H^{1/2})/r^{5/6}$ for $r/H > 0.15$

Where u_{jet} = ceiling jet velocity (m/sec)

Q = heat release rate of the fire (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the sprinkler (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.00 $r/H > 0.15$

u_{jet} = (0.195 Q^1/3 H^1/2)/r^5/6

u_{jet} = 1.354 m/sec

Sprinkler Activation Time Calculation

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\,(\ln\,(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation} =$ 312.45 sec

The sprinkler will respond in approximately 5.21 minutes **Answer**

NOTE: If $t_{activation}$ = "NUM" Sprinkler does not activate

NOTE

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