



A SunCam online continuing education course

An Introduction to Heat Transfer in Structure Fires

by

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Part 1: Introduction

Besides the fire triangle (fuel, heat, oxygen), heat transfer is the driving factor behind how fires start, grow, and potentially threaten life and property. This course provides an introduction to methods for calculating conduction, convection, and radiation which occur in a typical structure fire. Methods for calculating temperatures and velocities inside a compartment during a fire are reviewed. Activation time for sprinklers based on the temperature and flow velocities created by a compartment fire are also discussed. As a reminder, conduction is the transfer of thermal energy through solid objects. Convection is the transfer of thermal energy involving a fluid and is a mixture of advection (movement of fluids) and conduction. For the purposes of this course we will be talking about radiation as the transfer of thermal energy through electromagnetic waves. When we talk about radiation we are referring to non-ionizing thermal radiation which is mostly in the infrared spectrum. Radiation is how thermal energy is transferred to a target at a distance during fire events and will be a large portion of the content covered in this course. To demonstrate the thermal radiation given off by a typical fire, figure 1 shows a comparison of a 4 ft. diameter kerosene pool fire recorded using a visual and an infrared camera. This thermal radiation is utilized by modern fire fighters when they use infrared cameras also called “thermal imaging cameras” to better be able to see where fires are in a smoke filled compartment, find hotspots in walls, and for search and rescue operations. (If you are interested, a demonstration of using a thermal imaging camera to see inside of a smoke filled compartment compared with a normal camera view is shown in this video:

<https://www.youtube.com/watch?v=Lo2OwlekzPY>.)



Figure 1: Comparison of visual image with thermal imaging camera of a 4ft diameter Kerosene fire



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Part 2: Review of Conduction and Convection

In structure fire growth and development, conduction's main role is as a part of convection and flame propagation once burning is established. Once a compartment has been heated by a fire, it is possible for conduction to cause ignition inside of a wall, on object touching a hot wall, and to help in rekindling a fire that is thought to be extinguished. In early compartment fire growth convection is the driving factor for flame spread and fire growth. When dealing with heat transfer, fire scientists are often interested in the heat flux, specifically is there enough heat flux to cause ignition. Most materials will ignite with a heat flux of between 10-20 kW/m² [1]. The amount of time required to ignite at a given heat flux varies and will be discussed later on in this course. Parameters such as how much water has been absorbed by the material and the ambient temperature will also change the ignition behavior.

For those students who have not studied heat transfer in a while, the following section provides a brief introduction into one dimensional (1D) steady state conduction and convection equations with example calculations. If you are more familiar with these concepts, feel free to skip to the compartment upper gas layer temperature section. In this course heat transfer calculations are done in the absolute temperature scale of Kelvin (K). For those who do not remember, Kelvin is the temperature in Celsius plus 273.15 (to get from Fahrenheit to Celsius subtract 32 and multiply by 5/9). Room temperature in Kelvin is often taken to be 298K ($\approx 25^{\circ}\text{C}$ or $\approx 77^{\circ}\text{F}$) and this will be used in this course. To keep the course on track and since there are a plethora of temperature conversion apps and websites available, I will not go into any more detail on temperature scale conversions. I am going to attempt to stay focused on heat transfer and fire in this specific course, more information on basic fire behavior/ fire dynamics can be found in the *Fire Dynamics* 2nd edition textbook by Gorbett, Pharr, and Rockwell.

Equation 1 shows the one dimensional (1D) steady state heat transfer equation for conduction. A diagram for this equation is shown in Fig 2. This is a function of the thermal conductivity of the material and the temperature difference between the two locations of the solid in question.

$$\dot{q}'' = k \frac{T_1 - T_2}{L}$$

k - thermal conductivity [kW/(m K)]

L - Thickness of material [m]

T_1 - temperature at point 1 [K]

T_2 - temperature at point 2 [K]

\dot{q}'' - heat flux [kW/m²]

(1)



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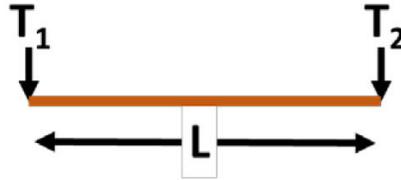


Figure 2: One dimensional heat transfer diagram

To use this analysis we must make several assumption including steady state conditions, one dimensional conduction, a constant thermal conductivity which is independent of temperature, and the material has a linear temperature distribution throughout its length. Example 1 provides sample calculations using equation 1. Excel spread sheet calculations for 1D conduction are included in the provided excel file in the tab titled “1D Conduction”.

