CHAPTER 11. ESTIMATING SMOKE DETECTOR RESPONSE TIME

11.1 Objectives

This chapter has the following objectives:

- Introduce the critical factors that influence smoke detector performance.
- Identify the various types of smoke detectors.
- Describe how to estimate the response time of a smoke detector.

11.2 Introduction

Reliable fire detection is an essential part of the fire protection program in nuclear power plants (NPPs), it relates to both fire control or extinguishment and safe evacuation of occupants. Most of the devices associated with fire detection and suppression are typically located near the ceiling surfaces. In the event of a fire, hot gases in the fire plume rise directly above the burning fuel and impinge upon the ceiling. The ceiling surface causes the flow to turn and move horizontally beneath the ceiling to other areas of the building located at some distance from the fire. The response of detection devices (heat/smoke detectors) and sprinklers installed below the ceiling submerged in this hot flow of combustion products provides the basis for the building's active fire protection features.

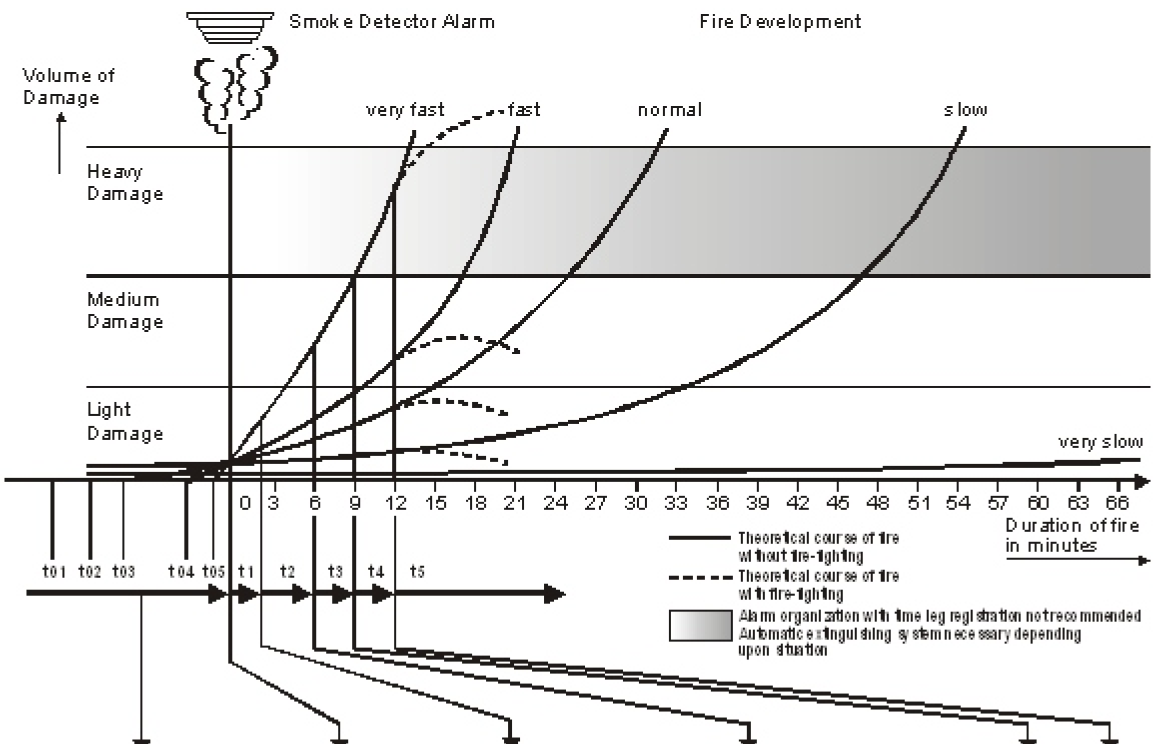
Smoke and heat detectors are best suited for fire detection in confined spaces, where rapid heat generation can be expected in the event of a fire. Smoke and heat detectors have been installed extensively in most NPPs. Generally, such detectors are installed as part of a building-wide alarm system, which typically alarms in the main control room (MCR). The purpose of such systems is to provide early warning to building occupants, and rapid notification of the fire brigade. Some detection devices will also perform the function of automatically actuating suppression systems and interfacing with other building systems such as heating, ventilation, and air-conditioning (HVAC).

Detection is critical to fire safety in NPPs since a potential fire hazard may jeopardize safe plant shutdown. Consequently, safety-related systems must be protected before redundant safety-related systems become damaged by a fire.

Throughout the nuclear industry there has been considerable responsive action relative to the nuclear safety-related fire protection and incorporating sound fire protection principles in nuclear facility design. New standards, regulatory guides, and criteria have been publicized since the fire at the 1975 Browns Ferry Nuclear Power Plant (BFNP). Recognizing the unique characteristics of fires in NPPs, requirements have been established for locating smoke detectors. Particular emphasis has been given to establishing criteria for early warning detection of electrical cable fires. Figure 11-1 shows a qualitative relationship between time and damage for different rates of fire development and average detection reaction and fire fighting.

11.3 Characteristics of Smoke Production

Two essential factors influencing the performance of smoke detectors are the particle size of the smoke and the fire-induced air velocities. The velocities created by the thermal column tend to diffuse the smoke through the upper wall and ceiling regions of the enclosure where the particles enter the detector and activate the unit. For example, residential detectors respond effectively to air flow velocities above 0.25 m/sec (50 ft/min) generated by flaming combustion. The same detectors may fail to respond when the fire-induced thermal column velocities created by the smoldering fire are below 0.15 (30 ft/min).



Incident	Start of fire	Incipient phase before fire detection by fire alarm	Early warning detector detects fire	Start of RS check 1*	Reaction of operating personnel	Cancelling of RS check 1*	Start of RS check 2*	Investigate source of signal	Decision: –Emergency: Press alarm push-button, alerting fire department	Start of initial rescue and fire-fighting operations	Assembly time of fire department	Turn-out time of fire department	Start co-ordinating fire-fighting
Time point	t01 – t05	t01 – t05/t1	t1	t1	t1 – t2	t2	t2	t2 – t3	t3	t3	t3 – t4	t4 – t5	t5
Time requirement ϕ	—	unknown	—	—	ca. 2 min.	—	—	ca. 4 min.	—	—	ca. 3 min.	ca. 3 min.	—
ϕ Time requirement total	—	—	—	—	—	ca. 2 min.	—	—	ca. 6 min.	—	—	ca. 12 min.	—
Detection phase				Reaction, assembly and fire-fighting phase									

* RS check = Reconnaissance squad check

Figure 11-1 Qualitative Relationship Between Time and Damage
for Different Speeds of Fire Development and Average Detection, Reaction, and Fire Fighting
(NUREG/CR-2409, "Requirements for Establishing Detector Siting Criteria in Fires Involving Electrical Materials")

Smoke production of a given fuel material varies with the sample size, arrangement, and configuration of the fuel; material moisture content; and ignition energy. Custer and Bright (1974) report that the earliest indication of a fire occurrence usually involves the heating of materials during the pre-ignition stage, which produces submicron particles ranging in size from $5x10^{-4}$–$1x10^{-3}$ micrometer. Custer and Bright also reported that the size of the particle produced by the diffusion flame combustion varies with the heating of the atmosphere and the development of the fire progressing from smoldering to flaming combustion. Larger particles are formed by coagulation, with the particle size distribution varying between 0.1 micrometer and 4.0 micrometers. The smaller particles, below 0.1 micrometer, tend to disappear as a result of the formation of larger particles by coagulation, while the larger particles tend to settle out through the process of sedimentation. The particle size appears to be one of the most critical variables relative to the operation and performance of the specific smoke detector unit, considering that the detector is suitably located to be exposed to the smoke concentrations, and it is designed to enhance the entry of smoke into the detector unit.

Budnick (1984) states that the critical variables affecting the activation of a smoke detector are as follows:

> *A smoke detector responds to an accumulation of smoke particulate within the device's sensing chamber. In a developing fire, the response will depend on a complex interrelationship of environmental factors such as fire size and growth rate, fuel type and smoke generation rate, room geometry and ventilation, and detector characteristics such as location, smoke entry characteristics and predetermined detector sensitivity thresholds*.

Relative to the rate of fire development, diffusion flame combustion appears to vary with the velocity of the flame spread (which is influenced by fuel arrangement and configuration), ventilation velocity, oxygen concentrations, and energy input at ignition.

11.4 Operating Principles of Smoke Detectors

Typically, a smoke detector will detect most fires more rapidly than a heat detector. Visible products of combustion consist primarily of unconsumed carbon and carbon-rich particles, while invisible products of combustion consist of solid particles smaller than 5 microns, as well as various gases and ions. NFPA 72, "National Fire Alarm Code®," defines the types of listed smoke detectors in the following manner:

- **Photoelectric light obscuration smoke detection** is the principle of using a light source and a photosensitive sensor onto which the principal portion of the source emission is focused. When smoke particles enter the light path, some of the light is scattered and some is absorbed, thereby reducing the light reaching the receiving sensor. The light reduction signal is processed and used to convey an alarm condition when it meets preset criteria (see Figure 11-2).
- **Photoelectric light scattering smoke detection** is the principle of using a light source and a photosensitive sensor arranged so that the rays from the light source do not normally fall onto the photosensitive sensor. When smoke particles enter the light path, some of the light is scattered bu reflection and refraction onto the sensor. The light signal is processed and used to convey an alarm condition when it meets preset criteria (see Figure 11-2).

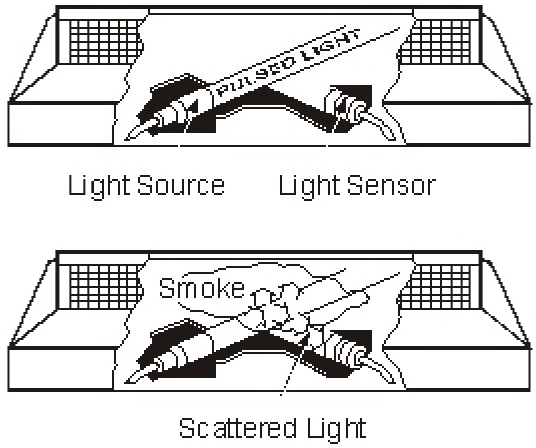


Figure 11-2 Illustration of the Photoelectric Principle

- **Ionization smoke detection** is the principle of using a small amount of radioactive material to ionize the air between two differentially charged electrodes to sense the presence of smoke particles. Smoke particles entering the ionization volume decrease the conductance of the air by reducing ion mobility. The reduced conductance signal is processed and used to convey an alarm condition when it meets preset criteria (see Figure 11-3).

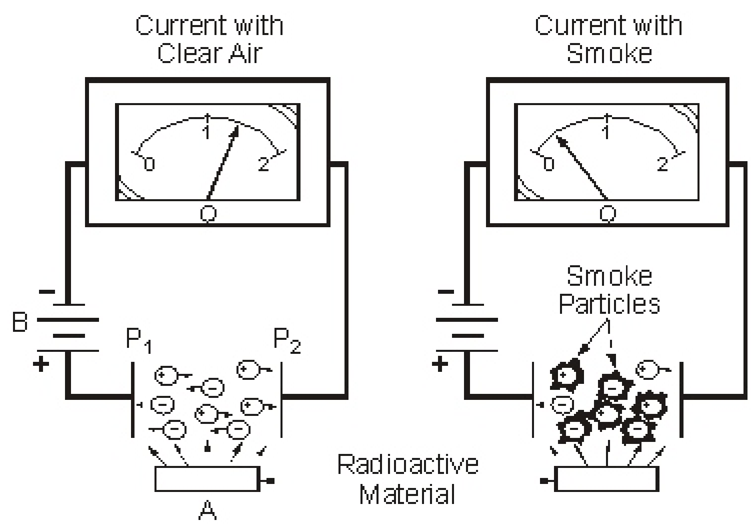


Figure 11-3 Illustration of the Ionization Principle

- **Combination detection** either responds to more than one of the fire phenomena or employs more than one operating principle to sense these phenomena. Typical examples are a combination of heat and smoke detectors or a combination of rate-of-rise and fixed-temperature heat detectors.

- **Projected beam detection** uses the principle of photoelectric light obscuration smoke detection, but the beam spans the protected area.
- **Air sampling detection** uses a piping or tubing distribution network that runs from the detector to the area(s) to be protected. An aspiration fan in the detector housing draws air from the protected area back to the detector through air sampling ports, piping, or tubing. At the detector, the air is analyzed for fire products.

As a class, smoke detectors using the ionization principle provide a somewhat faster response to high-energy (open flaming) fires, since such fires produce large numbers of the smaller smoke particles. Smoke detectors operating on the photoelectric principle tend to respond faster to the smoke generated by low-energy (smoldering) fires, which generally produce more of the larger smoke particles. However, each type of smoke detector is subjected to, and must pass, the same fires at testing laboratories in order to be listed by Underwriters Laboratories (UL).

Combustion product detectors of the ionization type are called spot detectors (meaning that the element is concentrated at a particular location), and those of the photoelectric type are available as both spot detectors and line detectors. A line detector means that detection is continuous along a path. Ionization detectors are usually found as spot detectors for area protection, and may be modified with air shields or sampling tubes for installation as air duct detectors. Projected beam photoelectric detectors are most often applied as line detectors for large open area protection. Line detectors are also beneficial in areas with high ceilings. They give the earliest warnings of abnormal conditions in these applications by responding to the smoke particles produced by fires. By contrast spot detectors are typically located in various areas of the building. They typically protect areas up to 84 m^2 (900 ft^2) depending on ceiling surface conditions and room height. Ionization and photoelectric detectors offer the greatest potential in residential safety. Some ionization and photoelectric detectors are also manufactured with dual modes of operation. Specifically, a fixed-temperature, thermal-activation device is also located in the detector.

Most conventional smoke detectors provide a binary go/no-go form of detection. This means that other than *alarm* or *no-alarm* condition, no other information is transmitted to the fire alarm control unit. In order to provide a stable smoke detector, the system design must ensure that the sensitivity level of the detector matches the environment in the facility to be protected. Newer types of spot smoke detectors are now capable of providing information on the level of smoke at the device.

Current standards (such as NFPA 72, National Fire Alarm Code®) stipulate the spacing of smoke detectors based upon tests performed by nationally recognized testing laboratories such as Underwriters Laboratories (UL 268). An alternative performance design method can be found in Appendix B to NFPA 72 and is limited to flaming fires no ceilings higher than 8.5 m (30 ft). This method was developed from an experimental study conducted in the late 1970s for the Fire Detection Institute (FDI), however, it suffers from certain limitations related to the scope of the experiments conducted. Nevertheless, this design method introduced some important concepts, including design of a detection system to activate for a critical fire size (HRR) representing an acceptable threat level for the protected space. This is a departure from the earlier concept of detection “as quickly as possible,” which often led to oversensitivity.

