PDHonline Course M312 (4 PDH)

Fire Dynamics Series: Estimating Fire Flame Height and Radiant Heat Flux From Fire

Instructor: Lawrence J. Marchetti, PE, CFPS

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
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CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL

5.1 Objectives

This chapter has the following objectives:

- Introduce the three modes of heat transfer.
- Explain how to calculate the heat flux from a flame to a target outside the flame.
- Discuss point source radiation models and solid flame radiation models.
- Identify the difference between solid flame radiation models at ground level and solid flame radiation models above ground level with and without wind.
- Define relevant terms, including, conduction, convection, radiation, heat flux, emissive power, and configuration factor.

5.2 Introduction

Fire normally grows and spreads by direct burning, which results from impingement of the flame on combustible materials, or from heat transfer to other combustibles by means of conduction, convection, or radiation. All three of these modes of heat transfer may be significant, depending on the specifics of a given fire scenario. Conduction is particularly important in allowing heat to pass through a solid barrier (e.g., fire wall) to ignite material on the other side. Nevertheless, most of the heat transfer in fires typically occurs by means of convection and/or radiation. In fact, it is estimated that in most fires, approximate 70-percent of the heat emanates by convection (heat transfer through a moving gas or liquid). Consider, for example, a scenario in which a fire produces hot gas which is less dense than the surrounding air. This hot gas then rises, carrying heat. The hot products of combustion rising from a fire typically have a temperature in the range of 800–1,200 °C (1,472–2,192 °F) and a density that is one-quarter that of ambient air. In the third mode of heat transfer, known as radiation, radiated heat is transferred directly to nearby objects. One type of radiation, known as thermal radiation, is the significant mode of heat transfer for situations in which a target is located laterally to the exposure fire source. This would be the case, for example, for a floor-based fire adjacent to an electrical cabinet or a vertical cable tray in a large compartment. Thermal radiation is electromagnetic energy occurring in wavelengths from 2 to 16 m (infrared). It is the net result of radiation emitted by the radiating substances such as water (H_2O), carbon dioxide (CO_2), and soot in the flame.

Chapter 2 discussed various methods of predicting the temperature of the hot gas layer and the height of the smoke layer in a room fire with natural or forced ventilation. However, those methods are not applicable when analyzing a fire scenario in a very large open space or compartment. In large spaces, such as the reactor building in a boiling water reactor (BWR) or an open space in a turbine building, the volume of the space is too large for a uniform hot gas layer to accumulate. For such scenarios, fire protection engineers must analyze other forms of heat transfer, such as radiation. A floor-mounted electrical cabinet is an example of a ground-level target. A typical target above ground level is an overhead cable tray.

5.3 Critical Heat Flux to a Target

Radiation from a flame, or any hot gas, is driven by its temperature and emissivity. The emissivity is a measure of how well the hot gas emits thermal radiation (emissivity is defined as the ratio of radiant energy emitted by a surface to that emitted by a black body of the same temperature). Emmisivity is reported as a value between 0 and 1, with 1 being a perfect radiator. The radiation that an observer feels is affected by the flame temperature and size (height) of the flame.

The incident heat flux (the rate of heat transfer per unit area that is normal to the direction of heat flow. It is a total of heat transmitted by radiation, conduction, and convection) required to raise the surface of a target to a critical temperature is termed the critical heat flux. Measured critical heat flux levels for representative cable samples typically range from 15 to 25 kW/m^2 (1.32 to 2.2 Btu/ft^2-sec). For screening purposes, it is appropriate to use value of 10 kW/m^2 (0.88 Btu/ft^2-sec) for IEEE-383 qualified cable and 5 kW/m^2 (0.44 Btu/ft^2-sec) for IEEE-383 unqualified cable. These values are consistent with selected damage temperatures for both types of cables based on the Electrical Power Research Institute (EPRI), "Fire-Induced Vulnerability Evaluation (FIVE)," methodology.

Researchers have developed numerous methods to calculate the heat flux from a flame to a target located outside the flame. Flames have been represented by cylinders, cones, planes, and point sources in an attempt to evaluate the effective configuration factors[1] between the flame and the target. Available predictive methods range from those that are very simple to others that are very complex and involve correlations, detailed solutions to the equations of radiative heat transfer, and computational fluid mechanics. Routine FHAs are most often performed using correlationally based approaches, because of the limited goals of the analyses and the limited resources available for routine evaluation. As a result of their widespread use, a great deal of effort has gone into the development of these methods. Burning rates, flame heights, and radiative heat fluxes are routinely predicted using these approaches.

Fire involving flammable and combustible liquids typically have higher heat release rates (for the same area of fuel involved) than ordinary combustibles fires. The flame from a liquid fire is typically taller, making it a better radiator. Hydrocarbon liquid fires are also quite luminous because of the quantity of soot in the flames. Sooty fires are better emitters of thermal radiation. Thus, an observer approaching a flammable/combustible liquid fire feels more heat than an observer approaching an ordinary combustibles fire of comparable size.

The methods presented in this chapter are drawn from the *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, which examines the accuracy of these methods by comparisons with available experimental data (these methods also presented in the SFPE Engineering Guide, "Assessing Flame Radiation to External Targets from Pool Fires," June 1999).

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1 The configuration factor is a purely geometric quantity, which gives the fraction of the radiation leaving one surface that strikes another surface directly.

5.3.1 Point Source Radiation Model

A point source estimate of radiant flux is conceptually the simplest representation configurational model of a radiant source used in calculating the heat flux from a flame to target located outside the flame. To predict the thermal radiation field of flames, it is customary to model the flame based on the point source located at the center of a flame[2]. The point source model provides a simple relationship that varies as the inverse square of the distance, R. For an actual point source of radiation or a spherical source of radiation, the distance R is simply the distance from the point or from the center of the sphere to the target.

The thermal radiation hazard from a fire depends on a number of parameters, including the composition of the fuel, the size and the shape of the fire, its duration, proximity to the object at risk, and thermal characteristics of the object exposed to the fire. The point source method may be used for either fixed or transient combustibles. They may involve an electrical cabinet, pump, liquid spill, or intervening combustible at some elevation above the floor. For example, the top of a switchgear or motor control center (MCC) cabinet is a potential location for the point source of a postulated fire in this type of equipment. By contrast, the point source of a transient combustible liquid spill or pump fire is at the floor.

The point source model assumes that radiant energy is released at a point located at the center of the fire. The radiant heat flux at any distance from the source fire is inversely related to the horizontal separation distance (R), by the following equation (Drysdale, 1998):

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi R^2} \qquad (5\text{-}1)$$

Where:

- $\dot{q}''$ = radiant heat flux (kW/m^2)
- $\dot{Q}$ = heat release rate of the fire (kW)
- R = radial distance from the center of the flame to the edge of the target (m)
- $_r$ = fraction of total energy radiated

In general, $_r$ depends on the fuel, flame size, and flame configuration, and can vary from approximately 0.15 for low-sooting fuels (e.g., alcohol) to 0.60 for high sooting fuels (e.g., hydrocarbons). For large fires (several meters in diameter), cold soot enveloping the luminous flames can reduce $_r$ considerably. See Figure 5-1 for a graphic representation of the relevant nomenclature.

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[2] More realistic radiator shapes give rise to very complex configuration factor equations.

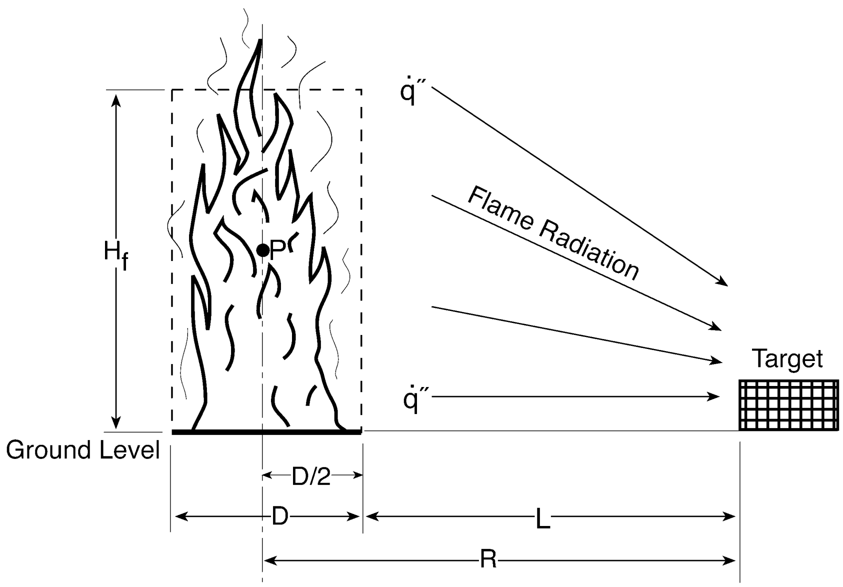

Figure 5-1 Radiant Heat Flux from a Pool Fire
to a Floor-Based Target Fuel (Point Source Model)

The HRR of a fire can be determined by laboratory or field testing. In the absence of experimental data, the maximum HRR for the fire $(\dot{Q})$, is given by the following equation (Babrauskas, 1995):

$$\dot{Q} = \dot{m}'' \Delta H_{c,eff} A_f (1 - e^{-k\beta D}) \tag{5-2}$$

Where:

$\dot{Q}$ = heat release rate of the fire (kW)
$\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)
$H_{c,eff}$ = effective heat of combustion (kJ/kg)
A_f = horizontal burning area of the fuel (m^2)
$k\beta$= empirical constant (m^{-1})
D = diameter of burning area (m)

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

$$D = \sqrt{\frac{4A_f}{\pi}} \tag{5-3}$$

Where:

A_f = surface area of the non-circular pool (m^2)
D = diameter of the fire (m)

5.3.2 Solid Flame Radiation Model with Target At and Above Ground Level

The solid flame spreadsheet associated with this chapter provides a detailed method for assessing the impact of radiation from pool fires to potential targets using configuration factor algebra. This method covers a range of detailed calculations, some of which are most appropriate for first order initial hazard assessments, while others are capable of more accurate predictions.

