CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE, HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

3.1 Objectives

This chapter has the following objectives:

- Identify the predominant flammable material in a nuclear power plant (NPP).
- Introduce the methods that are used to estimate the heat release rate.
- Identify the factors that influence the heat release rate and burning rate.
- Explain how to analyze pool fires in NPPs.
- Explain how to analyze the burning duration of pool fires.
- Identify the zones of a candle and the categories of a flame.
- Describe the importance of ceiling configurations.
- Explain turbulent diffusion flames.
- Introduce the factors that determine how fast an object will heat.
- Define relevant terms, including heat release rate, heat of combustion, burning duration, flame height, adiabatic flame, laminar, and turbulent flames.

3.2 Heat Release Rate

Fire development is generally characterized in terms of heat release rate (HRR) vs. time. Thus, determining the HRR (or burning rate)[1] is an essential aspect of a fire hazard analysis (FHA). The relationship between HRR (or $\dot{Q}$) and time for a certain scenario is termed the design fire curve for that scenario, as illustrated in Figure 3-1.

For a routine FHA, it is acceptable to broadly approximate the burning rates (HRRs). For instance, post-flashover structure analyses are often based on the fire duration or severity associated with an aggregate fuel loading (combustible load per unit floor area). However, if it is essential to estimate specific fire effects within an enclosure, it is essential to more accurately determine the burning rate characteristics (i.e., HRR history).

The HRR is not a fundamental property of a fuel and, therefore, cannot be calculated from the basic material properties. It is usually determined from testing. Table 3-1 lists some HRR characteristic values obtained by burning various fuel packages and recording the heat output from various sources. Estimates of fire source intensities (i.e., HRR) can be based either on direct measurements of the burning rates of similar large fuel configurations or the extrapolation of small-scale test data obtained under simulated thermal conditions. In the absence of measured HRR data, the fire protection engineer (FPE) must estimate the HRR history for a particular fuel. While not as accurate as laboratory testing, sufficient information exists in the literature to permit estimates of initial fire growth, peak burning rates, and fire duration for various fuels and fuel geometries.

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[1] The heat release rate may be thought of as the “power” of the fire and is some times referred to as fire “power.”

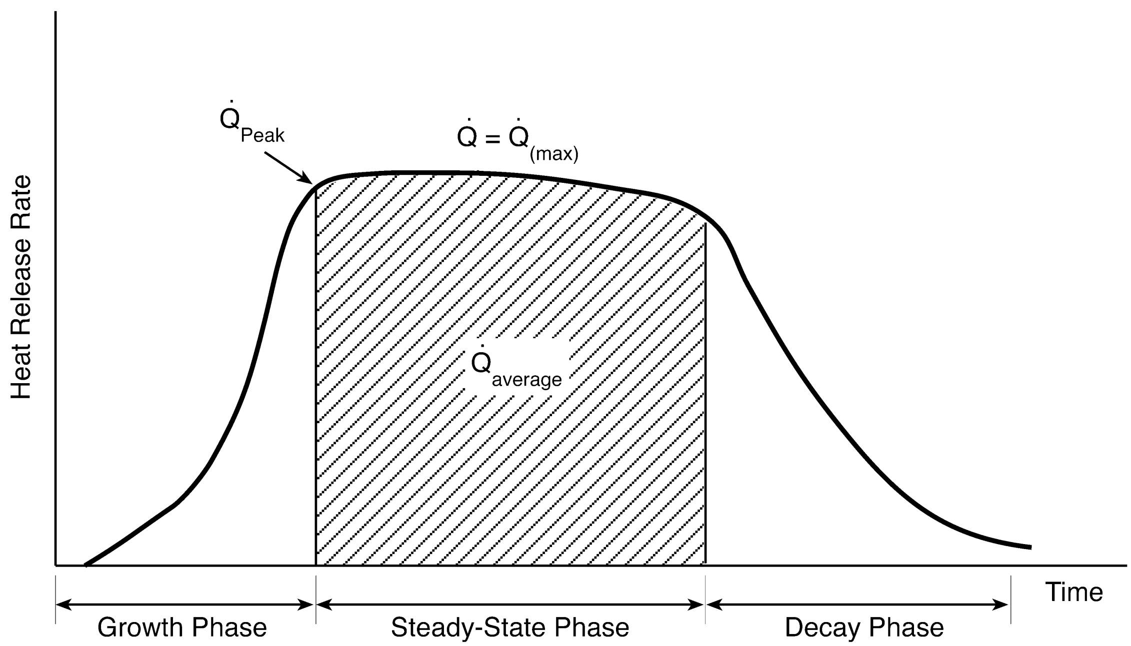


Figure 3-1 A Simple Design Fire Curve

Table 3-1. Rough Measure of Heat Generated from Various Sources
(Karlsson and Quintiere, 1999, © CRC Press, LLC. With permission.)

Fuel	**Heat Release Rate** $(\dot{Q})$
A burning cigarette	5 W
A typical light bulb	60 W
A burning candle	80 W
A human being at normal exertion	100 W
A burning wastepaper basket	100 kW
A burning 1 m^2 pool of gasoline	2.5 MW
Burning wood pallets, stacked to a height of 3 m	7 MW
Burning polystyrene jars, in 2 m^2 cartons 4.9 m high	30–40 MW
Output from a typical reactor at an NPP	3,250–3,411 MW
Note: 1 kW = 1,000 W and 1 MW = 1,000 kW	

Various studies (Lee, 1985, Nowlen, 1986, and 1987, Chavez, 1987, and Babrauskas, 1991) have measured and reported representative unit HRR values for a number of fuels present in an NPP, such as electrical cables, electrical cabinets, and transient combustibles (e.g., flammable/combustible liquids and trash). Flammable/combustible liquid spill fires and trash fires are the most commonly postulated transient fuel exposure fires, while electrical cable and cabinet fires are the most commonly postulated fixed fuel fires in NPPs. In fact, the plastic insulation and jackets on electrical cables are usually the predominant flammable material in an NPP.

The most common method to measure HRR is known as "oxygen consumption calorimetry" (ASTM E1354). The basis of this method is that most gases, liquids, and solids release a constant amount of energy for each unit mass of oxygen consumed. This constant has been found to be 13,100 kJ/kg oxygen consumed and is considered to be accurate within ±5 percent for most hydrocarbon fuels. After ignition, all of the combustion products are collected in a hood and removed through an exhaust duct in which the flow rate and composition of the gases is measured to determine how much oxygen has been used for combustion. The HRR then can be computed using the constant relationship between oxygen consumed and energy released.

Another common method of assessing HRR is to measure the burning rate, which is also known as the mass loss rate. This is done by weighing the fuel package as it burns, using weighing devices or a load cell. Estimating the HRR based on the mass loss rate requires knowledge of the effective heat of combustion. The HRR is then calculated using the following equation:

$$\dot{Q} = \dot{m}\Delta H_{c,eff} \qquad (3\text{-}1)$$

Where:

$\dot{Q}$ = heat release rate (kW)
$\dot{m}$ = burning or mass loss rate (kg/sec)
$H_{c,eff}$ = effective heat of combustion (kJ/kg)

The average burning rates for many products and materials have been experimentally determined in free-burning tests. For many materials, the burning rate is reported per horizontal burning area in units of kg/m^2-sec. If the area of the fuel and the effective heat of combustion are known, the above equation becomes:

$$\dot{Q} = \dot{m}''\Delta H_{c,eff}\, A_f \left(1 - e^{-k\beta D}\right) \qquad (3\text{-}2)$$

Where:

$\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)
A_f = horizontal burning area of the fuel (m^2)
$k\beta$= empirical constant (m^{-1})
D = diameter of burning area (m)

The average burning rate per unit area per unit time, heat of combustion, and fuel-specific properties have been tabulated for a number of different fuels. (See Table 3-2 for free-burning fire characteristics of various fuels.)

Table 3-2. Large-Pool Fire Burning Rate Data
(Babrauskas, 2002, © SFPE. With permission.)

Material	**Mass Loss Rate** $\dot{m}''$ **(kg/m^2-sec)**	**Heat of Combustion** $H_{c,\,eff}$ **(kJ/kg)**	**Density (kg/m^3)**	**Empirical Constant** $k\beta$ **(m^{-1})**
Cryogenics				
Liquid H_2	0.017	12,000	70	6.1
LNG (mostly CH_4)	0.078	50,000	415	1.1
LPG (mostly C_3H_8)	0.099	46,000	585	1.4
Alcohols				
Methanol (CH_3OH)	0.017	20,000	796	100 **
Ethanol (C_2H_5OH)	0.015	26,800	794	100 **
Simple Organic Fuels				
Butane (C_4H_{10})	0.078	45,700	573	2.7
Benzene (C_6H_6)	0.085	40,100	874	2.7
Hexane (C_6H_{14})	0.074	44,700	650	1.9
Heptane (C_7H_{16})	0.101	44,600	675	1.1
Xylene (C_8H_{10})	0.090	40,800	870	1.4
Acetone (C_3H_6O)	0.041	25,800	791	1.9
Dioxane ($C_4H_8O_2$)	0.018	26,200	1,035	5.4
Diethyl ether ($C_4H_{10}O$)	0.085	34,200	714	0.7
Petroleum Products				
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosene	0.039	43,200	820	3.5
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, hydrocarbon	0.039	46,400	760	0.7
Fuel Oil, heavy	0.035	39,700	940–1,000	1.7
Crude Oil	0.022–0.045	42,500–42,700	830–880	2.8
Solids				
Polymethylmethacrylate $(C_5H_8O_2)_n$	0.020	24,900	1,184	3.3
Polypropylene $(C_3H_6)_n$	0.018	43,200	905	100 **
Polystyrene $(C_8H_8)_n$	0.034	39,700	1,050	100 **
Miscellaneous				
561® Silicon Transformer Fluid	0.005	28,100	960	100 **

** these values are to be used only for computation purposes; the true values are unknown.

The effective heat of combustion (sometimes called the chemical heat of combustion) is a measure of how much energy is released when a unit mass of material is oxidized. This value is typically given in kJ/kg. It is important to distinguish between the complete heat of combustion and the effective heat of combustion. The complete heat of combustion is the measure of energy released when combustion is complete, leaving no residual fuel and releasing all of the chemical energy of the material. The effective heat of combustion is more appropriate for a fire in which combustion is not necessarily complete and some residue remains. This is also sometimes termed the chemical heat of combustion.

For example, Babrauskas (1983 and 1986) distinguishes four burning modes of pool fires as defined by size in Table 3-3.

Table 3-3. Pool Fire Burning Modes

Pool Fire Diameter (m)	**Burning Mode**
<0.05 (2 in)	Convective, laminar
<0.2 (8 in)	Convective, turbulent
0.2 to 1.0 (8 in to 3.3 ft)	Radiative, optically thin
>1.0 (3.3 ft)	Radiative, optically thick

3.2.1 Enclosure Effects on Mass Loss Rate

When an object (fuel) burns inside a compartment, the two main factors that influence the fire growth are energy released and burning or mass loss rate of the fuel. The smoke and hot gases will accumulate at the compartment ceiling level and heat the compartment boundaries (ceiling and walls). These compartment boundary surfaces and the hot gases radiate heat toward the fuel surface, thereby increasing the fuel burning rate. Second, the compartment openings (doors, windows, and other leakage areas) may restrict the availability of oxygen needed for combustion, thereby decreasing the amount of fuel consumed and increasing in the concentration of unburned gases. If the ventilation opening is small, the limited availability of oxygen causes incomplete combustion, thereby decreasing the HRR, which in turn reduces the gas temperature and heat transfer to the fuel surface, while the fuel continues to release volatile gases at a similar or somewhat lower rate. When partial combustion of the gases occurs within the compartment, the gas leaving the compartment mixes with oxygen and flames appear at the ventilation opening. In summary, compartment heat transfer can increase the burning or mass loss rate of the fuel, while compartment ventilation of the available air near the floor decreases the mass loss rate.

3.2.2 Pool Fires

A pool fire involves a horizontal, upward-facing, combustible fuel. The term implies the fuel in the liquid phase (pool), but it can also apply to flat slabs of solids fuels which decompose in a manner similar to liquids [e.g., Polymethylmethacrylate (PMMA or Plexiglass) and Polyethylene (PE)]. Liquid fuel may burn in an open storage container or on the ground in the form of a spill. For a given amount of fuel, spills with a large surface area burn with a high HRR for a short duration, and spills with a smaller surface area burn with a lower HRR for a longer duration. When spilled, the flammable/combustible liquid may form a pool of any shape and thickness, and may be controlled by the confinement of the area geometry such as a dike or curbing. Once ignited, a pool fire spreads rapidly over the surface of the liquid spill area. The burning rate of a given fuel can also be affected by its substrate (i.e., gravel and sand) in a spill. For flammable/combustible liquids, flame spread rates range from approximately 10 cm/sec (4 in/sec) to 2 m/sec (6.6 ft/sec). Pool fires in NPPs can result from leakage of the reactor coolant pump (RCP) at the gland or the seal, oil spill from electrical transformers, and pumps or fuel spray from pipe flanges on equipment such as standby diesel generator (SBDGs). Transient fuels such as liquids used for cleaning and painting are sources of pool fire in an NPP. Figure 3-2 depicts the dynamic feature of a pool fire. Table 3-4 summarizes the burning rate of combustible liquids and solids found in typical NPPs.

Table 3-4. Burning Rates of Some Common Combustible Materials
Found in Nuclear Power Plants*

Fuel	**Mass Burning Rate** $\dot{m}''$ **(kg/m^2-sec)**	**Heat of Combustion** $H_{c,eff}$ **(kJ/kg)**	**Density (kg/m^3)**
Cable Materials			
PE/PVC	0.0044	25,100	-
XPE/FRXPE	0.0037	28,300	-
XPE/Neoprene	0.0043	10,300	-
PE, PP/Cl.S.PE	0.0026	26,800	-
FRXPE/Cl.S.PE	0.0033	17,300	-
PE, Nylon/PVC, Nylon	0.0034	10,200	-
Silicone, glass braid, asbestos	0.0045	24,000	-
XPE/XPE	0.0044	12,500	-
FEP - Teflon™	0.007	3,200	-
ETFE - Tefzel™	0.014	12,600	-
Flammable/Combustible Liquid			
Diesel Oil	0.044	44,400	918
Gasoline	0.055	43,700	740
Kerosene	0.039	43,200	820
Transformer Oil	0.039	46,000	760
Lube Oil (used in RCP motors and turbine lubrication)**	-	-	-
Cellulose Material			
Wood	0.055	13,000–15,000	420–640

*Empirical constants ($k\beta$) are unknown. Use $k\beta$ = 100m^{-1} as a conservative estimate.

**For lubricating oil, use properties of transformer oil (has similar burning characteristics).

CL.S.PE-Chlorosulfonated Polyethylene; FR-Fire Retardant; PE-Polyethylene; PP-Polypropylene; PVC-Polyvinylchloride; Teflon™ - FEP-Fluorinated Polyethylene- Propylene; Tefzel™- ETFE-Ethylenetetrafluoroethylene; XLPE-Crosslinked Polyethylene.

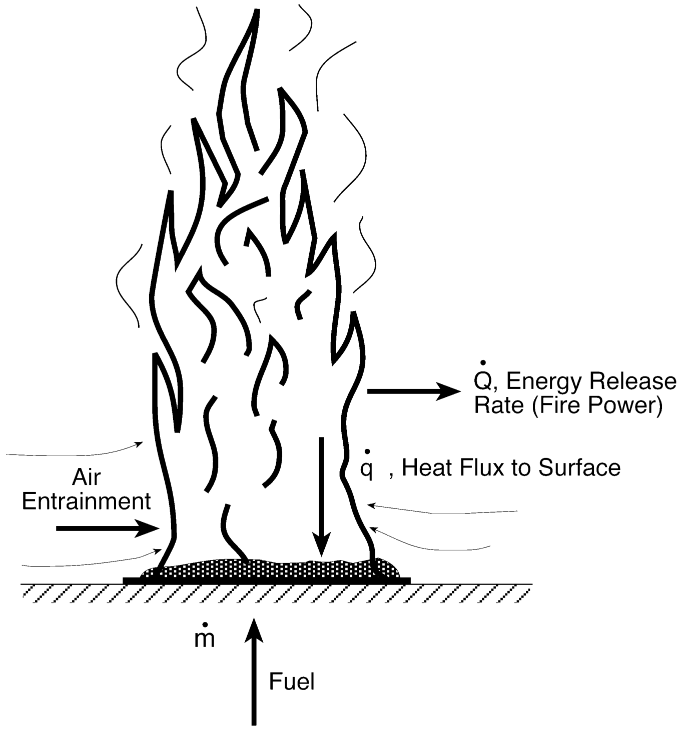


Figure 3-2 Dynamic Features of a Pool Fire

3.3 Burning Duration

The burning rate of a given fuel is controlled by both its chemistry and its form. Fuel chemistry refers to its composition (e.g., cellulosic *vs.* petrochemical). Common cellulosic materials include wood, paper, cotton, and fabric. Petrochemical materials include liquids or plastics that are largely petroleum based. The form (or shape) of the fuel material also has an effect on its burning rate. A particularly important form factor is the surface area to mass ratio of the fuel, which is defined as the surface area available to combust as compared to the total mass of the material.

The concept of burning duration is a way of characterizing the hazard of a compartment fire in terms of the length of time the fuel in the compartment could be expected to burn, which depends on the total amount of fuel available. Fuel loading is the concept that describes the expected burning duration, provided that the necessary amount of air is available (i.e., fuel-controlled fire). A fire burning at a constant HRR consumes fuel mass at a constant rate. Thus, the mass of material being burned per second and the amount of material available to be consumed, it is possible to estimate the total burning duration of a fuel.