Technology improvements in microprocessor use in fire alarm systems have led to development of new smoke detector concepts. These new sensors use analog technology to measure the conditions in the protected area, or space, and transmit that information to the computer-based fire alarm control unit. Thus, the new sensors can report when components are too dirty to function properly or too sensitive as result of any number of conditions in the protected space. Analog sensors provide an essentially false-alarm-free system with regard to the conditions that are normally found in a building. This sensor technology also allows the system designer to adjust the sensor's sensitivity to accommodate the ambient environment or use an extra-sensitive setting to protect a high-value or mission-sensitive area. These sensors are available as photoelectric; ionization; or combination thermal, photoelectric, and ionization units. As fire alarm system technology continues to advance and existing NPPs are upgraded, the analog sensors will be the sensors of choice for any system application, regardless of system size.

11.5 Smoke Detector Response

The response characteristics of smoke detectors are not as well understood as those of sprinklers and thermal detectors. Smoke detector alarm conditions depend on more than smoke concentration. Smoke particle sizes and optical or particle scattering properties can affect the smoke concentration value necessary to reach the alarm condition. For sprinklers and thermal detectors, measured values of response time index (RTI) characterize the lag time between gas temperature and sensing element temperature. For smoke detectors, there is no analogous method to characterize the lag time between gas flow smoke concentration and the smoke concentration within the sensing chamber. In the absence of understanding the many processes affecting smoke detector response, smoke detectors can be approximated as low-temperature heat detectors with no thermal lag (i.e., low-RTI devices).

The time required for automatic actuation of a smoke detector is dependent on fire size, geometry, type of detector, and environment conditions within the compartment. In many installations, ceiling-mounted spot smoke detectors have been suggested as one means of fire detection. In some cases, the actuation time for ceiling-mounted spot smoke detectors may be unacceptably long. Projected beam smoke detectors may be the preferable means of fire detection. The actuation time of ceiling-mounted smoke detectors can be estimated by considering the temperature of the smoke layer (Heskestad and Delichatsios, 1977).

11.5.1 Method of Alpert

Smoke detector activation is identical to that for a heat detector, with the exception of the response of smoke detectors to a modest rise in the ceiling jet temperature. Heskestad and Delichatsios (1977) correlated a smoke temperature change of 10 °C (18 °F) from typical fuels.

For steady-state fire, the method for estimating the response of a smoke detector is based on the correlations developed by Alpert (1972) for activation of a sprinkler and is given by the following equation (Budnick, Evans, and Nelson, 1997):

$$t_{activation} = \frac{RTI}{\sqrt{u_{jet}}} \ln\left(\frac{T_{jet} - T_a}{T_{jet} - T_{activation}}\right) \qquad (11\text{-}1)$$

Where:

$t_{activation}$ = sprinkler head activation time (sec)
RTI = Response Time Index (m-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 detector (°C)

Factory Mutual Research Corporation (FMRC) developed the RTI concept to be a fundamental measure of thermal detector sensitivity. A detector's RTI is determined in plunge tests with a uniform gas flow of constant temperature and velocity and can be used to predict the detector's activation time in any fire environment. For the purpose of calculating smoke detector response time, it is assumed that the smoke detectors are low-RTI devices.

The ceiling jet temperature and velocity correlations of a fire plume in Equation 11-1 are given by the following expression:

$$T_{jet} - T_a = \frac{16.9 \ \dot{Q}^{\frac{2}{3}}}{H^{\frac{5}{3}}} \quad \text{for} \frac{r}{H} \leq 0.18 \qquad (11\text{-}2)$$

$$T_{jet} - T_a = \frac{5.38 \ \left(\frac{\dot{Q}}{r}\right)^{\frac{2}{3}}}{H} \quad \text{for} \frac{r}{H} > 0.18 \qquad (11\text{-}3)$$

$$u_{jet} = 0.96 \ \left(\frac{\dot{Q}}{H}\right)^{\frac{1}{3}} \quad \text{for} \frac{r}{H} \leq 0.15 \qquad (11\text{-}4)$$

$$u_{jet} = \frac{0.195 \ \dot{Q}^{\frac{1}{3}} \ H^{\frac{1}{2}}}{r^{\frac{5}{6}}} \quad \text{for} \frac{r}{H} > 0.15 \qquad (11\text{-}5)$$

Where:

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

11.5.2 Method of Mowrer

Mowrer (1990) developed a smoke detector response time correlation based on the concept of smoke transport lag time for quasi-steady fires. The response time of a smoke detector comprises two separate times, including the transport lag time of the plume and the transport lag time of the ceiling jet, as illustrated by the following equation:

$$t_{activation} = t_{pl} + t_{cj} \qquad (11\text{-}6)$$

Where:

$t_{activation}$ = detector activation time (sec)
t_{pl} = transport lag time of plume (sec)
t_{cj} = transport lag time of ceiling jet (sec)

The transport lag time of the plume, t_{pl}, is the time for the fire gases to reach the ceiling at the plume centerline and can be represented by the following correlation:

$$t_{pl} = C_{pl} \frac{H^{\frac{4}{3}}}{\dot{Q}^{\frac{1}{3}}} \qquad (11\text{-}7)$$

Where:

t_{pl} = transport lag time of plume (sec)
C_{pl} = plume lag time constant = 0.67 (experimentally determined)
H = height of ceiling above top of fuel (m)
$\dot{Q}$ = heat release rate of the fire (kW)

The transport lag time of the ceiling jet, t_{cj}, is the time for the fire gases to reach the detector at the plume centerline and can be represented by the following correlation:

$$t_{cj} = \frac{1}{C_{cj}} \frac{r^{\frac{11}{6}}}{\dot{Q}^{\frac{1}{3}} H^{\frac{1}{2}}} \qquad (11\text{-}8)$$

Where:

t_{cj} = transport lag time of plume (sec)
r = radial distance to the detector (m)
C_{cj} = ceiling jet lag time constant = 1.2 (experimentally determined)
H = height of ceiling above top of fuel (m)
$\dot{Q}$ = heat release rate of the fire (kW)

11.5.3 Method of Milke

Milke (1990) presented a method for estimating smoke detector response time based on the enclosure fire testing described in NUREG/CR-4681. The operation of detectors for smoke from typical fuels has been correlated to a temperature change from the following correlation:

$$t_{activation} = \frac{XH^{\frac{4}{3}}}{\dot{Q}^{\frac{1}{3}}} \quad (11\text{-}9)$$

Where:

$t_{activation}$ = detector activation time (sec)
H = height of ceiling above top of fuel (m)
$\dot{Q}$ = heat release rate of the fire (kW)

$$X = 4.6 \times 10^{-4}\, Y^2 + 2.7 \times 10^{-15}\, Y^6 \quad (11\text{-}10)$$

$$Y = \frac{\Delta T_c H^{\frac{5}{3}}}{\dot{Q}^{\frac{2}{3}}} \quad (11\text{-}11)$$

Where:

H = height of ceiling above top of fuel (m)
$\dot{Q}$ = heat release rate of the fire (kW)
T_c = temperature rise of gases under the ceiling for smoke detector to activate

Before estimating smoke detector response time, stratification effects can be calculated. The potential for stratification relates to the difference in temperature between the smoke and surrounding air at any elevation and is given by the following correlation (NFPA 92B, Section A.3.4).

$$H_{max} = \frac{74\dot{Q}_c^{\frac{2}{5}}}{\Delta T_{f\rightarrow c}} \quad (11\text{-}12)$$

Where:

H_{max} = the maximum ceiling clearance to which a plume can rise (ft)
$\dot{Q}_c$ = convective heat release rate of the fire (Btu/sec)
$T_{f\text{->}c}$ = difference in ambient gas temperature between the fuel location and ceiling level (°F)

The convective portion of the heat release rate, $\dot{Q}_c$, can be estimated as 70 percent of the total heat release rate. Thus, $\dot{Q}_c$ is given by the following equation:

$$\dot{Q}_c = \chi_c \dot{Q}$$

Where:

χ_c = convective heat release fraction (0.70)

$\dot{Q}$ = heat release rate of the fire (Btu/sec)

Difference in ambient gas temperature between the fuel location and ceiling level can be estimated from the following equation:

$$\Delta T_{f \to c} = \frac{1300 \dot{Q}_c^{\frac{2}{3}}}{H^{\frac{5}{3}}}$$

Where:

$\Delta T_{f->c}$ = difference in ambient gas temperature between the fuel location and ceiling level (°F)

$\dot{Q}_c$ = convective heat release rate of the fire (Btu/sec)

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

If the H_{max} is greater than H, the smoke would be expected to reach the ceiling-mounted smoke detector and result in activation.

11.6 Assumptions and Limitations

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

(1) The fire is steady state.

(2) The forced ventilation system is off. As ventilation is increased, detector response times increase.

(3) Both flaming and non-flaming fire sources can be used.

(4) Caution should be exercised with this method when the overhead area is highly obstructed.

(5) The detectors are located at or very near to ceiling. Very near to ceiling would include code compliant detectors mounted on the bottom flange of structural steel beams. This method is not applicable to detectors mounted well below ceiling in free air.

11.7 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) ceiling height of the compartment (ft)

(3) radial distance from the centerline of the plume (ft)

11.8 Cautions

(1) Use (10_Detector_Activation_Time.xls) and select “Smoke” spreadsheet in the CD-ROM for calculations.

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

(3) Remember that there are broad assumptions within each calculation method because of the statistical makeup of the test methods. Although a specific method may be a good estimate, use the results with caution.

11.9 Summary

This chapter discusses three methods of calculating the activation time of smoke detectors under unobstructed ceilings in response to steady-state fires. In the first method, smoke detector activation is identical to that for a heat detector, with the exception that the response of the smoke detector to a modest rise in the ceiling jet temperature has been assumed. In the second method, the response time of a smoke detector was estimated using the transport lag time of the plume and the transport lag time of the ceiling jet. In the third method, the operation of smoke detectors was estimated using the stratification of smoke.

11.10 References

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Budnick, E.K., D.D. Evans, and H.E. Nelson, "Simplified Fire Growth Calculations" Section 3, Chapter 9, *NFPA Fire Protection Handbook*, 19th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 2003.

Budnick, E.K., "Estimating Effectiveness of State-of-the-Art Detectors and Automatic Sprinklers on Life Safety in Residential Occupancies," *Fire Technology*, Volume 20, No. 3, pp. 5–21, 1984.

Custer, R.L.P., and R.G. Bright, "Fire Detection: The State of the Art," Technical Note 839, Center of Fire Research, National Bureau of Standards, Washington, DC, 1974.

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Milke, J., "Smoke Management for Covered Malls and Atria," *Fire Technology*, Volume 26, No. 3, pp. 223–243, August 1990.

Morwer, F., "Lag Time Associated With Fire Detection and Suppression," *Fire Technology*, Volume 26, No. 3, pp. 244–265, August 1990.

NFPA 72, National Fire Alarm Code®, 1999 Edition, Appendix B: Engineering Guide for Automatic Fire Detection Spacing, National Fire Protection Association, Quincy, Massachusetts.

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NUREG/CR-2409, "Requirements for Establishing Detector Siting Criteria in Fires Involving Electrical Materials," U.S. Nuclear Regulatory Commission, Washington, DC, July 1982.

NUREG/CR-4681, "Enclosure Experiment Characterization Testing for the Base Line Validation of Computer Fire Simulation Codes," U.S. Nuclear Regulatory Commission, Washington, DC, March 1987.

UL 268, "Smoke Detectors for Fire Protective Signaling Systems," 4th Edition, Underwriters Laboratory, Northbrook, Illinois, 1996.

11.11 Additional Readings

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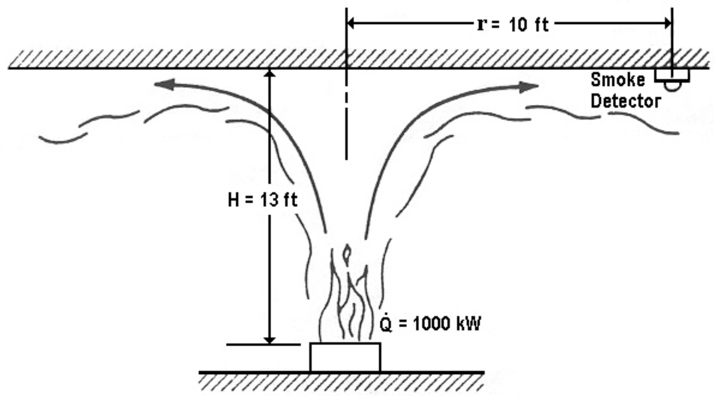
Schifiliti, R.P., and W.E. Pucci, "Fire Detection Modeling State-of-the-Art," Fire Detection Institute (FDI), May 1996.

11.12 Problems

Example Problem 11.12-1

Problem Statement
Estimate the response time of a smoke detector that is located 10 ft radially from the centerline of a 1,000-kW pool fire in a 13-ft-tall compartment.



Example Problem 11-1: Fire Scenario with Smoke Detector

Solution

Purpose:

(1) Determine the response time of the smoke detector for the fire scenario.

Assumptions:

(1) The fire is steady state
(2) The forced ventilation system is off
(3) There is no heavily obstructed overhead

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

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

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 1,000 kW
-Ceiling Height (H) = 13 ft
-Radial Distance from the Plume Centerline to the Smoke Detector (r) = 10 ft

Results*

Heat Release Rate $\dot{Q}$ (kW)	Smoke Detector Activation Time (t_R) (sec)		
1,000	Method of Alpert	Method of Mowrer	Method of Milke
	0.42	0.74	0.26

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 10_Detector_Activation_Time.xls (Smoke_Detector)

CHAPTER 11. ESTIMATING SMOKE DETECTOR RESPONSE TIME

Version 1805.0

The following calculations estimate smoke detector response time.
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) (Steady State)	1000.00	kW	947.82 Btu/sec
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	10.00	ft	3.05 m
Height of Ceiling above Top of Fuel (H)	13.00	ft	3.96 m
Activation Temperature of the Smoke Detector ($T_{activation}$)	86.00	°F	30.00 °C
Smoke Detector Response Time Index (RTI)	5.00	$(m\text{-}sec)^{1/2}$	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		
Plume Lag Time Constant (C_{pl}) (Experimentally Determined)	0.67		
Ceiling Jet Lag Time Constant (C_{cl}) (Experimentally Determined)	1.2		
Temperature Rise of Gases Under the Ceiling (ΔT_c) for Smoke Detector to Activate	18.00	°F	10 °C
r/H =	0.77		

Calculate

ESTIMATING SMOKE DETECTOR RESPONSE TIME
METHOD OF ALPERT

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

$t_{activation} = (RTI/(u_{jet})^{1/2}) (\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

This method assume smoke detector is a low RTI device with a fixed activation temperature

Where
$t_{activation}$ = detector activation time (sec)
RTI = detector 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 detector (°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 detector (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 = 0.77 r/H > 0.15

>0.15	50.92	<0.15	134.28

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

$T_{jet} - T_a$ = 50.92

T_{jet} = 75.92 (°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 detector (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.77 r/H > 0.15

>0.15	1.53	<0.15	6.07

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

u_{jet} = 1.533 m/sec

Smoke Detector Response Time Calculation

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

$t_{activation}$ = 0.42 sec **Answer**

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

METHOD OF MOWRER

References: *Mowrer, F., "Lag Times Associated With Fire Detection and Suppression," Fire Technology, August 1990, p. 244.*

$t_{activation} = t_{pl} + t_{cj}$

Where $t_{activation}$ = detector activation time (sec)

t_{pl} = transport lag time of plume (sec)

t_{cj} = transport lag time of ceiling jet (sec)

Transport Lag Time of Plume Calculation

$t_{pl} = C_{pl}\ (H)^{4/3}/(Q)^{1/3}$

Where t_{pl} = transport lag time of plume (sec)

C_{pl} = plume lag time constant

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

Q = heat release rate of the fire (kW)

t_{pl} = 0.42 sec

Transport Lag Time of Ceiling Jet Calculation

$t_{cj} = (r)^{11/6}/(C_{cj})\ (Q)^{1/3}\ (H)^{1/2}$

Where t_{cj} = transport lag time of ceiling jet (sec)

C_{cj} = ceiling jet lag time constant

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

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

Q = heat release rate of the fire (kW)

t_{cj} = 0.32 sec

Smoke Detector Response Time Calculation

$t_{activation} = t_{pl} + t_{cj}$

$t_{activation}$ = 0.74 sec **Answer**

METHOD OF MILKE

References: Milke, J., "Smoke Management for Covered Malls and Atria," Fire Technology, August 1990, p. 223.
NFPA 92B, "Guide for Smoke Management Systems in Mall, Atria, and Large Areas," 2000 Edition, Section A.3.4.