The solid flame model assumes that, (1) the fire can be represented by a solid body of a simple geometrical shape, (2) thermal radiation is emitted from its surface, and, (3) non-visible gases do not emit much radiation. (See Figures 5-2 and 5-3 for general nomenclature.) To ensure that the fire volume is not neglected, the model must account for the volume because a portion of the fire may be obscured as seen from the target. The intensity of thermal radiation from the pool fire to an element outside the flame envelope for no-wind conditions and for windblown flames is given by the following equation (Beyler, 2002):

$$\dot{q}'' = EF_{1\rightarrow 2} \tag{5-4}$$

Where:

$\dot{q}''$ = incident radiative heat flux (kW/m^2)
E = average emissive power at flame surface (kW/m^2)
$F_{1\rightarrow 2}$ = configuration factor

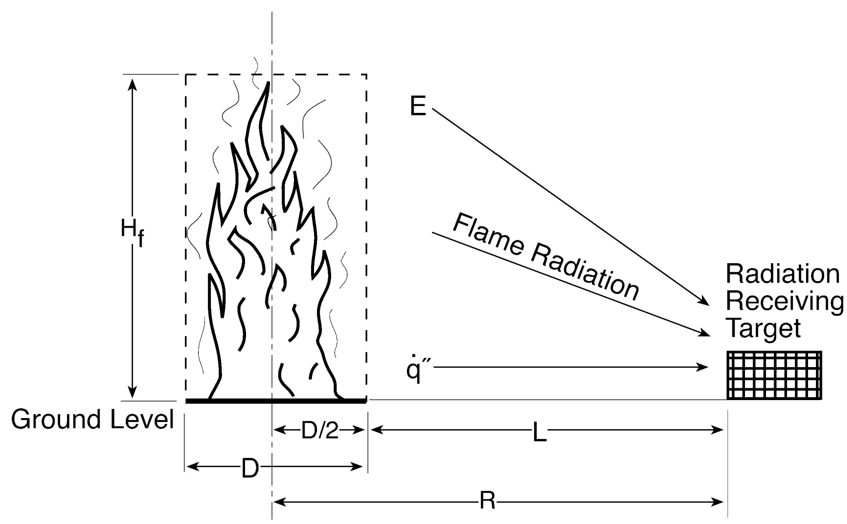

Figure 5-2 Solid Flame Radiation Model with No Wind and Target at Ground Level

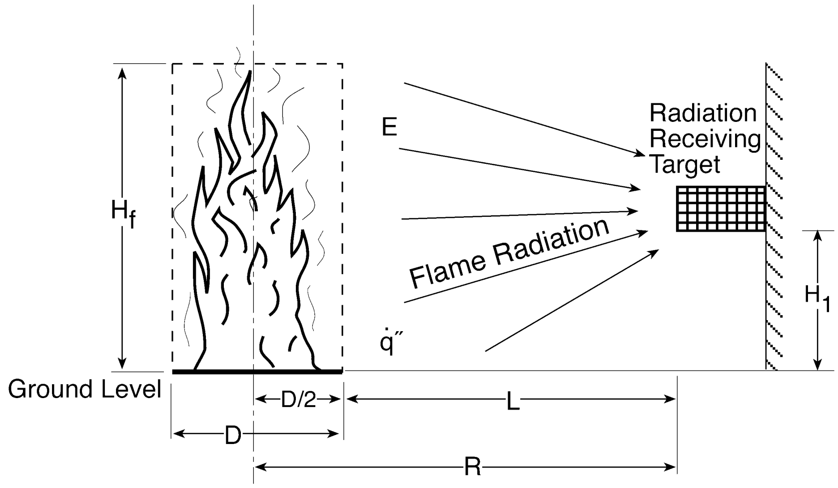

Figure 5-3 Solid Flame Radiation Model with No Wind and Target Above Ground

5.3.2.1 Emissive Power

Emissive power is the total radiative power leaving the surface of the fire per unit area per unit time. Emissive power can be calculated using of Stefan's law, which gives the radiation of a black body in relation to its temperature. Because a fire is not a perfect black body (black body is defined as a perfect radiator; a surface with an emissivity of unity and, therefore, a reflectivity of zero), the emissive power is a fraction ( ) of the black body radiation (Beyler, 2002):

$$E = \varepsilon \ \sigma \ T^4 \tag{5-5}$$

Where:

E = flame emissive power (kW/m^2)
 = flame emissivity
 = Stefan-Boltzmann constant = 5.67 x 10^{-11} (kW/m^2-K^4)
T = temperature of the fire (K)

The use of the Stefan-Boltzmann constant to calculate radiation heat transfer requires knowledge of the temperature and emissivity of the fire; however, turbulent mixing causes the fire temperature to vary. Consequently, Shokri and Beyler (1989) correlated experimental data of flame radiation to external targets in terms of an average emissive power of the flame. For that correlation, the flame is assumed to be a cylindrical, black body, homogeneous radiator with an average emissive power. Thus, effective power of the pool fire in terms of effective diameter is given by:

$$E = 58 \left(10^{-0.00823D}\right) \tag{5-6}$$

Where:

E = flame emissive power (kW/m^2)
D = diameter of pool fire (m)

This represents the average emissive power over the whole of the flame and is significantly less than the emissive power that can be attained locally. The emissive power is further reduced with increasing pool diameter as a result of the increasing prominence of black smoke outside the flame, which obscures the radiation from the luminous flame.

For non-circular pools, the effective diameter is defined as the diameter of a circular pool with an area equal to the actual pool area given by Equation 5-3.

5.3.2.2 Configuration Factor $F_{1\rightarrow 2}$ under Wind-Free Conditions

The configuration factor[3] is a purely geometric quantity, which provides the fraction of the radiation leaving one surface that strikes another surface directly. In other words the configuration factor gives the fraction of hemispherical surface area seen by one differential element when looking at another differential element on the hemisphere.

The configuration factor is a function of target location, flame size (height), and fire diameter, and is a value between 0 and 1. When the target is very close to the flame, the configuration factor approaches 1, since everything viewed by the target is the flame. The flame is idealized with a diameter equal to the pool diameter, D, and a height equal to the flame height, H_f. If the pool has a length-to-width ratio near 1, an equivalent area circular source can be used in determining the flame length, H_f, for non-circular pools. (See Figure 5-4 and 5-5 for general definitions applicable to the cylindrical flame model under wind-free conditions.)

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3 The configuration factor is also commonly referred to as the "view factor".

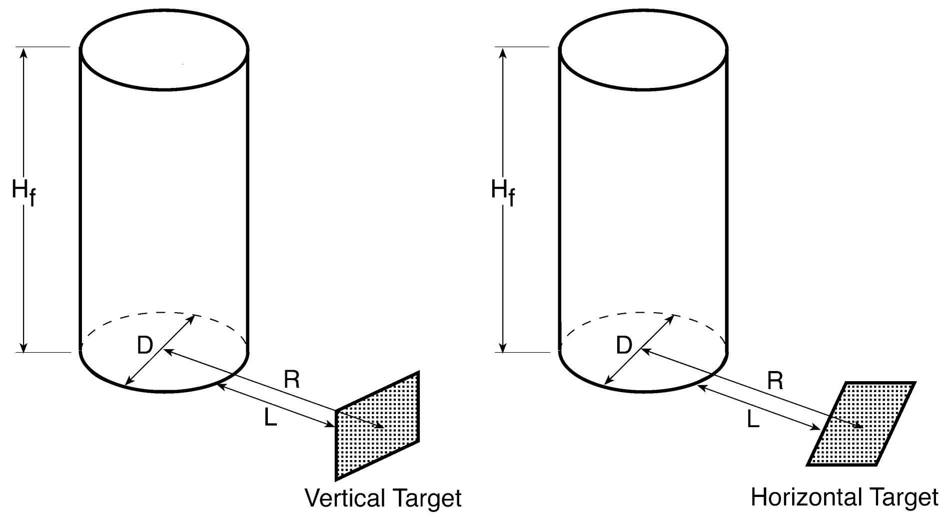

Figure 5-4 Cylindrical Flame Shape Configuration Factor Geometry for Vertical and Horizontal Targets at Ground Level with No Wind

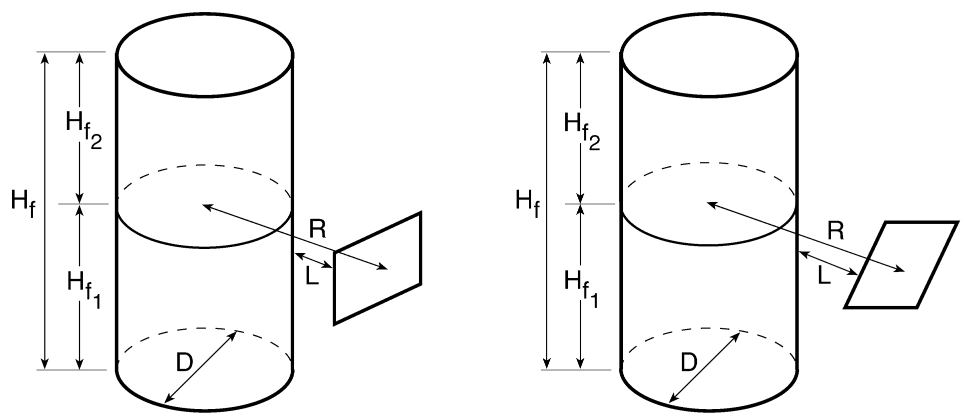

Figure 5-5 Cylindrical Flame Shape Configuration Factor Geometry for Vertical and Horizontal Targets Above Ground with No Wind

Flame height of the pool fire is then determined using the following correlation (Heskestad, 1995):

$$H_f = 0.235 \ \dot{Q}^{\frac{2}{5}} - \ 1.02 \ D \tag{5-8}$$

Where:

H_f = flame height (m)

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

D = diameter of the burning area (m)

The HRR of the fire can be determined by laboratory or field testing. In the absence of experimental data, the maximum HRR for the fire $(\dot{Q})$, is given by Equation 5-2.

The radiation exchange factor between a fire and an element outside the fire depends on the shape of the flame, the relative distance between the fire and the receiving element, and the relative orientation of the element. The turbulent diffusion flame can be approximated by a cylinder. Under wind-free conditions, the cylinder is vertical (Figure 5-4). If the target is either at ground level or at the flame height, a single cylinder can represent the flame. However, if the target is above the ground, two cylinders should be used to represent the flame.