Example 1: 1D Conduction Calculations

What is the one dimensional (1D) steady state conduction through a 0.5m copper rod with a temperature of 373K (approximate boiling point of water at sea-level) at one end and a temperature of 298K (room temperature) at the other end?

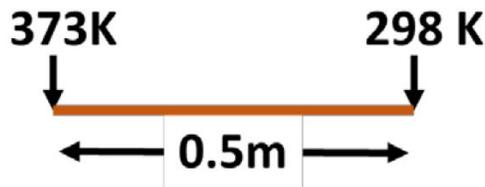


Figure 3: 1D Conduction Example Diagram

Solution:

Using resource texts or the internet we find that the thermal conductivity for copper is 0.387 kW/(m K). Therefore the heat flux through the rod can be calculated as:

$$\dot{q}'' = (0.387 \text{ kW}/(\text{m K})) \frac{373 \text{ K} - 298 \text{ K}}{0.5 \text{ m}} = 58.1 \text{ kW}/\text{m}^2$$

This can also be solved using the “1D Conduction” tab of the excel spreadsheet provided with the course as shown below:



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This spreadsheet calculates 1D conductive heat transfer corresponding with Equation 1 in the course material.		
T_1	373	K
T_2	298	K
L	0.5	m
k	0.387	kW/(m K)
\dot{q}''	58.1	kW/m ²

One dimensional convection can be described mathematically in a similar way to conduction with the use of a convective heat transfer coefficient (h). This parameter is difficult to determine for all but the simplest geometries. (h is often determined based on the Nusselt number but this is outside the scope of this course) For buoyant flows in air, h is often on the order of 0.005-0.01 kW/(m² K) [1] but can vary significantly based on boundary layer conditions. To calculate the steady state, 1D convective heat transfer from a liquid to a solid surface the following equation can be used:

$$\dot{q}'' = h(T_f - T_s)$$

\dot{q}'' - heat flux [kW/m²]
 h - convective heat transfer coefficient [kW/(m² K)] (2)
 T_f - temperature of fluid [K]
 T_s - temperature of solid [K]

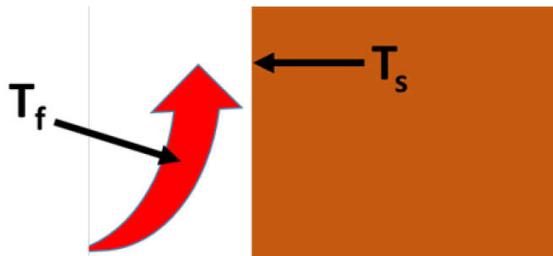


Figure 4: Diagram of 1D steady state convection

To use this analysis we must once again make several assumption including steady state conditions, one dimensional, a constant heat transfer coefficient. Example 2 shows a sample



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calculation using equation 2. Excel spread sheet calculations for 1D convection equations are included in the provided excel file in the tab titled “1D Convection”.

Example 2: 1D Convection

What is the convective heat flux to a wooden wall with a temperature of 298K from the heated buoyant flow from a fire with an average temperature of 700K? Assume a convective heat transfer coefficient of 0.008 kW/(m² K). Is this likely to be enough heat flux to ignite the wall?

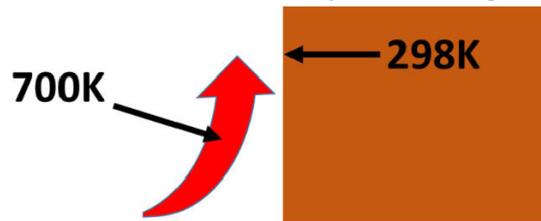


Figure 5: 1D Convection Example Diagram

Solution:

$$\dot{q}'' = 0.008 \text{ kW} / \text{m}^2 \text{ K} (700 \text{ K} - 298 \text{ K}) = 3.22 \text{ kW} / \text{m}^2$$

This is not likely to be enough heat flux by itself to ignite the wall, this would require 10-20 kW/m² depending on duration of exposure. Ignition of materials will be discussed in more detail later on in this course.