3.3.1 Burning Duration of a Pool Fire

When a spilled liquid is ignited, a pool fire develops. Provided that an ample supply of oxygen is available, the amount of surface area of the given liquid becomes the defining parameter. The diameter of the pool fire depends upon the release mode, release quantity (or rate), and burning rate. In some instances, the spill is unrestricted by curbs or dikes, allowing it to spread across the ground and establish a large exposed surface area. Liquid pool fires with a given amount of fuel can burn for long periods of time if they have a small surface area, or for short periods of time over a large spill area. For a fixed mass or volume of flammable/combustible liquid, the burning duration (t_b) for the pool fire is estimated using the following expression:

$$t_b = \frac{4V}{\pi D^2 \nu} \qquad (3\text{-}3)$$

Where:

V = volume of liquid (gallons or m^3)
D = pool diameter (m)
= regression rate (m/sec)

As a pool of liquid combusts and the fuel is consumed, its depth decreases. The rate of burning, also called the regression rate ( ), is defined as a volumetric loss of liquid per unit surface area of the pool per unit time, as illustrated by the following expression:

$$\nu = \frac{\dot{m}''}{\rho} \qquad (3\text{-}4)$$

Where:

$\dot{m}''$ = mass burning rate of fuel per unit area (kg/m^2-sec)
= liquid fuel density (kg/m^3)

3.4 Flame Height

A flame is a body or stream of gaseous material involved in the combustion process, which emits radiant energy at specific wavelength bands depending on the combustion chemistry of the fuel involved. In most cases, some portion of the emitted radiant energy is visible to the human eye as the glowing, gaseous portion of a fire, which is typically referred to as its flame.

The flame generally consists of a mixture of oxygen (air) and another gas, typically a combustible substance such as hydrogen, carbon monoxide, or a hydrocarbon. The brightest flames are not always the hottest. For example, hydrogen exhibits a high flame temperature. However it combines with oxygen when burning to form water, hydrogen has an almost invisible flame under ordinary circumstances. When hydrogen is absolutely pure and the air around it is completely free of dust, the hydrogen flame cannot be seen, even in a dark room.

In order to gain a better understanding of flames, a burning candle can be used as an example. When the candle is lit, the heat of the match melts the wax, which is carried up the wick and vaporized by the heat. As it is broken down by the heat, the vaporized wax combines with the oxygen of the surrounding air and produces heat and light in the form of a flame. The candle flame consists of three zones, which are easily distinguished. The innermost, nonluminous zone is composed of a gas/air mixture at a comparatively low temperature. In the second luminous zone, hydrogen (H_2) and carbon monoxide (CO) (two of many products from the decomposition of the wax) react with oxygen to form combustion products, which include water (H_2O) and carbon dioxide (CO_2). In this zone, the temperature of the flame is 590–680 °C (1,094–1,256 °F), which is sufficiently intense to dissociate the gases in the flame and produce free carbon particles. These particles are heated to incandescence and then consumed. Outside the luminous zone is a third, invisible zone in which the remaining CO and H_2 are finally consumed. This zone is not visible to the human eye. Figure 3-3 shows the temperature distribution through the flame of a burning candle.

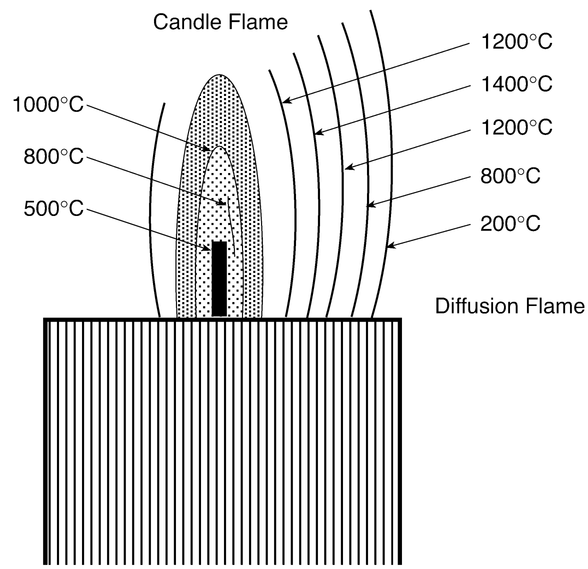


Figure 3-3 Temperature Distribution in the Flame of a Burning Candle

All combustible substances require a finite amount of oxygen for complete burning. (A flame can be sustained in an atmosphere of pure chlorine, but combustion cannot complete.) In the burning of a candle or solids such as wood or coal, the surrounding atmosphere supplies this oxygen. In gas burners, air or pure oxygen is mixed with the gas at the base of the burner so that the carbon is consumed almost instantaneously at the mouth of the burner. This is an example of a premixed flame. The hottest portion of the flame of a Bunsen burner has a temperature of approximately 1,600 °C (2,912 °F). By contrast, the hottest portion of the oxygen-acetylene flames (torch) used for cutting and welding metals reaches approximately 3,500 °C (6,330 °F) because the increased oxygen in the case of the torch yields a significantly higher flame temperature. Any time the oxygen rate is increased (e.g., wind- or airflow-aided combustion or an oxygen-enriched atmosphere), the temperatures obtained will be higher than for the fuel combusting in a normal atmosphere.

A flame can be thought of in two distinct categories, including diffusion flame (Figure 3-4) and premixed flame (Figure 3-5). A diffusion flame is one in which the fuel and oxygen are transported (diffused) from opposite sides of the reaction zone (flame). A premixed flame is one in which the oxygen is mixed with the combustible gas by some mechanical device prior to combustion. Figure 3-6 illustrates a laminar diffusion flame produced by a burning candle. (Laminar means that the flow streamlines are smooth and do not bounce around significantly.) Figure 3-7 illustrates practical examples of premixed flames.

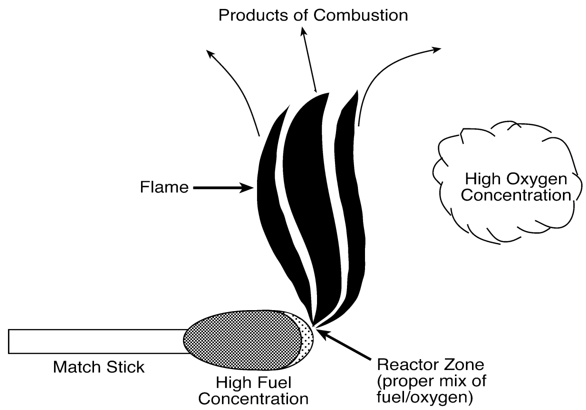


Figure 3-4 Diffusion Flame

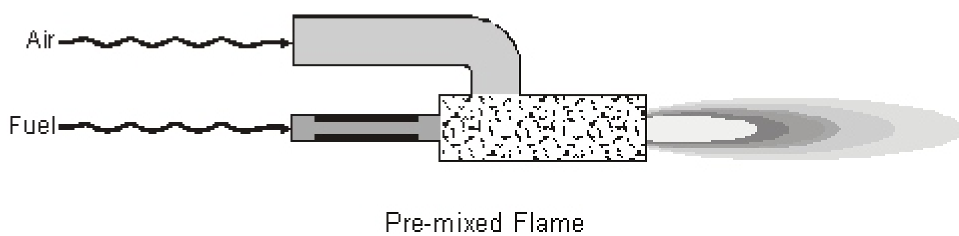


Figure 3-5 Premixed Flame

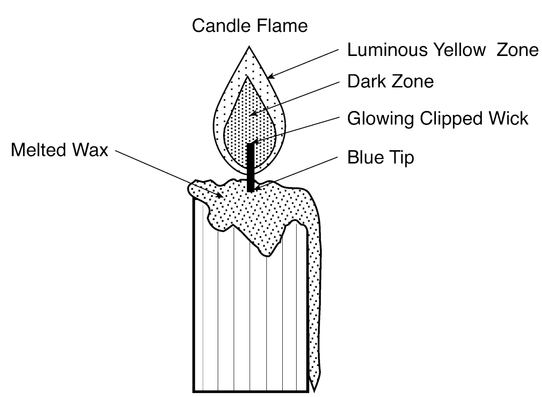
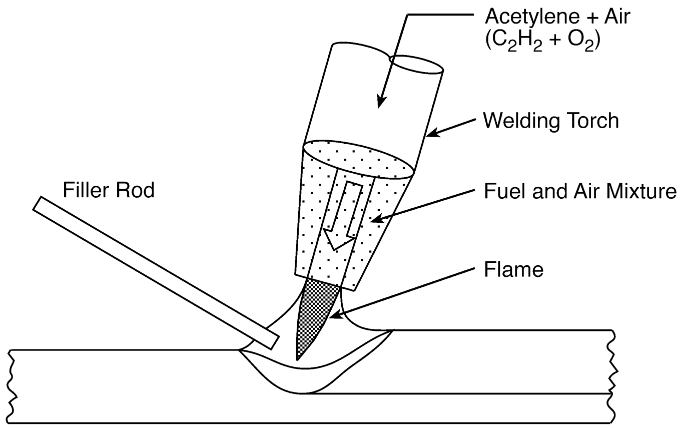
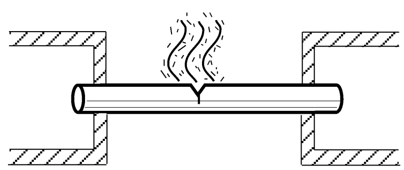


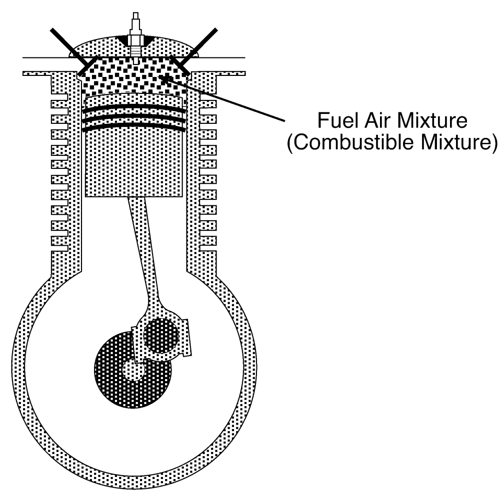
Figure 3-6 Laminar Diffusion Flame



Oxy-Acetylene Flame



Gas Leaking Pipe Break



Internal Combustion (IC) Engine

Figure 3-7 Turbulent Premixed Flames

Most turbulent premixed flames occur in engineered combustion systems, such as a boiler, furnace, process heater, gas burner, oxyacetylene torch, gasoline engine, or home gas cooking range. Most natural flaming processes produce diffusion flames, since no burner or other mechanical device exists to mix fuel and air. Common examples include a candle flame, a trash can fire, a hydrocarbon pool fire, or a forest fire.

3.4.1 Flame Extensions Under Ceiling

Most fire protection engineering (FPE) applications are concerned with the buoyant axisymmetric plume, which is caused by a turbulent diffusion flame above the burning fuel. When a flame impinges on an unconfined ceiling, the unburnt gases spread out radially and entrain air for combustion. A circular flame is then established under the ceiling, forming what is known as a ceiling jet. The ceiling configuration is very important for at least two reasons:

(1) Fire detection devices and automatic sprinklers are generally mounted just under the ceiling, and knowledge of the time of arrival and properties of a potential ceiling jet are crucial for predicting when the devices will be actuated.

(2) The downward thermal radiation from a ceiling jet, and from the hot ceiling itself, is a major factor in preheating and igniting combustible items that are not yet involved in the fire. This radiation heat transfer is very important in affecting the rate of fire spread. Figure 3-8 shows flame extensions under a smooth ceiling.

3.4.2 Flame Impingement

Flame that directly impacts a surface is called flame impingement. Direct flame impingement generally transfers large quantities of heat to the surface. Flame impingement occurs when gases from a buoyant stream rise above a localized area. The buoyant gas stream is generally turbulent except when the fire source is very small.

3.4.3 Flame Temperature

The pulsing behavior of a flame affects its temperature. The temperature varies across the width and height of the flame and the temperature at a fixed position will fluctuate widely, particularly around the edges and near the top of the flame. Therefore, any discussion of flame temperature usually involves reporting the centerline temperature or average flame temperature, which is determined by measuring the temperature at different times and different locations within the flame.

Table 3-5 summarizes the average flame temperature for a range of common fuel types. Notice that the flame temperature for flames involving gasoline is approximately the same as for flames involving wood. While these values may seem odd, they are explained by the different radiation properties of the flames produced by the respective materials.

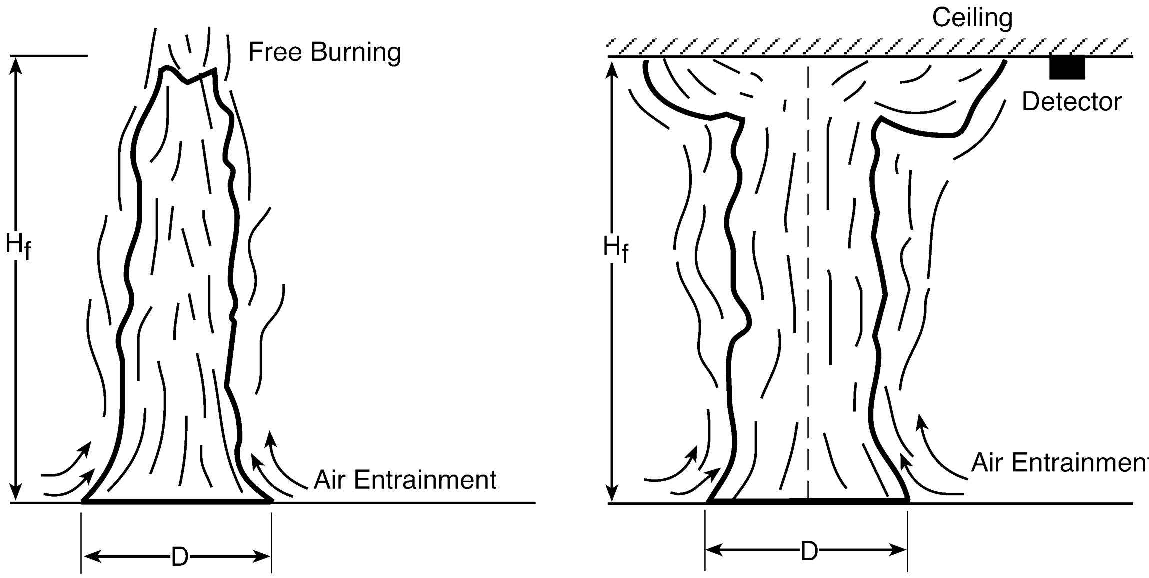


Figure 3-8 Flame Extensions with a Free-Burning Flame
and Under a Smooth Ceiling

Table 3-5. Flame Temperatures of Selected Fuels

Fuel Source (Flames)	**Flame Temperature °C (°F)**
Benzene	921 (1,690)
Gasoline	1,026 (1,879)
JP-4	927 (1,701)
Kerosene	990 (1,814)
Methanol	1,200 (2,192)
Wood	1,027 (1,881)

For convenience, we can subdivide the turbulent diffusion flames from potentially hazardous fires into flames in the open, and room fires as described in the following sections.

3.4.4 Flames Temperatures of Open Fires

The starting point for discussing the flame temperatures of open fires can be the work of the McCaffrey (1979), who extensively studied temperatures in turbulent diffusion flames. McCaffrey used gas burners in a “pool fire” mode (i.e., non-premixed) and studied various characteristics of such fire plumes. He described three different regimes in such a fire plume:

(1) The continuous flame region begins slightly above the base of the fire, where the temperatures are constant and slightly below 900 °C (1,652 °F).

(2) The intermittent flame region is above the continuous flame region. Here the temperatures drop as a function of distance up the plume. The visible flame tips have a temperature of about 320 °C (608 °F).

(3) The thermal plume region is beyond the flame tips, where no more flames are visible and the temperature continues to drop as height increases away from the flame.

French researchers at the University of Poitiers recently made the same types of measurements (Audoin et al., 1995) and reported numerical values indistinguishable from McCaffrey’s (Cox and Chitty, 1980). The French researchers measured similar plumes and obtained very similar results of a temperature of 900 °C (1,652 °F) in the continuous flame region, and a temperature of around 340 °C (644 °F) at the flame tips.

Taking all of the above information into account, it appears that flame tip temperatures for turbulent diffusion flames should be estimated as being around 320 to 400 °C (608 to 752 °F). For small flames (less than about 1 m base diameter), continuous flame region temperatures of around 900 °C (1,652 °F) should be expected. For large pools, the latter value can rise to 1,100 to 1,200 °C (2,012 to 2,192 °F).

3.4.5 Flame Temperatures in Room Fires

The fire science community generally agrees that flashover is reached when the average upper gas temperature in the room exceeds 600 °C (1,112 °F). There will be zones with flame temperature of 900 °C (1,652 °F), but wide spatial variations will be seen. Of interest, however, is the peak fire temperature normally associated with room fires. This peak value is governed by ventilation and fuel supply characteristics. As a result of these variables, peak fire temperature values will form a wide frequency distribution (Babrauskas and Williamson, 1979). The maximum value is around 1,200 °C (2,192 °F), although a typical post-flashover room fire will more commonly have a peak temperature of 900 to 1,000 °C (1,652 to 1,832 °F). The time-temperature curve (TTC) for the standard fire endurance test (ASTM E119) extends to 1,260 °C (2,300 °F), as is reached in 8 hours. Note that no jurisdiction demands fire endurance periods of more than 4 hours, at which time, the curve only reaches 1,093 °C (1,999 °F).

The peak temperatures expected in room fires are slightly greater than those found in free-burning open flames. Heat losses from the flame determine how far below the adiabatic flame temperature the actual temperature will be[2]. When a flame is far away from any walls and does not heat the enclosure, it radiates to surroundings which are typically at a starting temperature of 20 °C (68 °F). If the flame is large enough, or the room small enough, for the walls to heat up substantially, the flame exchanges radiation with a body that is several hundred degrees Celsius; the consequence is smaller heat losses leading to a higher flame temperature.

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[2] Adiabatic flame temperature is defined as the flame temperature with no heat loss.