For horizontal and vertical target orientations at ground level with no-wind conditions, given the diameter and height of the flame, the configuration (or view factor) $F_{1\rightarrow 2}$ under wind-free conditions is determined using the following equations related to cylindrical radiation sources (Beyler, 2002):

$$F_{1\rightarrow 2,H} = \left(\frac{\left(B - \frac{1}{S}\right)}{\pi\sqrt{B^2 - 1}} \tan^{-1}\sqrt{\frac{(B+1)(S-1)}{(B-1)(S+1)}} - \frac{\left(A - \frac{1}{S}\right)}{\pi\sqrt{A^2 - 1}} \tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}} \right) \tag{5-9}$$

$$F_{1\rightarrow 2,V} = \left(\frac{1}{\pi S} \tan^{-1}\left(\frac{h}{\sqrt{S^2 - 1}}\right) - \frac{h}{\pi S} \tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \frac{Ah}{\pi S\sqrt{A^2 - 1}} \tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}} \right) \tag{5-10}$$

Where:

$$A = \frac{h^2 + S^2 + 1}{2S}, \quad B = \frac{1 + S^2}{2S}$$

$$S = \frac{2L}{D}, \quad h = \frac{2H_f}{D}$$

And:

L = the distance between the center of the cylinder (flame) to the target (m)

H_f = the height of the cylinder (flame) (m)

D = the cylinder (flame) diameter (m)

The maximum configuration factor (or view factor) at a point is given by the vectorial sum of the horizontal and vertical configuration factors:

$$F_{1\rightarrow 2,max(no-wind)} = \sqrt{F_{1\rightarrow 2,H}^2 + F_{1\rightarrow 2,V}^2} \qquad (5\text{-}11)$$

As previously stated, for targets above the ground, two cylinders should be used to represent the flame. In such instances, one cylinder represents the flame below the height of the target, while the other represents the flame above the height of the target (See Figure 5-5). Thus, the following expressions are used to estimate the configuration factor (or view factor) under wind-free conditions for targets above ground level:

$$F_{1\rightarrow 2,V_1} = \left(\begin{array}{l} \dfrac{1}{\pi S}.\tan^{-1}\left(\dfrac{h_1}{\sqrt{S^2-1}}\right) - \dfrac{h_1}{\pi S}\tan^{-1}\sqrt{\dfrac{(S-1)}{(S+1)}} + \\ \dfrac{A_1 h_1}{\pi S\sqrt{A_1{}^2-1}}\tan^{-1}\sqrt{\dfrac{(A_1+1)(S-1)}{(A_1-1)(S+1)}} \end{array} \right) \qquad (5\text{-}12)$$

Where:

$$S = \frac{2L}{D}$$

$$h_1 = \frac{2H_{f_1}}{D}$$

$$A_1 = \frac{h_1^2 + S^2 + 1}{2S}$$

$$F_{1\rightarrow 2,V_2} = \left(\begin{array}{l} \dfrac{1}{\pi S}.\tan^{-1}\left(\dfrac{h_2}{\sqrt{S^2-1}}\right) - \dfrac{h_2}{\pi S}\tan^{-1}\sqrt{\dfrac{(S-1)}{(S+1)}} + \\ \dfrac{A_2 h_2}{\pi S\sqrt{A_2{}^2-1}}\tan^{-1}\sqrt{\dfrac{(A_2+1)(S-1)}{(A_2-1)(S+1)}} \end{array} \right) \qquad (5\text{-}13)$$

Where:

$$S = \frac{2L}{D}$$

$$h_2 = \frac{2H_{f_2}}{D}$$

$$A_2 = \frac{h_2^2 + S^2 + 1}{2S}$$

And:

L = the distance between the center of the cylinder (flame) to the target (m)
H_f = the height of the cylinder (flame) (m)
D = the cylinder (flame) diameter (m)

The total configuration factor or (view factor) at a point is given by the sum of two configuration factor as follows:

$$F_{1\rightarrow 2,V(no-wind)} = F_{1\rightarrow 2,V1} + F_{1\rightarrow 2,V2} \qquad (5\text{-}14)$$

5.3.2.3 Configuration Factor $F_{1\rightarrow 2}$ in Presence of Wind

As discussed in pervious section, in the solid flame radiation model the turbulent flame is approximated by a cylinder. Under wind-free conditions, the cylinder is vertical, in the presence of wind, the flame may not remain vertical and thermal radiation to the surrounding objects will change in the presence of a significant wind. The flame actually follows a curved path and makes an angle of tilt or an angle of deflection approximate to its curved path. Figures 5-6 and 5-7 describe the flame configuration in presence of wind velocity (u_w) for target at and above ground level.

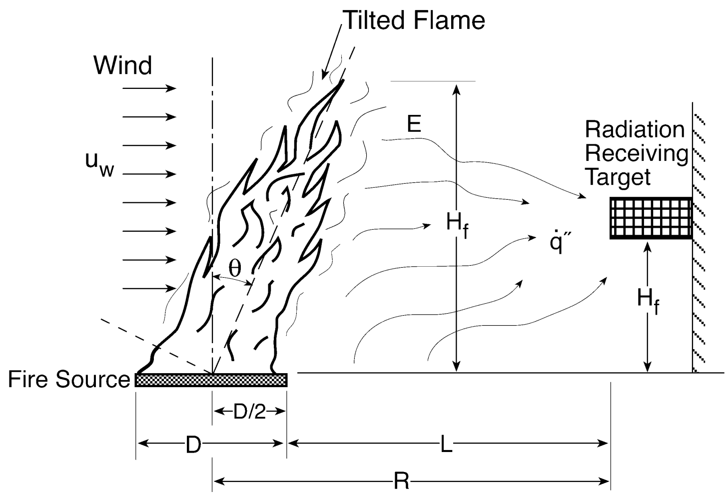

Figure 5-6 Solid Flame Radiation Model in Presence of Wind and Target Above Ground Level

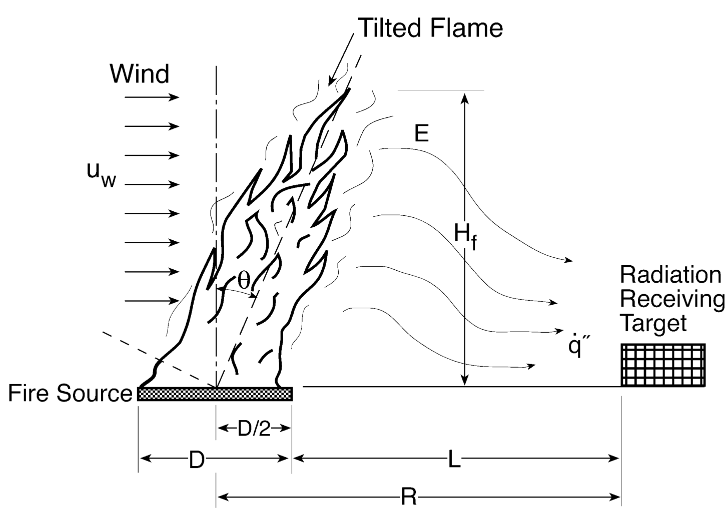

Figure 5-7 Solid Flame Radiation Model in Presence of Wind and Target at Ground Level

For horizontal and vertical target orientations at ground level in presence of wind, the expression for estimating the configuration factors is expressed by the following equations (Beyler, 2002):

$$\pi F_{1\to 2,H} = \left(\begin{array}{l} \tan^{-1}\dfrac{\sqrt{\dfrac{b+1}{b-1}}}{\pi\sqrt{B^2-1}} - \dfrac{a^2+(b+1)^2-2(b+1+ab\sin\theta)}{\sqrt{AB}}\tan^{-1}\sqrt{\dfrac{A}{B}}\sqrt{\dfrac{(b-1)}{(b+1)}} + \\ \dfrac{\sin\theta}{\sqrt{C}}\left(\tan^{-1}\dfrac{ab-(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\dfrac{(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}}\right) \end{array} \right) \quad (5\text{-}15)$$

$$\pi F_{1\to 2,V} = \left(\begin{array}{l} \dfrac{a\cos\theta}{b-a\sin\theta}\dfrac{a^2+(b+1)^2-2b(1+a\sin\theta)}{\sqrt{AB}}\tan^{-1}\sqrt{\dfrac{A}{B}}\sqrt{\dfrac{(b-1)}{(b+1)}} + \\ \dfrac{\cos\theta}{\sqrt{C}}\left(\tan^{-1}\dfrac{ab-(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\dfrac{(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}}\right) - \\ \dfrac{a\cos\theta}{(b-a\sin\theta)}\tan^{-1}\sqrt{\dfrac{b-1}{b+1}} \end{array} \right) \quad (5\text{-}16)$$

Where:

$$a = \frac{H_f}{r}$$

$$b = \frac{R}{r}$$

$$A = a^2 + (b+1)^2 - 2a(b+1)\sin\theta$$

$$B = a^2 + (b-1)^2 - 2a(b-1)\sin\theta$$

$$C = 1 + (b^2-1)\cos^2\theta$$

And:

H_f = the height of the tilted cylinder (flame) (m)
r = the cylinder (flame) radius (m)
R = distance from center of the pool fire to edge of the target (m)
= flame title or angle of deflection (radians)

The maximum configuration factor for a target at ground level in the presence of wind at a point is given by the vectorial sum of the horizontal and vertical configuration factors:

$$F_{1\to 2,max(wind)} = \sqrt{F^2_{1\to 2,H} + F^2_{1\to 2,V}} \quad (5\text{-}17)$$