This can also be solved using the “1D Convection” tab of the excel spreadsheet provided with the course as shown below:

This spreadsheet calculates 1D convective heat transfer corresponding with Equation 2 in the course material.		
T _f	700	K
T _s	298	K
h	0.008	kW/(m ² K)
\dot{q}''	3.2	kW/m ²



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2.1 Time dependent conduction and convection

Calculating time dependent 1D heat transfer through a solid with a hot fluid on one side and a cold fluid on the other, side such as the wall of a compartment containing a fire, becomes more complicated than the simple one 1D examples. To do this an iterative scheme is often used that breaks the solid wall into small sections each with its own temperature. Heat transfer is then calculated using an iterative scheme. The boundary condition for the solid next to a hot fluid can be calculated using [2]:

$$T_s(t + \Delta t) = T_s(t) + \frac{h\Delta t}{\rho c_p \Delta x} (T_{fluid} - 2T_s(t) + T_{s,t=0}) \quad (3)$$

The interior of the solid is then broken up into discrete sections, each with a length Δx . The temperature in each discrete section, represented by T_n , can be calculated from one section to the next using:

$$T_n(t + \Delta t) = T_n(t) + \frac{k}{\rho c_p (\Delta x)^2} (T_{n-1} - 2T_n + T_{n+1}) \quad (4)$$

Figure 6 shows a diagram of how these equations can be used based on a solid divided into four sections. As with any iterative computational scheme the smaller the time steps and divisions in the solid object the more accurate the computational model will be but the longer the calculation will take. Programming these types of equations into a spreadsheet program like excel is doable but cumbersome, it is more efficient to use a computer programming language such as MATLAB or Fortran. As an illustration, figure 7 shows a comparison of heat transfer into a 2D solid from a single hot surface using two different size divisions (Δx). The MATLAB script for this heat transfer model is available at www.firesciencetools.com in the MATLAB section.

Multidimensional time dependent convective and conductive heat transfer is solved in a similar way to Eqs. 3 and 4 but taking into account the nodes surrounding the location of interest in the other dimension. These multidimensional equations along with the mechanics of programming these types of equations into a computer program is outside the scope of this course and delving into these would distract from the goal of understanding the role heat transfer plays in unintentional fires so I will not go into any more detail here.



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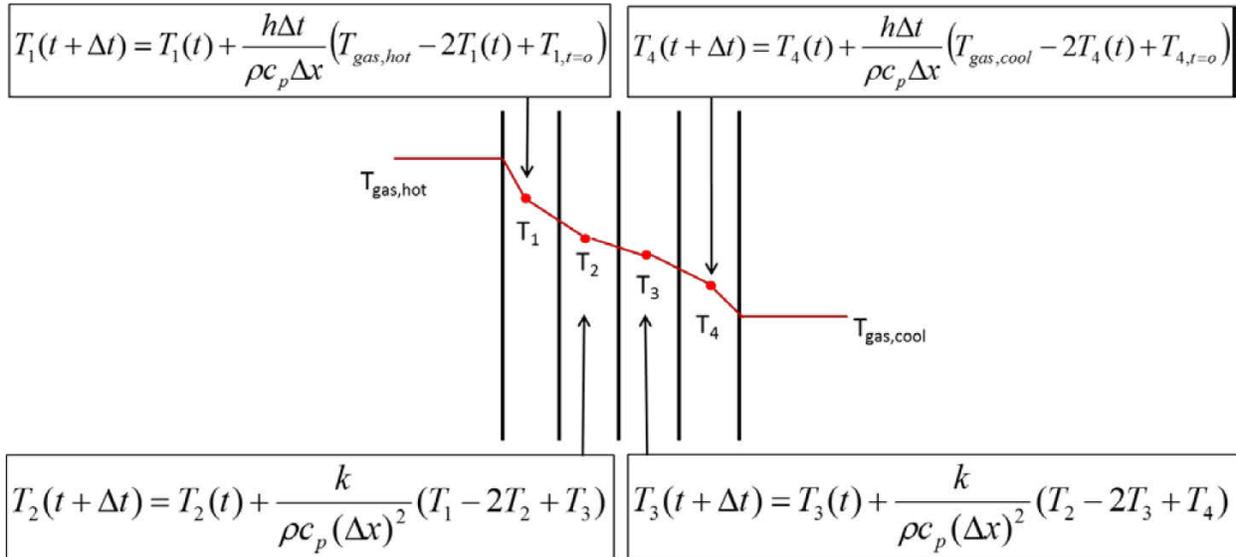