3.4.6 Adiabatic Flame Temperature

Adiabatic means without losing heat. Thus, adiabatic flame temperatures would be achieved in a (theoretical) combustion system in which there are no heat losses and, hence, no radiation losses from the flame. Because this cannot be achieved in practice (given the inefficiencies of combustion) and is never achieved in a fire situation, adiabatic flame temperatures are calculated values.

The amount of energy or heat released from the combustion reaction of fuel and air (or oxygen) is the heat of combustion. If all of the energy released by this chemical reaction were used to raise the temperature of the products (CO_2, H_2O, and N_2) with no heat losses, the resultant temperature would be the adiabatic flame temperature, which represents the maximum possible theoretical temperature for a particular fuel/oxidant combustion. Table 3-6 gives adiabatic flame temperatures for a variety of fuels. Remember from the earlier discussion, a given fuel will always have a higher adiabatic flame temperature when burned in pure oxygen than it will when burned in normal air (21-percent oxygen). This is because the heat of combustion must be used to raise the temperature of the nitrogen in air and, therefore, does not contribute to the energy release.

Table 3-6. Adiabatic Flame Temperatures of Selected Fuels

Fuel Source	**Adiabatic Flame Temperature K (°C) (°F)**
Hydrogen (H_2)	2,525 (2,252) (4,085)
Carbon Monoxide (CO)	2,660 (2,387) (4,329)
Methane (CH_4)	1,446 (1,173) (2,143)
Ethane (C_2H_6)	1,502 (1,129) (2,064)
Ethylene (C_2H_4)	2,565 (2,289) (4,152)
Acetylene (C_2H_2)	2,910 (1,281) (2,338)
Propane (C_3H_8)	1,554 (2,117) (3,843)
Propylene (C_3H_6)	2,505 (2,232) (4,050)
n-Butane (n-C_4H_{10})	1,612 (1,339) (2,442)
n-Octane (n-C_8H_8)	1,632 (1,359) (2,478)
n-Heptane	1,692 (1,419) (2,586)
n-Pentane	1,564 (1,291) (2,356)

The energy required to raise the temperature of the combustion products is determined by the mass of the products, their heat capacities, and the difference between the initial and final temperatures. Specific heat is defined as the amount of energy required to raise the temperature of a given amount of product 1 °C (or K).

3.4.7 Temperatures of Objects

It is common practice for investigators to assume that an object next to a flame of a certain temperature will also be of that same temperature. This assumption is not entirely accurate. If a flame is exchanging heat with an object that was initially at room temperature, it will take a finite amount of time for the temperature of that object to increase to a value similar to that of the flame. Exactly how long this will take is a question for the study of heat transfer, which is usually presented to engineering students over several semesters of university classes. It should be clear that simple rules-of-thumb for first order approximations would not be expected. Here, we will merely point out that the rate at which target objects gain heat is largely governed by their size, density, and thermal conductivity. Small, low-density, low-conductivity objects will heat much faster than massive, dense, highly conductive objects.

3.4.8 Flame Height Calculations

The height of a flame is a significant indicator of the hazard posed by the flame. Flame height directly relates to flame heat transfer and the propensity of the flame to impact surrounding objects. As a plume of hot gases rises above a flame, the temperature, velocity, and width of the plume changes as the plume mixes with its surroundings. The size (height) and temperature of the flame are important in estimating the ignition of adjacent combustibles. Figure 3-9 shows a characteristic sketch of the flame height fluctuations associated with the highly intermittent pulsing structure of a flame, particularly along its perimeter and near its top. This intermittence is driven largely by the turbulent mixing of air and subsequent combustion, and the pulsing behavior, in turns affects the temperature of the flame. Thus the temperature at a fixed position fluctuates widely, particularly around the edges and near the top of the flame. This is why flame temperature is usually reported in terms of the centerline temperature or average flame temperature.

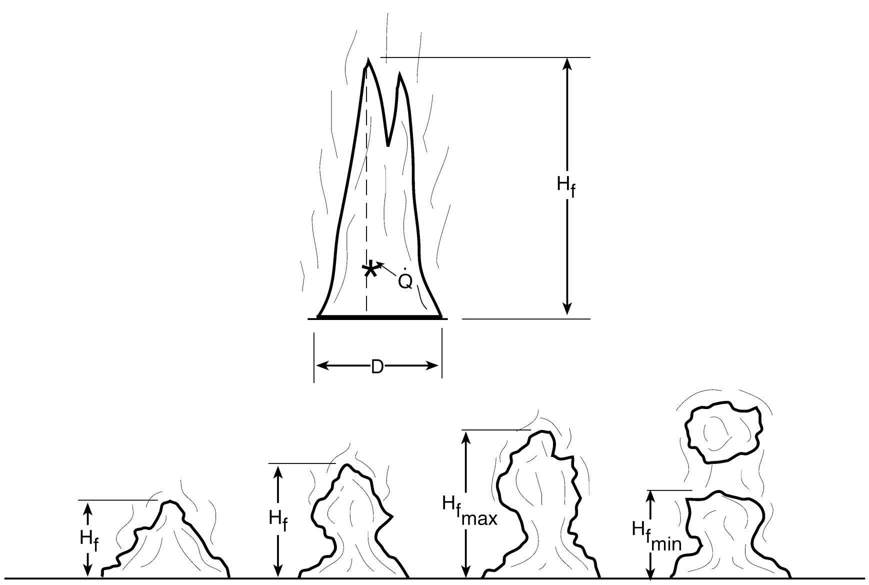

Figure 3-9 Characteristics of Flame Height Fluctuations

Researchers define flame height as the height at which the flame is observed at least 50-percent of the time. Above the fuel source, the flaming region is characterized by high temperature and is generally luminous. Flames from pool fires fluctuate periodically so that the tip of the flame is significantly different from the length of the continuous combustion (or luminous) region. Consequently, flame height has been defined by various criteria in order to correlate data.

The flame height is an important quantitative characteristic of a fire and may affect fire detection and suppression system design, fire heating of building structures, smoke filling rates, and fire ventilation. Flame height typically depends on whether the flame is laminar or turbulent. In general laminar flames are short, while turbulent flames are tall. The following two correlations are widely used to determine the flame height of pool fires (Heskestad, 1995 and Thomas, 1962) respectively:

$$H_f = 0.235\dot{Q}^{\frac{2}{5}} - 1.02D \qquad (3\text{-}6)$$

Where:

- H_f = flame height (m)
- $\dot{Q}$ = heat release rate of the fire (kW)
- D = diameter of the fire (m)

$$H_f = 42\,D\left(\frac{\dot{m}''}{\rho_a\sqrt{gD}}\right)^{0.61} \qquad (3\text{-}7)$$

Where:

- H_f = flame height (m)
- D = diameter of the fire (m)
- $\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)
- $_a$ = ambient air density (kg/m^3)
- g = gravitational acceleration (m/sec^2)

The above correlations can also be used to determine the length of the flame extension along the ceiling and to estimate radiative heat transfer to objects in the enclosure.

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 is given by the following equation:

$$\dot{Q} = \dot{m}''\,DH_{c,eff}\,A_f\,(1 - e^{-k\beta D}) \qquad (3\text{-}8)$$

Where:

- $\dot{m}''$ = 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)
- kβ= 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:

$$D = \sqrt{\frac{4A_f}{\pi}} \qquad (3\text{-}9)$$

Where:

A_f is the surface area of the non-circular pool

3.5 Assumptions and Limitations

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

(1) The pool fire is burning in the open and is characterized by instantaneous, complete involvement of the flammable/combustible liquid.

(2) There is no fire growth period. (Real liquid pool fires grow very quickly, and it is realistic to assume that the pool fire instantaneously reaches its maximum HRR.)

In addition, the following assumptions and limitations apply to burning duration:

(1) The pool is circular or nearly circular and contains a fixed mass or volume of flammable/combustible liquid. The mass or volume of any spill with a non-circular circumference must be approximated as a circular measurement. For example an accidental fuel is ignited in a pump room and causes cable trays to be exposed to a pool fire. The spill area is a rectangular dike with dimensions of 4-ft x 5-ft. The equivalent diameter of the pool fire is given by Equation 3-9:

$$D = \sqrt{\frac{4A_f}{\pi}}$$

Where:

A_f = the surface area of noncircular pool

Therefore, the equivalent diameter of the non-circular pool is as follows:

$$D = \sqrt{\frac{4x20}{\pi}} = 5ft$$

(2) There is no fire growth period. (As stated above, real liquid pool fires grow very quickly, and it is realistic to assume that the pool fire instantaneously reaches its maximum HRR.)

In addition, the following assumptions and limitations apply to flame height:

(1) The flame height correlation described in this chapter was developed for horizontal pool fire sources in the center or away from the center of the compartment. The turbulent diffusion flames produced by fires burning near or close to a wall or in a corner configuration of a compartment effect the spread of the fire. The flame height correlations of fires burning near walls and corners is presented in Chapter 4.

(2) The size of the fire (flame height) depends on the diameter of the fuel and the HRR attributable to the combustion.

(3) This correlation is developed for two-dimensional sources (primarily pool fires) and this method assumes that the pool is circular or nearly circular.

(4) There is no fire growth period. (As stated above, real liquid pool fires grow very quickly, and it is realistic to assume that the pool fire instantaneously reaches its maximum HRR.)

3.6 Required Input for Spreadsheet Calculations

The user must obtain the following values before attempting a calculation using the characteristics of liquid pool fire spreadsheet:

(1) fuel spill volume (gallons)

(2) fuel spill area or dike area (ft^2)

(3) fuel type

3.7 Cautions

(1) Use (03_HRR_Flame_Height_Burning_Duration_Calculation.xls) spreadsheet on the CD-ROM.

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

3.8 Summary

An engineering approach to pool fire burning characterization requires a classification according to the dominant heat transfer mechanism, which can be expressed as being dependent on pool diameter. The pool shall include fires resulting from spilled liquids, fires in diked or curbed areas, and fires in open areas. These fires will be typically considered to be circular.

Estimating the burning duration of a pool fire involves the following steps:

(1) Determine the regression rate of the pool fire.
(2) Calculate the equivalent diameter of the pool fire.
(3) Calculate the burning duration of the pool fire.

The flame height is generally defined as the height at which (or above which) the flame is observed at least 50-percent of the time. Visual observations tend to yield slight overestimations of flame height.

Estimating the flame height from a pool fire involves the following steps:

(1) Determine the HRR of the pool fire.
(2) Calculate the equivalent diameter of the pool fire.
(3) Determine the height of the pool fire flame.

3.9 References

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3.10 Additional Readings

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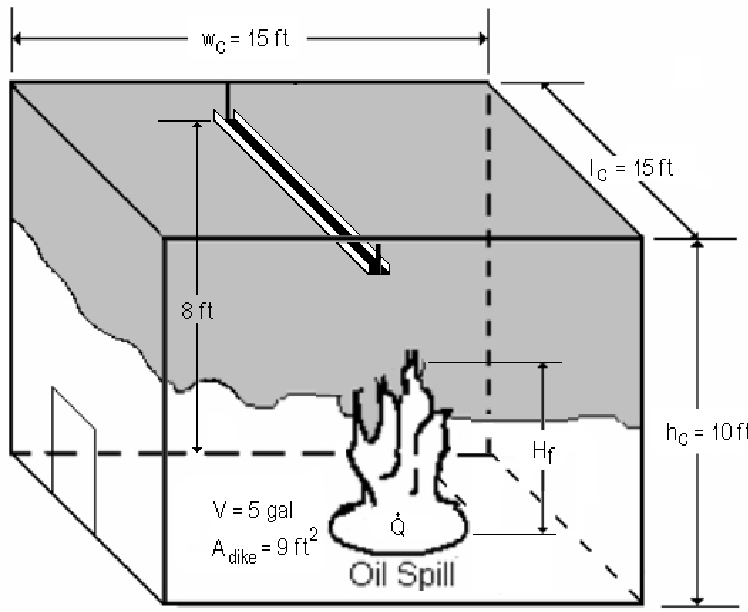
3.11 Problems

Example Problem 3.10-1

Problem Statement
A pool fire scenario arises from a breach (leak or rupture) in an auxiliary cooling water pump oil tank. This event allows the fuel contents of the pump to spill and spread over the compartment floor. A 5-gallon, 9.0-ft^2 surface area spill of flammable liquid (lubricating oil) leads to consideration of a pool fire in a compartment with a concrete floor. The fuel is ignited and spreads rapidly over the surface, reaching steady burning almost instantly. Compute the HRR, burning duration, and flame height of the pool fire. The dimensions of the compartment are 15 ft wide x 15 ft deep x 10 ft heigh. The cable tray is located 8 ft above the pool fire. Determine whether the flame will impinge upon the cable tray. Assume instantaneous and complete involvement of the liquid pool with no fire growth and no intervention by the plant fire department or automatic suppression systems.



Example Problem 3-1: Compartment with Pool Fire

Solution

Purpose:

(1) Determine the Heat Release Rate (HRR) of the fire source.
(2) Determine the burning duration of the pool fire.
(3) Determine the flame height of the pool fire.
(4) Determine whether the flame will impinge upon the cable tray.

Assumptions:

(1) Instantaneous and complete involvement of the liquid in the pool fire
(2) The pool fire is burning in the open
(3) No fire growth period (instantaneous HRR_{max})
(4) The pool is circular or nearly circular and contains a fixed mass of liquid volume
(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

FDT^s Input Parameter:

-Fuel Spill Volume (V) = 5 gallons

-Fuel Spill Area or Dike Area (A_{dike}) = 9.0 ft^2

-Select Fuel Type: **Lube Oil**

Results*

Heat Release Rate (HRR) $\dot{Q}$ kW (Btu/sec)	Burning Duration (t_b) (min.)	Pool Fire Flame Height (H_f) m (ft)	
		Method of Heskestad	Method of Thomas
772 (731)	7.35	2.31 (7.6)	2.67 (8.75)

*see spreadsheet on next page

Both methods for pool fire flame height estimation show that pool fire flame will impinge upon the cable tray.

Spreadsheet Calculations

FDT^s: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls (HRR-Calculations)

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE, HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
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

Fuel Spill Volume (V)	5.00	gallons	0.0189 m^3
Fuel Spill Area or Dike Area (A_{dike})	9.00	ft^2	0.836 m^2
Mass Burning Rate of Fuel ($\dot{m}''$)	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Density (ρ)	760	kg/m^3	
Empirical Constant ($k\beta$)	0.7	m^{-1}	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec^2	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Calculate

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

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate $\dot{m}''$ (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter 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

Click on selection

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference : *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-25.

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

Where Q = pool fire heat release rate (kW)

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

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = 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)

Pool Fire Diameter Calculation

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

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

D = pool fire diamter (m)

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

D = 1.032 m

Heat Release Rate Calculation

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

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	771.52 kW	731.26 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference : *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where t_b = burning duration of pool fire (sec)

V = volume of liquid (m^3)

D = pool diameter (m)

v = regression rate (m/sec)

Calculation for Regression Rate

$v = m''/\rho$

Where v = regression rate (m/sec)

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

ρ = liquid fuel density (kg/m^3)

v = 0.000051 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b =	441.12 sec	7.35 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference : *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 2-10.

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

Where H_f = pool fire flame height (m)

Q = pool fire heat release rate (kW)

D = pool fire diameter (m)

Pool Fire Flame Height Calculation

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

H_f =	2.31 m	7.56 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-204.

$H_f = 42\ D\ (\dot{m}''/\rho_a \sqrt{(g\ D)})^{0.61}$

Where H_f = pool fire flame height (m)

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

ρ_a = ambient air density (kg/m^3)

D = pool fire diameter (m)

g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation

$H_f = 42\ D\ (\dot{m}''/\rho_a \sqrt{(g\ D)})^{0.61}$

H_f =	2.67 m	8.75 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	7.56
METHOD OF THOMAS	8.75

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft^2)	Area (m^2)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	85.72	3970.11	3.42	4.08
2	0.19	0.49	171.45	1985.05	4.41	5.19
3	0.28	0.60	257.17	1323.37	5.10	5.97
4	0.37	0.69	342.90	992.53	5.66	6.60
5	0.46	0.77	428.62	794.02	6.13	7.13
6	0.56	0.84	514.35	661.68	6.55	7.60
7	0.65	0.91	600.07	567.16	6.92	8.02
8	0.74	0.97	685.80	496.26	7.25	8.40
9	0.84	1.03	771.52	441.12	7.56	8.75
10	0.93	1.09	857.25	397.01	7.85	9.07
11	1.02	1.14	942.97	360.92	8.12	9.38
12	1.11	1.19	1028.69	330.84	8.37	9.67
13	1.21	1.24	1114.42	305.39	8.61	9.94
14	1.30	1.29	1200.14	283.58	8.84	10.20
15	1.39	1.33	1285.87	264.67	9.05	10.45
20	1.86	1.54	1714.49	198.51	10.01	11.55
25	2.32	1.72	2143.11	158.80	10.82	12.48
50	4.65	2.43	4286.23	79.40	13.73	15.87
75	6.97	2.98	6429.34	52.93	15.76	18.28
100	9.29	3.44	8572.46	39.70	17.35	20.20

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation does not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

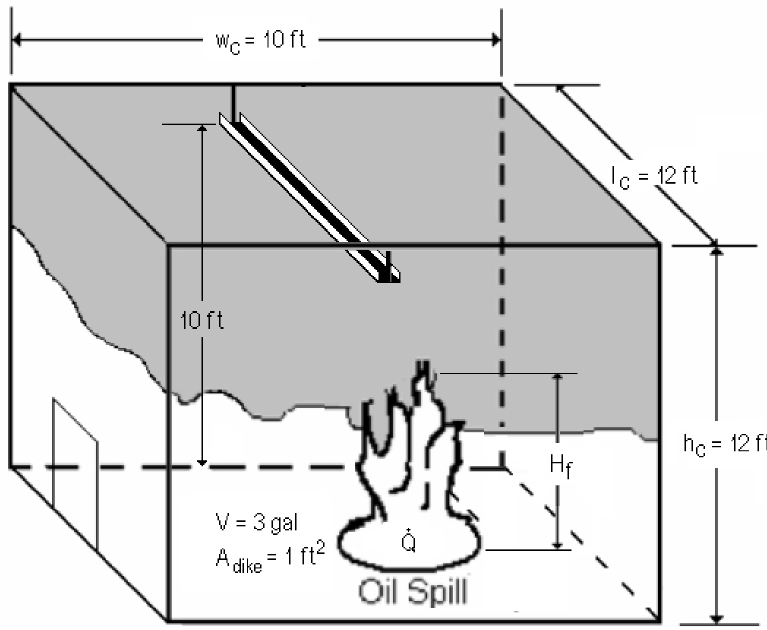
NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 3.10-2

Problem Statement

A standby diesel generator (SBDG) room in a power plant has a 3-gallon spill of diesel fuel over a 1-ft^2 diked area. This event allows the diesel fuel to form a pool. The diesel is ignited and fire spreads rapidly over the surface, reaching steady burning almost instantly. Compute the HRR, burning duration, and flame height of the pool fire. The dimensions of the compartment are 10 ft wide x 12 ft deep x 12 ft high. The cable tray is located 10 ft above the pool fire. Determine whether flame will impinge upon the cable tray. Also, determine the minimum area required of the pool fire for the flame to impinge upon the cable tray. Assume instantaneous, complete involvement of the liquid pool with no fire growth and no intervention by plant fire department or automatic suppression.