$t_{activation} = X\ H^{4/3}/Q^{1/3}$

Where $t_{activation}$ = detector activation time (sec)
$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-15}\ Y^6$
H = height of ceiling above top of fuel (ft)
Q = heat release rate from steady fire (Btu/sec)

Where $Y = \Delta T_c\ H^{5/3} / Q^{2/3}$
ΔT_c = temperature rise of gases under the ceiling for smoke detector to activate (°F)

Before estimating smoke detector response time, stratification effects can be calculated. NFPA 92B, 2000 Edition, Section A.3.4 provides following correlation to estimate smoke stratification in a compartment.

$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f\text{-}c}^{3/5}$

Where H_{max} = the maximum ceiling clearance to which a plume can rise (ft)
Q_c = convective portion of the heat release rate (Btu/sec)
$\Delta T_{f\text{-}c}$ = difference in temperature due to fire between the fuel location and ceiling level (°F)

Convective Heat Release Rate Calculation
$Q_c = Q\ \chi_c$

Where Q_c = convective portion of the heat release rate (Btu/sec)
Q = heat release rate of the fire (Btu/sec)
χ_c = convective heat releas rate fraction

Q_c = 663.47 Btu/sec

Difference in Temperature Due to Fire Between the Fuel Location and Ceiling Level
$\Delta T_{f\text{-}c} = 1300\ Q_c^{2/3} / H^{5/3}$

Where $\Delta T_{f\text{-}c}$ = difference in temperature due to fire between the fuel location and ceiling level (°F)
Q_c = convective portion of the heat release rate (Btu/sec)
H = ceiling height above the fire source (ft)

$\Delta T_{f\text{-}c}$ = 1375.90 °F

Smoke Stratification Effects
$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f\text{-}c}^{3/5}$

H_{max} = 13.03 ft

In this case the highest point of smoke rise is estimated to be 13.03 ft
Thus, the smoke would be expected to reach the ceiling mounted smoke detector.

$Y = \Delta T_c\ H^{5/3} / Q^{2/3}$

Y = 13.41

$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-16}\ Y^6$

X = 0.08

Smoke Detector Response Time Calculation
$t_{activation} = X\ H^{4/3}/Q^{1/3}$

$t_{activation}$ = 0.26 sec **Answer**

Summary of Result:

Calculation Method	Smoke Detector Response Time (sec)
METHOD OF ALPERT	0.42
METHOD OF MOWRER	0.74
METHOD OF MILKE	0.26

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19^{h} Edition, 2003, method described in Fire Technology, 1990, and NFPA 92B, "Guide for Smoke Management Systems in Malls, Atria, and Large Areas," 2000 Edition, Section A.3.4. 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 situations and, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 11.12-2

Problem Statement

During a routine inspection, an NRC resident inspector finds a stack of 4-ft-high wooden pallets left in the NPP after a recent MOV modification. When the inspector questions the licensee about this transient combustible, the licensee assures the inspector that if the transient ignited, the smoke detection system would alarm in less than 1 minute.

The SFPE Handbook provides test data for a stack of 4-ft-high wooden pallets, from which the HRR can be estimated at 3.5 MW.

The compartment has a 25-ft ceiling with the smoke detectors spaced 30 ft on center. The pallets are located in the worst position (i.e., in the center of four smoke detectors).

How long does it take the smoke detector to alarm?

Solution

Purpose:

(1) Determine the response time of the smoke detector for the fire scenario.

Assumptions:

(1) The fire is steady-state.
(2) The forced ventilation system is off.
(3) There is no heavily obstructed overhead.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

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

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 3,500 kW

-Ceiling Height (H) = 25 ft

-Radial Distance from the Plume Centerline to the Smoke Detector (r) = 21.2 ft

Results*

Heat Release Rate $\dot{Q}$ (kW)	Smoke Detector Activation Time (t_R) (sec)		
	Method of Alpert	Method of Mowrer	Method of Milke
3,500	0.55	1.27	0.67

*see spreadsheets on next page

Therefore, it can be assumed that the smoke detectors would alarm within 1 minute.

Spreadsheet Calculations

FDT[s]: 10_Detector_Activation_Time.xls (Smoke_Detector)

CHAPTER 11. ESTIMATING SMOKE DETECTOR RESPONSE TIME

Version 1805.0

The following calculations estimate smoke detector response time.

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 ($\dot{Q}$) (Steady State)	3500.00	kW	3317.37 Btu/sec
Radial Distance to the Detector (r) "never more than 0.707 or 1/2√2 of the listed spacing"	21.20	ft	6.46 m
Height of Ceiling above Top of Fuel (H)	25.00	ft	7.62 m
Activation Temperature of the Smoke Detector ($T_{activation}$)	86.00	°F	30.00 °C
Smoke Detector Response Time Index (RTI)	5.00	(m-sec)$^{1/2}$	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		
Plume Lag Time Constant (C_p) (Experimentally Determined)	0.67		
Ceiling Jet Lag Time Constant (C_j) (Experimentally Determined)	1.2		
Temperature Rise of Gases Under the Ceiling (ΔT_c) for Smoke Detector to Activate	18.00	°F	10 °C

r/H = 0.85

Calculate

ESTIMATING SMOKE DETECTOR RESPONSE TIME

METHOD OF ALPERT

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

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

This method assume smoke detector is a low RTI device with a fixed activation temperature

Where
- $t_{activation}$ = detector activation time (sec)
- RTI = detector 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 detector (°C)

Ceiling Jet Temperature Calculation

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

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

Where
- T_{jet} = ceiling jet temperature (°C)
- T_a = ambient air temperature (°C)
- $\dot{Q}_c$ = 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 detector (m)

Convective Heat Release Rate Calculation

$\dot{Q}_c = \chi_c\,\dot{Q}$

Where
- $\dot{Q}_c$ = convective portion of the heat release rate (kW)
- $\dot{Q}$ = heat release rate of the fire (kW)
- χ_c = convective heat release rate fraction

$\dot{Q}_c$ = 2450 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.85 r/H > 0.15

>0.15	36.99	<0.15	104.09

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

$T_{jet} - T_a =$ 36.99

$T_{jet} =$ 61.99 (°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 detector (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.85 r/H > 0.15

>0.15	1.73	<0.15	7.41

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

$u_{jet} =$ 1.726 m/sec

Smoke Detector Response Time Calculation

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

$t_{activation} =$ 0.55 sec **Answer**

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

METHOD OF MOWRER

References: *Mowrer, F., "Lag Times Associated With Fire Detection and Suppression," Fire Technology, August 1990, p. 244.*

$t_{activation} = t_{pl} + t_{cj}$

Where $t_{activation}$ = detector activation time (sec)

t_{pl} = transport lag time of plume (sec)

t_{cj} = transport lag time of ceiling jet (sec)

Transport Lag Time of Plume Calculation

$t_{pl} = C_{pl}\ (H)^{4/3}/(Q)^{1/3}$

Where t_{pl} = transport lag time of plume (sec)

C_{pl} = plume lag time constant

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

Q = heat release rate of the fire (kW)

$t_{pl} =$ 0.66 sec

Transport Lag Time of Ceiling Jet Calculation

$t_{cj} = (r)^{11/6}/(C_{cj})\ (Q)^{1/3}\ (H)^{1/2}$

Where t_{cj} = transport lag time of ceiling jet (sec)

C_{cj} = ceiling jet lag time constant

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

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

Q = heat release rate of the fire (kW)

$t_{cj} =$ 0.61 sec

Smoke Detector Response Time Calculation

$t_{activation} = t_{pl} + t_{cj}$

$t_{activation} =$ 1.27 sec **Answer**

METHOD OF MILKE

References: Milke, J., "Smoke Management for Covered Malls and Atria," Fire Technology, August 1990, p. 223.
NFPA 92B, "Guide for Smoke Management Systems in Mall, Atria, and Large Areas," 2000 Edition, Section A.3.4.

$t_{activation} = X\, H^{4/3}/Q^{1/3}$

Where $t_{activation}$ = detector activation time (sec)
$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-15}\ Y^6$
H = height of ceiling above top of fuel (ft)
Q = heat release rate from steady fire (Btu/sec)

Where $Y = \Delta T_c\, H^{5/3} / Q^{2/3}$
ΔT_c = temperature rise of gases under the ceiling for smoke detector to activate (°F)

Before estimating smoke detector response time, stratification effects can be calculated.
NFPA 92B, 2000 Edition, Section A.3.4 provides following correlation to estimate smoke stratification in a compartment.

$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f\text{-}c}^{3/5}$

Where H_{max} = the maximum ceiling clearance to which a plume can rise (ft)
Q_c = convective portion of the heat release rate (Btu/sec)
$\Delta T_{f\text{-}c}$ = difference in temperature due to fire between the fuel location and ceiling level (°F)

Convective Heat Release Rate Calculation
$Q_c = Q\ \chi_c$

Where Q_c = convective portion of the heat release rate (Btu/sec)
Q = heat release rate of the fire (Btu/sec)
χ_c = convective heat releas rate fraction

Q_c = 2322.16 Btu/sec

Difference in Temperature Due to Fire Between the Fuel Location and Ceiling Level
$\Delta T_{f\text{-}c} = 1300\ Q_c^{2/3} / H^{5/3}$

Where $\Delta T_{f\text{-}c}$ = difference in temperature due to fire between the fuel location and ceiling level (°F)
Q_c = convective portion of the heat release rate (Btu/sec)
H = ceiling height above the fire source (ft)

$\Delta T_{f\text{-}c}$ = 1066.53 °F

Smoke Stratification Effects
$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f\text{-}c}^{3/5}$

H_{max} = 25.05 ft

In this case the highest point of smoke rise is estimated to be 25.05 ft
Thus, the smoke would be expected to reach the ceiling mounted smoke detector.

$Y = \Delta T_c\ H^{5/3} / Q^{2/3}$

Y = 17.30

$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-16}\ Y^6$

X = 0.14

Smoke Detector Response Time Calculation
$t_{activation} = X\, H^{4/3}/Q^{1/3}$

$t_{activation}$ = 0.67 sec Answer

Summary of Result:

Calculation Method	Smoke Detector Response Time (sec)
METHOD OF ALPERT	0.55
METHOD OF MOWRER	1.27
METHOD OF MILKE	0.67

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19h Edition, 2003, method described in Fire Technology, 1990, and NFPA 92B, "Guide for Smoke Management Systems in Malls, Atria, and Large Areas," 2000 Edition, Section A.3.4. 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 situations and, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 11.12-3

Problem Statement

During a triennial inspection, an NRC inspector discovers that every other smoke detector has inadvertently been painted and is not functional. The detection system in the compartment is single-zoned to arm a pre-action sprinkler system. The detectors are 20 ft on center. The ceiling is 23 ft. The sprinkler system uses 165 °F sprinklers, 10 ft on center, 4 inches from the ceiling. The licensee states that even with half the smoke detectors inoperable, a smoke detector would alarm and charge the pre-action system before a quick-response link-type sprinkler head fuses. The expected fire in the compartment is approximately 750 kW. Is the licensee's statement true?

Solution

Purpose:

(1) Determine the response time of the smoke detector for the fire scenario.
(2) Determine the response time of the sprinkler system.

Assumptions:

(1) The fire is steady-state.
(2) The forced ventilation system is off.
(3) There is no heavily obstructed overhead.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (click on *Smoke-Detector*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 750 kW
-Ceiling Height (H) = 23 ft
-Radial Distance from the Plume Centerline to the Smoke Detector (r) = 20 ft

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

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 750 kW
-Select Quick Response Link
-Select Ordinary
-Ceiling Height (H) = 23 ft
-Radial Distance from the Plume Centerline to the Sprinkler (r) = 7.1 ft

Results*

Heat Release Rate $\dot{Q}$ (kW)	Smoke Detector Activation Time (t_R) (sec)		
	Method of Alpert	Method of Mowrer	Method of Milke
3,500	2.0	1.94	6.0

The sprinkler heads do not activate.
*see spreadsheet on next page

Therefore, the licensee's statement is true; however, the non-activation of the sprinkler heads should be of great concern.