Figure 6: Time dependent temperature equations for a solid divided into four discrete sections

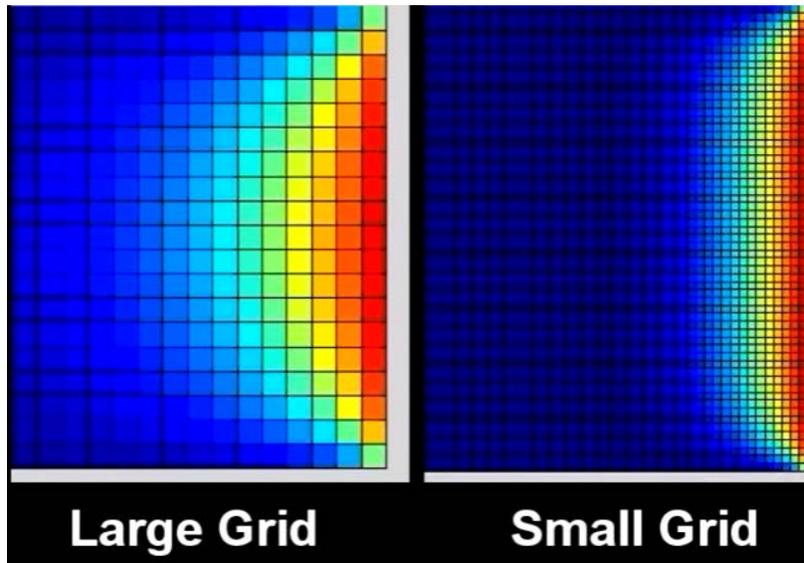


Figure 7: Comparison of large and small grid on 2D heat transfer

If you would like to learn about programming heat transfer equations into MATLAB I have created several YouTube videos on this subject which are available here: <https://www.youtube.com/user/SRcombexp/videos> and the MATLAB code described in the videos (including the one I wrote to create Figure 7 above) are available in the MATLAB section of www.firesciencetools.com. Rather than recreating the wheel so to speak, and programming



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these fundamental heat transfer equations, in all but the simplest geometries/conditions, I recommend engineers use one of the variety of fire or heat/fluid transfer models which have already been created to solve problems. Some of the available programs are free/open source such as OpenFOAM (<http://openfoam.org/>) and some are commercial products such as ANSYS Fluent (<http://www.ansys.com/Products/Fluids/ANSYS-Fluent>). At the end of this course we will discuss a range of modern computer fire models which are available for use to help solve design and investigation problems dealing with structure fires.



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Part 3: Temperatures in a Compartment Fire

To minimize the complication of the mathematics of heat transfer when dealing with the gas temperatures in a compartment fire, fire scientists have developed an “effective heat transfer coefficient (h_k)” which takes into account the convection to and conduction through the walls of a compartment. The effective heat transfer coefficient (h_k) can be calculated using the following equation [3]:

$$\text{if } t < t_p : h_k = \sqrt{k\rho c_p / t}, \text{ if } t > t_p : h_k = \frac{k}{\delta}$$

c_p - interior lining specific heat [kJ/(kg K)]
 h_k - heat transfer coefficient [kW/(m²K)]
 k - interior lining thermal conductivity [kW/(m K)]

$$t_p - \text{thermal penetration time [s]; } t_p = \left(\frac{\rho c_p}{k} \right) \left(\frac{\delta}{2} \right)^2$$

ρ - interior lining density [kg/m³]
 δ - interior lining thickness [m]

(5)