For targets above the ground in presence of wind, two cylinders must be used to represent the flame. In such instances, one cylinder represents the flame below the height of the target, while the other represents the flame above the height of the target. The following expressions are used to estimate the configuration or view factor in presence of wind for targets above ground level:

$$\pi F_{1\to 2,V1} = \left(\begin{array}{l} \dfrac{a_1\cos\theta}{b - a_1\sin\theta}\dfrac{a_1^2+(b+1)^2-2b(1+a_1\sin\theta)}{\sqrt{AB}}\tan^{-1}\sqrt{\dfrac{A_1}{B_1}}\sqrt{\dfrac{(b-1)}{(b+1)}} + \\ \dfrac{\cos\theta}{\sqrt{C}}\left(\tan^{-1}\dfrac{a_1 b-(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\dfrac{(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}}\right) - \\ \dfrac{a_1\cos\theta}{(b-a_1\sin\theta)}\tan^{-1}\sqrt{\dfrac{b-1}{b+1}} \end{array} \right) \tag{5-18}$$

$$\pi F_{1\to 2,V} = \left(\begin{array}{l} \dfrac{a_2\cos\theta}{b - a\sin\theta}\dfrac{a_2^2+(b+1)^2-2b(1+a_2\sin\theta)}{\sqrt{AB}}\tan^{-1}\sqrt{\dfrac{A_2}{B_2}}\sqrt{\dfrac{(b-1)}{(b+1)}} + \\ \dfrac{\cos\theta}{\sqrt{C}}\left(\tan^{-1}\dfrac{a_2 b-(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\dfrac{(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}}\right) - \\ \dfrac{a_2\cos\theta}{(b-a_2\sin\theta)}\tan^{-1}\sqrt{\dfrac{b-1}{b+1}} \end{array} \right) \tag{5-19}$$

Where:

$$a_1 = \frac{2H_{f1}}{r} = \frac{2H_1}{r}$$

$$a_2 = \frac{2H_{f2}}{r} = \frac{2(H_f - H_{f1})}{r}$$

$$b = \frac{R}{r}$$

$$A_1 = a_1^2 + (b+1)^2 - 2a_1(b+1)\sin\theta$$

$$A_2 = a_2^2 + (b+1)^2 - 2a_2(b+1)\sin\theta$$

$$B_1 = a_1^2 + (b-1)^2 - 2a_1(b-1)\sin\theta$$

$$B_2 = a_2^2 + (b-1)^2 - 2a_2(b-1)\sin\theta$$

$$C = 1 + (b^2-1)\cos^2\theta$$

And:

$H_1 = H_{f1}$ = vertical distance of target from ground level (m)
H_f = the height of the tilted cylinder (flame) (m)
r = the cylinder (flame) radius (m)
R = distance from center of the pool fire to edge of the target (m)
= flame title or angle of deflection (radians)

The total configuration or view factor at a point is given by the sum of two configuration factors, as follows:

$$F_{1\rightarrow 2,V(wind)} = F_{1\rightarrow 2,V1} + F_{1\rightarrow 2,V2} \qquad (5\text{-}20)$$

In presence of wind, the expression for estimating flame height is expressed by the following correlation, based on the experimental data (Thomas, 1962):

$$H_f = 55D \left(\frac{\dot{m}''}{\rho_a \sqrt{gD}}\right)^{0.67} \left(u^*\right)^{-0.21} \qquad (5\text{-}21)$$

Where:

D = diameter of pool fire (m)
$\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)
$_a$ = ambient air density (kg/m^3)
g = gravitational acceleration (m/sec^2)
u* = nondimensional wind velocity

The nondimensional wind velocity is given by:

$$u^* = \frac{u_w}{\left(\frac{g\dot{m}''D}{\rho}\right)^{\frac{1}{3}}} \qquad (5\text{-}22)$$

Where:

u* = nondimensional wind velocity
u_w = wind speed or wind velocity (m/sec)
g = gravitational acceleration (m/sec^2)
$\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)
D = diameter of pool fire (m)
= density of ambient air (kg/m^3)

The correlation relating to angle of tilt or angle of deflection ( ), of the flame from the vertical are expressed by the following equations based on the American Gas Association (AGA) data:

$$\begin{aligned} \text{Cos}\theta &= \{1 \qquad \text{for} \quad u^* \leq 1 \\ \text{Cos}\theta &= \left\{\frac{1}{\sqrt{u^*}} \qquad \text{for} \quad u^* \geq 1\right. \end{aligned} \qquad (5\text{-}23)$$

Where:

= angle of tilt or angle of deflection (radians)
u* = nondimensional wind velocity

5.4 Method of Estimating Thermal Radiation from Hydrocarbon Fireball

For industrial processes, many substances that are gases at ambient conditions are stored in container or vessel under pressure in a saturated liquid/vapor form. A rupture of a such vessel will result in a violent incident as the liquid expands into its gaseous form. This phase change forms blast waves with energy equivalent to the change in internal energy of the liquid/vapor; this phenomenon is called the BLEVE. BLEVE is an acronym of Boiling Liquid, Expanding Vapor Explosion. National Fire Protection Association (NFPA), defined a BLEVE as the failure of a major container into two or more pieces, occurring at a moment when the contained liquid is at temperature above its boiling point at normal atmospheric pressure. Typically, a BLEVE occurs in a metal container that has been overheated above 538 °C (1,000 °F) (Nolan 1996). The metal may not be able to withstand the internal stress and therefore failure occurs. The contained liquid space of the vessel normally acts as a heat absorber, so the wetted portion of the container is usually not at risk, only the surfaces of the internal vapor space. Most BLEVEs occur when containers are less than ½ to ⅓ full of liquid.

A container can fail for a number of reasons. It can be damaged by impact from an object, thus causing a crack to develop and grow, either as a result of internal pressure, vessel material brittleness, or both. Thus, the container may rupture completely after impact. Weakening the container's metal beyond the point at which it can withstand internal pressure can also cause large cracks, or even cause the container to separate into two or more pieces. Weakening can result from corrosion, internal overheating, or manufacturing defects, etc.

5.4.1 Radiation Due to BLEVEs with Accompanying Fireball

In additional to the container becoming a projectile, the hazard posed by a BLEVE is the fireball and the resulting radiation. The rapid failure of the container is followed by a fireball or major fire, which produces a powerful radiant heat flux.

Four parameters often used to determine a fireball's thermal radiation hazard are the mass of fuel involved and the fireball's diameter, duration, and thermal emissive power. Radiation hazards can then be calculated from empirical relation.

Radiation received by an object relatively distant from the fireball can be calculated by the following expression (Hasegawa and Sato, 1977 and Roberts, 1982):

$$\dot{q}_r'' = \frac{828\ m_F^{0.771}}{R^2} \qquad (5\text{-}24)$$

Where:

$\dot{q}_r''$ = thermal radiation from fireball (kW/m^2)
m_F = mass of fuel vapor (kg)
R = distance from the center of the fireball to the target (m)

The distance from the center of the fireball to the target is given by the following relation:

$$R = \sqrt{Z_p^2 + L^2} \qquad (5\text{-}25)$$

Where:

R = distance from the center of the fireball to the target (m)
Z_p = fireball flame height (m)
L = distance at ground level from the origin (m)

The fireball flame height is given by the following expression (Fay and Lewis 1976):

$$Z_p = 12.73 \; (V_F)^{\frac{1}{3}} \qquad (5\text{-}26)$$

Where:

Z_p = fireball flame height (m)
V_F = volume of fuel vapor (m^3)

The volume of fireball can be calculated from the following relation:

$$V_F = \frac{m_F}{\rho_F} \qquad (5\text{-}27)$$

Where:

V_F = volume of fuel vapor (m^3)
m_F = mass of fuel vapor (kg)
${}_F$ = fuel vapor density (kg/m^3)

5.5 Assumptions and Limitations

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

The following assumption applies to **all** radiation models:

(1) The pool is circular or nearly circular.

The following assumptions and limitations apply to point source radiation models:

(1) Except near the base of pool fires, radiation to the surroundings can be approximated as being isotropic or emanating from a point source.

(2) The point source model overestimates the intensity of thermal radiation at the observer's (target) locations close to the fire. This is primarily because the near-field radiation is greatly influenced by the flame size, shape, and tilt, as well as the relative orientation of the observer (target).

(3) A theoretical analysis of radiation from small pool fire by Modak (1977) indicated that the point source model is within 5-percent the correct incident heat flux when L/D >2.5.

(4) The energy radiated from the flame is a specified fraction of the energy released during combustion.

(5) The model can be used to determine thermal radiation hazards in scenarios for which a conservative estimate of the hazard is generally acceptable.

The following limitation applies to solid flame radiation models at and above ground level:

(1) The correlation of emissive power was developed on the basis of data from experiments that included kerosene, fuel oil, gasoline, JP-4, JP-5[4], and liquified natural gas (LNG). With the exception of the LNG, these are quite luminous flames, so the correlation should be suitable for most fuels. The pool diameters ranged from 1 to 50 m.

5.6 Required Input for Spreadsheet Calculations

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

(1) fuel type (material)
(2) fuel spill area or curbed area (ft^2)
(3) distance between fire and target (ft)
(4) vertical distance of target from ground level (ft)
(5) wind speed (ft/min)

5.7 Cautions

(1) Use the appropriate spreadsheet (05.1_Heat_Flux_Calculations_Wind_Free.xls or 05.2_Heat_Flux_Calculations_Wind) on the CD-ROM for the calculation.

(2) Make sure units are correct on input parameters.

4 Common jet fuel.

5.8 Summary

Estimating the thermal radiation field surrounding a fire involves the following steps:

(1) Characterize the geometry of the pool fire; that is, determine its HRR and physical dimensions. In calculating thermal radiation, the size of the fire implies the time-averaged size of the visible envelope.

(2) Characterize the radiative properties of the fire; that is, determine the average irradiance of the flames (emissive power).

(3) Calculate the radiant intensity at a given location. This can be accomplished after determining the geometry of the fire; its radiation characteristics; and the location, geometry, and orientation of the target.Determine the HRR from Equation 5-2 or from experimental data available in the literature.

(4) Determine the height of the pool fire.

(5) Calculate the view or configuration factor.

(6) Determine the effective emissive power of the flame.

(7) Calculate the radiative heat flux to the target.