Spreadsheet Calculations

(a) FDT[s]: 10_Detector_Activation_Time.xls (Smoke_Detector)

CHAPTER 11. ESTIMATING SMOKE DETECTOR RESPONSE TIME

Version 1805.0

The following calculations estimate smoke detector response time.
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 ($\dot{Q}$) (Steady State)	750.00	kW	710.87 Btu/sec
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	20.00	ft	6.10 m
Height of Ceiling above Top of Fuel (H)	23.00	ft	7.01 m
Activation Temperature of the Smoke Detector ($T_{activation}$)	86.00	°F	30.00 °C
Smoke Detector Response Time Index (RTI)	5.00	(m-sec)$^{1/2}$	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		
Plume Lag Time Constant (C_p) (Experimentally Determined)	0.67		
Ceiling Jet Lag Time Constant (C_c) (Experimentally Determined)	1.2		
Temperature Rise of Gases Under the Ceiling (ΔT_c) for Smoke Detector to Activate	18.00	°F	10 °C
r/H = 0.87			

Calculate

ESTIMATING SMOKE DETECTOR RESPONSE TIME
METHOD OF ALPERT

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

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

This method assume smoke detector is a low RTI device with a fixed activation temperature

Where
- $t_{activation}$ = detector activation time (sec)
- RTI = detector 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 detector (°C)

Ceiling Jet Temperature Calculation

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

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

Where
- T_{jet} = ceiling jet temperature (°C)
- T_a = ambient air temperature (°C)
- $\dot{Q}_c$ = 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 detector (m)

Convective Heat Release Rate Calculation

$\dot{Q}_c = \chi_c \dot{Q}$

Where
- $\dot{Q}_c$ = convective portion of the heat release rate (kW)
- $\dot{Q}$ = heat release rate of the fire (kW)
- χ_c = convective heat release rate fraction

$\dot{Q}_c$ = 525 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.87 r/H > 0.15

>0.15	14.97	<0.15	42.83

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

$T_{jet} - T_a =$ 14.97

$T_{jet} =$ 39.97 (°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 detector (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.87 r/H > 0.15

>0.15	1.04	<0.15	4.56

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

$u_{jet} =$ 1.040 m/sec

Smoke Detector Response Time Calculation

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

$t_{activation} =$ 1.99 sec Answer

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

METHOD OF MOWRER

References: *Mowrer, F., "Lag Times Associated With Fire Detection and Suppression," Fire Technology, August 1990, p. 244.*

$t_{activation} = t_{pl} + t_{cj}$

Where $t_{activation}$ = detector activation time (sec)

t_{pl} = transport lag time of plume (sec)

t_{cj} = transport lag time of ceiling jet (sec)

Transport Lag Time of Plume Calculation

$t_{pl} = C_{pl}\ (H)^{4/3}/(Q)^{1/3}$

Where t_{pl} = transport lag time of plume (sec)

C_{pl} = plume lag time constant

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

Q = heat release rate of the fire (kW)

$t_{pl} =$ 0.99 sec

Transport Lag Time of Ceiling Jet Calculation

$t_{cj} = (r)^{11/6}/(C_{cj})\ (Q)^{1/3}\ (H)^{1/2}$

Where t_{cj} = transport lag time of ceiling jet (sec)

C_{cj} = ceiling jet lag time constant

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

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

Q = heat release rate of the fire (kW)

$t_{cj} =$ 0.95 sec

Smoke Detector Response Time Calculation

$t_{activation} = t_{pl} + t_{cj}$

$t_{activation} =$ 1.94 sec Answer

METHOD OF MILKE

References: Milke, J., "Smoke Management for Covered Malls and Atria," Fire Technology, August 1990, p. 223.
NFPA 92B, "Guide for Smoke Management Systems in Mall, Atria, and Large Areas," 2000 Edition, Section A.3.4.

$t_{activation} = X H^{4/3}/Q^{1/3}$

Where $t_{activation}$ = detector activation time (sec)
$X = 4.6\ 10^{-4} Y^2 + 2.7\ 10^{-15} Y^6$
H = height of ceiling above top of fuel (ft)
Q = heat release rate from steady fire (Btu/sec)

Where $Y = \Delta T_c H^{5/3} / Q^{2/3}$
ΔT_c = temperature rise of gases under the ceiling for smoke detector to activate (°F)

Before estimating smoke detector response time, stratification effects can be calculated. NFPA 92B, 2000 Edition, Section A.3.4 provides following correlation to estimate smoke stratification in a compartment.

$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f-c}^{3/5}$

Where H_{max} = the maximum ceiling clearance to which a plume can rise (ft)
Q_c = convective portion of the heat release rate (Btu/sec)
ΔT_{f-c} = difference in temperature due to fire between the fuel location and ceiling level (°F)

Convective Heat Release Rate Calculation
$Q_c = Q\ \chi_c$

Where Q_c = convective portion of the heat release rate (Btu/sec)
Q = heat release rate of the fire (Btu/sec)
χ_c = convective heat releas rate fraction

Q_c = 497.61 Btu/sec

Difference in Temperature Due to Fire Between the Fuel Location and Ceiling Level
$\Delta T_{f-c} = 1300\ Q_c^{2/3} / H^{5/3}$

Where ΔT_{f-c} = difference in temperature due to fire between the fuel location and ceiling level (°F)
Q_c = convective portion of the heat release rate (Btu/sec)
H = ceiling height above the fire source (ft)

ΔT_{f-c} = 438.85 °F

Smoke Stratification Effects
$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f-c}^{3/5}$

H_{max} = 23.05 ft

In this case the highest point of smoke rise is estimated to be 23.05 ft
Thus, the smoke would be expected to reach the ceiling mounted smoke detector.

$Y = \Delta T_c\ H^{5/3} / Q^{2/3}$

Y = 42.04

$X = 4.6\ 10^{-4} Y^2 + 2.7\ 10^{-16}\ Y^6$

X = 0.81

Smoke Detector Response Time Calculation
$t_{activation} = X H^{4/3}/Q^{1/3}$

$t_{activation}$ = 5.96 sec Answer

Summary of Result:

Calculation Method	Smoke Detector Response Time (sec)
METHOD OF ALPERT	1.99
METHOD OF MOWRER	1.94
METHOD OF MILKE	5.96

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19h Edition, 2003, method described in Fire Technology, 1990, and NFPA 92B, "Guide for Smoke Management Systems in Malls, Atria, and Large Areas," 2000 Edition, Section A.3.4. 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 situations and, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT[s]: 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)	750.00	kW	
Sprinkler Response Time Index (RTI)	34	$(m\text{-}sec)^{1/2}$	
Activation Temperature of the Sprinkler ($T_{activation}$)	165	°F	73.89 °C
Height of Ceiling above Top of Fuel (H)	23.00	ft	7.01 m
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	7.10	ft	2.16 m
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		

r/H = 0.31

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
Quick 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. 211-218.*

*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 = 525 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.31 r/H > 0.15

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

$T_{jet} - T_a$ = 29.85

T_{jet} = 54.85 (°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 = 0.31 r/H > 0.15

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

u_{jet} = 2.465 m/sec

Sprinkler Activation Time Calculation

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

$t_{activation}$ = #NUM! sec

The sprinkler will respond in approximately	#NUM!	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.

CHAPTER 12. ESTIMATING HEAT DETECTOR RESPONSE TIME

12.1 Objectives

This chapter has the following objectives:

- Explain where heat detectors are located.
- Identify the various types of heat detectors and how they work.
- Describe how to calculate the activation time of a heat detector.

12.2 Introduction

Heat detectors are one of the oldest forms of automatic fire detection devices, and they typically have the lowest false alarm rate of all automatic fire detection devices. Nonetheless, they are generally the slowest to detect fires because they do not detect smoke. Rather, they respond either when the detecting element reaches a predetermined fixed temperature or when the temperature changes at a specified rate. Thus, heat detectors usually do not provide enough early warning in case of a life-threatening situation. As a result, heat detectors are best suited for fire detection in a small confined space where rapidly building high-heat-output fires are expected, in areas where ambient conditions would not allow the use of other fire detection devices, or where speed of detection is not a primary consideration.

Heat detectors are generally located on or near the ceiling, where they can respond to the convected thermal energy of a fire. They may be used in combination with smoke detectors, since smoke detectors usually activate before the flames and heat would are sufficient to alarm the heat detector. In general, heat detectors are designed to operate when heat causes a prescribed change in a physical or electrical property of a material or gas.

The following excerpts are from the procedure specified by Underwriters' Laboratories, Inc., for using thermal detectors in automatic fire detection systems. Notice that to prevent false alarms, detectors should be installed only after considering the limitation on their operational rating and the prevalent ceiling temperatures. For example, ordinary detectors rated from 57–74 °C (135–165 °F) should be installed only where ceiling temperatures do not exceed 37.7 °C (100 °F).

12.3 Underwriters' Laboratories, Inc., Listing Information for Heat-Detecting Automatic Fire Detectors

"A heat-detecting type of automatic fire detector is an integral assembly of heat-responsive elements and non-coded electrical contacts, which function automatically under conditions of increased air temperature." Listing under this heading applies to fire alarm heat detectors only and not to wiring or other appliances of which they form a part. Fire alarm heat detectors are of the fixed-temperature, combination fixed-temperature, and rate-of-rise or rate compensation types. There are basically two types: (1) spot-type is one in which the thermally sensitive element is a compact unit of small area, and (2) line-type is one in which the thermally sensitive element is continuous along the line. These heat detectors have been investigated for indoor use only unless otherwise indicated in the individual listing.

Ordinarily, heat detectors are intended for locations where normal ceiling temperatures prevail below 37.7 °C (100 °F). Locations where ceiling temperatures are likely to be unduly high, from sources of heat other than fire conditions such as boiler rooms, dry kilns, etc., demand special consideration and selection of heat detectors operating normally at higher temperatures, and which are capable of withstanding high temperatures for long periods of time.

Care should be exercised to select heat detectors having the proper temperature rating to guard against false alarms from premature operation. These detectors are intended to be installed in accordance with NFPA 72E-Automatic Fire Detectors. For ceiling temperatures exceeding 37.7 °C (100 °F), install 57.2–73.8 °C (135–165 °F) (ordinary) rating thermostats. For ceiling temperatures exceeding 37.7 °C (100 °F), but not 65.5 °C (150 °F), install 79.4–107.2 °C (175–225 °F) (intermediated) rating thermostats. For ceiling temperatures exceeding 65.5 °C (150 °F), but not 107.2 °C (225 °F), install 121.1 to 148.8 °C (250–300 °F) (high) rating thermostats. For ceiling temperatures exceeding 107.2 °C (225 °F), but not 148.8 °C (300 °F), install 162.7–182.2 °C (325–360 °F) (extra high) rating thermostats.

Low-degree rated heat detectors are intended only for installation in areas having controlled temperature conditions at least -6.6 °C (20 °F) below rating. The spacings specified are for flat, smooth ceiling construction of ordinary height, generally regarded as the most favorable condition for distribution of heated air currents resulting from a fire. Under other forms of ceiling construction, reduced spacings may be required.

The fire tests conducted to determine the suitability of the spacings are conducted in an 18.3 x 18.3 m (60 x 60 ft) room having a 4.8-m (15-ft, 9-in.) high smooth ceiling and minimum air movement. The test fire (denatured alcohol) is located approximately 0.91 m (3 ft) above the floor and is of a magnitude so that sprinkler operation is obtained in approximately 2 minutes. For comparative purposes, automatic sprinklers rated at 71.7 °C (160 °F) are installed on a 3.05 x 3.05 m (10 x 10 ft) spacing schedule in an upright position with the deflectors approximately 17.5 cm (7 in) below the ceiling. At the maximum permissible spacing for the heat detectors, they must operate prior to operation of the sprinklers.

The placement and spacing of heat detecting devices should be based on consideration of the ceiling construction, ceiling height, room or space areas, spaced subdivisions, normal room temperature, possible exposure of the devices to abnormal heat (such as uninsulated steam pipes) or to draft conditions likely to be encountered at the time of a fire.

12.4 Operating Principle of Heat Detectors

Spot type heat detectors respond to temperature changes in the surrounding environment. They are designed to respond to the convected thermal energy of a fire. They detect at either a predetermined fixed temperature or at a specified rate of temperature rise. In general, a heat detector is designed to sense a prescribed change in a physical or electrical property of its material when exposed to heat.

12.4.1 Fixed-Temperature Heat Detectors

Fixed-temperature detectors are intended to alarm when the temperature of their operating elements reaches specific points. The air temperature at the time of operation may be higher than the rated temperature due to the thermal inertia of the operating elements. This condition is called thermal lag. Fixed-temperature heat detectors are available to cover a wide range of operating temperatures from 57 °C (135 °F) and higher. Higher temperature detectors are sometimes necessary so that detection can be provided in areas normally subjected to high ambient (nonfire) temperatures. Fixed-temperature heat detectors are manufactured in seven temperature range groups, and the proper detector is selected based on the highest ambient temperature of the room for which it is designed. Fixed-temperature detectors are available in several types.

12.4.1.1 Fusible-Element Type

One type of fusible-element spot detector is the eutectic (fusible) metal type. Eutectic metal employs a mixture of either bismuth, lead, tin or cadmium which melts at a predetermined temperature. Eutectic metals that melt rapidly at a predetermined temperature are used to actuate the operating elements of the heat detector. When the element fuses (i.e., melts), the spring action closes contacts and initiates an alarm. Devices using eutectic elements cannot be restored. When their element fuses, alarms are signaled by various mechanical or electrical means (typically by a closed set of contacts).

12.4.1.2 Continuous Line Type

One type of line detector uses a pair of wires in a normally open circuit enclosed in a braided sheath to form a single-cable assembly. When the predetermined temperature is reached, the insulation, which holds the conductors apart melts, and the two wires come in contact which initiates the alarm. The fused section of the cable must be replaced to restore the system. Alternatively, this type of detector may use a stainless steel capillary tube containing a coaxial center conductor separated from the tube wall by a temperature-sensitive glass semiconducting material. As the temperature rises, the semiconductor decreases and allows more current to flow, thereby initiating the alarm.

12.4.1.3 Bimetallic Type

These spot detectors are generally of two types, including (1) the bimetal strip and (2) the bimetal snap disc. As it is heated, the bimetal strip deforms in the direction of the contact point. The operating element of a snap disc device is a bimetal disc composed of two metals with different thermal growth rates formed into a concave shape in its unstressed condition. Generally, a heat detector is attached to the detector frame to speed the transfer of heat from the room air to the bimetal. As the disc (not part of the electrical circuit) is heated, the stresses developed in the two different metals cause it to suddenly reverse the curvature and become convex. This provides a rapid positive action that closes the alarm contacts. These devices are typically self-restoring after heat is removed.

12.4.2 Rate Compensation Heat Detectors

These spot type detectors respond when the temperature of the air surrounding the detector reaches a predetermined temperature, regardless of the rate of temperature rise. A typical example is a spot-type detector with a tubular casing of metal that tends to expand lengthwise as it is heated, and an associated contact mechanism that will close at a certain point in the elongation. A second metallic element inside the tube exerts an opposing force on the contacts, tending to hold them open. The forces are balanced so that, with a slow rate of temperature rise, there is more time for heat to penetrate to the inner element. This inhibits contact closure until the total device has been heated to its rated temperature level. However, with a fast rate of temperature rise, there is less time for heat to penetrate to the inner element. The element therefore exerts less of an inhibiting effect, so contact closure is obtained when the total device has been heated to a lower level. This, in effect, compensates for thermal lag.

12.4.3 Rate-of-Rise Heat Detectors

These spot type detectors operate when the room temperature rises at a rate which exceeds a predetermined value. For example, the effect of a flaming fire on the surrounding area is to rapidly increase air temperature in the space. A fixed-temperature detector will not initiate an alarm until the air temperature near the ceiling exceeds the design operating point. The rate-of-rise detector, however, will function when the rate of temperature increase exceeds a predetermined value, typically around 7 to 8 °C (12 to 15 °F) per minute. Rate-of-rise detectors are designed to compensate for the normal changes in ambient temperature [less than 6.7 °C (12 °F) per minute] that are expected under non-fire conditions.

12.4.4 Pneumatic Heat Detectors

In a pneumatic spot type heat detector, air heated in a tube or chamber expands, increasing the pressure in the tube or chamber. This exerts a mechanical force on a diaphragm that close the alarm contacts. If the tube or chamber were hermetically sealed, slow increases in ambient temperature, a drop in the barometric pressure, or both, would cause the detector to initiate an alarm regardless of the rate of temperature change. To overcome this, pneumatic detectors have a small orifice to vent the higher pressure that builds up during slow increases in temperature or during a drop in barometric pressure. The vents are sized so that when the temperature changes rapidly, as in a fire, the rate of expansion exceeds the venting rate and pressure rises. When the temperature rise exceeds 7 to 8 °C (12 to 15 °F) per minute, the pressure is converted to mechanical action by a flexible diaphragm. Pneumatic heat detectors are available for both line- and spot-type detectors.