As can be seen, h_k varies as a function of temperature, time, and a variety of other conditions but for an initial approximation it can be estimated as $h_k = 0.025\text{kW}/(\text{m}^2\text{K})$. The effective heat transfer coefficient is used in an empirical equation shown as Eq. 6 [3]. This equation involves the calculation of the total internal surface area of the compartment. A diagram of a typical compartment is shown in Figure 8. When dealing with the temperature rise in the upper layer of a compartment both convection and conduction must be taken into account (technically radiation also plays a role but it is less important during the fire growth stages). The size of a fire, or its power output, has a direct impact amount of heat transfer it can induce. The power of a fire is usually described as a heat release rate (HRR) which often uses the symbol \dot{Q} with units of Kilowatts (kW). To give some context for this a trashcan fire is around 100kW where a couch fire is around 1000kW. Some instructors use a lightbulb analogy when describing heat release rate. For instance a 1 kW fire has the same power output as ten 100W lightbulbs. To see video of various items burning and their associated heat release rate based on oxygen consumption calorimetry you can go to the website of the National Institute of Standards and Technology (NIST) (<https://www.nist.gov/el/fire-research-division-73300/fire-web>). Equation 5 assumes a steady state fire, a compartment with a single horizontal door/vent, no mechanical ventilation



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and a two zone model where all of the hot smoke and combustion products are contained in the upper layer and the lower layer is comprised of cool air not influenced by the heat from the fire. While the two zone approximation is a major assumption, it has shown to be reasonable in many compartment fire situations. In-fact, this two layer approximation is the backbone of the two zone computer fire models we will discuss later on in the course. Example 3 provides a sample calculation for estimating the upper layer temperature in a compartment fire.

$$T_g = T_\infty + 6.85 \left(\frac{\dot{Q}^2}{A_0 \sqrt{H_0} h_k A_T} \right)^{1/3}$$

A_0 – Area of opening $[m^2]$; $A_0 = W_0 H_0$
 A_T – Total Internal surface area of compartment $[m^2]$
 $A_T = 2(LW) + 2(WH) + 2(LH) - A_0$ (6)
 h_k – effective heat transfer coefficient $[kW / m^2 K]$
 H_0 – Height of opening $[m]$
 T_g – Upper layer gas temperature $[K]$
 T_∞ – Ambient temperature $[K]$
 \dot{Q} – Heat release rate (HRR) $[kW]$

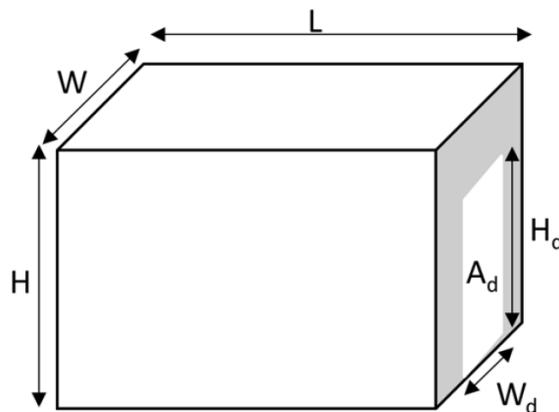


Figure 8: Diagram of typical Compartment for Upper Gas Layer Temperature Equation



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Example 3: Upper layer gas temperature in a compartment fire

A steady state 350 kW fire occurs in the room shown below, if the plastic used in a ceiling light fixture will melt at 473K (200°C), will this fixture melt? Assume: $T_{\infty}=298\text{K}$, and $h_k = 0.025 \text{ kW}/(\text{m}^2\text{K})$.

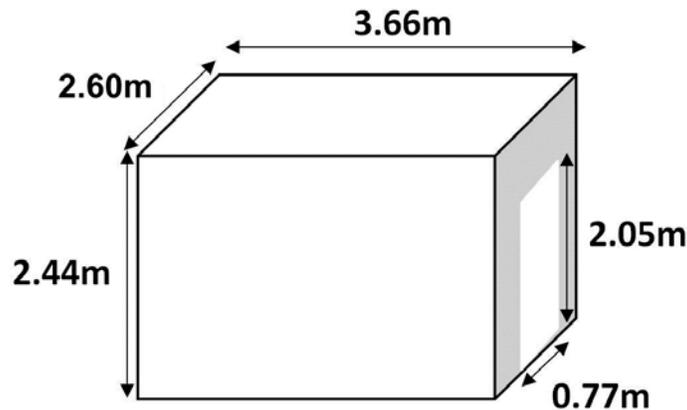


Figure 9: Upper layer Temperature Example Diagram

Solution:

$$A_0 = W_0 H_0 = (0.77\text{m})(2.05\text{m}) = 1.58\text{m}^2$$

$$A_T = 2(LW) + 2(WH) + 2(LH) - A_0 = 2(3.66 * 2.60) + 2(2.60 * 2.44) + 2(3.66 * 2.44) - 1.58 = 48\text{m}^2$$

$$T_g = T_{\infty} + 6.85 \left(\frac{\dot{Q}^2}{A_0 \sqrt{H_0} h_k A_T} \right)^{1/3} = 298 + 6.85 \left(\frac{(350\text{kW})^2}{1.58\text{m}^2 (\sqrt{2.05\text{m}}) \left(0.025 \frac{\text{kW}}{\text{m}^2\text{K}} \right) (48\text{m}^2)} \right)^{1/3}$$

$$T_g = 541.95\text{K} \cong 542\text{K}$$

Therefore we would expect the plastic in the light fixture to melt during the fire. When dealing with this kind of calculation where errors can easily occur, it is a good idea to think about if this answer is reasonable. The calculated answer is higher than the ambient temperature which is what we would expect when dealing with a fire. The temperature is above the boiling point of water but less than the maximum temperature we would expect in a fully involved compartment therefore it seems like a reasonable answer. To give an example of an unreasonable answer, if the (1/3) exponent is forgotten the calculation solves as 309,685 K, this is hotter than the surface



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of the sun which would indicated that the work should be double checked.
This can also be solved using the “Upper Layer Gas Temperature” tab of the excel spreadsheet provided with the course as shown below:

This spreadsheet calculates the upper layer gas temperature of a steady state compartment fire corresponding with Equation 5 in the course material.		
\dot{Q}	350	kW
T_{∞}	298	K
L	3.66	m
W	2.6	m
H	2.44	m
L_0	0.77	m
H_0	2.05	m
h_k	0.025	KW/m ² K
A_0	1.5785	m ²
A_T	48.0023	m ²
T_g	541.9	K

It is of interest to note that the maximum temperature usually seen in a compartment fire has been calculated to be approximately 1473K ($\approx 1200^{\circ}\text{C}$) [4] but post-flashover/fully involved compartment fire temperatures are more often 1173K - 1273K [5]. The upper gas layer temperature calculation is included in the excel spread sheet provided with this course in the “Upper Layer Gas Temp” tab. This calculation used a constant effective heat transfer coefficient. As can be seen, in reality this parameter varies as a function of the compartments conditions. When we discuss computer fire models towards the end of this course, one of the NRC’s Fire Dynamic Tool spreadsheets completes this calculation including a varying effective heat transfer coefficient for a variety of common building materials.



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Part 4: Review of Thermal Radiation

Besides the effect of radiation on fire growth which is discussed further on in this course, of particular interest to Fire Protection Engineers is the amount of radiative heat flux that will cause pain/injury to a person and or cause damage to a building. The threshold for pain on human bare skin has been shown to be 1.7 kW/m^2 for the average person [6]. The US Department of Housing and Urban Development [7] lists exposure limits for people and buildings of 1.4 kW/m^2 and 31.5 kW/m^2 respectively. Along with this, the time to pain caused by thermal radiation can be estimated using equation 7 [6]. Example 4 provides sample calculations for using equation 7. This equation can be programmed into a spreadsheet program such as Microsoft Excel. This is included in the Excel file provided with the course in the “Radiation – Time to Pain” tab including logic to automatically use the correct safety factor coefficient based on the incident radiative heat flux.

$$t_p = \eta \left(\frac{35}{\dot{q}''} \right)^{1.33}$$

t_p - time to pain [s]
 \dot{q}'' - radiative heat flux [kW/m^2]
 η - safety factor coefficient
(if $\dot{q}'' \leq 6 \text{ kW/m}^2$ $\eta = 1/2$)
(if $\dot{q}'' > 6 \text{ kW/m}^2$ $\eta = 1/4$)

(7)

Example 4: Calculating Time for pain on Exposed Skin due to Thermal Radiation

If a steady state stove top fire is creating an incident heat flux to a child sitting in a high chair at the kitchen table of 3 kW/m^2 , how long will it take for the child to start feeling pain from thermal radiation exposure?