5.9 References

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5.10 Additional Readings

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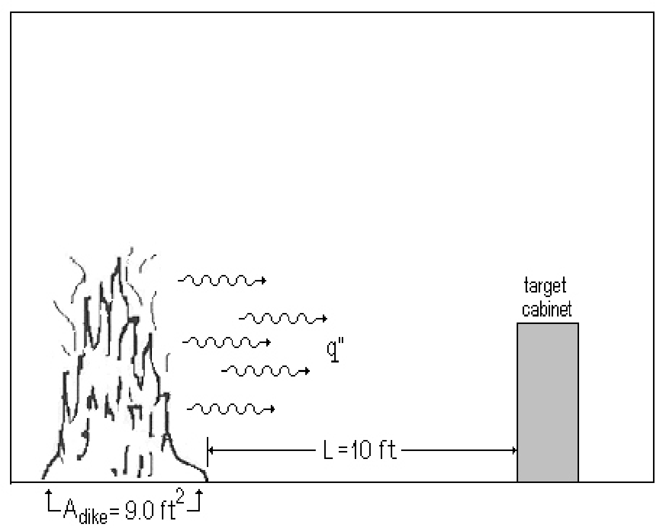
5.11 Problems

Example Problem 5.11-1

Problem Statement

A pool fire scenario arises from a breach (leak or rupture) in a transformer. This event allows the fuel contents of the transformer to spill and spread over the compartment floor. The compartment is very large and has a high ceiling (e.g., typical reactor building elevation of a BWR, turbine building open area). A pool fire ensues with a spill area of 9.0 ft^2 on the concrete floor. Calculate the flame radiant heat flux to a target (cabinet) at ground level with no wind using: a) point source radiation model and b) solid flame radiation model. The distance between the fire source and the target edge is assumed to be 10 ft.



Example Problem 5-1: Radiant Heat Flux from a Pool Fire to a Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the pool fire to the target cabinet using the point source and solid flame radiation models.

Assumptions:

(1) The pool is circular or nearly circular.

(2) Radiation to the surroundings can be approximated as being isotropic or emanating from a point source (valid for point source radiation model only).

(3) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_ Heat_Flux_Calculations_Wind_Free.xls

(click on *Point Source* and *Solid Flame 1* for point source and solid flame analysis respectively).

FDT^s Input Parameters: (For both spreadsheets)
-Fuel Spill Area or Curb Area (A_{curb}) = 9.0 ft^2
-Distance between Fire Source and Target (L) = 10 ft
-Select Fuel Type: **Transformer Oil, Hydrocarbon**

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)
Point Source	1.45 (0.13)
Solid Flame	3.05 (0.27)

* see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 05.1_ Heat_Flux_Calculations_Wind_Free.xls (Point Source)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION POINT SOURCE RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m")		0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	46000	kJ/kg	
Empirical Constant (kβ)		0.7	m^{-1}	
Heat Release Rate (Q)		771.52	kW	
Fuel Area or Dike Area (A_{dike})		9.00	ft^2	0.84 m^2
Distance between Fire and Target (L)		10.00	ft	3.048 m
Radiative Fraction (χ_r)		0.30		

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

Transformer Oil, Hydrocarbon

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-272.*

POINT SOURCE RADIATION MODEL

$q'' = Q \chi_r / 4 \pi R^2$

Where
- q'' = incident radiative heat flux on the target (kW/m^2)
- Q = pool fire heat release rate (kW)
- χ_r = radiative fraction
- R = distance from center of the pool fire to edge of the target (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

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

Where
- A_{dike} = surface area of pool fire (m^2)
- D = pool fire diamter (m)

D = 1.03 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_f$

Where
- Q = pool fire heat release rate (kW)
- m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ΔH_c = effective heat of combustion of fuel (kJ/kg)
- A_f = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 771.52 kW

Distance from Center of the Fire to Edge of the Target Calculation

R = L+D/2

Where
- R = distance from center of the pool fire to edge of the target (m)
- L = distance between pool fire and target (m)
- D = pool fire diameter (m)

R = 3.56 m

Radiative Heat Flux Calculation

$q'' = Q \chi_r / 4 \pi R^2$

q'' =	1.45 kW/m^2	0.13 Btu/ft^2-sec	Answer

NOTE

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

Calculations are based on certain assumptions and 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.

FDT^{s}: 05.1_ Heat_Flux_Calculations_Wind_Free.xls (Solid Flame 1)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m")		0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	46000	kJ/kg	
Empirical Constant (kβ)		0.7	m^{-1}	
Heat Release Rate (Q)		771.52	kW	
Fuel Area or Dike Area (A_{dike})		9.00	ft^2	0.84 m^2
Distance between Fire and Target (L)		10.00	ft	3.048 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

Transformer Oil, Hydrocarbon

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276*.

SOLID FLAME RADIATION MODEL

$q'' = EF_{1\to2}$

Where
q'' = incident radiative heat flux on the target (kW/m^2)
E = emissive power of the pool fire flame (kW/m^2)
$F_{1\to2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

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

Where
A_{dike} = surface area of pool fire (m^2)
D = pool fire diameter (m)

D = 1.03 m

Emissive Power Calculation

E = $58\,(10^{-0.00823D})$

Where
E = emissive power of the pool fire flame (kW/m^2)
D = diameter of the pool fire (m)

E = 56.88 kW/m^2

View Factor Calculation

$F_{1\to2,H} = (B-1/S)/\pi(B^2-1)^{1/2}\tan^{-1}((B+1)(S-1)/(B-1)(S+1))^{1/2} - (A-1/S)/(\pi(A^2-1)^{1/2})\tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$

$F_{1\to2,V} = 1/(\pi S)\tan^{-1}(h/(S^2-1)^{1/2}) - (h/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + Ah/\pi S(A^2-1)^{1/2}\tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$

$A = (h^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h = 2H_f/D$

$F_{1\to2,max} = \sqrt{(F^2_{1\to2,H} + F^2_{1\to2,V})}$

Where
$F_{1\to2,H}$ = horizontal view factor
$F_{1\to2,V}$ = vertical view factor
$F_{1\to2,max}$ = maximum view factor
R = distance from center of the pool fire to edge of the target (m)
H_f = height of the pool fire flame (m)
D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where
R = distance from center of the pool fire to edge of the target (m)
L = distance between pool fire and target (m)
D = pool fire diameter (m)

$R = L + D/2 =$ 3.564 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D})A_{dike}$

Where
Q = pool fire heat release rate (kW)
m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
ΔH_c = effective heat of combustion of fuel (kJ/kg)
A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
$k\beta$ = empirical constant (m^{-1})
D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 771.52 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\,Q^{2/5} - 1.02\,D$

Where
H_f = flame height (m)
Q = heat release rate of fire (kW)
D = fire diameter (m)

H_f = 2.305 m

$S = 2R/D =$ 6.908
$h = 2H_f/D =$ 4.468
$A = (h^2+S^2+1)/2S =$ 4.971
$B = (1+S^2)/2S =$ 3.526

Radiative Heat Flux Calculation

$q'' = EF_{1\rightarrow 2}$

q'' =	3.05	kW/m^2	0.27	Btu/ft^2-sec	Answer

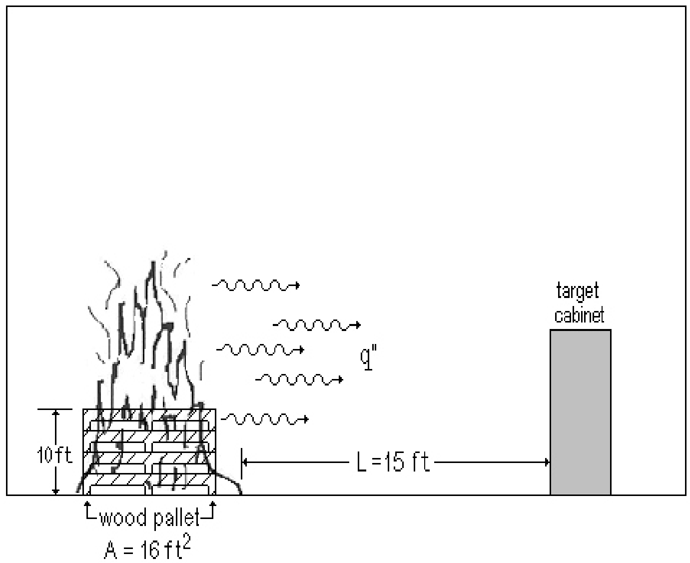
NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and 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 5.11-2

Problem Statement

A transient combustible fire scenario may arise from burning wood pallets (4 ft x 4 ft = 16 ft^2), stacked 10 ft high on the floor of a compartment with a very high ceiling. Calculate the flame radiant heat flux to a target (safety-related cabinet) at ground level with no wind, using the point source radiation model and the solid flame radiation model. The distance between the fire source and the target edge (L) is assumed to be 15 ft.



Example Problem 5-2: Radiant Heat Flux from a Burning Pallet to a Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the fire source to the target cabinet using the point source and solid flame radiation models.

Assumptions:

(1) The fire source will be nearly circular.
(2) Radiation to the surroundings can be approximated as being isotropic or emanating from a point source (valid for point source radiation model only).
(3) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls

(click on *Point Source* and *Solid Flame 1* for point source and solid flame analysis respectively)

FDT^s Inputs: (For both spreadsheets)

-Fuel Spill Area or Curb Area (A_{curb}) = 16 ft^2

-Distance between Fire Source and Target (L) = 15 ft

-Select Fuel Type: **Douglas Fir Plywood**

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)
Point Source	0.15 (0.01)
Solid Flame	0.45 (0.04)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Point Source)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION POINT SOURCE RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m'')		0.01082	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	10900	kJ/kg	
Empirical Constant ($k\beta$)		100	m^{-1}	
Heat Release Rate ($\dot{Q}$)		175.31	kW	
Fuel Area or Dike Area (A_{dike})		16.00	ft^2	1.49 m^2
Distance between Fire and Target (L)		15.00	ft	4.572 m
Radiative Fraction (χ_r)		0.30		

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-26.*

Select Fuel Type

Douglas Fir Plywood

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-272.*

POINT SOURCE RADIATION MODEL

$q" = Q \chi_r / 4 \pi R^2$

Where
- $q"$ = incident radiative heat flux on the target (kW/m^2)
- Q = pool fire heat release rate (kW)
- χ_r = radiative fraction
- R = distance from center of the pool fire to edge of the target (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

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

Where
- A_{dike} = surface area of pool fire (m^2)
- D = pool fire diamter (m)

D = 1.38 m

Heat Release Rate Calculation

$Q = m"\Delta H_{c,eff}(1 - e^{-k\beta D}) A_f$

Where
- Q = pool fire heat release rate (kW)
- $m"$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ΔH_c = effective heat of combustion of fuel (kJ/kg)
- A_f = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 175.31 kW

Distance from Center of the Fire to Edge of the Target Calculation

$R = L+D/2$

Where
- R = distance from center of the pool fire to edge of the target (m)
- L = distance between pool fire and target (m)
- D = pool fire diameter (m)

R = 5.26 m

Radiative Heat Flux Calculation

$q" = Q \chi_r / 4 \pi R^2$

q" =	0.15 kW/m^2	0.01 Btu/ft^2-sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and 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 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION
SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m")		0.01082	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	10900	kJ/kg	
Empirical Constant (kβ)		100	m^{-1}	
Heat Release Rate (Q)		175.31	kW	
Fuel Area or Dike Area (A_{dike})		16.00	ft^2	1.49 m^2
Distance between Fire and Target (L)		15.00	ft	4.572 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Select Fuel Type

Douglas Fir Plywood

Scroll to desired fuel type then Click on selection

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-26*.