12.4.4.1 Line-Type Heat Detectors

The line-type consists of metal tubing, in a loop configuration, attached to the ceiling of the area to be protected. Lines of the tubing are normally spaced not more than 9.1 m (30 ft) apart, not more than 4.5 m (15 ft) from a wall, and with no more than 305 m (1,000 ft) of tubing on each circuit. Also, a minimum of at least 5-percent of each tube circuit or 7.6 m (25 ft) of tube, whichever is greater, must be in each protected area. Without this minimum amount of tubing exposed to a fire condition, insufficient pressure would build up to achieve proper response.

In small areas where the line-type tube detector might have insufficient tubing exposed to generate sufficient pressures to close the alarm contacts, air chambers or rosettes of tubing are often used. These units act like a spot-type detector by providing the volume of air required to meet the 5-percent or 7.6 m (25 ft) requirement. Since a line-type rate-of-rise detector is an integrating detector, it will actuate either when a rapid heat rise occurs in one area of exposed tubing, or when a slightly less rapid heat rise takes place in several areas when tubing on the same loop is exposed. The pneumatic principle is also used to close contacts within spot-type detector. The difference between the line-and spot-type detectors is that the spot-type contains all of the air in a single container rather than in a tube that extends from the detectors assembly to the protected area(s).

12.4.5 Combination Heat Detectors

Many spot type heat detectors are available that utilize both the rate-rise and fixed-temperature principles. The advantage of units such as these is that the rate-of-rise elements will respond quickly to rapidly developing fires, while the fixed-temperature elements will respond to slowly developing smoldering fires when design alarm temperature is reached. The most common combination detector uses a vented air chamber and a flexible diaphragm for the rate-of-rise function, while the fixed-temperature element is usually leaf-spring restrained by a eutectic metal. When the fixed-temperature element reaches its design operating temperature, the eutectic metal fuses and releases the spring, which closes the contacts.

12.4.6 Electronic Spot-Type Thermal Detectors

These detectors utilize a sensing element consisting of one or more thermistors, which produce a change in electrical resistance in response to an increase in temperature. This resistance is monitored by associated electronic circuitry, and the detector responds when the resistance changes at an abnormal rate (rate-of-rise type) or when the resistance reaches a specific value (fixed-temperature type).

12.5 Fixed-Temperature Heat Detector Activation

Fixed-temperature heat detectors are generally modeled by calculating the heat transfer from the fire gases to the detector element, and the resultant temperature change. To simplify the calculation, all current detector models treat the detector as a "lumped mass." A lumped mass model assumes that there are no temperature gradients within the detector element. This assumption is reasonable for solder-type heat detectors, since the operating element has a low mass. With bimetallic-type detectors, the lumped mass assumption may introduce some error, since heat must be transferred to two slightly different parts.

Analytical methods for calculating detector temperature require that equations for temperature and velocity of fire gases as a function of time must be inserted into the basic heat transfer equation. The resulting differential equation must be integrated to arrive at an analytical solution to the heat transfer equation.

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

$$t_{activation} = \frac{RTI}{\sqrt{u_{jet}}} \ln\left(\frac{T_{jet} - T_a}{T_{jet} - T_{activation}}\right) \qquad (12\text{-}1)$$

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 detector (°C)

The RTI concept was developed by Factory Mutual Research Corporation (FMRC) to be a fundamental measure of thermal detector sensitivity. A detector's RTI is determined in plunge tests with a uniform gas flow of constant temperature and velocity and can be used to predict the detector's activation time in any 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 detector, which is related to the mass and surface area of the detector element. Faster detectors have low response time indices and smaller time constants. Detector elements with low time constants have low ratios of mass to surface area. The RTI is defined by the following equation:

$$RTI = \frac{m_e c_{p(e)}}{h_e A_e} \sqrt{u_{jet}} \qquad (12\text{-}2)$$

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 detector (m/sec)

The flow of heat and ceiling jet into a heat detector sensing element is not instantaneous; it occurs over a period of time. A measure of the speed with which heat transfer occurs (the thermal coefficient) is needed to accurately predict heat detector response. Called the detector time constant ($_0$), this measure should be determined by a validated test (Heskestad, 1976). For a given detector, the convective heat transfer coefficient (h_e) and are approximately proportional to the square root of the velocity (u) of the gases passing the detector. This relationship can be expressed as the characteristic response time index, RTI, for a given detector:

$$RTI \cong \tau u^{\frac{1}{2}} \cong \tau_0 u_0^{\frac{1}{2}} \quad (12\text{-}3)$$

Where:

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

$_0$ = detector time constant (sec)

u_0 = gas velocity (m/sec)

The detector time constant, $_0$, is measured in the laboratory at some reference velocity, u_0. This expression can be used to determine the detector's RTI.

UL-listed detector spacing can be used as a measure of detector sensitivity. Heskestad and Delichatsios (1977), analyzed UL test data and calculated the time constant, $_0$, for various combinations of UL-listed spacing and detector-operated temperature. The Subcommittee of NFPA 72 expanded that table to include a larger selection of detectors. The table is reproduced here as Table 12-1.

Table 12-1. Time Constant of Any Listed Detector

Listed Spacing (ft)	**Underwriter's Laboratories, Inc. (UL) Temperature Rating (°F)**						**FMRC (All Temperatures)**
	128	**135**	**145**	**160**	**170**	**196**	
	Detector Time Constant, $_0$ (sec)						
10	400	330	262	195	160	97	196
15	250	190	156	110	89	45	110
20	165	135	105	70	52	17	70
25	124	100	78	48	32	-	48
30	95	80	61	36	22	-	36
40	71	57	41	18	-	-	-
50	59	44	30	-	-	-	-
70	36	24	9	-	-	-	-
Note: These time constants are based on an analysis of the UL and FMRC listing test procedures. This table is reproduced from NFPA 72, Appendix B, 1999 Edition.							

The time constants listed in Table 12-1 are based on a reference velocity of 1.5 m/sec (5 ft/sec). These time constants can be converted to RTI values be using Equation 12-4, as follows:

$$RTI = \tau_0 \sqrt{1.5} \left(\frac{m}{sec}\right)^{\frac{1}{2}} \qquad (12\text{-}4)$$

Table 12-2 provides the calculated values of RTI based on the detector time constant ($_0$) in Table 12-1.

Table 12-2. Detector Response Time Index of Any Listed Detector

Listed Spacing (ft)	**Underwriter's Laboratories, Inc. (UL) Temperature Rating (°F)**						**FMRC (All Temperatures)**
	128	**135**	**145**	**160**	**170**	**196**	
	Detector RTI (m-sec)$^{1/2}$						
10	490	404	321	239	196	119	240
15	306	233	191	135	109	55	135
20	325	165	129	86	64	21	86
25	152	123	96	59	39	-	59
30	116	98	75	44	27	-	44
40	87	70	50	22	-	-	-
50	72	54	37	-	-	-	-
70	44	29	11	-	-	-	-

The expressions for estimating the maximum ceiling jet temperature and velocity as a function of ceiling height, radial position, and HRR were developed from an analysis of experiments with large-scale fires having HRRs 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 expression:

$$T_{jet} - T_a = \frac{16.9 \ \dot{Q}^{\frac{2}{3}}}{H^{\frac{5}{3}}} \qquad \text{for} \ \frac{r}{H} \leq 0.18 \qquad (12\text{-}5)$$

$$T_{jet} - T_a = \frac{5.38 \left(\frac{\dot{Q}}{r}\right)^{\frac{2}{3}}}{H} \qquad \text{for} \ \frac{r}{H} > 0.18 \qquad (12\text{-}6)$$

$$u_{jet} = 0.96 \left(\frac{\dot{Q}}{H}\right)^{\frac{1}{3}} \qquad \text{for} \ \frac{r}{H} \leq 0.15 \qquad (12\text{-}7)$$

$$u_{jet} = \frac{0.195 \ \dot{Q}^{\frac{1}{3}} \ H^{\frac{1}{2}}}{r^{\frac{5}{6}}} \qquad \text{for} \ \frac{r}{H} > 0.15 \qquad (12\text{-}8)$$

Where:

- T_{jet} = ceiling jet temperature (°C)
- T_a = ambient air temperature (°C)
- $\dot{Q}$ = heat release rate of the fire (kW)
- H = distance from the top of the fuel package to the ceiling level (m)
- r = radial distance from the plume centerline to the detector (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. So, for example, for regions where r/H>0.18, Equation 12-6 should be used. Based on the cases where the hot gases have begun to spread under a ceiling located above the fire, Equation 12-5 applies for a small radial distance, r, from the impingement point (see Figure 12-1).

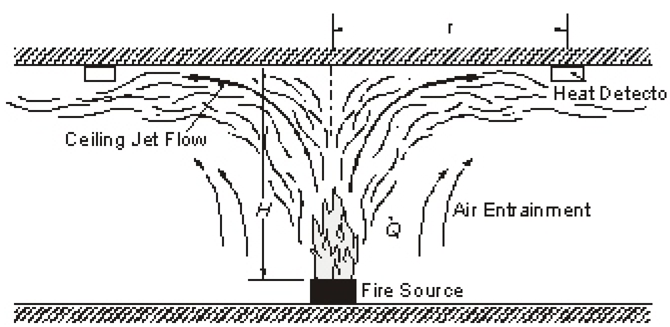


Figure 12-1 Ceiling Jet Flow Beneath and Unconfined Ceiling Showing a Heat Detector

As with the temperatures 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 detector response time. The temperature and velocity of a ceiling jet varies 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, where the maximum occurs along the plume centerline. With the knowledge of plume ceiling jet temperature and velocity, we can estimate the actuation time of a fixed-temperature if we also know the spacing and the speed or thermal inertia of the detector. The response of a fixed-temperature heat detector is given by its RTI.

12.6 Assumptions and Limitations

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

(1) 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.

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

(3) The plume ceiling jet correlations are valid for unconfined flat ceilings, as the environments outside the ceiling jet are uniform in temperature and are atmospheric ambient. Caution should be exercised with this method when the ceiling has an irregular surface such as beam pockets.

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

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

(6) 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.

(7) Caution should be exercised with this method when the overhead area is highly obstructed.

(8) The detectors are located at or very near to the ceiling. Very near to the ceiling would include code compliant detectors mounted on the bottom flange of structural steel beams. These methods are not applicable to detectors mounted well below the ceiling in free air.

12.7 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) listed spacing of detectors (ft)

(3) activation temperature of detectors (°F)

(4) height to ceiling (ft)

(5) ambient room temperature (°F)

12.8 Cautions

(1) Use (10_Detector_Activation_Time.xls) and select “FTHDetector” spreadsheet on the CD-ROM for calculations.

(2) Make sure all inputs are recorded in the correct units.

12.9 Summary

This chapter discusses a method of calculating the response time of heat detectors under unobstructed ceilings in response to steady-state fires without forced ventilation.

12.10 References

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.

Heskestad, G., and H.F. Smith, “Investigation of a New Sprinkler Sensitivity Approval Test: The Plunge Test,” FMRC Serial No. 22485, Factory Mutual Research Corporation, Norwood, Massachusetts, December 1976.

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12.11 Additional Readings

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

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Moore, W.D., “Automatic Fire Detectors” Sec. 5, Ch. 2, *NFPA Fire Protection Handbook*, 18th Ed., A.E. Cote, Editor-in-Chief, National Fire Protection Assoc., Quincy, Massachusetts, 1997.

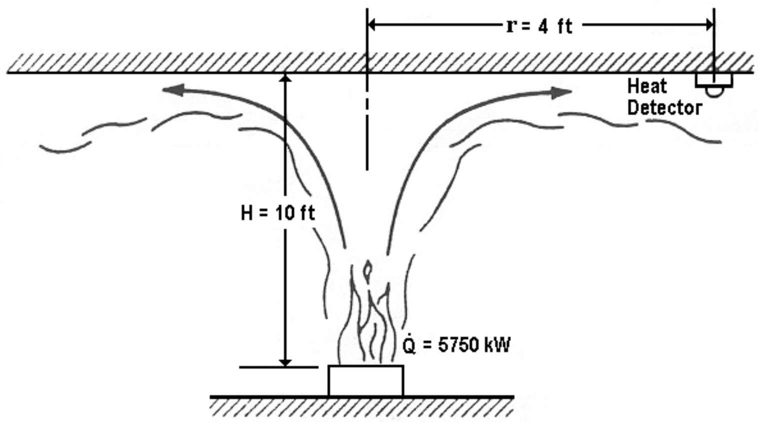
Schifiliti, R.P., B.J. Meacham, and R.P. Custer, Chapter 1, Section 4, “Design of Detection Systems,” *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

12.12 Problems

Example Problem 12.12-1

Problem Statement

A 34.5-ft^2 (3.20-m^2) lube oil pool fire with $\dot{Q}$ = 5,750 kW occurs in a space protected with fixed-temperature heat detectors. Calculate the activation time for the fixed-temperature heat detectors, using 10-ft (3.05-m) spacing, in an area with a ceiling height of 10 ft (3.05 m). The detector activation temperature is 128 °F (53 °C), the radial distance to the detector is 4 ft (1.22 m), and the ambient temperature is 77 °F (25 °C).



Example Problem 12-1: Fire Scenario with Heat Detectors

Solution

Purpose:

(1) Determine the response time of the fixed-temperature heat detectors for the fire scenario.