Solution:

$$t_p = \frac{1}{2} \left(\frac{35}{3 \text{ kW/m}^2} \right)^{1.33} = 13.1 \text{ s}$$

Based on this analysis it would take approximately 13 seconds for the child to begin feeling pain from thermal radiation exposure. Methods for estimating what the radiative heat flux is from a given fire at a given distance are discussed later on in this course.



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This can also be solved using the “Radiation – Time to Pain” tab of the excel spreadsheet provided with the course as shown below:

This spreadsheet calculates the time for a heat flux to cause pain on exposed skin corresponding with Equation 7 in the course material.	
\dot{q}''	3 kW/m ²
t_pain	13.1 s

Once fires grow to a sufficient size to heat the upper layer in a compartment significantly (around approximately 600°C) thermal radiation takes over as the dominant driving factor fire growth inside the compartment. This increase in radiation from the hot upper layer can lead to a phenomenon called “flashover” where all of the combustible items in a compartment ignite nearly simultaneously. Due to the rapidity of this transition it a very hazardous situation for firefighters and leads to injuries and fatalities every year. A picture of a post flashover compartment with flames extending out of the doorway and window is shown in Fig. 10. Radiation is also the dominant mode of heat transfer in large flashfires and fireballs. An example of a flash fire fueled by wood dust is shown in Fig. 11, we will not cover it in this course but one of the NRC FDT models discussed at the end of the course calculated the radiant exposure from large hydrocarbon fireballs.



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Figure 10: Flashover/full room involvement in a compartment with flame extension out of doors and windows.



Figure 11: Ignition of 15lb of 35 micron wood meal dispersed and ignited in a compartment

The equation many engineers are familiar with is the typical blackbody radiation equation that is a function of temperature to the 4th power. For use in a compartment fire



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situation it is important to add a second component to take into account the potential for a hot environment which is radiating back to the surface emitting radiation as shown in Eq. 8. Example 5 provides sample calculations for estimating the total heat flux from a black body. This example can also be solved using the spreadsheet in the “Radiation T4” tab of the excel file provided with this course.

$$\dot{q}'' = \varepsilon\sigma(T_o^4 - T_\infty^4)$$

ε - emissivity of object [-]
 σ - stefan - Boltzmann constant [5.67x10⁻¹¹ kW/(m²K⁴)] (8)
 T_o - temperature of object [K]
 T_∞ - temperatuere of surroundings (walls, etc.) [K]
 \dot{q}'' - heat flux [kW/m²]

Example 5: Total Radiative Heat Flux using Blackbody Emission Equation

What is the total radiative heat flux from a table with a surface temperature of 400K in a compartment with uniform wall temperatures of 350K? Assume the table is a blackbody radiator with an emissivity of 1.

Solution:

$$\dot{q}'' = (1)(5.67 \times 10^{-11} \text{ kW}/(\text{m}^2 \text{K}^4))((400 \text{ K})^4 - (350 \text{ K})^4) = 0.6 \text{ kW}/\text{m}^2$$

This can also be solved using the “Radiation - T4” tab of the excel spreadsheet provided with the course as shown below:

This spreadsheet calculates the total radiative heat flux from a black body radiator corresponding with Equation 8 in the course material.		
T_o	400	K
T_∞	350	K
emissivity	1	[-]
sigma	5.67E-11	kW/(m ² K ⁴)
\dot{q}''	0.60	kW/m ²



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This blackbody radiation method fairly straight forward when dealing with solid objects but dealing with flames can get more complicated. Not only is a major assumption about emissivity required but the flame temperature will vary depending on the fuel type and ventilation conditions. Since the temperature is raised to the 4th power these errors can get quite large. Some guidance is available in the literature such as the Industrial Fire Protection Engineering textbook by Zalosh [8] and this has been used to do calculations to assist with some firefighter training with regard to the dangers of rollover in a hallway which is described in more detail later on in the course. To get around the uncertainties of the flame temperature fire scientists have come up with several ways to calculate the radiative heat flux of a variety of fires without having to estimate a specific flame temperature. The next section will cover an empirical radiation calculation for pool fires and two geometrically based models for estimating radiant heat flux exposure that use a percentage of the fires heat release rate or other methods rather than the flame temperature to estimate the radiative output.