Example Problem 3-2: Compartment with Pool Fire

Solution

Purpose:

(1) Determine the Heat Release Rate (HRR) of the fire source.
(2) Determine the burning duration of the pool fire.
(3) Determine the flame height of the pool fire.
(4) Determine whether the flame will impinge upon the cable tray.
(5) Determine the minimum dike area required for the flame to impinge upon the cable tray.

Assumptions:

(1) Instantaneous and complete involvement of the liquid in the pool fire
(2) The pool fire is burning in the open
(3) No fire growth period (instantaneous HRR_{max})
(4) The pool is circular or nearly circular and contains a fixed mass of liquid volume
(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

FDTs Input Parameter:

-Fuel Spill Volume (V) = 3 gallons

-Fuel Spill Area or Dike Area (A_{dike}) = 1.0 ft^2

-Select Fuel Type: **Diesel**

Results*

Heat Release Rate (HRR) $\dot{Q}$ kW (Btu/sec)	Burning Duration (t_b) (min.)	Pool Fire Flame Height (H_f) m (ft)	
		Method of Heskestad	Method of Thomas
95 (90)	42	1.1 (3.6)	1.4 (4.5)

*see spreadsheet on next page

Both methods for pool fire flame height estimation show that pool fire flame will not impinge the cable tray.

To determine the minimum dike area required for the flame to impinge upon the cable tray, the user must substitute different values for the area in the spreadsheet until we obtain a flame height value of 10 ft (cable tray height). The user must keep the input values used for the previous results, and change only the area value. This trial and error procedure is shown in the following table.

Trial	A_{dike} (ft^2)	Pool Fire Flame Height (H_f) m (ft)	
		Method of Heskestad	Method of Thomas
1	9	2.4 (8.0)	2.9 (9.6)
2	10	2.6 (8.4)	3.0 (9.9)
3	11	2.6 (8.6)	3.1 (10.2)

To be conservative, we are going to consider the method that gets first the 10-ft flame height. The method of Heskestad tells that the pool fire flame will impinge upon the cable tray if the dike area is 6.1 ft^2. For practical purposes, we could say that a spill pool area around 5–6 ft^2 would be a risk for the cable tray integrity.

Spreadsheet Calculations

FDT^s: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls (HRR-Calculations)

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE, HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
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

Fuel Spill Volume (V)	3.00	gallons	0.0114 m^3
Fuel Spill Area or Dike Area (A_{dike})	1.00	ft^2	0.093 m^2
Mass Burning Rate of Fuel (m")	0.045	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	44400	kJ/kg	
Fuel Density (ρ)	918	kg/m^3	
Empirical Constant ($k\beta$)	2.1	m^{-1}	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec^2	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Calculate

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

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25

Select Fuel Type

Diesel

Scroll to desired fuel type
Click on selection

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 3-25.

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

Where
Q = pool fire heat release rate (kW)
m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)
$A_f = A_{dike}$ = 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)

Pool Fire Diameter Calculation

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

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

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

D = 0.344 m

Heat Release Rate Calculation

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

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	95.47 kW	90.49 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference: *SFPE Handbook of Fire Protection Engineering*, 2[nd] Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where
t_b = burning duration of pool fire (sec)
V = volume of liquid (m^3)
D = pool diameter (m)
v = regression rate (m/sec)

Calculation for Regression Rate

$v = m''/\rho$

Where
v = regression rate (m/sec)
m'' = mass burning rate of fuel (kg/m^2-sec)
ρ = liquid fuel density (kg/m^3)

v = 0.000049 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b =	2493.65 sec	41.56 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference: *SFPE Handbook of Fire Protection Engineering*, 2[nd] Edition, 1995, Page 2-10.

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

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

Pool Fire Flame Height Calculation

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

H_f =	1.10 m	3.62 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-204.

$H_f = 42\ D\ (m''/\rho_a \sqrt{(g\ D)})^{0.61}$

Where
- H_f = pool fire flame height (m)
- m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ρ_a = ambient air density (kg/m^3)
- D = pool fire diameter (m)
- g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation

$H_f = 42\ D\ (m''/\rho_a \sqrt{(g\ D)})^{0.61}$

H_f =	1.36 m	4.45 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	3.62
METHOD OF THOMAS	4.45

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft^2)	Area (m^2)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	95.47	2493.65	3.62	4.45
2	0.19	0.49	190.95	1246.82	4.67	5.66
3	0.28	0.60	286.42	831.22	5.42	6.52
4	0.37	0.69	381.89	623.41	6.01	7.20
5	0.46	0.77	477.36	498.73	6.52	7.78
6	0.56	0.84	572.84	415.61	6.96	8.29
7	0.65	0.91	668.31	356.24	7.36	8.75
8	0.74	0.97	763.78	311.71	7.72	9.16
9	0.84	1.03	859.25	277.07	8.05	9.55
10	0.93	1.09	954.73	249.36	8.36	9.90
11	1.02	1.14	1050.20	226.70	8.64	10.24
12	1.11	1.19	1145.67	207.80	8.92	10.55
13	1.21	1.24	1241.14	191.82	9.17	10.85
14	1.30	1.29	1336.62	178.12	9.42	11.13
15	1.39	1.33	1432.09	166.24	9.65	11.40
20	1.86	1.54	1909.45	124.68	10.68	12.60
25	2.32	1.72	2386.81	99.75	11.55	13.61
50	4.65	2.43	4773.63	49.87	14.70	17.32
75	6.97	2.98	7160.44	33.25	16.89	19.94
100	9.29	3.44	9547.25	24.94	18.62	22.04

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation does not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

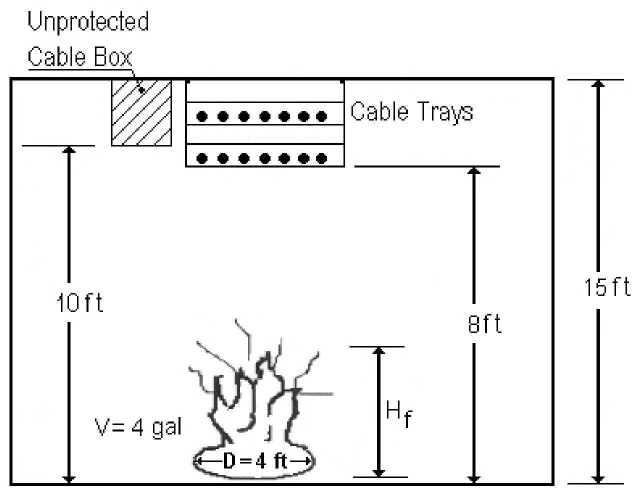
NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 3.10-3

Problem Statement

In one NPP, it was important to determine whether a fire involving a 4-gallon spill of lubricating oil from an auxiliary feedwater (AFW) pump could cause damage to an unprotected electrical cable pull box and cable trays. The unprotected pull box and cable trays were located 10 ft and 8 ft above the AFW pump, respectively. The pump room had a floor area of 20 ft x 20 ft and a ceiling height of 15 ft with a vent opening of 5 ft x 15 ft. Compute the HRR, burning duration, and flame height of the pool fire with a diameter of 4 ft. The lowest cable tray is located 8 ft above the pool. Determine whether flame will impinge upon the cable tray or cable pull box. Assume instantaneous, complete involvement of the liquid pool with no fire growth and no intervention by the plant fire department or automatic suppression systems.



Example 3-3: Compartment with Pool Fire

Solution

Purpose:

(1) Determine the Heat Release Rate (HRR) of the fire source.
(2) Determine the burning duration of the pool fire.
(3) Determine the flame height of the pool fire.
(4) Determine whether the flame will impinge upon the cable tray or cable pull box.

Assumptions:

(1) Instantaneous and complete involvement of the liquid in the pool fire
(2) The pool fire is burning in the open
(3) No fire growth period (instantaneous HRR_{max})
(4) The pool is circular or nearly circular and contains a fixed mass of liquid volume
(5) The fire is located at the center of the compartment or away from the walls

Pre FDT^s Calculations:
The input parameters of the FDT^s assigned for this problem are the fuel spill volume, dike area and fuel material. As we can see, the problem statement does not give the dike area but the pool diameter is given. The dike area can be obtained from the formula of the area of a circle, since we assume that the pool has circular shape.

$$A_{dike} = \frac{\pi}{4} D^2 = \frac{\pi}{4}(4 \quad ft)^2 = 12.56 \quad ft^2$$

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

FDT^s Inputs: (for both spreadsheets)

-Fuel Spill Volume (V) = 4 gallons
-Fuel Spill Area or Dike Area (A_{dike}) = 12.56 ft^2
-Select Fuel Type: **Lube Oil**

Results*

Heat Release Rate (HRR) $\dot{Q}$ kW (Btu/sec)	Burning Duration (t_b) (min.)	Pool Fire Flame Height (H_f) m (ft)	
		Method of Heskestad	Method of Thomas
1,202 (1,139)	4.2	2.8 (9.1)	3.0 (9.8)

*see spreadsheet on next page

Both methods for pool fire flame height estimation show that pool fire flame will impinge upon the cable tray and cable pull box.

Spreadsheet Calculations

FDT^s: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls (HRR-Calculations)

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE, HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
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

Fuel Spill Volume (V)	4.00	gallons	0.0151 m^3
Fuel Spill Area or Dike Area (A_{dike})	12.56	ft^2	1.167 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Density (ρ)	760	kg/m^3	
Empirical Constant ($k\beta$)	0.7	m^{-1}	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec^2	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Calculate

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

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Fuel Type

Lube Oil

Scroll to desired fuel type
Click on selection

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-25.

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

Where Q = pool fire heat release rate (kW)

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

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = 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)

Pool Fire Diameter Calculation

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

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

D = pool fire diamter (m)

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

D = 1.219 m

Heat Release Rate Calculation

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

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	1201.50 kW	1138.81 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where t_b = burning duration of pool fire (sec)

V = volume of liquid (m^3)

D = pool diameter (m)

v = regression rate (m/sec)

Calculation for Regression Rate

$v = m''/\rho$

Where v = regression rate (m/sec)

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

ρ = liquid fuel density (kg/m^3)

v = 0.000051 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b =	252.87 sec	4.21 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 2-10.

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

Where H_f = pool fire flame height (m)

Q = pool fire heat release rate (kW)

D = pool fire diameter (m)

Pool Fire Flame Height Calculation

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

H_f =	2.77 m	9.07 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-204.

$H_f = 42\, D\, (\dot{m}''/\rho_a \sqrt{g\, D})^{0.61}$

Where H_f = pool fire flame height (m)

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

ρ_a = ambient air density (kg/m^3)

D = pool fire diameter (m)

g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation

$H_f = 42\, D\, (\dot{m}''/\rho_a \sqrt{g\, D})^{0.61}$

H_f =	2.99 m	9.82 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	9.07
METHOD OF THOMAS	9.82

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft^2)	Area (m^2)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	95.66	3176.09	3.63	4.08
2	0.19	0.49	191.32	1588.04	4.68	5.19
3	0.28	0.60	286.98	1058.70	5.42	5.97
4	0.37	0.69	382.64	794.02	6.02	6.60
5	0.46	0.77	478.30	635.22	6.52	7.13
6	0.56	0.84	573.97	529.35	6.97	7.60
7	0.65	0.91	669.63	453.73	7.36	8.02
8	0.74	0.97	765.29	397.01	7.72	8.40
9	0.84	1.03	860.95	352.90	8.06	8.75
10	0.93	1.09	956.61	317.61	8.36	9.07
11	1.02	1.14	1052.27	288.74	8.65	9.38
12	1.11	1.19	1147.93	264.67	8.93	9.67
13	1.21	1.24	1243.59	244.31	9.18	9.94
14	1.30	1.29	1339.25	226.86	9.43	10.20
15	1.39	1.33	1434.91	211.74	9.66	10.45
20	1.86	1.54	1913.22	158.80	10.69	11.55
25	2.32	1.72	2391.52	127.04	11.56	12.48
50	4.65	2.43	4783.05	63.52	14.71	15.87
75	6.97	2.98	7174.57	42.35	16.91	18.28
100	9.29	3.44	9566.09	31.76	18.64	20.20

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation does not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

NOTE

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

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

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

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

CHAPTER 4. ESTIMATING WALL FIRE FLAME HEIGHT, LINE FIRE FLAME HEIGHT AGAINST THE WALL, AND CORNER FIRE FLAME HEIGHT

4.1 Objectives

This chapter has the following objectives:

- Identify the three regions of a diffusion flame.
- Explain how corners and walls affect flames.
- Define relevant terms, including persistent flame region, intermittent flame region, flame height, and flame extension.

4.2 Introduction

If a fire is located close to a wall or a corner (i.e., formed by the intersection of two walls), the resulting restriction on free air entrainment will have a significant effect on fire growth and spread. The primary impact of walls and corners is to reduce the amount of entrained air available to the flame or plume. This lengthens flames and causes the temperature in a plume to be higher at a given elevation than it would be in the open. Remember that the expression for estimating flame height given in Chapter 3 assumes that the fire source is located away from the walls and corners.

When a diffusion flame develops and is in contact with the wall, its structure can be subdivided into three regions, which are commonly identified as the persistent flame region, the intermittent flame region, and the buoyant plume region. As the plume rises to the ceiling, its direction changes from vertical (upward) to horizontal. Until the point where the flow changes direction, the plume is primarily driven by buoyancy. Thereafter, the plume is driven by its residual momentum and becomes a jet, which is referred to as the "ceiling jet."

The flame heats the wall material with which it comes in contact. The heat flux to the wall is a function of location and is highest in the persistent flame region. The flame height depends on the amount of air entrained which, in turn, is proportional to the fuel heat release rate. On occasions, it may also be necessary to calculate the flame projections against a wall from the spill of flammable liquid in a trench or flames emerging from a burning electrical cabinet.

4.3 Flame Height Correlations for Walls Fires, Line Fires, and Corner Fires

In a wall flame, the wall-side heat flux appears to be governed by the flame radiation, while the heat flux in the far field is primarily attributable to convection. This implies that flame height can be a scaling factor representing the distribution of wall heat transfer. Using the analogy of unconfined fires, the flame height is expected to depend only on the gross heat release rate of the fuel. The terms "flame height" and "flame extension" designate the lengths of flame in the vertical and horizontal directions, respectively. A wall flame generated from a fire located against a wall can only entrain air from half of its perimeter. Thus, wall flame can be considered to be geometrically half of an axisymmetric flame and its mass flow rate, in turn, is half of that from an axisymmetric flame.

A flame generated from a fire located in a corner of a compartment (typically where the intersecting walls form a 90° angle) is referred to as corner flame. Corner fires are more severe than wall fires because of the radiative heat exchange between the two burning walls. However, the physical phenomena controlling fire growth in corner and wall scenarios are very similar, if not identical.

4.3.1 Wall Fire Flame Height Correlation

Delichatsios (1984) reported by Budnick, Evans, and Nelson (1997) developed a simple correlation of flame height for elongated fire based on experimental data. Figure 4-1 depicts the configuration used in developing the correlation for wall flame height. In the following correlation, the flame height is based on the rate of HRR per unit length of the fire:

$$H_{f(Wall)} = 0.034\dot{Q}'^{\frac{2}{3}} \qquad (4\text{-}1)$$

Where:

$H_{f(Wall)}$ = wall flame height (m)
0.034 = entrainment coefficient
$\dot{Q}'$ = HRR per unit length of the fire (kW/m)

The above correlation can be used to determine the length of the flame against the wall and to estimate radiative heat transfer to objects in the enclosure.

4.3.2 Line Fire Flame Height Correlation

Delichatsios (1984) reported by Budnick et. al., (1997) also developed a flame height correlation for line fires against a wall. Like the wall fire flame height correlation, this correlation is based on experimental data. The geometry for this case is shown in Figure 4-2. Delichatsios' correlation is expressed by the following equation based on the rate of HRR per unit length of the fire:

$$H_{f(Wall,Line)} = 0.017\dot{Q}'^{\frac{2}{3}} \qquad (4\text{-}2)$$

Where:

$H_{f(Wall, Line)}$ = line fire flame height (m)
0.017 = entrainment coefficient
$\dot{Q}'$ = HRR per unit length of the fire (kW/m)

The above correlation can be used to determine the length of the flame against the wall from a line fire source and can be used to estimate radiative heat transfer to objects in the enclosure.