Assumptions:

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

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

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

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 5,750 kW

-Radial Distance to the Detector (r) = 4 ft

-Activation Temperature of the Fixed-Temperature Heat Detector ($T_{activation}$) = 128 °F

-Distance from the Top of the Fuel Package to the Ceiling (H) = 10 ft

-Ambient Air Temperature (T_a) = 77 °F

-Click on the option button (⊙) for FTH detectors with $T_{activation}$ = 128 °F

-Select Detector Spacing: 10

Results*

Detector Type	Heat Detector Activation Time ($t_{activation}$) (min.)
Fixed-Temperature	0.27

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 10_Detector_Activation_Time.xls (FTHDetector)

CHAPTER 12. ESTIMATING HEAT DETECTOR RESPONSE TIME

Version 1805.0

The following calculations estimate fixed temperature heat detector 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 Detector 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)	5750.00	kW	
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	4.00	ft	122 m
Activation Temperature of the Fixed Temperature Heat Detector ($T_{activation}$)	145	°F	6278 °C
Detector Response Time Index (RTI)	321.00	(m-sec)$^{1/2}$	
Height of Ceiling above Top of Fuel (H)	10.00	ft	305 m
Ambient Air Temperature (T_a)	68.00	°F	2000 °C
			29300 K
Convective Heat Release Fraction (χ_c)	0.70		
r/H = 0.40	Calculate		

INPUT DATA FOR ESTIMATING HEAT DETECTOR RESPONSE TIME

Activation Temperature $T_{activation}$

◉ T= 128 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	490	128
15	306	128
20	325	128
25	152	128
30	116	128
40	87	128
50	72	128
70	44	128
User Specified Value	Enter Value	Enter Value

Select Detector Spacing
10
Scroll to desired spacing then Click on selection

○ T= 135 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	404	135
15	233	135
20	165	135
25	123	135
30	98	135
40	70	135
50	54	135
70	20	135
User Specified Value	Enter Value	Enter Value

Select Detector Spacing
Scroll to desired spacing then Click on selection

○ T= 145 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	321	145
15	191	145
20	129	145
25	96	145
30	75	145
40	50	145
50	37	145
70	11	145
User Specified Value	Enter Value	Enter Value

Select Detector Spacing
Scroll to desired spacing then Click on selection

T= 160 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	239	160
15	135	160
20	86	160
25	59	160
30	44	160
40	22	160
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 170 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	196	170
15	109	170
20	64	170
25	39	170
30	27	170
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 196 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	119	196
15	55	196
20	21	196
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then

Click on selection

Reference: *NFPA Standard 72, National Fire Alarm Code, Appendix B, Table B-3.2.5.1, 1999, Edition.*

ESTIMATING FIXED TEMPERATURE HEAT DETECTOR 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 $t_{activation}$ = detector activation time (sec)

RTI = detector 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 detector (°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 detector (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\ Q$

Where Q_c = convective heat release rate (kW)

Q = heat release rate of the fire (kW)

χ_c = convective heat release fraction

Q_c = 4025 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.40 r/H > 0.15

>0.15	391.35	<0.15	667.38

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

$T_{jet} - T_a =$ 391.35

$T_{jet} =$ 411.35 (°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 detector (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.40 r/H > 0.15

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

$u_{jet} =$ 5.171 m/sec

Detector Activation Time Calculation

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

$t_{activation} =$ 16.34 sec

The detector will respond in approximately	0.27 minutes	Answer

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

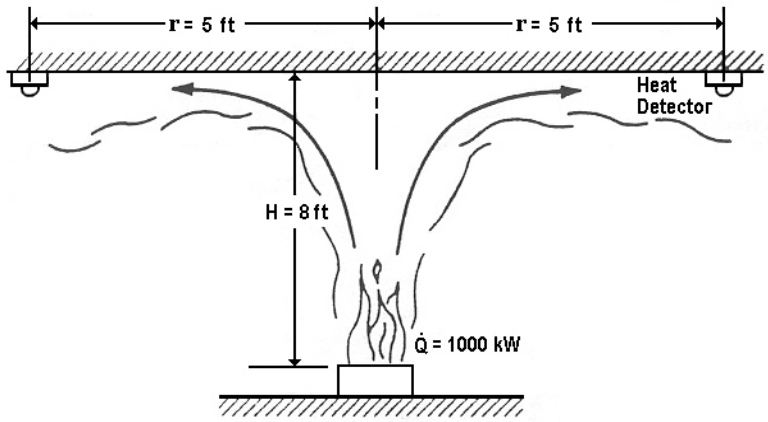
NOTE

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.

Example Problem 12.12-2

Problem Statement

A trash fire with $\dot{Q}$ = 1,000 kW occurs in a space protected with fixed-temperature heat detectors. Calculate the activation time for the fixed-temperature heat detectors, using 10 ft (3.05 m) spacing, in an area with a ceiling height of 8 ft (2.43 m). The fire is located directly between heat detectors. The detector activation temperature is 160 °F (71 °C), and the ambient temperature is 77 °F (25 °C).



Example Problem 12-2: Fire Scenario with heat detectors that are equidistant from the fire source

Solution

Purpose:

(1) Determine the response time of the fixed-temperature heat detectors for the fire scenario.

Assumptions:

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

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

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

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 1,000 kW

-Radial Distance to the Detector (r) = 5 ft

-Activation Temperature of the Fixed-Temperature Heat Detector ($T_{activation}$) = 160 °F

-Distance from the Top of the Fuel Package to the Ceiling (H) = 8 ft

-Ambient Air Temperature (T_a) = 68 °F

-Click on the option button (⊙) for FTH detectors with $T_{activation}$ = 160 °F

-Select Detector Spacing: 10

Results*

Detector Type	Heat Detector Activation Time ($t_{activation}$) (min.)
Fixed-Temperature	1.34

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 10_Detector_Activation_Time.xls (FTHDetector)

CHAPTER 12. ESTIMATING HEAT DETECTOR RESPONSE TIME

Version 1805.0

The following calculations estimate fixed temperature heat detector 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 Detector 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	
Radial Distance to the Detector (r) "never more than 0.707 or 1/2√2 of the listed spacing"	5.00	ft	1.52 m
Activation Temperature of the Fixed Temperature Heat Detector ($T_{activation}$)	160	°F	71.11 °C
Detector Response Time Index (RTI)	239.00	(m-sec)$^{1/2}$	
Height of Ceiling above Top of Fuel (H)	8.00	ft	2.44 m
Ambient Air Temperature (T_a)	68.00	°F	20.00 °C
			293.00 K
Convective Heat Release Fraction (χ_c)	0.70		

r/H = 0.63

Calculate

INPUT DATA FOR ESTIMATING HEAT DETECTOR RESPONSE TIME

Activation Temperature $T_{activation}$

T= 128 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	490	128
15	306	128
20	325	128
25	152	128
30	116	128
40	87	128
50	72	128
70	44	128
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 135 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	404	135
15	233	135
20	165	135
25	123	135
30	98	135
40	70	135
50	54	135
70	20	135
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 145 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	321	145
15	191	145
20	129	145
25	96	145
30	75	145
40	50	145
50	37	145
70	11	145
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 160 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	239	160
15	135	160
20	86	160
25	59	160
30	44	160
40	22	160
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

10

Scroll to desired spacing then Click on selection

T= 170 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	196	170
15	109	170
20	64	170
25	39	170
30	27	170
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 196 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	119	196
15	55	196
20	21	196
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then

Click on selection

Reference: *NFPA Standard 72, National Fire Alarm Code, Appendix B, Table B-3.2.5.1, 1999, Edition.*

ESTIMATING FIXED TEMPERATURE HEAT DETECTOR 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 $t_{activation}$ = detector activation time (sec)

RTI = detector 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 detector (°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 detector (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\, Q$

Where Q_c = convective heat release rate (kW)

Q = heat release rate of the fire (kW)

χ_c = convective heat release fraction

Q_c = 700 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.63 r/H > 0.15

>0.15	131.35	<0.15	301.61

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

$T_{jet} - T_a =$ 131.35

$T_{jet} =$ 151.35 (°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 detector (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.63 r/H > 0.15

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

$u_{jet} =$ 2.143 m/sec

Detector Activation Time Calculation

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

$t_{activation} =$ 80.46 sec

The detector will respond in approximately 1.34 minutes Answer

NOTE: If $t_{activation}$ = "NUM" Detector 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.

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER

13.1 Objectives

This chapter has the following objectives:

- Explain the incipient stage of a fire.
- Characterize flashover and its stages.
- Describe how to predict the HRR required for flashover and post-flashover temperature in a compartment.

13.2 Introduction

Following ignition, a compartment fire experiences a slow growth period, which is often referred to as the "incipient stage." During this stage, all of the measurable fire parameters [heat release rate (HRR), rate of fuel or oxygen consumption, and temperature of the compartment gases] are low and increase at a low rate.

After the incipient stage, the fire begins to grow more rapidly, as in the parabolic fire growth curves described by the t^2 fires. (See Appendix B for details.) The HRR and rate of fuel/oxygen consumption also increase rapidly. This acceleration, in turn, also increases the compartment gas temperature. In an adequately ventilated compartment, the rate of air entering the compartment also increases. At some point in the history of a given fire, the rate of fire growth increases so rapidly that all combustibles in the compartment reach their ignition temperature and become involved in the combustion process and "flashover" is achieved. Flashover is a complex topic and a number of theories and calculation methods will be presented. Figure 13-1 illustrates of the post-flashover compartment fire in which the fire is assumed to be volumetric rather than point source.

At the high temperatures that occur in the gas layer of a post-flashover fire, significant radiative heat transfer occurs from the carbon dioxide gas, water vapor, and soot particles in the smoke. The gas layer and flames radiate to the floor, walls and ceiling, back to the fire and fuel sources, to any other objects that may be present in the compartment, and out through any openings in the enclosure. In addition, the heated walls, ceiling, and other heated objects are re-radiating heat back within the enclosure.

Often, a post-flashover fire may have significant fuel to continue burning, but the air entering the room may be limited. The fire, which might otherwise continue to grow if it were burning in unconfined space, enters a period where it is said to be "ventilation controlled," meaning that the fire ceases to grow because of a lack of oxygen. The rates of fuel consumption and heat release stall, and the compartment temperature ceases to climb as rapidly it did before flashover. These parameters may then begin to decrease slightly as a result of the less-than-stoichiometric air-fuel mixture. The fire may continue to decay until the air supply ratio become stoichiometric or greater, thereby allowing further fire growth. At this point, the fire may become "fuel-controlled," meaning the amount of available fuel (rather than the available air supply) dictates the rate of burning.

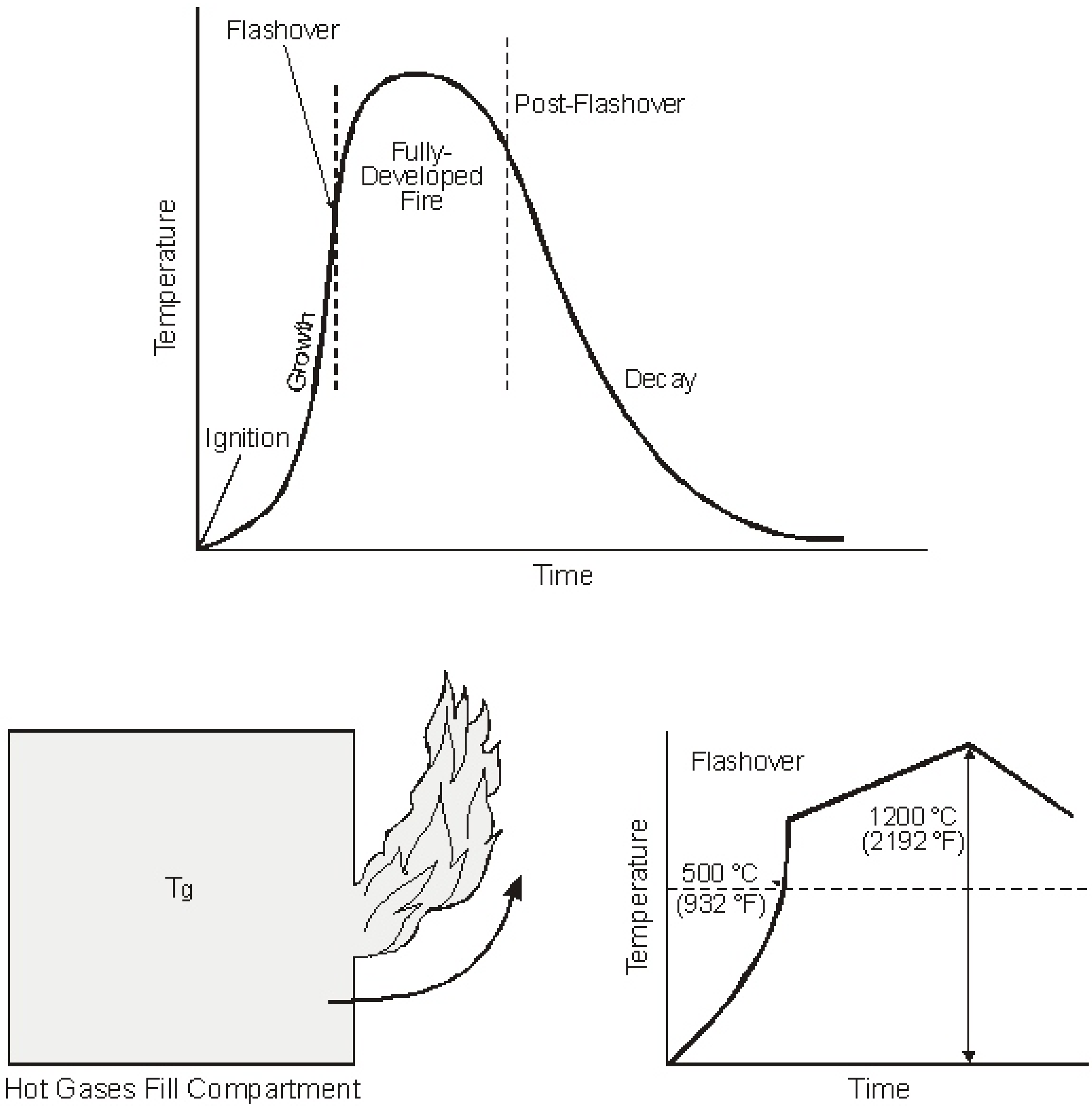


Figure 13-1 Flashover and Postflashover Compartment Fire

The fire may again grow to a ventilation controlled condition and continue in a transient state alternate between ventilation and fuel control throughout the remaining active burning period of the fire. It is during this post-flashover stage that the fire barrier system must function at its highest efficiency to contain the fire. Eventually, the fire will enter its final fuel-controlled state as the fuel is totally consumed and the fire decays to extinction.

Several physical processes may be described in order to characterize the event that is frequently referred to as flashover. Fire fighters generally recognize flashover as the condition characterized by emission of flames through the open doorway of a fire compartment. It is the transition from the fire growth stage to the fully developed stage in the development of a compartment fire that is stages demarcates pre-flashover and post-flashover. Flashover is the phenomenon that defines the point of time at which all combustibles in the compartment are involved in the fire and flames appear to fill the entire volume. Gas temperatures of 300 to 650 °C (572 to 1,202 °F) have been associated with the onset of flashover, although temperatures of 500 to 600 °C (932 to 1,112 °F) are more widely accepted.

The International Standards Organization (ISO), "Glossary of Fire Terms and Definitions" (ISO/CD 13943), defines "flashover" as "the rapid transition to a state of total surface involvement in a fire of combustion material within an enclosure," Flashover is the term given to the relatively abrupt change from a localized fire to the complete involvement of all combustibles within a compartment.

Flashover is described by four fire stages. The hot buoyant plume develops during the first stage following ignition, and then reaches the ceiling and spreads as a ceiling jet (second stage). During the third and fourth stages, the hot layer expands and deepens, and flow through the opening is established.

When a fire in a compartment is allowed to grow without intervention, temperatures in the hot upper layer increase, thereby increasing radiant heat flux to all objects in the room. If a critical level of heat flux is reached, all exposed combustible items in the room will begin to ignite and burn, leading to a rapid increase in both heat release rate and temperatures. This transition is called "flashover". The fire is then referred to as "post-flashover fire," a "fully developed fire," or a fire that has reached "full room involvement."

The above descriptions of flashover are somewhat general. In order to more clearly define the specific point at which flashover occurs, we must use some definite physical characteristics:

(1) Flashover is the time at which the temperature rise in the hot gas reaches 500 °C (932 °F). [600 °C (1112 °F) is sometimes also used to define flashover].

(2) Flashover is the time at which the radiant heat flux density at the floor of the compartment reaches a minimum value of 20 kW/m^2 throughout.