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276*.

SOLID FLAME RADIATION MODEL

$q" = EF_{1\to 2}$

Where
- $q"$ = incident radiative heat flux on the target (kW/m^2)
- E = emissive power of the pool fire flame (kW/m^2)
- $F_{1\to 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

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

Where
- A_{dike} = surface area of pool fire (m^2)
- D = pool fire diameter (m)

$D =$ 1.38 m

Emissive Power Calculation

$E = 58\ (10^{-0.00823D})$

Where
- E = emissive power of the pool fire flame (kW/m^2)
- D = diameter of the pool fire (m)

$E =$ 56.51 kW/m^2

View Factor Calculation

$F_{1\to 2,H} = (B-1/S)/\pi(B^2-1)^{1/2}\ \tan^{-1}((B+1)(S-1)/(B-1)(S+1))^{1/2} - (A-1/S)/(\pi(A^2-1)^{1/2})\ \tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$

$F_{1\to 2,V} = 1/(\pi S)\ \tan^{-1}(h/(S^2-1)^{1/2}) - (h/\pi S)\ \tan^{-1}((S-1)/(S+1))^{1/2} + Ah/\pi S(A^2-1)^{1/2}\ \tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$

$A = (h^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h = 2H_f/D$

$F_{1\to 2,max} = \sqrt{(F^2_{1\to 2,H} + F^2_{1\to 2,V})}$

Where
- $F_{1\to 2,H}$ = horizontal view factor
- $F_{1\to 2,V}$ = vertical view factor
- $F_{1\to 2,max}$ = maximum view factor
- R = distance from center of the pool fire to edge of the target (m)
- H_f = height of the pool fire flame (m)
- D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where
- R = distance from center of the pool fire to edge of the target (m)
- L = distance between pool fire and target (m)
- D = pool fire diameter (m)

$R = L + D/2 =$ 5.260 m

Heat Release Rate Calculation

$Q = m"\Delta H_{c,eff}\ (1 - e^{-k\beta D})\ A_{dike}$

Where
- Q = pool fire heat release rate (kW)
- $m"$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ΔH_c = effective heat of combustion of fuel (kJ/kg)
- A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

$Q =$ 175.31 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\ Q^{2/5} - 1.02\ D$

Where
- H_f = flame height (m)
- Q = heat release rate of fire (kW)
- D = fire diameter (m)

$H_f =$ 0.453 m

$S = 2R/D =$ 7.647

$h = 2H_f/D =$ 0.658

$A = (h^2+S^2+1)/2S =$ 3.917

$B = (1+S^2)/2S =$ 3.889

Radiative Heat Flux Calculation

$\dot{q}'' = E F_{1 \to 2}$

$\dot{q}''$ =	**0.45 kW/m^2**	**0.04 Btu/ft^2-sec**	**Answer**

NOTE

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

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

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

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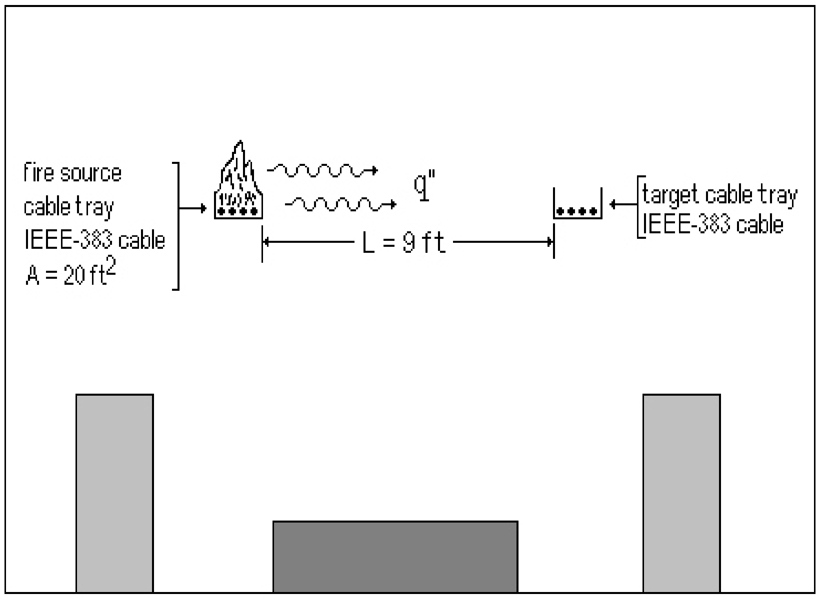
UNITED STATES NUCLEAR REGULATORY COMMISSION

Example Problem 5.11-3

Problem Statement

A fire scenario may arise from a horizontal cable tray burning in a very large compartment. The cables in the tray are IEEE-383 unqualified and made of PE/PVC insulation material (assume that the exposed area of the cable is 20 ft^2). Another safety-related cable tray also filled with IEEE-383 unqualified made of PE/PVC insulation material is located at a radial distance (L) of 9 ft from the fire source. Calculate the flame radiant heat flux to a target (safety-related cable tray) using the point source radiation model and solid flame radiation model. Is this heat flux sufficient to ignite the cable tray?



Example Problem 5-3: Radiant Heat Flux from a Burning Cable Tray to a Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the burning cable tray to the target cable tray using the point source and solid flame radiation models.

(2) Determine if the heat flux is sufficient to ignite the cable tray.

Assumptions:

(1) The fire source will be nearly circular.

(2) Radiation to the surroundings can be approximated as being isotropic or emanating from a point source (point source radiation model only).

(3) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls

(click on *Point Source* and *Solid Flame 1* for point source and solid flame analysis, respectively).

FDT^s Inputs: (For both spreadsheets)

-Mass Burning Rate of Fuel $(\dot{m}")$ = 0.0044 kg/m^2-sec

-Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$) = 25,100 kJ/kg

-Empirical Constant (kβ) = 100 m^{-1} (use this if actual value is unknown)

-Fuel Spill Area or Curb Area (A_{curb}) = 20 ft^2

-Distance between Fire Source and Target (L) = 9 ft

Note: Since the insulation material (PE/PVC) is not available in the thermal properties data of the spreadsheet, we have to input the mass burning rate and effective heat of combustion in the spreadsheet. Values of cable materials properties are available in Table 3-4. Select **User-Specified Value**, and enter the respective values.

Results*

Radiation Model	Radiant Heat Flux $\dot{q}"$ kW (Btu/ft^2-sec)
Point Source	0.4 (0.03)
Solid Flame	1.1 (0.10)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Point Source)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION POINT SOURCE RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m")		0.0044	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	25100	kJ/kg	
Empirical Constant (kβ)		100	m^{-1}	
Heat Release Rate (Q)		205.20	kW	
Fuel Area or Dike Area (A_{dike})		20.00	ft^2	1.86 m^2
Distance between Fire and Target (L)		9.00	ft	2.7432 m
Radiative Fraction (χ_r)		0.30		

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? ______ kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

User Specified Value

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-272.*

POINT SOURCE RADIATION MODEL

$q'' = Q\chi_r / 4\pi R^2$

Where q'' = incident radiative heat flux on the target (kW/m^2)
Q = pool fire heat release rate (kW)
χ_r = radiative fraction
R = distance from center of the pool fire to edge of the target (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

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

Where A_{dike} = surface area of pool fire (m^2)
D = pool fire diamter (m)

D = 1.54 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_f$

Where Q = pool fire heat release rate (kW)
m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
ΔH_c = effective heat of combustion of fuel (kJ/kg)
A_f = surface area of pool fire (area involved in vaporization) (m^2)
$k\beta$ = empirical constant (m^{-1})
D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 205.20 kW

Distance from Center of the Fire to Edge of the Target Calculation

$R = L+D/2$

Where R = distance from center of the pool fire to edge of the target (m)
L = distance between pool fire and target (m)
D = pool fire diameter (m)

R = 3.51 m

Radiative Heat Flux Calculation

$q'' = Q\chi_r / 4\pi R^2$

q'' =	0.40 kW/m^2	0.03 Btu/ft^2-sec	Answer

NOTE

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CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m")		0.0044	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	25100	kJ/kg	
Empirical Constant (kβ)		100	m^{-1}	
Heat Release Rate (Q)		1026.02	kW	
Fuel Area or Dike Area (A_{dike})		100.00	ft^2	9.29 m^2
Distance between Fire and Target (L)		9.00	ft	2.7432 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

User Specified Value

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276.*

SOLID FLAME RADIATION MODEL

$\dot{q}'' = E F_{1\rightarrow 2}$

Where	$\dot{q}''$ = incident radiative heat flux on the target (kW/m^2)
	E = emissive power of the pool fire flame (kW/m^2)
	$F_{1\rightarrow 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

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

Where	A_{dike} = surface area of pool fire (m^2)
	D = pool fire diameter (m)
D =	3.44 m

Emissive Power Calculation

E =	$58 (10^{-0.00823 D})$
Where	E = emissive power of the pool fire flame (kW/m^2)
	D = diameter of the pool fire (m)
E =	54.34 kW/m^2

View Factor Calculation

$F_{1\rightarrow 2,H}$ =	$(B-1/S)/\pi(B^2-1)^{1/2} \tan^{-1}((B+1)(S-1)/(B-1)(S+1))^{1/2} - (A-1/S)/(\pi(A^2-1)^{1/2}) \tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$
$F_{1\rightarrow 2,V}$ =	$1/(\pi S) \tan^{-1}(h/(S^2-1)^{1/2}) - (h/\pi S) \tan^{-1}((S-1)/(S+1))^{1/2} + Ah/\pi S(A^2-1)^{1/2} \tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$
A =	$(h^2+S^2+1)/2S$
B =	$(1+S^2)/2S$
S =	2R/D
h =	$2H_f/D$
$F_{1\rightarrow 2,max}$ =	$\sqrt{(F^2_{1\rightarrow 2,H} + F^2_{1\rightarrow 2,V})}$