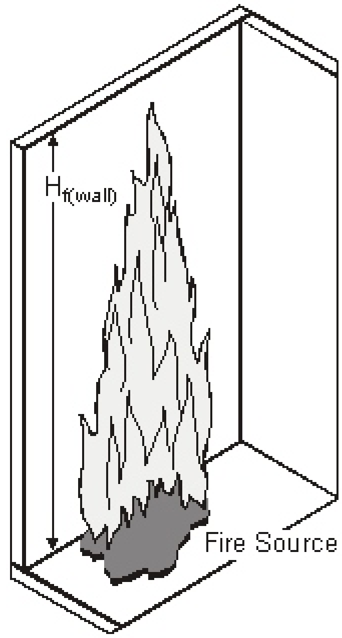


Figure 4-1 Wall Fire Flame Configuration

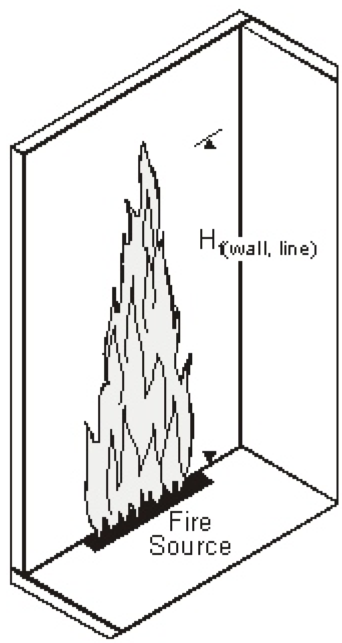


Figure 4-2 Line Fire Flame Against a Wall

4.3.3 Corner Fire Flame Height Correlation

A corner fire may be modeled using a pool fire and specifying the center coordinates as the apex of the corner. At the start of the fire, a diffusion flame develops and makes contact with the walls. As flames spread along the intersection of wall and ceiling, they eventually reach another corner. With a noncombustible ceiling, flames also spread downward. By contrast, with a combustible wall, the heat transfer between two walls in contact with the fire source results in a much more rapid fire spread. Figure 4-3 depicts the configuration used in developing the corner flame height correlation from experimental data. Hasemi and Tokunaga (1983 and 1984) suggest the following expression, based on the correlation of an extensive number of fire tests:

$$H_{f(Corner)} = 0.075\dot{Q}^{\frac{3}{5}} \qquad (4\text{-}3)$$

Where:

$H_{f(Corner)}$ = corner fire flame height (m)
0.075 = entrainment coefficient
$\dot{Q}$ = HRR of the fire (kW)

The above correlation can be used to determine the length of the flame against the intersection of two walls and to estimate radiative heat transfer to objects in the enclosure.

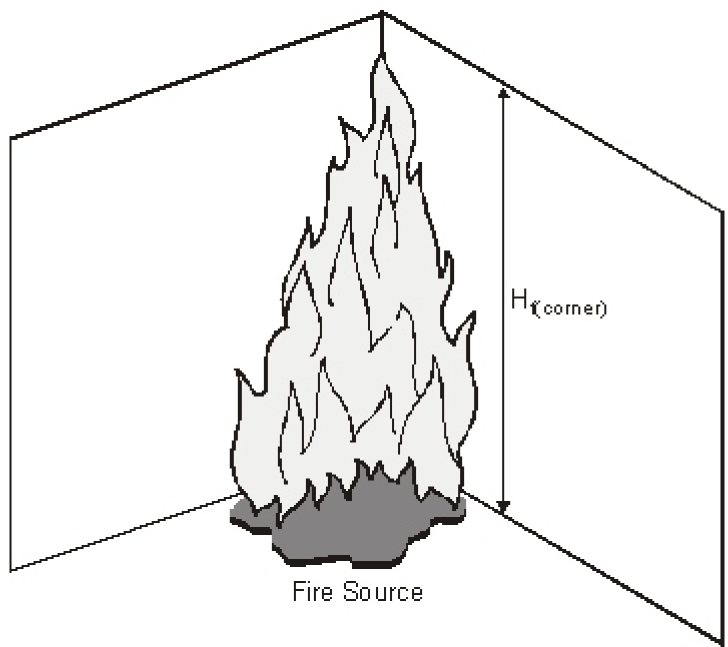


Figure 4-3 Corner Fire Flame Configuration

4.4 Assumptions and Limitations

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

(1) This method includes correlations for flame height for liquid fire.

(2) The size of the fire (flame height) depends on the length of the fire.

(3) This correlation is developed for two-dimensional sources.The turbulent diffusion flames produced by fires burning at or near a wall configuration of a compartment affect the spread of the fire.

(4) Air is entrained only from one side during the combustion process.

4.5 Required Input for Spreadsheet Calculations

The user must obtain the following information to use the spreadsheet:

(1) fuel type (material)
(2) fuel spill volume (gallons)
(3) fuel spill area (ft^2)

4.6 Cautions

(1) Use the appropriate spreadsheet (04_Flame_Height_Calculations.xls) on the CD-ROM for wall fire flame height, line fire flame height, and corner fire flame height calculations.

(2) Use the page that best represents the fire configuration.

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

4.7 Summary

This chapter describes methods of calculating the height of a flame and its buoyant gases when the fire source is near a wall or a corner. These fire scenarios are often used as idealized representatives of situations of much greater complexity. The correlations presented were obtained from laboratory scale fires providing local measurements of gas temperature and velocity both below and above the flame tips, as well as measurements of visual flame length.

4.8 References

Budnick, E.K., D.D. Evans, and H.E. Nelson, "Simple Fire Growth Calculations," Section 11 Chapter 10, *NFPA Fire Protection Handbook*, 18th Edition, National Fire Protection Association, Quincy, Massachusetts, 1997.

Delichatsios, M.A., "Flame Heights of Turbulent Wall Fire with Significant Flame Radiation," *Combustion Science and Technology*, Volume 39, pp. 195–214, 1984.

Hasemi Y., and T.Tokunaga, "Modeling of Turbulent Diffusion Flames and Fire Plumes for the Analysis of Fire Growth," Proceedings of the 21st National Heat Transfer Conference, American Society of Mechanical Engineers (ASME), 1983.

Hasemi Y., and T.Tokunaga, "Some Experimental Aspects of Turbulent Diffusion Flames and Buoyant Plumes from Fire Sources Against a Wall and in Corner of Walls," *Combustion Science and Technology*, Volume 40, pp. 1–17, 1984.

4.9 Problems

Example Problem 4.9-1

Problem Statement

A pool fire scenario arises from a breach (leak or rupture) in an oil-filled transformer. This event allows the fuel contents of the transformer to spill 2 gallons along a wall with an area of 9 ft^2. A cable tray is located 8 ft above the fire. Calculate the wall flame height of the fire and determine whether the flame will impinge upon the cable tray.

Solution

Purpose:

(1) Calculate the wall flame height.
(2) Determine whether the flame will impinge upon the cable tray.

Assumptions:

(1) Air is entrained only from one side during the combustion process.
(2) The fire is located at or near a wall configuration of a compartment that affects the spread of the fire.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 04_Flame_Height_Calculations.xls (click on *Wall_Flame _Height*)

FDTs Input Parameters:

-Fuel spill volume (V) = 2 gallons
-Fuel Spill Area or Dike Area (A_{dike}) = 9.0 ft^2
-Select Fuel Type: **Transformer Oil, Hydrocarbon**

Results*

Fuel	Wall Fire Flame Height ($H_{f(Wall)}$) m (ft)	Cable Tray Impingement
Transformer Oil, Hydrocarbon	3.0 (10.0)	Yes

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 04_Flame_Height_Calculations.xls (click on Wall_Flame _Height)

CHAPTER 4. ESTIMATING WALL FIRE FLAME HEIGHT

Version 1805.0

The following calculations estimate the wall fire flame height.
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

Fuel Spill Volume (V)	2.00	gallons	0.0076 m^3
Fuel Spill Area or Dike Area (A_{dike})	9.00	ft^2	0.836 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Empirical Constant (kβ)	0.7	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON 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
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	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	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

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

Select Fuel Type

Transformer Oil, Hydrocarbon

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25.*

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

Where Q = pool fire heat release rate (kW)

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

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A = A_{dike}$ = 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)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

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 = 1.032 m

Heat Release Rate Calculation

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

Q = 771.52 kW 731.26 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where Q' = heat release rate per unit length (kW/m)

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

L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 0.836 m^2

L = 0.914 m

$Q' = Q/L$

Q' = 843.75 kW/m

ESTIMATING WALL FIRE FLAME HEIGHT

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-134.*

$H_{(wall)} = 0.034\,Q'^{2/3}$

Where $H_{(wall)}$ = wall fire flame height (m)

Q' = rate of heat release per unit length of the fire (kW/m)

$H_{(wall)} = 0.034\,Q'^{2/3}$

$H_{(wall)}$ =	3.04 m	9.96 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, and NFPA Fire Protection Handbook, 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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

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

Example Problem 4.9-2

Problem Statement

A pool fire scenario arises from a transient combustible liquid spill. This event allows the fuel contents of a 15 gallon can to form along a wall with an area of 30 ft^2. A cable tray is located 12 ft above the fire. Determine the line wall fire flame height and whether the flame will impinge upon the cable tray if the spilled liquids are (a) diesel, (b) acetone, and (c) methanol.

Solution

Purpose:
(1) Calculate the line wall fire flame height using three transient combustibles.
(2) Determine whether the flame will impinge upon the cable tray in each case.

Assumptions:
(1) Air is entrained only from one side during the combustion process.
(2) The fire is located at or near a wall configuration of a compartment that affects the spread of the fire.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 04_Flame_Height_Calculations.xls (click on *Wall_Line_Flame _Height*)

FDT^s Input Parameters:

-Fuel spill volume (V) = 15 gallons
-Fuel Spill Area or Dike Area (A_{dike}) = 30.0 ft^2
-Select Fuel Type: Diesel, Acetone, and Methanol

Results*

Fuel	Wall Line Fire Height ($H_{f(Wall\ Line)}$) m (ft)	Cable Tray Impingement
Diesel	3.8 (12.3)	Yes
Acetone	2.44(8.0)	No
Methanol	1.2 (3.8)	No

*See spreadsheets on next page

Spreadsheet Calculations

FDT[s]: 04_Flame_Height_Calculations.xls (click on Wall_Line_Flame _Height)

(a) Diesel

CHAPTER 4. ESTIMATING LINE FIRE FLAME HEIGHT AGAINST THE WALL

Version 1805.0

The following calculations estimate the line fire flame height against the wall.
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

Fuel Spill Volume (V)	15.00	gallons	0.0568 m^3
Fuel Spill Area or Dike Area (A_{dike})	30.00	ft^2	2.787 m^2
Mass Burning Rate of Fuel (m")	0.045	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	44400	kJ/kg	
Empirical Constant (kβ)	2.1	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON 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
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	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	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

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

Select Fuel Type

Diesel

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

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

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

Where Q = pool fire heat release rate (kW)

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

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = 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)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

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 = 1.884 m

Heat Release Rate Calculation

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

Q = 5462.02 kW 5177.01 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where Q' = heat release rate per unit length (kW/m)

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

L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 2.787 m^2

L = 1.669 m

$Q' = Q/L$

Q' = 3271.73 kW/m

ESTIMATING LINE WALL FIRE FLAME HEIGHT

Reference: *NFPA Fire Protection Handbook, 19[th] Edition, 2003, Page 3-134.*

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

Where $H_{f(wall\ line)}$ = wall fire flame height (m)

Q' = rate of heat release per unit length of the fire (kW/m)

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

$H_{f(wall\ line)}$ =	3.75 m	12.29 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3[rd] Edition, 2002, and NFPA Fire Protection Handbook, 19[th] Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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

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

FDT[s]: 04_Flame_Height_Calculations.xls (click on Wall_Line_Flame _Height)
(b) Acetone

CHAPTER 4. ESTIMATING LINE FIRE FLAME HEIGHT AGAINST THE WALL
Version 1805.0

The following calculations estimate the line fire flame height against the wall.
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

Fuel Spill Volume (V)	15.00	gallons	0.0568 m^3
Fuel Spill Area or Dike Area (A_{dike})	30.00	ft^2	2.787 m^2
Mass Burning Rate of Fuel (m")	0.041	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	25800	kJ/kg	
Empirical Constant (kβ)	1.9	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON 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
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	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	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

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

Select Fuel Type
Acetone
Scroll to desired fuel typ
Click on selection

Heat Release Rate Calculation

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25.*

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

Where
- Q = pool fire heat release rate (kW)
- $\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m²-sec)
- $\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)
- $A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m²)
- $k\beta$ = empirical constant (m⁻¹)
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

Pool Fire Diameter Calculation

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

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

Where
- A_{dike} = surface area of pool fire (m²)
- D = pool fire diameter (m)

D = 1.884 m

Heat Release Rate Calculation

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

Q = 2865.94 kW 2716.39 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where
- Q' = heat release rate per unit length (kW/m)
- Q = fire heat release rate of the fire (kW)
- L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 2.787 m²

L = 1.669 m

$Q' = Q/L$

Q' = 1716.69 kW/m

ESTIMATING LINE WALL FIRE FLAME HEIGHT

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-134.*

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

Where
- $H_{f(wall\ line)}$ = wall fire flame height (m)
- Q' = rate of heat release per unit length of the fire (kW/m)

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

$H_{f(wall\ line)}$ =	2.44 m	8.00 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, and NFPA Fire Protection Handbook, 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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

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

FDT[s]: 04_Flame_Height_Calculations.xls (click on Wall_Line_Flame _Height)
(c) Methanol

CHAPTER 4. ESTIMATING LINE FIRE FLAME HEIGHT AGAINST THE WALL

Version 1805.0

The following calculations estimate the line fire flame height against the wall.
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

Fuel Spill Volume (V)	15.00	gallons	0.0568 m^3
Fuel Spill Area or Dike Area (A_{dike})	30.00	ft^2	2.787 m^2
Mass Burning Rate of Fuel (m")	0.017	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	20000	kJ/kg	
Empirical Constant (kβ)	100	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON 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
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	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	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

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

Select Fuel Type

Methanol

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25.*

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

Where Q = pool fire heat release rate (kW)

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

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = 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)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

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 = 1.884 m

Heat Release Rate Calculation

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

Q = 947.61 kW 898.16 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where Q' = heat release rate per unit length (kW/m)

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

L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 2.787 m^2

L = 1.669 m

$Q' = Q/L$

Q' = 567.62 kW/m

ESTIMATING LINE WALL FIRE FLAME HEIGHT

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-134.*

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

Where $H_{f(wall\ line)}$ = wall fire flame height (m)

Q' = rate of heat release per unit length of the fire (kW/m)

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

$H_{f(wall\ line)}$ =	1.17 m	3.82 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, and NFPA Fire Protection Handbook, 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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

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

Example Problem 4.9-3

Problem Statement

A pool fire scenario arises from a rupture in a diesel generator fuel line. This event allows diesel fuel to spill 1.5 gallons along the corner of walls with an area of 10 ft^2. An unprotected junction box is located 12 ft above the fire. Determine whether the flame will impinge upon the junction box.

Solution

Purpose:

(1) Calculate the line wall fire flame height.
(2) Determine whether the flame will impinge upon the junction box.

Assumptions:

(1) Air is entrained only from one side during the combustion process.
(2) The fire is located at or near a wall configuration of a compartment that affects the spread of the fire.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 04_Flame_Height_Calculations.xls (click on *Corner_Flame _Height*)

FDTs Input Parameters:

-Fuel spill volume (V) = 1.5 gallons
-Fuel Spill Area or Dike Area (A_{dike}) = 10 ft^2
-Select Fuel Type: **Diesel**

Results*

Fuel	Corner Fire Flame Height ($H_{f(Corner)}$) m (ft)	Junction Box Impingement
Diesel	6.4 (21.1)	Yes

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 04_Flame_Height_Calculations.xls (click on Corner_Flame _Height)

CHAPTER 4. ESTIMATING CORNER FIRE FLAME HEIGHT

Version 1805.0

The following calculations estimate the corner fire flame height.
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

Fuel Spill Volume (V)	1.50	gallons	0.0057 m^3
Fuel Spill Area or Dike Area (A_{dike})	10.00	ft^2	0.929 m^2
Mass Burning Rate of Fuel ($\dot{m}''$)	0.045	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	44400	kJ/kg	
Empirical Constant ($k\beta$)	2.1	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate $\dot{m}''$ (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
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	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	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

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

Select Fuel Type

Diesel

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-25.

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

Where Q = pool fire heat release rate (kW)

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

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = 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)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

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 = **1.088** m

Heat Release Rate Calculation

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

Q = **1667.09** kW **1580.10** Btu/sec

ESTIMATING CORNER FIRE FLAME HEIGHT

Reference: *Hesemi and Tokunaga, "Modeling of Turbulent Diffusion Flames and Fire Plumes for the Analysis of Fire Growth," Growth," Proceeding of the 21st National Heat Transfer Conference, American Society of Mechanical Engineers (ASME), 1983.*

$H_{f(corner)} = 0.075\, Q^{3/5}$

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

$H_{f(corner)} = 0.075\, Q^{3/5}$

$H_{f(corner)}$ =	**6.43 m**	**21.10 ft**	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002 and Hesemi and Tokunage, 1983.

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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UNITED STATES NUCLEAR REGULATORY COMMISSION

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.