(3) Flashover may be defined in terms of the rate of heat release ($\dot{Q}_{FO}$) from the fire in comparison to the total area of the compartment enclosing surfaces (A_T), the area of any ventilation openings (A_v), and the height of any ventilation openings (H_v), is illustrated by the following expression:

$$\dot{Q}_{FO} \propto \sqrt{A_T A_v \sqrt{H_v}} \qquad (13\text{-}1)$$

The first definition, in terms of temperature of the ceiling layer, is based upon experimental observation. Some compartment fire tests define the flashover point as the time at which flames just begin to emerge through openings in the compartment. Examination of the empirical data from testing has shown that the flame emergence point generally corresponds to a ceiling layer temperature between 500 °C to 600 °F (932 °F to 1,112 °F).

The second definition of flashover is given in terms of heat flux at the floor of the compartment. In essence, this definition describes the heat flux that would be necessary to establish simultaneous ignition of most ordinary combustibles throughout the enclosure. A radiant heat flux density of 20 kW/m^2 is sufficient for piloted ignition of most ordinary combustibles. In most cases, a ceiling layer at 500 °C (932 °F) will radiate to the floor at a minimum rate of 20 kW/m^2 in a typical compartment.

The third definition, which correlates HRR and compartment geometries, is more descriptive and more useful for predicting the physical conditions that might be necessary to establish either of the criteria required by the first two definitions. While researchers use different definitions for the onset of flashover, they reach some level of agreement on the temperature and heat flux necessary for the onset of flashover.

Hägglund, Jannson, and Onnermark (1974) experimentally observed flames exiting the doorway when the gas temperature about 10 mm (0.40 in) below the ceiling reached 600 °C (1,112 °F). Babrauskas (1977) applied this criterion to a series of 10 full-scale mattress fires; however, only 2 exhibited a potential to flashover the test compartment. These two mattress fires led to maximum gas temperatures well in excess of 600 °C (1,112 °F), with flashover observed near that temperature. In experiments conducted in a full-scale compartment at the National Bureau of Standards (NBS), now the National Institute of Standards and Technology (NIST), Fang (1975) reported an average upper room temperature ranging from 450 to 650 °C (842 to 1,202 °F) provided sufficient a level of radiation transfer to result in the ignition of crumpled newspaper indicators at floor level in the compartment. The average upper room gas temperature necessary for spontaneous ignition of newsprint was 540 ± 40 °C (1,004 ± 104 °F). It should be noted that this average included low temperatures at the mid-height of the compartment, and that temperatures measured 25 mm (1 in.) below the ceiling in this test series usually exceeded 600 °C (1,112 °F).

Fang (1975) also found that strips of newspaper placed at floor level in room burn tests ignited by fluxes of 17 to 25 kW/m^2, while 6.4 mm (1/4 in.) thick fir plywood ignited at 21 to 33 kW/m^2. Lee and Breese (1979) reported average heat fluxes at floor level of 17 to 30 kW/m^2 at flashover for full-scale tests of submarine compartments.

The NFPA 555 "Guide on Methods for Evaluating Potential for Room Flashover," (NFPA 555) define as room flashover in terms of temperature rise and heat flux at floor level. According to the NFPA guide, a gas temperature rise at flashover of 600 °C (1,112 °F) is a reasonable expectation, as is heat flux 20 kW/m^2 at floor level at flashover.

13.3 Compartment Flashover

Researchers have extensively studied the minimum HRR needed to cause flashover in a compartment. The studies suggest that minimum rate increases with the size of the compartment and depends, in a complex way, on the ventilation in the compartment. If there is too little ventilation, flashover cannot occur. If there is an excessive amount of ventilation, the excess air flow dilutes and cools the smoke, so a larger HRR is needed to reach the critical temperature condition for flashover. The construction materials and thickness of the ceiling and upper walls are also important factors in determining whether flashover will occur. These factors also determine the time required for flashover in a compartment that does reach the critical temperature.

Researchers have used several approaches to estimate the onset of flashover within a compartment. These approaches are typically based on simplified mass and energy balances in a single-compartment fire along with correlations to fire experiments. Visually, researchers report flashover as a discrete event in full-scale fire tests and actual fire incidents. Numerous variables can affect the transition of a compartment fire to flashover. Thermal influences are clearly important where radiative and convective heat flux are assumed to be driving forces. Ventilation conditions, compartment volume, and chemistry of the hot gas layer can also influence the occurrence of flashover. Rapid transition to flashover adds to the uncertainty of attempts to quantify the onset of flashover with laboratory measurements.

Although the flashover process is not easy to quantify in terms of measurable physical parameters, a working definition can be formulated from the considerable body of flashover-related full-scale fire test data accumulated from a variety of sources.

13.3.1 Method of Predicting Compartment Flashover HRR

The occurrence of flashover within a compartment is the ultimate signal of untenable conditions within the compartment of fire origin as well as a sign of greatly increased risk to other compartments within the structure. A number of experimental studies of full-scale fire have been performed provide simple correlations to predict HRR required for flashover.

13.3.1.1 Method of McCaffrey, Quintiere, and Harkleroad (MQH)

McCaffrey, Quintiere, and Harkleroad (1981) found that their data for predicting compartment hot gas temperature may extend to predict the HRR required to result in flashover in the compartment and obtained the following expression:

$$\dot{Q}_{FO} = 610 \sqrt{h_k A_T A_v \sqrt{h_v}} \qquad (13\text{-}2)$$

Where:

$\dot{Q}_{FO}$ = heat release rate to cause flashover (kW)
h_k = effective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surfaces (m^2), excluding area of vent opening
A_v = area of the ventilation openings (m^2)
h_v = height of the ventilation openings (m)

13.3.1.2 Method of Babrauskas

Babrauskas (1980) developed a simplified relationship that represent values correlated to experiments produce flashover. Based on the 33 compartment fire tests with HRR range from 11 to 3,840 kW with fuels primarily of wood and polyurethane, Babrauskas found that the HRR required to cause flashover is describe by the following relation:

$$\dot{Q}_{FO} = 750 \ A_v \sqrt{h_v} \quad (13\text{-}3)$$

Where:

$\dot{Q}_{FO}$ = heat release rate to cause flashover (kW)
A_v = area of the ventilation openings (m^2)
h_v = height of the ventilation openings (m)

Equation 13-3 is an extremely simply and easy to use relation, though it does not take into account the area and thermal properties of compartment enclosing surfaces.

13.3.1.3 Method of Thomas

Thomas (1981) (also reported by Walton and Thomas, 1995) developed a semi-empirical calculation of the HRR required to cause flashover in a compartment. He presented a simple model of flashover in a compartment, which he used to study the influence of wall-lining materials and thermal feedback to the burning items. He predicted a temperature rise of 520 °C (968 °F) and a black body radiation level of 22 kW/m^2 to an ambient surface away from the neighborhood of burning wood fuel at the predicted critical heat release rate necessary to cause flashover. Thomas' flashover is the result of simplifications applied to an energy balance of a compartment fire. The resulting correlation yields the minimum HRR for flashover:

$$\dot{Q}_{FO} = 7.8 A_T + 378 A_v \sqrt{h_v} \quad (13\text{-}4)$$

Where:

$\dot{Q}_{FO}$ = heat release rate to cause flashover (kW)
A_T = total area of the compartment enclosing surfaces (m^2), excluding area of vent opening
A_v = area of the ventilation openings (m^2)
h_v = height of the ventilation openings (m)

The constants in Equation 13-4 represent values derived from experiments producing flashover. This correlation assumes that conduction has become stationary. The thermal penetration time is long for compartments with thick concrete walls, and it is unlikely that a fire slowly and gradually grows up to Q_{FO} in a number of hours. A reasonable time frame for estimating the likelihood of flashover is in the range of a few minutes up to around 30 minutes. We note that firefighter reaction time is usually also within this range (Karlsson and Quintiere, 1999).

13.3.2 Method of Predicting Compartment Post-Flashover Temperature

After flashover has occurred, the exposed surfaces of all combustibles items in the compartment will be burning and the HRR will developed to a maximum, producing high temperatures (see Figure 13-1). Typically, this may be as high as 1,100 °C (2,012 °F), but much higher temperatures can be obtained under certain conditions[1] (Drysdale, 1998). These will be maintained until the rate of generation of flammable volatile begins to decrease as a result of fuel consumption. It is during the period of the fully developed fire that building elements may reach temperatures at which they may fail.

Thomas (1974) developed an approach to estimate peak compartment temperature based on post-flashover enclosure fire data. Law (1978) extended this approach to include both natural and forced ventilation through the evaluation of extensive pre-flashover compartment fire test data. The results indicate that the predictions reasonably, but not exactly, predict the temperatures reported in the test fires.

Drawing on data gathered in the Conseil Internationale du Batiment (CIB) Research Program of fully developed compartment fires Thomas (1974) and Law (1978) found following correlation to predict post-flashover compartment temperature with natural ventilation:

$$T_{FO(max)} = 6000 \; \frac{\left(1 - e^{-0.1\Omega}\right)}{\sqrt{\Omega}} \qquad (13\text{-}5)$$

$$\Omega = \frac{A_T - A_v}{A_v\sqrt{h_v}} \qquad (13\text{-}6)$$

Where:

$\dot{Q}_{FO}$ = heat release rate to cause flashover (kW)
 = ventilation factor
A_T = total area of the compartment enclosing surfaces (m^2), excluding area of vent opening
A_v = area of the ventilation openings (m^2)
h_v = height of the ventilation openings (m)

Note that Equation 13-5 does not consider variations in the thermophysical properties of compartment enclosing surfaces.

---

[1]We occasionally encounter temperatures in excess of 1300–1400 °C (2,372–2,552 °F), which is sufficient to cause the surface of bricks to fuse (melt). For example, the Summit Rail Tunnel Fire (Department of Transport, 1984) produced sufficiently high temperatures to cause the faces of brick-lined ventilation shafts to fuse.

13.4 Fire Severity

Fires burn with differing intensities and produce significant spatial variability in terms of severity. The fundamental step in designing structures (fire barriers) for fire safety is to verify that the fire resistance of the structure (or each part of the structure is greater than the severity of the fire to which the structure is exposed. The verification requires that the following condition be satisfied:

$$\text{FireResistance} \geq \text{FireSeverity}$$

Where fire resistance is measure of the ability of the structure to resist collapse, fire spread or other failure during exposure to a fire of specified severity, and fire severity is a measure of the potential destructive impact of the burnout of all the available fuel in a compartment (Buchanan, 2001) most often it defined in terms of a period of exposure to the standard test fire.

Damage to a structure is largely dependent on the amount of heat absorbed by the structural elements. Heat transfer from post-flashover fires is primarily radiative which is proportional to the forth power of the absolute temperature. Hence, the severity of a fire is largely dependent on the temperatures reached and the duration of the high temperatures.

13.4.1 Method of Margaret Law

Law (1974) developed a correlation to predict fire severity (duration) based on data developed through an international research program. The fire severity correlation predicts the potential impact of a pos-flashover fire in terms of equivalent exposure in a fire endurance furnace fired to follow the European equivalent standard similar to ASTM E119 and NFPA 251.

The fire severity of available fuel load in a compartment with at least one opening can be estimated from the following equation:

$$t_f = \frac{K L_{eq}}{\left(A_v A_T\right)^{\frac{1}{2}}} \qquad (13\text{-}7)$$

Where:

t_f = fire severity or duration (sec)
K = correlational constant
L_{eq} = total fire or fuel load in equivalent of wood (kg)
A_v = area of ventilation opening (m^2)
A_T= total area of the compartment enclosing boundaries excluding area of vent opening (m^2)

Total fire or fuel load in compartment equivalent of wood with a given mass if given by:

$$L_{eq} = \frac{LDH_c}{DH_{c,wood}} \qquad (13\text{-}8)$$

Where:

L_{eq} = total fire or fuel load in equivalent of wood (kg)
L = total fire or fuel load in compartment (kg)
H_c = effective heat of combustion (kJ/kg)
$H_{c,\ wood}$ = wood heat of combustion (kJ/kg)

The compartment interior surface area can be calculated as follows:

A_T = ceiling + floor 2 (w_c x l_c)
+ 2 large walls 2 (h_c x w_c)
+ 2 small walls 2 (h_c x l_c)
- total area of vent opening(s) (A_0)

$$A_T = [2\ (w_c \text{ x } l_c) + 2\ (h_c \text{ x } w_c) + 2\ (h_c \text{ x } l_c)] - A_v \qquad (13\text{-}9)$$

Where:

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

The total area of ventilation opening is given by:

$$A_v = w_v \text{ x } h_v \qquad (13\text{-}10)$$

Where:

A_v = total area of ventilation opening(s) (m^2)
w_v = vent width (m)
h_v = vent height (m)

13.5 Assumptions and Limitations

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

(1) The correlations were developed from a simplified mass and energy balance on a single compartment with ventilation openings.

(2) The experimental data used to develop the correlation included compartments with thermally thick walls and fires of wood cribs. Typically, heat transfer through compartment surfaces is accounted for with a semi-infinite solid approximation.

(3) The fire severity correlation is not appropriate for compartment that do not have openings for ventilation. While no precise minimum can be stated, it is suggested that this method not be used unless the size of the opening is at least 0.4 m^2 (4 ft^2).

13.6 Required Input for Spreadsheet Calculations

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

(1) compartment width (ft)

(2) compartment length (ft)

(3) compartment height (ft)

(4) vent width (ft)

(5) vent height (ft)

13.7 Cautions

(1) Use spreadsheet (13_Compartment_ Flashover_Calculations.xls) on the CD-ROM for calculations.

(2) Make sure input parameters are recorded in the correct units.

13.8 Summary

Flashover is a complex topic. Determination of temperatures associated with compartment fires provides a means of assessing the likelihood of the occurrence of flashover. Danger of flashover is assumed to occur if the analysis indicates a smoke layer temperature in excess of 450 °C (842 °F). Typically, flashover occurs when the smoke layer temperature reaches between 500 °C (932 °F) and 600 °F (1,112 °F). Hot smoke layers are considered to be close to black body radiators. At 450 °C (842 °F) the radiation from the smoke would be approximately 15 kW/m^2 (1.32 Btu/ft^2-sec). Temperatures above the 450 °C (842 °F) level generate a higher incident heat flux on the burning fuel in a compartment than if the fire were in the open.

13.9 References

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13.10 Problems

Example Problem 13.10-1

Problem Statement
Consider a compartment 20 ft wide x 25 ft long x 12 ft high (w_c x l_c x h_c), with an opening 3 ft wide and 8 ft high (w_v x h_v). The interior lining material of the compartment is 6 in. concrete. Calculate the HRR necessary for flashover, $\dot{Q}_{FO}$, and the post-flashover compartment temperature, T_{PFO}.

Solution

Purpose:
(1) Determine the heat release rate for flashover for the given compartment.