Where	$F_{1\rightarrow 2,H}$ = horizontal view factor
	$F_{1\rightarrow 2,V}$ = vertical view factor
	$F_{1\rightarrow 2,max}$ = maximum view factor
	R = distance from center of the pool fire to edge of the target (m)
	H_f = height of the pool fire flame (m)
	D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

R = L + D/2

Where	R = distance from center of the pool fire to edge of the target (m)
	L = distance between pool fire and target (m)
	D = pool fire diameter (m)
R = L + D/2 =	4.463 m

Heat Release Rate Calculation

$Q = \dot{m}'' \Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

Where	Q = pool fire heat release rate (kW)
	$\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
	ΔH_c = effective heat of combustion of fuel (kJ/kg)
	A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
	$k\beta$ = empirical constant (m^{-1})
	D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)
Q =	1026.02 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where	H_f = flame height (m)
	Q = heat release rate of fire (kW)
	D = fire diameter (m)
H_f =	0.255 m

S = 2R/D =	2.595
h = $2H_f/D$ =	0.148
A = $(h^2+S^2+1)/2S$ =	1.494
B = $(1+S^2)/2S$ =	1.490

Radiative Heat Flux Calculation

$\dot{q}'' = EF_{1\rightarrow 2}$

$\dot{q}''$ =	**1.14** kW/m^2	**0.10** Btu/ft^2-sec

Answer

NOTE

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

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

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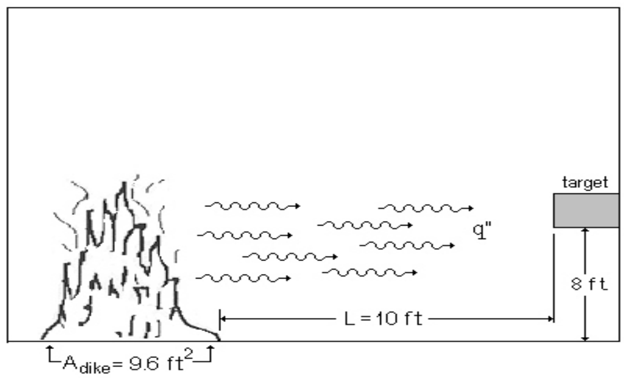
Example Problem 5.11-4

Problem Statement

A pool fire scenario may arise from a leak in a pump. This event allows the lubricating oil to spill and spread over the compartment floor. A pool fire ensues with a spill of 9.6 ft^2 is considered in a compartment with a concrete floor. The distance (L) between the pool fire and the target edge is assumed to be 10 ft. Calculate the flame radiant heat flux to a vertical target (safety-related) 8 ft high above the floor with no wind, using the solid flame radiation model. If the vertical target contains IEEE-383 unqualified cables, could there be cable failure in this fire scenario?



Example Problem 5-4: Radiant Heat Flux from a Pool Fire to a Vertical Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the pool fire to the vertical target using the solid flame radiation model.

(2) Determine if the IEEE-383 unqualified cables are damaged.

Assumptions:

(1) The fire source will be nearly circular.

(2) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls (click on *Solid Flame* 2)

FDT^s Inputs:

-Fuel Spill Area or Curb Area (A_{curb}) = 9.6 ft^2

-Distance between Fire Source and Target (L) = 10 ft

-Vertical Distance of Target from Ground ($H_1 = H_{f1}$) = 8 ft

-Select Fuel Type: **Lube Oil**

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)	Cable Failure
Solid Flame	3.0 (0.26)	No $\dot{q}_r'' < \dot{q}_{critical}''$

*see spreadsheet on next page

Spreadsheet Calculations
FDT^s: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Solid Flame 2)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL ABOVE GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire above ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m'')		0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	46000	kJ/kg	
Empirical Constant ($k\beta$)		0.7	m^{-1}	
Heat Release Rate (Q)		841.15	kW	
Fuel Area or Dike Area (A_{dike})		9.60	ft^2	0.89 m^2
Distance between Fire and Target (L)		10.00	ft	3.048 m
Vertical Distance of Target from Ground ($H_T - H_F$)		8.00	ft	2.4384 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

Lube Oil

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276.*

SOLID FLAME RADIATION MODEL

$q'' = E F_{1\rightarrow 2}$

Where
- q'' = incident radiative heat flux on the target (kW/m^2)
- E = emissive power of the pool fire flame (kW/m^2)
- $F_{1\rightarrow 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

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

Where
- A_{dike} = surface area of pool fire (m^2)
- D = pool fire diameter (m)

$D =$ 1.07 m

Emissive Power Calculation

$E = 58\ (10^{-0.00823\ D})$

Where
- E = emissive power of the pool fire flame (kW/m^2)
- D = diameter of the pool fire (m)

$E =$ 56.84 (kW/m^2)

View Factor Calculation

$F_{1\rightarrow 2,V1} = 1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2}) - (h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_1h_1/\pi S(A_1^2-1)^{1/2}\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$

$F_{1\rightarrow 2,V2} = 1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2}) - (h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_2h_2/\pi S(A_2^2-1)^{1/2}\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$

$A_1 = (h_1^2+S^2+1)/2S$

$A_2 = (h_2^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h_1 = 2H_{f1}/D$

$h_2 = 2H_{f2}/D$

$F_{1\rightarrow 2,V} = F_{1\rightarrow 2,V1} + F_{1\rightarrow 2,V2}$

Where
- $F_{1\rightarrow 2,V}$ = total vertical view factor
- R = distance from center of the pool fire to edge of the target (m)
- H_f = height of the pool fire flame (m)
- D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where
- R = distance from center of the pool fire to edge of the target (m)
- L = distance between pool fire and target (m)
- D = pool fire diameter (m)

$R = L+D/2 =$ 3.581 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}\ (1 - e^{-k\beta D})\ A_{dike}$

Where
- Q = pool fire heat release rate (kW)
- m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ΔH_c = effective heat of combustion of fuel (kJ/kg)
- A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

$Q =$ 841.15 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\ Q^{2/5} - 1.02\ D$

Where
- H_f = flame height (m)
- Q = heat release rate of fire (kW)
- D = fire diameter (m)

$H_f =$ 2.389 m

$S = 2R/D =$ 6.721

$h_1 = 2H_{f1}/D =$ 4.576

$h_2 = 2H_{f2}/D =$ $2(H_f - H_{f1})/D =$ -0.094

$A_1 = (h_1^2+S^2+1)/2S =$ 4.993

Radiative Heat Flux Calculation

$q'' = EF_{1\rightarrow 2}$

q'' =	2.99	kW/m^2	0.26	Btu/ft^2-sec	Answer

NOTE

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

Calculations are based on certain assumptions and 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.

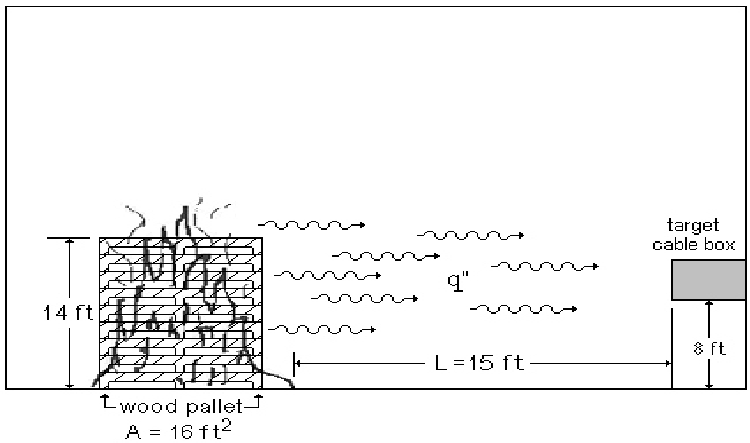
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

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 5.11-5

Problem Statement

A transient combustible fire scenario may arise from burning wood pallets (4 ft x 4 ft = 16 ft^2), stacked 14 ft high on the floor of a compartment. Calculate the flame radiant heat flux from exposure fire to a vertical target (safety-related electrical junction box) located 8 ft high above the floor, with no wind, using the solid flame radiation model. The distance (L) between the transient fire and the target edge is assumed to be 15 ft.



Example Problem 5-5: Radiant Heat Flux from a Burning Pallet to a Vertical Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the burning pallet to the vertical target fuel using the solid flame radiation model.

Assumptions:

(1) The fire source will be nearly circular.

(2) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls (click on *Solid Flame 2*)

FDT^s Inputs:

-Fuel Spill Area or Curb Area (A_{curb}) = 16 ft^2

-Distance between Fire Source and Target (L) = 15 ft

-Vertical Distance of Target from Ground (H_1 = H_{f1}) = 8 ft

-Select Fuel Type: **Douglas Fir Plywood**

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)
Solid Flame	0.30 (0.03)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Solid Flame 2)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL ABOVE GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire above ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m'')		0.01082	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	10900	kJ/kg	
Empirical Constant ($k\beta$)		100	m^{-1}	
Heat Release Rate (Q)		175.31	kW	
Fuel Area or Dike Area (A_{dike})		16.00	ft^2	1.49 m^2
Distance between Fire and Target (L)		15.00	ft	4.572 m
Vertical Distance of Target from Ground ($H_1 = H_2$)		8.00	ft	2.4384 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

Douglas Fir Plywood

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, *Page 3-276*.