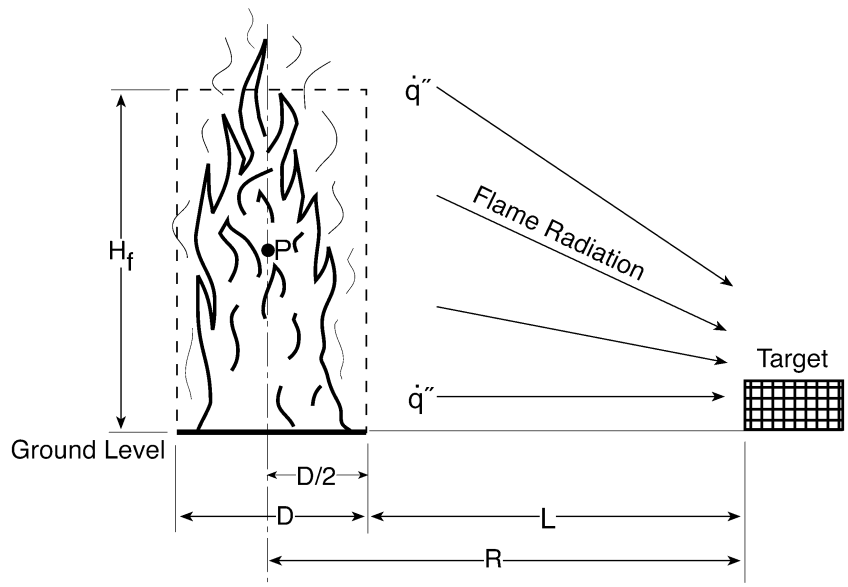

Figure 5-1 Radiant Heat Flux from a Pool Fire
to a Floor-Based Target Fuel (Point Source Model)

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:

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

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):

$$\dot{q}'' = EF_{1\rightarrow 2} \qquad (5\text{-}4)$$

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

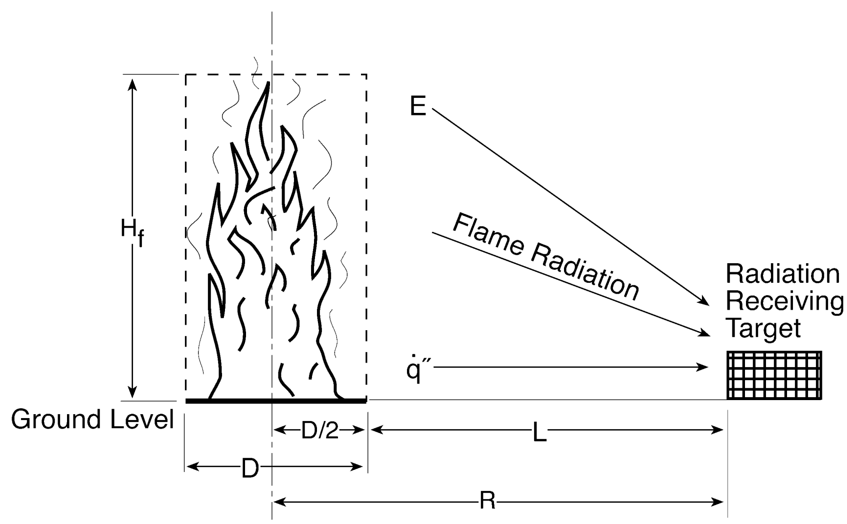

Figure 5-2 Solid Flame Radiation Model with No Wind and Target at Ground Level

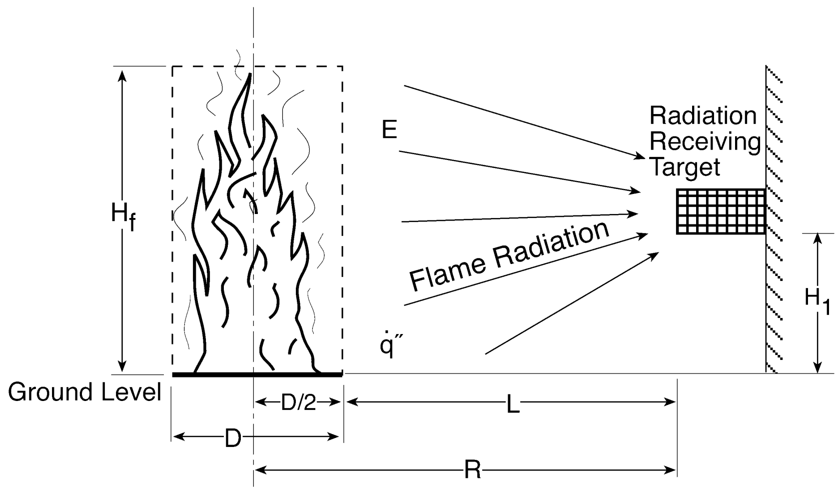

Figure 5-3 Solid Flame Radiation Model with No Wind
and Target Above Ground

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:

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

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”.

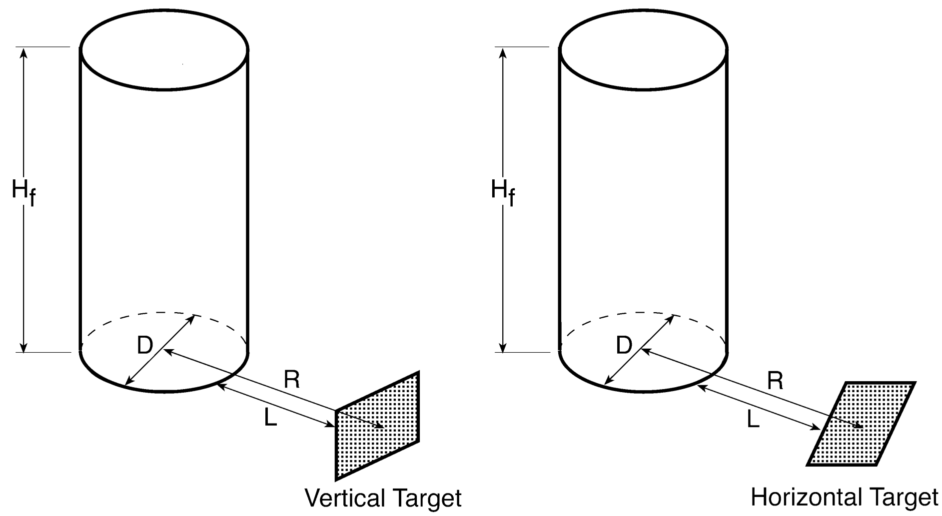

Figure 5-4 Cylindrical Flame Shape Configuration Factor Geometry for Vertical and Horizontal Targets at Ground Level with No Wind

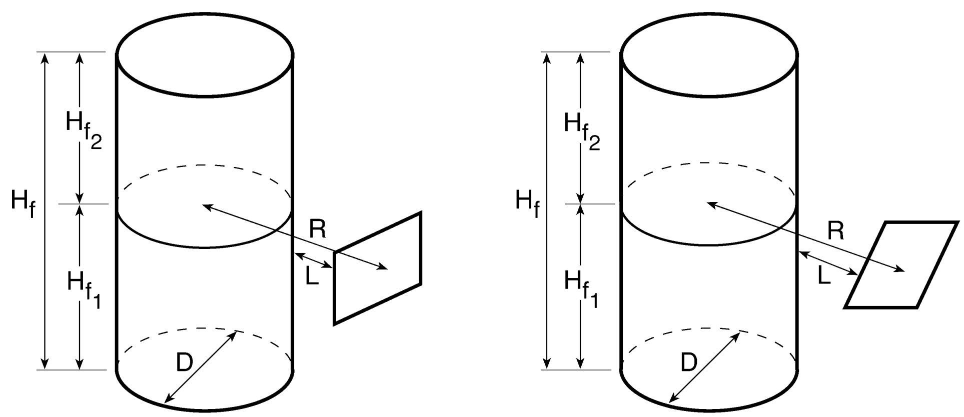

Figure 5-5 Cylindrical Flame Shape Configuration Factor Geometry for Vertical and Horizontal Targets Above Ground with No Wind

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

$$H_f = 0.235\ \dot{Q}^{\frac{2}{5}} - 1.02\ D \qquad (5\text{-}8)$$

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) $F_{1\to 2}$ under wind-free conditions is determined using the following equations related to cylindrical radiation sources (Beyler, 2002):

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

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

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:

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

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:

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

Where:

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

$$h_1 = \frac{2H_f}{D}$$

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

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

Where:

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

$$h_2 = \frac{2H_f}{D}$$

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

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 $F_{1\rightarrow2}$ 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.

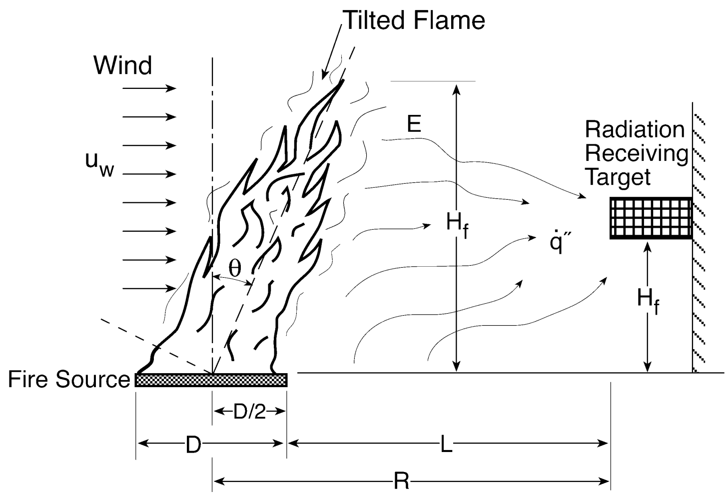

Figure 5-6 Solid Flame Radiation Model in Presence of Wind and Target Above Ground Level

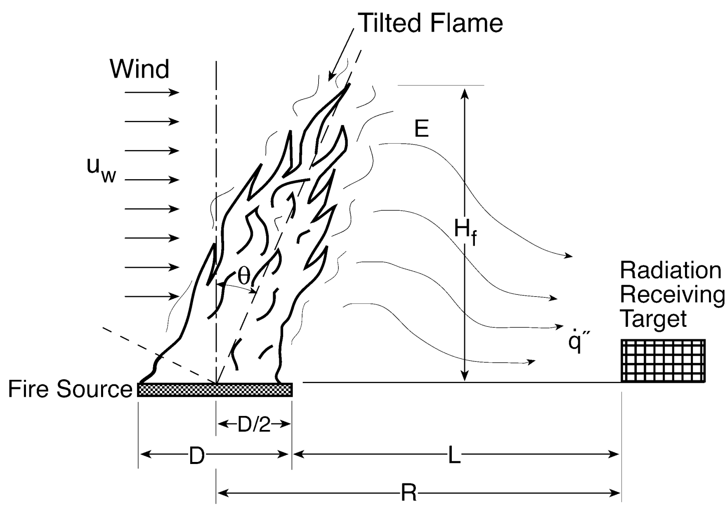

Figure 5-7 Solid Flame Radiation Model in Presence of Wind and Target at Ground Level

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):

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

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

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:

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

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:

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

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

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:

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

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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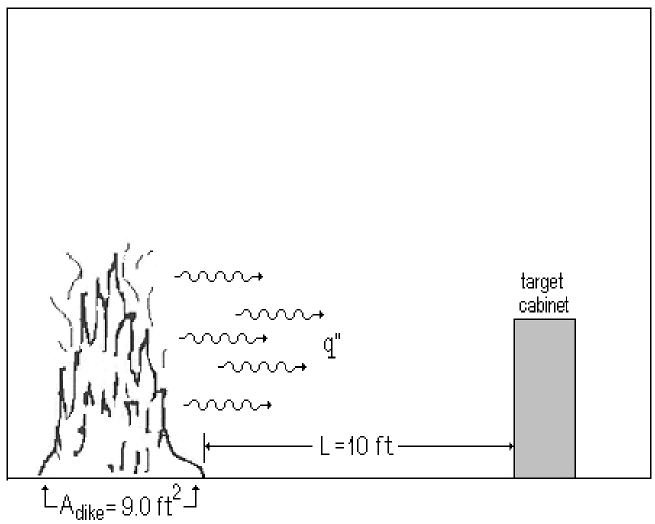
5.11 Problems

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 ($k\beta$)		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 $k\beta$ (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

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

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

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_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.

UNITED STATES NUCLEAR REGULATORY COMMISSION

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

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

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 = 1.03 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

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

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

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

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

$S = 2R/D$

$h = 2H_f/D$

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

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 = 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.

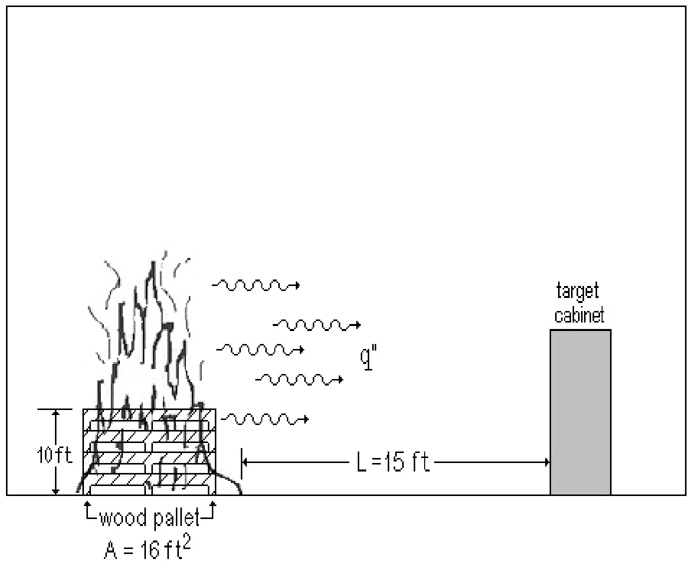
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

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 (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

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

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_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

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 3-276*.

SOLID FLAME RADIATION MODEL

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

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

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

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

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

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

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

$S = 2R/D$

$h = 2H_f/D$

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

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 the 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

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

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.

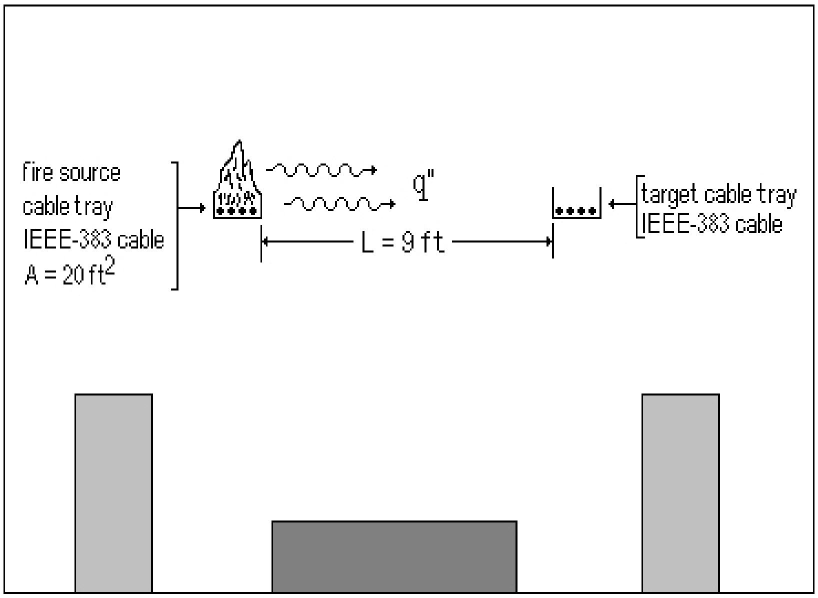
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

Example Problem 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 ($k\beta$)		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 $k\beta$ (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 3-272.*

POINT SOURCE RADIATION MODEL

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

Where q'' = incident radiative heat flux on the target (kW/m²)
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 (m²)
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/m²-sec)
ΔH_c = effective heat of combustion of fuel (kJ/kg)
A_f = surface area of pool fire (area involved in vaporization) (m²)
$k\beta$ = 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/m²	0.03 Btu/ft²-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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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")		0.0044	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

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

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 = 3.44 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 = 54.34 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 = 4.463 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 = 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

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

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.

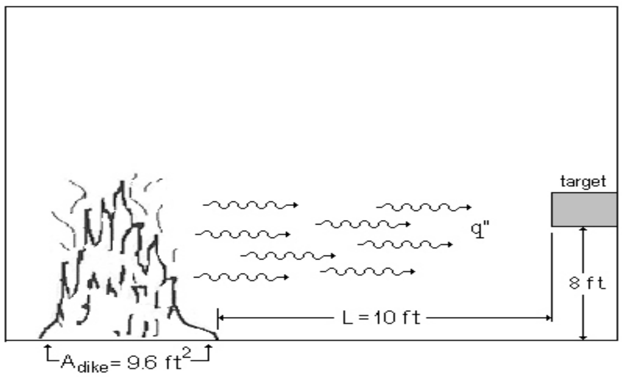
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

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 5.11-4

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 ($H_t = H_{f1}$)		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

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

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

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

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

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

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

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

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

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

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

$S = 2R/D$

$h_1 = 2H_{f1}/D$

$h_2 = 2H_{f2}/D$

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

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 $Btu/ft^2\text{-sec}$	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.

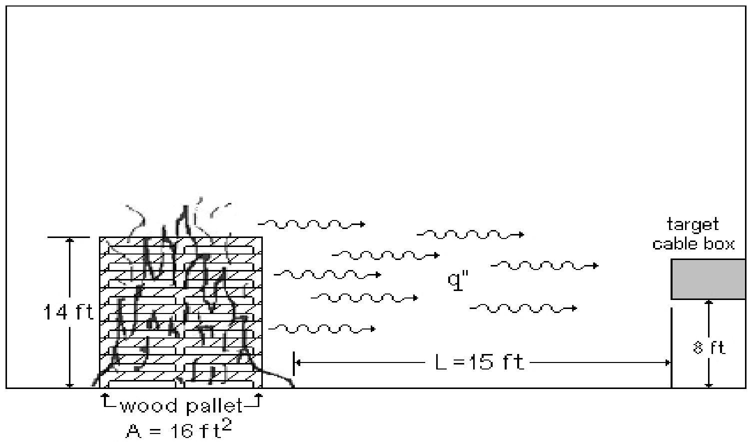
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

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 ($H_t = H_{f1}$)		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*, 3[rd] 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 3-276*.