Assumptions:
(1) Natural Ventilation

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 13_Compartment_Flashover_Calculations.xls
(click on *Post_Flashover_Temperature* to calculate the post-flashover temperature)
(click on *Flashover-HRR* to calculate the HRR for flashover)

FDT^s Input Parameters:
-Compartment Width (w_c) = 20 ft
-Compartment Length (l_c) = 25 ft
-Compartment Height (h_c) = 12 ft
-Vent Width (w_v) = 3 ft
-Vent Height (h_v) = 8 ft
-Interior Lining Thickness (δ) = 6 in. (*Flashover-HRR only*)
-Select Material: **Concrete** (*Flashover-HRR only*)

Results*

Post-Flashover Compartment Temperature (T_{PFO}) °C (°F)	HRR for Flashover ($\dot{Q}_{FO}$) (kW)		
Method of Law	Method of MQH	Method of Brabauskas	Method of Thomas
811 (1,492)	1,612	2,611	2,806

*see spreadsheet on next page

Spreadsheet Calculations

(a) FDT^s: 13_Compartment_Flashover_Calculations.xls (Post_Flashover_Temperature)

CHAPTER 13. PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE

Version 1805.0

The following calculations estimate the compartment post-flashover temperature.
Parameters in YELLOW CELLS are Entered by the User.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	8.00	ft	2.438 m

Calculate

PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
METHOD OF MARGARET LAW

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-183.*

$T_{PFO\,(max)} = 6000\,(1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

Where $T_{PFO\,(max)}$ = maximum compartment post-flashover temperature (°C)
Ω = ventilation factor

Where $\Omega = (A_T - A_v) / A_v (\sqrt{h_v})$
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Area of Ventilation Opening Calculation

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

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

A_v = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

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

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 191.01 m^2

Ventilation Factor Calculation

$\Omega = (A_T - A_v) / A_v (vh_v)$

Where Ω = ventilation factor

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

A_v = area of ventilation opening (m^2)

h_v = vent height (m)

Ω = 54.22 $m^{-1/2}$

Compartment Post-Flashover Temperature Calculation

$T_{PFO\,(max)} = 6000 (1 - e^{-0.1\Omega}) / (v\Omega)$

$T_{PFO\,(max)}$ =	811.24 °C	1492.23 °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 spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT^s: 13_Compartment_Flashover_Calculations.xls (Flashover_HRR)

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER HEAT RELEASE RATE

Version 1805.0

The following calculations estimate the minimum heat release rate required to compartment flashover.

Parameters in YELLOW CELLS are Entered by the User.

Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	3.00	ft	0.9144 m
Vent Height (h_v)	8.00	ft	2.4384 m
Interior Lining Thickness (δ)	6.00	in	0.1524 m
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

Material	Thermal Conductivity k (kW/m-K)
Aluminum (pure)	0.206
Steel (0.5% Carbon)	0.054
Concrete	0.0016
Brick	0.0008
Glass, Plate	0.00076
Brick/Concrete Block	0.00073
Gypsum Board	0.00017
Plywood	0.00012
Fiber Insulation Board	0.00053
Chipboard	0.00015
Aerated Concrete	0.00026
Plasterboard	0.00016
Calcium Silicate Board	0.00013
Alumina Silicate Block	0.00014
Glass Fiber Insulation	0.000037
Expanded Polystyrene	0.000034
User Specified Value	Enter Value

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

Select Material

Concrete

Scroll to desired material then Click on selection

PREDICTING FLASHOVER HEAT RELEASE RATE
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 610 \sqrt{(h_k A_T A_v \sqrt{h_v})}$

Where Q_{FO} = heat release rate necessary for flashover (kW)
h_k = effective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Heat Transfer Coefficient Calculation

$h_k = k/\delta$ Assuming that compartment has been heated thoroughly before flashover, i.e., $t > t_p$.

Where h_k = effective heat transfer coefficient (kW/m^2-K)
k = interior lining thermal conductivity (kW/m-K)
δ = interior lining thickness (m)

h_k = 0.010 kW/m^2-K

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

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

A_v = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

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

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 191.01 m^2

Minimum Heat Release Rate for Flashover

$Q_{FO} = 610 \sqrt{(h_k A_T A_v \sqrt{h_v})}$

Q_{FO} = 1611.84 kW	Answer

METHOD OF BABRAUSKAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 750 A_v \sqrt{h_v}$

Where Q_{FO} = heat release rate necessary for flashover (kW)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 750 A_v \sqrt{h_v}$

Q_{FO} = 2611.29 kW	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 7.8 A_T + 378 A_V (\sqrt{h_V})$

Where

Q_{FO} = heat release rate necessary for flashover (kW)

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

A_V = area of ventilation opening (m^2)

h_V = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 7.8 A_T + 378 A_V (\sqrt{h_V})$

Q_{FO} = 2805.96 kW **Answer**

Summary of Result

Calculation Method	Flashover HRR (kW)
METHOD OF MQH	1612
METHOD OF BABRAUSKAS	2611
METHOD OF THOMAS	2806

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 spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 13.10-2

Problem Statement

Consider a compartment 20 ft wide x 25 ft long x 12 ft high (w_c x l_c x h_c), with an opening 3 ft wide and 8 ft high (w_v x h_v). The interior lining material of the compartment is 5/8 in. gypsum. Calculate the HRR necessary for flashover, $\dot{Q}_{FO}$, and the post-flashover compartment temperature, T_{PFO}.

Solution

Purpose:

(1) Determine the heat release rate for flashover for the given compartment.

Assumptions:

(1) Natural Ventilation

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 13_Compartment_Flashover_Calculations.xls

(click on *Post_Flashover_Temperature* to calculate the post-flashover temperature)

(click on *Flashover-HRR* to calculate the HRR for flashover)

FDT^s Input Parameters:

-Compartment Width (w_c) = 20 ft
-Compartment Length (l_c) = 25 ft
-Compartment Height (h_c) = 12 ft
-Vent Width (w_v) = 3 ft
-Vent Height (h_v) = 8 ft
-Interior Lining Thickness (δ) = .63 in. (*Flashover-HRR only*)
-Select Material: **Gypsum Board** (*Flashover-HRR only*)

Results*

Post-Flashover Compartment Temperature (T_{PFO}) °C (°F)	HRR for Flashover $(\dot{Q}_{FO})$ (kW)		
Method of Law	Method of MQH	Method of Brabauskas	Method of Thomas
811 (1,492)	1,621	2,611	2,806

*see spreadsheet on next page

Spreadsheet Calculations

(a) FDT^s: 13_Compartment_Flashover_Calculations.xls (Post_Flashover_Temperature)

CHAPTER 13. PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE

Version 1805.0

The following calculations estimate the compartment post-flashover temperature.
Parameters in YELLOW CELLS are Entered by the User.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	8.00	ft	2.438 m

Calculate

PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
METHOD OF MARGARET LAW

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-183.*

$T_{PFO\,(max)} = 6000\,(1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

Where $T_{PFO\,(max)}$ = maximum compartment post-flashover temperature (°C)
Ω = ventilation factor

Where $\Omega = (A_T - A_v) / A_v (\sqrt{h_v})$
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Area of Ventilation Opening Calculation

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

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

A_v = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

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

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 191.01 m^2

Ventilation Factor Calculation

$\Omega = (A_T - A_v) / A_v (\sqrt{h_v})$

Where Ω = ventilation factor

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

A_v = area of ventilation opening (m^2)

h_v = vent height (m)

Ω = 54.22 $m^{-1/2}$

Compartment Post-Flashover Temperature Calculation

$T_{PFO\,(max)} = 6000\,(1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

$T_{PFO\,(max)}$ =	811.24 °C	1492.23 °F

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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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 spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT^s: 13_Compartment_Flashover_Calculations.xls (Flashover_HRR)

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER HEAT RELEASE RATE

Version 1805.0

The following calculations estimate the minimum heat release rate required to compartment flashover.

Parameters in YELLOW CELLS are Entered by the User.

Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	8.00	ft	2.44 m
Interior Lining Thickness (δ)	0.63	in	0.016002 m
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

Material	Thermal Conductivity k (kW/m-K)
Aluminum (pure)	0.206
Steel (0.5% Carbon)	0.054
Concrete	0.0016
Brick	0.0008
Glass, Plate	0.00076
Brick/Concrete Block	0.00073
Gypsum Board	0.00017
Plywood	0.00012
Fiber Insulation Board	0.00053
Chipboard	0.00015
Aerated Concrete	0.00026
Plasterboard	0.00016
Calcium Silicate Board	0.00013
Alumina Silicate Block	0.00014
Glass Fiber Insulation	0.000037
Expanded Polystyrene	0.000034
User Specified Value	Enter Value

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

Select Material

Gypsum Board

Scroll to desired material then Click on selection

PREDICTING FLASHOVER HEAT RELEASE RATE
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 610 \sqrt{(h_k A_T A_v (\sqrt{h_v}))}$

Where Q_{FO} = heat release rate necessary for flashover (kW)
h_k = effective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Heat Transfer Coefficient Calculation

$h_k = k/\delta$ Assuming that compartment has been heated thoroughly before flashover, i.e., $t > t_p$.

Where h_k = effective heat transfer coefficient (kW/m^2-K)
k = interior lining thermal conductivity (kW/m-K)
δ = interior lining thickness (m)

h_k = 0.011 kW/m^2-K

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

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

A_v = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

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

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 191.01 m^2

Minimum Heat Release Rate for Flashover

$Q_{FO} = 610 \sqrt{(h_k A_T A_v (\sqrt{h_v}))}$

Q_{FO} = 1621.40 kW	Answer

METHOD OF BABRAUSKAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 750 A_v (\sqrt{h_v})$

Where Q_{FO} = heat release rate necessary for flashover (kW)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 750 A_v (\sqrt{h_v})$

Q_{FO} = 2611.29 kW	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (\sqrt{h_v})$

Where Q_{FO} = heat release rate necessary for flashover (kW)

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

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (\sqrt{h_v})$

Q_{FO} =	2805.96 kW	Answer

Summary of Result

Calculation Method	Flashover HRR (kW)
METHOD OF MQH	1621
METHOD OF BABRAUSKAS	2611
METHOD OF THOMAS	2806

NOTE

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Example Problem 13.10-3

Problem Statement
Consider a compartment 20 ft wide x 25 ft long x 12 ft high (w_c x l_c x h_c), with an opening 6 ft wide and 8 ft high (w_v x h_v). The interior lining material of the compartment is 6 in. concrete. Calculate the HRR necessary for flashover, $\dot{Q}_{FO}$, and the post-flashover compartment temperature, T_{PFO}.

Solution

Purpose:
(1) Determine the heat release rate for flashover for the given compartment.

Assumptions:
(1) Natural Ventilation

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 13.1_Compartment_Flashover_Calculations.xls
(click on *Post_Flashover_Temperature* to calculate the post-flashover temperature)
(click on *Flashover-HRR* to calculate the HRR for flashover)

FDT^s Input Parameters:
-Compartment Width (w_c) = 20 ft
-Compartment Length (l_c) = 25 ft
-Compartment Height (h_c) = 12 ft
-Vent Width (w_v) = 6 ft
-Vent Height (h_v) = 8 ft
-Interior Lining Thickness (δ) = 6 in. (*Flashover-HRR only*)
-Select Material: **Concrete** (*Flashover-HRR only*)

Results*

Post-Flashover Compartment Temperature (T_{PFO}) °C (°F)	HRR for Flashover ($\dot{Q}_{FO}$) (kW)		
Method of Law	Method of MQH	Method of Brabauskas	Method of Thomas
1084 (1,982)	2,266	5,223	4,105

*see spreadsheet on next page

Spreadsheet Calculations

(a) FDT^s: 13_Compartment_Flashover_Calculations.xls (Post_Flashover_Temperature)

CHAPTER 13. PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
Version 1805.0

The following calculations estimate the compartment post-flashover temperature.
Parameters in YELLOW CELLS are Entered by the User.
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The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	6.00	ft	1.829 m
Vent Height (h_v)	8.00	ft	2.438 m

Calculate

PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
METHOD OF MARGARET LAW

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-183.

$T_{PFO\,(max)} = 6000\,(1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

Where $T_{PFO\,(max)}$ = maximum compartment post-flashover temperature (°C)
Ω = ventilation factor

Where $\Omega = (A_T - A_v) / A_v\,(\sqrt{h_v})$
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Area of Ventilation Opening Calculation

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

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

A_v = 4.46 m^2

Area of Compartment Enclosing Surface Boundaries

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

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 188.78 m^2

Ventilation Factor Calculation

$\Omega = (A_T - A_V) / A_V (\sqrt{h_V})$

Where Ω = ventilation factor

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

A_V = area of ventilation opening (m^2)

h_V = vent height (m)

Ω = 26.47 $m^{-1/2}$

Compartment Post-Flashover Temperature Calculation

$T_{PFO\,(max)} = 6000 (1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

$T_{PFO\,(max)}$ =	1083.57 °C	1982.42 °F

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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(b) FDT^s: 13_Compartment_Flashover_Calculations.xls (Flashover_HRR)

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER HEAT RELEASE RATE
Version 1805.0

The following calculations estimate the minimum heat release rate required to compartment flashover.

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).
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INPUT PARAMETERS
COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	6.00	ft	1.829 m
Vent Height (h_v)	8.00	ft	2.44 m
Interior Lining Thickness (δ)	6.00	in	0.1524 m
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

Material	Thermal Conductivity k (kW/m-K)
Aluminum (pure)	0.206
Steel (0.5% Carbon)	0.054
Concrete	0.0016
Brick	0.0008
Glass Plate	0.00076
Brick/Concrete Block	0.00073
Gypsum Board	0.00017
Plywood	0.00012
Fiber Insulation Board	0.00053
Chipboard	0.00015
Aerated Concrete	0.00026
Plasterboard	0.00016
Calcium Silicate Board	0.00013
Alumina Silicate Block	0.00014
Glass Fiber Insulation	0.000037
Expanded Polystyrene	0.000034
User Specified Value	Enter Value

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

Select Material

Concrete

Scroll to desired material then Click on selection

PREDICTING FLASHOVER HEAT RELEASE RATE
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_v\ (\sqrt{h_v}))}$

Where Q_{FO} = heat release rate necessary for flashover (kW)
h_k = effective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Heat Transfer Coefficient Calculation

$h_k = k/\delta$ Assuming that compartment has been heated thoroughly before flashover, i.e., $t > t_p$.

Where h_k = effective heat transfer coefficient (kW/m^2-K)
k = interior lining thermal conductivity (kW/m-K)
δ = interior lining thickness (m)

h_k = 0.010 kW/m^2-K

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

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

A_v = 4.46 m^2

Area of Compartment Enclosing Surface Boundaries

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

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 188.78 m^2

Minimum Heat Release Rate for Flashover

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_v\ (\sqrt{h_v}))}$

Q_{FO} =	2266.14 kW	Answer

METHOD OF BABRAUSKAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 750\ A_v\ (\sqrt{h_v})$

Where Q_{FO} = heat release rate necessary for flashover (kW)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 750\ A_v\ (\sqrt{h_v})$

Q_{FO} =	5222.58 kW	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 7.8\, A_T + 378\, A_v (\sqrt{h_v})$

Where Q_{FO} = heat release rate necessary for flashover (kW)

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

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 7.8\, A_T + 378\, A_v (\sqrt{h_v})$

Q_{FO} = 4104.66 kW **Answer**

Summary of Result

Calculation Method	Flashover HRR (kW)
METHOD OF MQH	2266
METHOD OF BABRAUSKAS	5223
METHOD OF THOMAS	4105

NOTE

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