SOLID FLAME RADIATION MODEL

$q'' = EF_{1\to 2}$

Where q'' = incident radiative heat flux on the target (kW/m^2)

E = emissive power of the pool fire flame (kW/m^2)

$F_{1\to 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

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

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diamter (m)

D = 1.38 m

Emissive Power Calculation

$E = 58\ (10^{-0.00823\ D})$

Where E = emissive power of the pool fire flame (kW/m^2)

D = diameter of the pool fire (m)

E = 56.51 (kW/m^2)

View Factor Calculation

$F_{1\to 2,V1} = 1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2})-(h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_1h_1/\pi S(A_1^2-1)^{1/2}\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$

$F_{1\to 2,V2} = 1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2})-(h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_2h_2/\pi S(A_2^2-1)^{1/2}\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$

$A_1 = (h_1^2+S^2+1)/2S$

$A_2 = (h_2^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h_1 = 2H_{f1}/D$

$h_2 = 2H_{f2}/D$

$F_{1\to 2,V} = F_{1\to 2,V1} + F_{1\to 2,V2}$

Where $F_{1\to 2,V}$ = total vertical view factor

R = distance from center of the pool fire to edge of the target (m)

H = height of the pool fire flame (m)

D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where R = distance from center of the pool fire to edge of the target (m)

L = distance between pool fire and target (m)

D = pool fire diameter (m)

R = L+D/2 = 5.260 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D})A_{dike}$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

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

A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 175.31 kW

Pool Fire Flame Height Calculation

$H = 0.235\ Q^{2/5} - 1.02\ D$

Where H = flame height (m)

Q = heat release rate of fire (kW)

D = fire diameter (m)

H = 0.453 m

$S = 2R/D =$ 7.647

$h_1 = 2H_{f1}/D =$ 3.545

$h_2 = 2H_{f2}/D =$ $2(H-H_{f1})/D =$ -2.887

$A_1 = (h_1^2+S^2+1)/2S =$ 4.710

Radiative Heat Flux Calculation

$q'' = EF_{1\rightarrow 2}$

q'' =	0.30 kW/m^2	0.03 Btu/ft^2-sec	Answer

NOTE

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

Calculations are based on certain assumptions and 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.

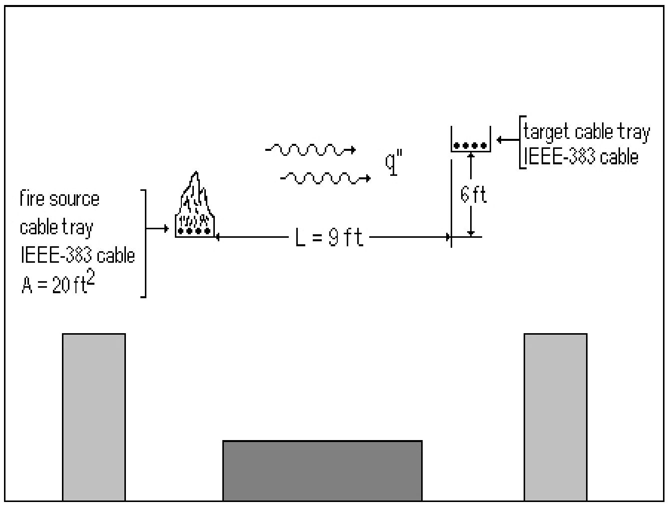
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

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 5.11-6

Problem Statement

A fire scenario may arise from a horizontal cable tray burning in a very large compartment. The cables in the tray are IEEE-383 unqualified and made of XPE/FRXPE insulation material (assume that the exposed area of the cable is 20 ft^2). A safety-related cable tray is also filled with IEEE-383 qualified made of XLPE insulation material located at a radial distance (L) of 9 ft from the fire source and 6 ft above the fire source. Calculate the flame radiant heat flux to a target (safety-related cable tray) using the solid flame radiation model. Is the IEEE-383 qualified cable tray damaged?



Example Problem 5-6: Radiant Heat Flux from a Burning Cable Tray to a Vertical Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the burning cable tray to the vertical target cable tray using the solid flame radiation model.

(2) Determine if the IEEE-383 cable tray (target) is damaged.

Assumptions:

(1) The fire source will be nearly circular.

(2) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls (click on *Solid Flame 2*)

FDT^s Inputs:

-Mass Burning Rate of Fuel ($\dot{m}''$) = 0.0037 kg/m^2-sec

-Effective Heat of Combustion of Fuel ($H_{c,eff}$) = 28,300 kJ/kg

-Fuel Spill Area or Curb Area (A_{curb}) = 20 ft^2

-Distance between Fire Source and Target (L) = 9 ft

-Vertical Distance of Target from Ground ($H_1 = H_{f1}$) = 6 ft

Note: Since the insulation material (XPE/FRXPE) is not available in the thermal properties data of the spreadsheet, we have to input the mass burning rate and effective heat of combustion in the spreadsheet. Values of cable materials properties are available in Table 3-4. Select **User-Specified Value**, and enter the $\dot{m}''$ and $H_{c,eff}$ values from Table 3-4.

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)	Cable Failure
Solid Flame	0.60 (0.05)	No, $\dot{q}''_r < \dot{q}''_{critical}$

*see spreadsheet on next page

Spreadsheet Calculations
FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Solid Flame 2)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL ABOVE GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire above ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m'')		0.0037	kg/m²-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	28300	kJ/kg	
Empirical Constant ($k\beta$)		20	m⁻¹	
Heat Release Rate (Q)		194.56	kW	
Fuel Area or Dike Area (A_{dike})		20.00	ft²	1.86 m²
Distance between Fire and Target (L)		9.00	ft	2.7432 m
Vertical Distance of Target from Ground ($H_1 = H_2$)		6.00	ft	1.8288 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE
Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? ______ kW

Calculate

THERMAL PROPERTIES DATA
BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m²-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m⁻¹)
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type
User Specified Value
Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276.*

SOLID FLAME RADIATION MODEL

$q'' = EF_{1\rightarrow 2}$

Where q'' = incident radiative heat flux on the target (kW/m^2)
E = emissive power of the pool fire flame (kW/m^2)
$F_{1\rightarrow 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

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

Where A_{dike} = surface area of pool fire (m^2)
D = pool fire diameter (m)

D = 1.54 m

Emissive Power Calculation

$E = 58\ (10^{-0.00823\ D})$

Where E = emissive power of the pool fire flame (kW/m^2)
D = diameter of the pool fire (m)

E = 56.33 (kW/m^2)

View Factor Calculation

$F_{1\rightarrow 2,V1} = 1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2}) - (h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_1h_1/\pi S(A_1^2-1)^{1/2}\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$

$F_{1\rightarrow 2,V2} = 1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2}) - (h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_2h_2/\pi S(A_2^2-1)^{1/2}\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$

$A_1 = (h_1^2+S^2+1)/2S$

$A_2 = (h_2^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h_1 = 2H_{f1}/D$

$h_2 = 2H_{f2}/D$

$F_{1\rightarrow 2,V} = F_{1\rightarrow 2,V1} + F_{1\rightarrow 2,V2}$

Where $F_{1\rightarrow 2,V}$ = total vertical view factor
R = distance from center of the pool fire to edge of the target (m)
H_f = height of the pool fire flame (m)
D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where R = distance from center of the pool fire to edge of the target (m)
L = distance between pool fire and target (m)
D = pool fire diameter (m)

R = L+D/2 = 3.512 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}\ (1 - e^{-k\beta D})\ A_{dike}$

Where Q = pool fire heat release rate (kW)
m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
ΔH_c = effective heat of combustion of fuel (kJ/kg)
A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
$k\beta$ = empirical constant (m^{-1})
D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 194.56 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\ Q^{2/5} - 1.02\ D$

Where H_f = flame height (m)
Q = heat release rate of fire (kW)
D = fire diameter (m)

H_f = 0.366 m

$S = 2R/D$ = 4.567

$h_1 = 2H_{f1}/D$ = 2.378

$h_2 = 2H_{f2}/D$ = $2(H_f-H_{f1})/D$ = -1.902

$A_1 = (h_1^2+S^2+1)/2S$ = 3.012

Radiative Heat Flux Calculation

$q'' = EF_{1\rightarrow 2}$

q" =	0.57 kW/m^2	0.05 Btu/ft^2-sec	Answer

NOTE

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

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

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

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

ERRATA

NUREG-1805 Fire Dynamics Tools (FDT)[s] - Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program

Page 5-12, Equation 5-15

Replace

$$\pi F_{1\rightarrow 2,H} = \left(\begin{array}{l} \tan^{-1} \dfrac{\sqrt{\dfrac{b+1}{b-1}}}{\pi\sqrt{B^2-1}} - \dfrac{a^2+(b+1)^2-2(b+1+ab\sin\theta)}{\sqrt{AB}}\tan^{-1}\sqrt{\dfrac{A}{B}}\sqrt{\dfrac{(b-1)}{(b+1)}} + \\ \dfrac{\sin\theta}{\sqrt{C}}\left(\tan^{-1}\dfrac{ab-(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\dfrac{(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}}\right) \end{array} \right)$$

by

$$\pi F_{1\rightarrow 2,H} = \left(\begin{array}{l} \tan^{-1} \sqrt{\dfrac{b+1}{b-1}} - \dfrac{a^2+(b+1)^2-2(b+1+ab\sin\theta)}{\sqrt{AB}}\tan^{-1}\sqrt{\dfrac{A}{B}}\sqrt{\dfrac{(b-1)}{(b+1)}} + \\ \dfrac{\sin\theta}{\sqrt{C}}\left(\tan^{-1}\dfrac{ab-(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\dfrac{(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}}\right) \end{array} \right)$$

Page 17-2, Table 17-1

Replace

Table 17-1. Standard Time-Temperature Curve Points

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

By

Table 17-1. Standard Time-Temperature Curve Points

Time	**Temperature ˚C (˚F)**
5 min	538 (1,000)
10 min	704 (1,300)
30 min	843 (1,550)
1 hr	927 (1,700)
2 hr	1,010 (1,850)
4 hr	1,093 (2,000)
8 hr	1,260 (2,300)

Page 2-12, Equation (2-6)

Replace

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

By

$$K_1 = \frac{2\ \left(0.4\sqrt{k\rho c}\right)\ A_T}{mc_p}$$

And:

ΔT_g = upper layer gas temperature rise above ambient (T_g - T_a) (K)
k = thermal conductivity of the interior lining (kW/m-K)
A_T = area of the compartment boundaries surface (m^2)
ρ = density of the interior lining (kg/m^3)
c = thermal capacity of the interior lining (kJ/kg-K)
$\dot{Q}$ = heat release rate of the fire (kW)
m = mass of the gas in the compartment (kg)
c_p = specific heat of air (kJ/kg-k)
t = exposure time (sec)