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

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

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

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

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

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

$S = 2R/D$

$h_1 = 2H_1/D$

$h_2 = 2H_2/D$

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

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

$h_1 = 2H_1/D =$ 3.545

$h_2 = 2H_2/D =$ $2(H-H_1)/D =$ -2.887

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

Radiative Heat Flux Calculation

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

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.

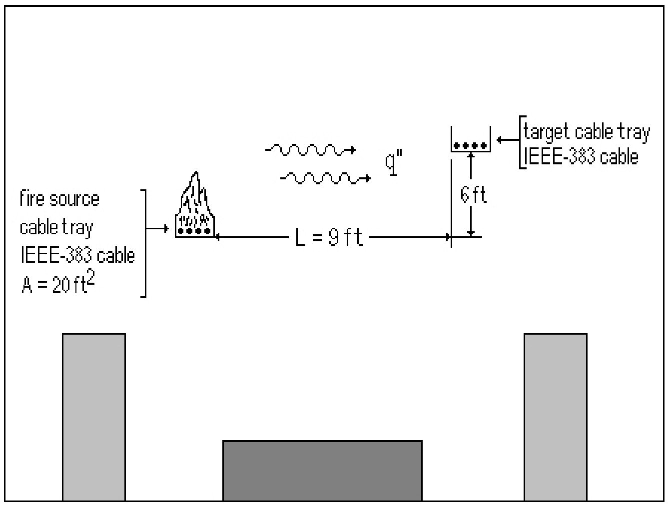
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

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 ($\dot{m}''$)		0.0037	kg/m^2-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 ($\dot{Q}$)		194.56	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
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 $\dot{m}''$ (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

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 $Btu/ft^2\text{-}sec$	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 6. ESTIMATING THE IGNITION TIME OF A TARGET FUEL EXPOSED TO A CONSTANT RADIATIVE HEAT FLUX

6.1 Objectives

This chapter has the following objectives:

- Explain the importance of the location of the ignition source.
- Explain the importance of the position, spacing, and orientation of the fuel(s).
- Describe ignition parameters.
- Discuss how to calculate ignition time.
- Define relevant terms, including ignition temperature, flash point, piloted ignition, and non-piloted ignition.

6.2 Introduction

When performing a fire hazard analysis (FHA), it is essential to understand ignition of materials since the ignition of a combustible material is typically the first step in any fire scenario. Moreover, once a fire starts, the ignition delay times of other materials, coupled with flame spread, will affect the rate at which the fire spreads and develops. Thus, secondary ignition of other materials is another important step in fire development.

Theories regarding ignition and flame spread on solids are based on the concept of a critical surface temperature called the ignition temperature, T_{ig}. This critical surface temperature is related to the flash point (the lowest temperature at which a flammable vapor/air mixture exists at the surface) in the ignition of liquids for the case of piloted ignition, or the auto-ignition temperature if no pilot is present. The flash point phenomenon can be observed with solids under conditions of surface heating, but cannot be defined in terms of a bulk temperature. Because solid fuel must decompose to create fuel vapors (rather than simply evaporating), there is not a unique flash point temperature for a solid fuel. Both piloted and automatic ignition occur in an identical fashion for the evaporated or decomposed fuel gases of liquid and solid fuels, respectively, as illustrated in Figure 6-1.

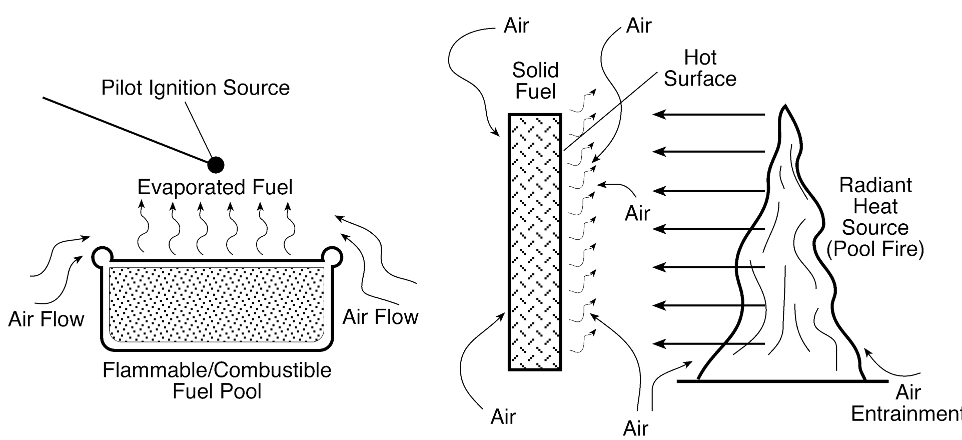


Figure 6-1 Ignition Processes for Liquid and Solid Fuels

For ignition to occur, the solid fuel must be heated sufficiently to vaporize and form a flammable pre-mixed system (see Figure 6-2). An ignition source, such as a spark or small flame must also be present, for piloted ignition or the gas mixture must be heated sufficiently to cause auto-ignition. The critical surface temperature at which these ignitions occur is called the ignition temperature, T_{ig}. Piloted ignition requires a much lower temperature than automatic (or spontaneous) ignition. For example, wood has a typical piloted ignition temperature of 350 °C (662 °F) and 600 °C (1,112 °F) for auto-ignition. Ignition temperature can be considered to be a property of the solid, but it is not truly constant and can vary with the rate of heating.

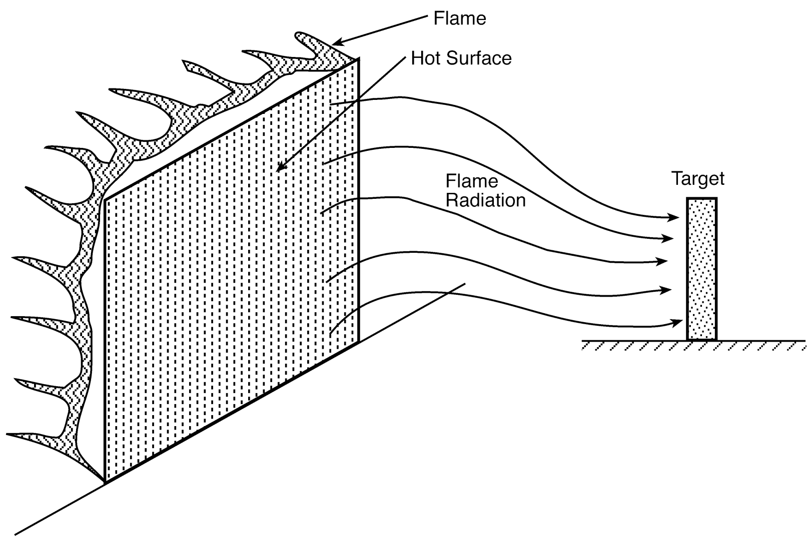


Figure 6-2 External Radiation to a Solid Target Object
from a Flame or Hot Surface at Elevated Temperature

Heating of solids to ignition can be accomplished by radiation from flames or hot gases, by flame contact, or by contact with hot gases. In any of these cases, the measure of the severity of the heating sources is the heat flux, usually measured in kW/m^2 (Btu/ft^2-sec). Table 6-1 lists typical heat fluxes from various sources, which clearly show the significance of radiation in fires.

Table 6-1. Typical Heat Fluxes from Various Sources

Source	**Heat Flux (kW/m^2)**	**Comment**
Flame radiation	0–200	Depends on size of flame and distance from the flame
Flame convection	10–20	Direct flame contact
Hot gas convection	0–10	Direct gas contact
Hot gas radiation	1–150	Depends on gas temperature, soot concentration, and distance from hot gases

6.3 Ignition Sources and Fire Development

An ignition source can consist of a spark with a low energy content, a heated surface, or a large pilot flame. The source of energy can be chemical, electrical, or mechanical. The greater the energy of the ignition source, the faster the fire will subsequently grow on the fuel source surface. A spark or a glowing cigarette may initiate smoldering combustion, which may continue to smolder for a long time before flaming combustion begins. The smoldering often producing low heat but considerable amounts of toxic gases. A pilot flame usually produces flaming combustion and results in quicker flame spread and fire growth.

The location of the ignition source is also very important. For example, a pilot flame positioned at the lower end of a window curtain may cause rapid upward flame spread and fire growth. By contrast, the same pilot flame placed at the top of the curtain would cause much slower fire growth with a slow, downward flame spread.

The position of the fuel can also have a marked effect on fire development. If the fuel is burning away from walls, the cool air is entrained into the plume from all directions. When the fuel is close to a wall, however, the entrainment of cold air is limited; this causes higher temperatures and higher flames since combustion must take place over a greater distance.

The spacing and orientation of the fuels are also important. The spacing in the compartment determines, to a considerable extent, how quickly the fire spreads between the fuel packages. Upward flame spread on a vertically oriented fuel surface will occur more rapidly than lateral spread along a horizontally oriented fuel surface. Similarly, a fuel package with a large surface area will burn more rapidly than an otherwise equivalent fuel package with a small surface area. A pile of wooden sticks, for example, will burn more rapidly than a single log of wood of the same mass.

6.4 Ignition Time for Thermally Thick Materials

Ignition time can be computed by calculating the time to achieve sufficient vaporization to result in a flammable mixture plus the time for the mixture to ignite. Except for cases of low ambient oxygen, the gas phase process is much faster than the heating time of a solid. Typical values of sufficient mass loss rates (burning rates) to enable ignition are on the order of 2 to 6 g/m^2. These values are associated with the initiation of pyrolysis (combustion). Hence, ignition time for a solid can be effectively computed by simple heat conduction theory. The surface of the solid must be heated to its ignition temperature, T_{ig}. Table 6-2 lists measured ignition times for typical thick solid fuels.

Table 6-2. Typical Ignition Times of Thick Solid Fuels (Quintiere, 1997)

Materials	**Heat Flux** $\dot{q}''_e$ **(kW/m^2)**	**Time to Ignition** t_{ig} **(sec)**
Plexiglas, Polyurethane foam, Acrylate carpet	10	300
Wool carpet	20	70
Paper of gypsum board	20	150
Wood particle board	20	250
Polyisocyanurate foam	30	5
Wool/nylon carpet	30	70
Hardboard	30	150

The steady-state surface temperature of a thermally thick fuel is independent of the material's physical properties. The rate of heating and the time required to reach steady-state are material dependent. At steady-state, the incident heat is entirely lost to the surrounding surface by convection and re-radiation, but the temperature of the fuel remains constant. The heat flux required to adjust the surface temperature to the ignition temperature, T_{ig}, is known as the critical heat flux (CHF). Ignition or flame spread is not possible below the threshold level of heating represented by the CHF.

6.4.1 Method of Tewarson

As a fuel surface is exposed to heat flux, most of the heat is transferred to the interior of the material. The ignition principle suggests that the rate with which heat is transferred depends on the ignition temperature (T_{ig}), ambient temperature, (T_a), material thermal conductivity (k), material specific heat (c), and the material density ( ). The combined effects are expressed by a parameter defined as the thermal response parameter (TRP), of the material as follows (Tewarson, 1995):

$$TRP = \Delta T_{ig}\sqrt{k\rho c} \qquad (6\text{-}1)$$

Where:

TRP = thermal response parameter (kW-sec$^{1/2}$/m^2)
T_{ig} = (T_{ig} - T_a) = ignition temperature above ambient (K)
k = material thermal conductivity (kW/m-K)
c = material specific heat (kJ/kg-K)
= material density (kg/m^3)

TRP is a useful parameter for engineering calculations to assess resistance to ignition and flame spread. The important material variables in the above equation are k c. These variables combine to form a material's thermal inertia. (See Chapter 2, Section 2.6.1 for a more detailed discussion of thermal inertia.) For most materials, c does not vary significantly, and the thermal conductivity is largely a function of the material density. This means that density is the most important material property. Low-density materials are excellent thermal insulators because heat does not readily pass the material, the surface of the material actually heats more rapidly and, as a result, can be ignited more quickly. For thin materials, the weight or thickness plays an important role.

The ignition principle suggests that, for thermally thick materials, the inverse of the square root of ignition time is expected to be a linear function of the external heat flux away from the CHF value (Tewarson, 1995):

$$\sqrt{\frac{1}{t_{ig}}} = \frac{\left(\dot{q}_e'' - CHF\right)\sqrt{\frac{4}{\pi}}}{TRP} \qquad (6\text{-}2)$$

$$t_{ig} = \frac{\pi}{4}\left(\frac{TRP}{\dot{q}_e'' - CHF}\right)^2 \qquad (6\text{-}3)$$

Where:

t_{ig} = ignition time (sec)
$\dot{q}_e''$ = external heat flux (kW/m^2)
CHF = critical heat flux for ignition (kW/m^2)
TRP = thermal response parameter (kW-sec$^{1/2}$/m^2)

The above equation applies to the transient period (before steady-state). Most common materials behave as thermally thick materials and satisfy Equation 6-3. The CHF and TRP values for materials are derived from the ignition data measured in the Flammability Apparatus, a commercial instrument designed by the Factory Mutual Research Corporation (FMRC) for measuring bench-scale HRR based on the oxygen consumption calorimetry. The CHF and TRP values for various materials are listed in Table 6-3. The CHF are extrapolated from the experimental correlation when the time to ignition goes to infinity, thus making CHF dependent on the model used for correlating the data. The minimum heat flux for ignition should not be confused with the CHF for ignition. Jenssens (1991) defined minimum heat flux for ignition and CHF for ignition as follows:

- Minimum heat flux for ignition is the heat flux below which ignition under practical condition (in bench-scale test or real-scale test cannot occur).
- CHF for ignition is an estimate of minimum heat flux derived from a correlation of experimental data.

Table 6-3. Critical Heat Flux and Thermal Response Parameters of Selected Materials
(Tewarson, 1995, © SFPE. With permission.)

Material	**Critical Heat Flux (CHF) (kW/m^2)**	**Thermal Response Parameter (TRP) ($kW\text{-}sec^{1/2}/m^2$)**
Electrical Cables: Power		
PVC/PVC	13–25	156–341
PE/PVC	15	221–244
PVC/PE	15	263
Silicone/PVC	19	212
Silicone/crosslinked polyolefine	25–30	435–457
EPR (ethylene-propylene rubber/EPR)	20–23	467–567
XLPE/XLPE	20–25	273–386
XLPE/EVA (ethyl-vinyl acetate)	12–22	442–503
XLPE/Neoprene	15	291
XLPO/XLPO	16–25	461–535
XLPO, PVF, (polyvinylidine fluoride)/XLPO	14–17	413–639
EPR/Chlorosulfonated PE	14–19	283–416
EPR, FR	14–28	289–448
Electrical Cables: Communications		
PVC/PVC	15	131
PE/PVC	20	183
XLPE/XLOP	20	461–535
Si/XLOP	20	457
EPR-FR	19	295
Chlorinated PE	12	217
ETFE/EVA	22	454
PVC/PVF	30	264
FEP/FEP	36	638–652
Synthetic Materials		
Polypropylene	15	193
Nylon	15	270
Polymethylmethacrylate (PMMA)	11	274
Polycarbonate	15	331
Polycarbonate panel	16	420
Natural Materials		
Wood (red oak)	10	134
Wood (Douglas fir)	10	138
Wood (Douglas fir/fire retardant, FR)	10	251
Corrugated paper (light)	10	152

For first order approximation of ignition of solids, this discussion is highly simplified and ignores several secondary aspects of the process. Nonetheless, the discussion shows that two properties of a thick solid fuel significantly affect its ignition behavior. The ignition temperature of the solid is clearly important and reflects the thermal stability of the material. Ignition temperature can be thought of as a chemical property. Materials that are thermally stable are difficult to ignite and exhibit higher ignition temperatures. The primary physical property of the material is its density. The surface of low density material heats more rapidly, causing more rapid ignition of the material. Table 6-4 summarizes typical ignition data for various materials.

Table 6-4. Ignition Temperature and Thermal Properties of Materials
(Quintiere, 1997)

Materials	**Ignition Temperature** T_{ig} (°C)	**Density** (kg/m^3)	**Thermal Conductivity** k (kW/m-K)	**Specific Heat** c (kJ/kg-K)	**Thermal Inertia** k c (kW/m^2-K)^2-sec
Polymethylmethacrylate (PMMA)	278	1200	0.00026	2.1	0.66
Polyurethane foam	280	20	0.000034	1.4	0.00095
Douglas fir particle board (1.23 cm)	382	650	0.00011	2.0	0.14
Plywood plain (1.23 cm)	390	540	0.00012	2.5	0.16
Polystyrene foam (5.08 cm)	630	20	0.000034	1.5	0.0010

To obtain ignition time, several correlations are available in the literature. Although each correlation uses the CHF and critical surface temperature criterion, each technique correlates the data differently resulting in method-specific values for pseudo material properties required in the analysis. Four more techniques are presented for calculating the time to ignition for thermally thick materials under constant radiative heat flux. These methods are based on the principles from SFPE Engineering Guide, “Piloted Ignition of Solid Materials Under Radiant Exposure.”

6.4.2 **Method of Mikkola and Wichman** (SFPE Engineering Guide, 2002)

The time to ignition can be calculated using following correlation:

$$t_{ig} = \frac{\pi}{4} \quad k\rho c \frac{\left(T_{ig} - T_a\right)^2}{\left(\dot{q}_r'' - \dot{q}_{crit}''\right)^2} \qquad (6\text{-}4)$$

Where:

t_{ig} = ignition time (sec)
$k \; c$ = material thermal inertia $(kW/m^2\ K)^2$-sec
T_{ig} = ignition temperature (°C)
T_a = ambient air temperature (°C)
$\dot{q}_r''$ = external heat flux (kW/m^2)
$\dot{q}_{crit}''$ = critical heat flux for ignition (kW/m^2)

6.4.3 **Method of Quintiere and Harkleroad** (SFPE Engineering Guide, 2002)

The time to ignition can be calculated using following correlation:

$$t_{ig} = \left(\frac{\dot{q}_{min}''}{b \quad \dot{q}_r''} \right)^2 \qquad (6\text{-}5)$$

Where:

t_{ig} = ignition time (sec)
$\dot{q}_{min}''$ = minimum heat flux (kW/m^2)
$\dot{q}_r''$ = critical heat flux for ignition (kW/m^2)
b = flame spread parameter $(1/\sqrt{sec})$

6.4.4 **Method of Janssens** (SFPE Engineering Guide, 2002)

The time to ignition can be calculated using following correlation:

$$t_{ig} = 0.563 \left(\frac{k\rho c}{h_{ig}^2}\right) \left(\frac{\dot{q}_e''}{\dot{q}_{crit}''} - 1\right)^{-1.83} \qquad (6\text{-}6)$$

Where:

t_{ig} = ignition time (sec)
k c = material thermal inertia $(kW/m^2\ K)^2$-sec
h_{ig} = heat transfer coefficient at ignition $(kW/m^2\text{-}K)$
$\dot{q}_e''$ = external heat flux (kW/m^2)
$\dot{q}_{crit}''$ = critical heat flux for ignition (kW/m^2)

The above three correlations used the material properties listed in Table 6-5.

Table 6-5. Ignition and Flame Spread Properties of Materials
(SFPE Engineering Guide, 2002. With permission.)

Materials	**Ignition Temperature** T_{ig} (°C)	**Thermal Inertia** $k\rho c$ $(kW/m^2\,K)^2$-sec	**Minimum Heat Flux for Ignition** $\dot{q}''_{min}$ (kW/m^2)	**Flame Spread Parameter** b $(1/\sqrt{sec})$
PMMA Polycast (1.59mm)	278	0.73	9	0.04
Hardboard (6.35 mm)	298	1.87	10	0.03
Carpet (Arcylic)	300	0.42	10	0.06
Fiber Insulation Board	355	0.46	14	0.07
Hardboard (3.175mm)	365	0.88	14	0.05
PMMA Type G (1.27 cm)	378	1.02	15	0.05
Asphalt Shingle	378	0.7	15	0.06
Douglas Fir Particle Board (1.27 cm)	382	0.94	16	0.05
Plywood Plain (1.27 cm)	390	0.54	16	0.07
Plywood Plain (0.635 cm)	390	0.46	16	0.07
Foam Flexible (2.54 cm)	390	0.32	16	0.09
GRP (2.24 mm)	390	0.32	16	0.09
Hardboard (Gloss Paint) (3.4 mm)	400	1.22	17	0.05
Hardboard (Nitrocellulose Paint)	400	0.79	17	0.06
GRP (1.14 mm)	400	0.72	17	0.06
Particle Board (1.27 cm Stock)	412	0.93	18	0.05
Carpet (Nylon/Wool Blend)	412	0.68	18	0.06

Table 6-5. Ignition and Flame Spread Properties of Materials (continued)
(SFPE Engineering Guide, 2002. With permission.)

Materials	**Ignition Temperature** T_{ig} **(°C)**	**Thermal Inertia** $k\rho c$ **$(kW/m^2 K)^2$-sec**	**Minimum Heat Flux for Ignition** $\dot{q}''_{min}$ **(kW/m^2)**	**Flame Spread Parameter** b **(1/ $\sqrt{sec}$)**
Gypsum Board, Wallboard (S142M)	412	0.57	18	0.07
Carpet # 2 (Wool Untreated)	435	0.25	20	0.11
Foam, Rigid (2.54 cm)	435	0.03	20	0.32
Fiberglass Shingle	445	0.5	21	0.08
Polyisocyanurate (5.08 cm)	445	0.02	21	0.36
Carpet # 2 (Wool Treated)	455	0.24	22	0.12
Carpet # 1 (Wool, Stock)	465	0.11	23	0.18
Aircraft Panel Epoxy Fiberite	505	0.24	28	0.13
Gypsum Board FR (1.27 cm)	510	0.4	28	0.1
Polycarbonate (1.52 mm)	528	1.16	30	0.06
Gypsum Board (Common) (1.52 mm)	565	0.45	35	0.11
Plywood FR (1.27 cm)	620	0.76	44	0.1
Polystyrene (5.08 cm)	630	0.38	46	0.14

6.4.5 Method of Toal, Silcock, and Shields (SFPE Engineering Guide, 2002)

The time to ignition can be calculated using following correlation:

$$t_{ig} = \frac{FTP_n}{\left(\dot{q}_r'' - \dot{q}_{crit}''\right)^n} \qquad (6\text{-}7)$$

Where:

t_{ig} = ignition time (sec)
FTP = flux time product $(kW\text{-}sec/m^2)^n$
$\dot{q}_r''$ = exposure or external heat flux (kW/m^2)
$\dot{q}_{crit}''$ = critical heat flux for ignition (kW/m^2)
n = flux time product index $(n \geq 1)$

Equation 6-7 uses the material properties listed in Table 6-6.

Table 6-6. Ignition and Flame Spread Properties of Materials
(SFPE Engineering Guide, 2002. With permission.)

Materials	**Flux Time Product FTP $(kW\text{-}sec/m^2)^n$**	**Critical Heat Flux $\dot{q}_{crit}''$ (kW/m^2)**	**Flux Time Product Index n**
Chipboard	5,370	6.4	1.49
Chipboard (Horizontal) (15 mm)	9,921	9	1.7
Chipboard (Vertical) (15 mm)	11,071	10	1.7
Fiberboard	3,981	8.3	1.66
Hardboard	8,127	8.1	1.49
Hardboard (Painted Gloss)	9,332	8.1	1.51
Hardwood	2,818	8.1	1.5
Plywood	6,164	10.6	1.51
Plywood (Horizontal) (12 mm)	5,409	8.5	1.5
Plywood (Vertical) (12 mm)	42,025	10	2

Table 6-6. Ignition and Flame Spread Properties of Materials (continued)
(SFPE Engineering Guide, 2002. With permission.)

Materials	**Flux Time Product FTP $(kW\text{-}sec/m^2)^n$**	**Critical Heat Flux $\dot{q}''_{crit}$ (kW/m^2)**	**Flux Time Product Index n**
Plywood (Painted Gloss)	6,761	11.4	1.5
PMMA (Cast) (3mm)	3,100	5	1.25
PMMA (Extruded) (2 mm)	1,290	9	1
Polyethylene (2mm)	2,220	12.5	1
Polypropylene (3.3 mm)	8,110	6.5	1.5
PVC (Extruded Gray) (3 mm)	5,130	15	1.5
PVC (Pressed White) (3 mm)	95,000	8	2
Softwood	5,130	13.7	1.53
Softwood (Horizontal) (20 mm)	44,079	10	2.2
Softwood (Vertical) (20 mm)	16,502	12	1.9
Softwood Intumescent Paint	4,569	13	1.5

6.5 Assumptions and Limitations

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

(1) For ignition to occur, a solid material must be heated sufficiently to vaporize and form a flammable mixture.

(2) Ignition occurs when the surface reaches a critical temperature defined as the ignition temperature.

(3) A heat source must be present to ignite the solid.

(4) The solid is assumed to be infinitely thick.

(5) The methods are all derived through the solid with radiant heating on the surface.

6.6 Required Input for Spreadsheet Calculations

(1) Target fuel type (material)

(2) Exposed radiative heat flux to target (kW/m^2)

6.7 Cautions

(1) Use (06_Ignition_Time_Calculations.xls) spreadsheet on the CD-ROM for calculations.

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

6.8 Summary

This chapter discusses ignition phenomena associated with thermally thick materials, as well as material properties that have major effects on ignition and flame spread. For thin materials, the weight or thickness of the material plays a very important role. For thick materials, the density of the material has a major impact on ignition and flame spread rates.

6.9 References

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

SFPE Engineering Guide, "Piloted Ignition of Solid Materials Under Radiant Exposure," Society of Fire Protection Engineers, Bethesda, Maryland, January 2002.

Tewarson, A., "Generation of Heat and Chemical Compounds in Fires," Section 3, Chapter 4, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

6.10 Additional Readings

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

Janssens, M.L., "Fundamental Thermophysical Characteristics of Wood and their Role in Enclosure Fire Growth," Doctor of Philosophy Dissertation, University of Gent, Belgium, September 1991.

Karlsson, B., and J.G. Quintiere, *Enclosure Fire Dynamics*, Chapter 2, "A Qualitative Description of Enclosure Fires," CRC Press LLC, New York, pp. 11–24, 1999.

6.11 Problems

Example Problem 6.11-1

Problem Statement

Calculate the ignition time for a PVC/PE power cable, assuming that a 6.5-ft (2-m) diameter pool fire produces a 25-kW/m^2 heat flux.

Solution

Purpose:
(1) Calculate the ignition time for a PVC/PE power cable.

Assumptions:
(1) The material is infinitely thick.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 06_Ignition_Time_Calculations.xls (click on *Ignition_Time _Calculations3*)

FDT^s Input Parameters:
-Exposure or External Radiative Heat Flux to Target Fuel $(\dot{q}''_e)$ = 25 kW/m^2
-Click on the option button (⊙) for Electrical Cables - Power
-Select Material: PVC/PE

Results*

Material	**Ignition Time** (t_{ig}) (min.) Method of Tewarson
PVC/PE	9.0

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 06_Ignition_Time_Calculations.xls (Ignition_Time _Calculations3)

CHAPTER 6. ESTIMATING THE IGNITION TIME OF A TARGET FUEL EXPOSED TO A CONSTANT RADIATIVE HEAT FLUX

Version 1805.0

The following calculations estimate time to ignition for flame spread of solid fuels exposed to a constant external radiative heat flux.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters.
This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Exposure or External Radiative Heat Flux to Target Fuel ($\dot{q}''_e$)	25.00	kW/m^2
Target Critical Heat Flux for Ignition (CHF)	15.00	kW/m^2
Target Thermal Response Parameter (TRP)	263	$kW\text{-}sec^{1/2}/m^2$
	Calculate	

CRITICAL HEAT FLUX AND THERMAL RESPONSE PARAMETER FOR MATERIALS

Materials	Critical Heat Flux for Ignition CHF (kW/m^2)	Thermal Response Parameter (TRP) ($kW\text{-}sec^{1/2}/m^2$)	
Electrical Cables - Power			
PVC/PVC	19.00	248.5	Select Material
PE/PVC	15.00	232.5	PVC/PE
PVC/PE	15.00	263	Scroll to desired material then
Silicone/PVC	19.00	212	Click on selection
Silicone/cross linked polyolefin (XLPO)	27.50	446	
EPR (ethylene-propylene rubber/EPR)	21.50	517	
XLPE/XLPE	22.50	329.5	
XLPE/EVA (ethylene vinyl acetate)	17.00	472.5	
XLPE/Neoprene	15.00	291	
XLPO/XLPO	20.50	498	
XLPO, PVF (polyvinylidine fluoride)/XLPO	15.50	526	
EPR/Chlorosulfonated PE	16.50	349.5	
EPR, FR	21.00	368.5	
User Specified Value	Enter Value	Enter Value	
Electrical Cables - Communications			Select Material
PVC/PVC	15.00	131	
PE/PVC	20.00	183	Scroll to desired material then
XLPE/XLOP	20.00	498	Click on selection
SI/XLOP	20.00	457	
EPR-FR	19.00	295	
Chlorinated PE	12.00	217	
ETFE/EVA	22.00	454	
PVC/PVF	30.00	264	
FEP/FEP	36.00	645	
User Specified Value	Enter Value	Enter Value	
Synthetic Materials			Select Material
Polypropylene	15.00	193	
Nylon	15.00	270	Scroll to desired material then
Polymethylmethacrylate (PMMA)	11.00	274	Click on selection
Polycarbonate	15.00	331	
Polycarbonate panel	16.00	420	
User Specified Value	Enter Value	Enter Value	
Natural Materials			Select Material
Wood (red oak)	10.00	134	
Wood (douglas fir)	10.00	138	Scroll to desired material then
Wood (douglas fir/fire retardant, FR)	10.00	251	Click on selection
Corrugated paper (light)	10.00	152	
User Specified Value	Enter Value	Enter Value	

Reference: SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-58.

ESTIMATING IGNITION TIME FOR COMBUSTIBLES
METHOD OF TEWARSON
THERMALLY THICK MATERIALS

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-53

$\sqrt{1/t_{ig}} = (\sqrt{4/\pi})(q''_e - CHF)/TRP$

$t_{ig} = (\pi/4)\,(TRP)^2/(q''_e - CHF)^2$

Where t_{ig} = target ignition time (sec)

q''_e = external radiative heat flux to target (kW/m²)

CHF = target critical heat flux for ignition (kW/m²)

TRP = thermal response parameter of target material (kW-sec$^{1/2}$/m²)

$t_{ig} = (\pi/4)\,(TRP)^2/(q''_e - CHF)^2$

t_{ig} =	543.25 sec	9.05 minutes	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 6.11-2

Problem Statement
Determine the time for 2-inch-thick Douglas fir plywood to ignite when it is subjected to a flame heat flux of 25 kW/m^2, assuming the surface of the plywood is initially at 68 °F (20 °C).

Solution

Purpose:
(1) Calculate the ignition time of Douglas fir plywood.

Assumptions:
(1) The material is infinitely thick.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:
(a) 06_Ignition_Time_Calculations.xls (click on *Ignition_Time _Calculations3*)

FDT^s Input Parameters:

-Exposure or External Radiative Heat Flux to Target Fuel $(\dot{q}_e'')$ = 25 kW/m^2

-Click on the option button (⊙) for Natural Materials
-Select Material: **Wood (Douglas fir)**

Note: The ignition time calculation method (Tewarson) provided in the spreadsheet *Ignition_Time _Calculations3* does not require the material thickness or initial surface temperature; therefore, material thickness and temperature are additional information only. However, if the initial temperature of the material is relatively high (compare with ambient temperature range), the ignition time value definitely will not be realistic based on this method. Also, we are assuming the material as infinitely thick to use the method; thus, we do not have to consider the thickness for this problem.

Results*

Material	Ignition Time (t_{ig}) (min.) Method of Tewarson
Wood (Douglas fir)	1.11

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 06_Ignition_Time_Calculations.xls (Ignition_Time _Calculations3)

CHAPTER 6. ESTIMATING THE IGNITION TIME OF A TARGET FUEL EXPOSED TO A CONSTANT RADIATIVE HEAT FLUX

Version 1805.0

The following calculations estimate time to ignition for flame spread of solid fuels exposed to a constant external radiative heat flux.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters.
This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Exposure or External Radiative Heat Flux to Target Fuel ($\dot{q}''_e$)	25.00	kW/m^2
Target Critical Heat Flux for Ignition (CHF)	10.00	kW/m^2
Target Thermal Response Parameter (TRP)	138	$kW\text{-}sec^{1/2}/m^2$
	Calculate	

CRITICAL HEAT FLUX AND THERMAL RESPONSE PARAMETER FOR MATERIALS

	Materials	Critical Heat Flux for Ignition CHF (kW/m^2)	Thermal Response Parameter (TRP) ($kW\text{-}sec^{1/2}/m^2$)	
Electrical Cables - Power				
	PVC/PVC	19.00	248.5	Select Material
	PE/PVC	15.00	232.5	
	PVC/PE	15.00	263	Scroll to desired material then
	Silicone/PVC	19.00	212	Click on selection
	Silicone/cross linked polyolefin (XLPO)	27.50	446	
	EPR (ethylene-propylene rubber/EPR)	21.50	517	
	XLPE/XLPE	22.50	329.5	
	XLPE/EVA (ethyl-vinyl acetate)	17.00	472.5	
	XLPE/Neoprene	15.00	291	
	XLPO/XLPO	20.50	498	
	XLPO, PVF (polyvinylidine fluoride)/XLPO	15.50	526	
	EPR/Chlorosulfonated PE	16.50	349.5	
	EPR, FR	21.00	368.5	
	User Specified Value	Enter Value	Enter Value	
Electrical Cables - Communications				Select Material
	PVC/PVC	15.00	131	
	PE/PVC	20.00	183	Scroll to desired material then
	XLPE/XLOP	20.00	498	Click on selection
	SI/XLOP	20.00	457	
	EPR-FR	19.00	295	
	Chlorinated PE	12.00	217	
	ETFE/EVA	22.00	454	
	PVC/PVF	30.00	264	
	FEP/FEP	36.00	645	
	User Specified Value	Enter Value	Enter Value	
Synthetic Materials				Select Material
	Polypropylene	15.00	193	
	Nylon	15.00	270	Scroll to desired material then
	Polymethylmethacrylate (PMMA)	11.00	274	Click on selection
	Polycarbonate	15.00	331	
	Polycarbonate panel	16.00	420	
	User Specified Value	Enter Value	Enter Value	
Natural Materials				Select Material
	Wood (red oak)	10.00	134	Wood (douglas fir)
	Wood (douglas fir)	10.00	138	Scroll to desired material then
	Wood (douglas fir/fire retardant, FR)	10.00	251	Click on selection
	Corrugated paper (light)	10.00	152	
	User Specified Value	Enter Value	Enter Value	

Reference: SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-55.

ESTIMATING IGNITION TIME FOR COMBUSTIBLES
METHOD OF TEWARSON
THERMALLY THICK MATERIALS

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-53.

$\sqrt{(1/t_{ig})} = (\sqrt{(4/\pi)}(q"_e - CHF))/TRP$

$t_{ig} = (\pi/4)(TRP)^2/(q"_e - CHF)^2$

Where

t_{ig} = target ignition time (sec)

$q"_e$ = external radiative heat flux to target (kW/m^2)

CHF = target critical heat flux for ignition (kW/m^2)

TRP = thermal response parameter of target material (kW-sec$^{1/2}$/m^2)

t_{ig} = $(\pi/4)(TRP)^2/(q"_e - CHF)^2$

t_{ig} =	66.48 sec	1.11 minutes	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.