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Part 5: Thermal Radiation Calculations for fires

Radiant heat flux theory is a topic in fire science that has high element interactivity because it combines a wide variety of disciplines, including fire behavior, fundamental physics, and conditional geometry. Methods for determining heat flux to a target from a pool fire are discussed in many different sources [2, 3, 7, 9-19]. The hand calculation methods presented here are mostly valid for a preliminary assessment in but can be used in actual design work depending on the accuracy required. As discussed by Drysdale [20], “a high degree of accuracy is seldom required in ‘real world’ fire engineering problems such as estimating what level of radiant flux an item of a plant might receive from a nearby fire.” Therefore, these calculations can be quite useful and if more accuracy is needed engineers can use the computer fire models discussed at the end of the course. The first hand calculation we will discuss is an empirical model based on a set of experimental data.

5.1 Empirical approach to radiative heat flux from a pool fire

The one of the simplest equation to calculate the radiant heat flux to a target is an empirical correlation for pool fires derived from experimental data by Shokri and Beyler [12]. This equation is simply a function of the distance from the center of the fire to the target and the diameter of the fire. The concept measuring the distance from the center of the fire to the target object can be confused with the distance from the edge of the fire to the object as the edge of the fire is what is actually doing the radiating. To reduce the confusion, it is convenient to express the equation in the form shown which breaks up the distance from the center of the fire to the target into two terms: half of the diameter and the distance from the edge of the fire to the target as shown in Fig. 12.

$$\dot{q}_{rad}'' = 15.4 \left(\frac{d_t + 0.5D_p}{D_p} \right)^{-1.59}$$

d_t - distance from the edge of the fire to the target [m] (9)
 D_p - diameter of pool of burning fuel [m]
 \dot{q}_{rad}'' - radiative heat flux [kW/m²]

It is important to understand the limitations and assumptions associated with this equation, it has been shown to match the majority of experimental data within $\pm 100\%$, and the original authors recommended a safety factor of 2 for design calculations [20]. The correlation was made with fire ratios of diameter to target distance of values of $0.7 < (d_t + 0.5D_p) / D_p < 15$ and should not



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be used with ratios of diameter to target distance of $(d_t + 0.5D_p) / D_p < 0.5$. This equation assumes no wind and is limited to vertical targets at ground level. Therefore, a more generic approach is needed for other situations. Example 6 provides sample calculations using this equation. A video recording of working this example is available on the authors YouTube channel: <https://www.youtube.com/watch?v=RNvhz9jLMxE> and a copy of the spreadsheet is included in the excel file provided with this course in the tab named “Radiation – Shokri&Beyler”.

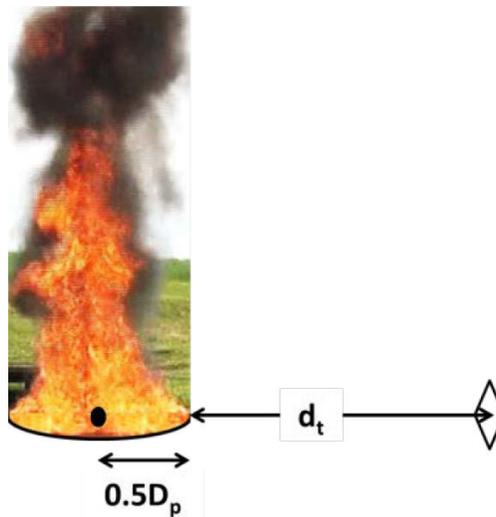


Figure 12: Diagram of flame radiation using empirical equation

Example 6: Shokri and Beyer Radiation Calculation

A 3.048m (10ft) diameter storage tank is burning 15.24m from a group of people, according to research the pain tenability limit for bare human skin is 1.7 kW/m², using the Shokri and Beyer empirical equation will the exposure rate in the crowd be above the tenability limit for pain?



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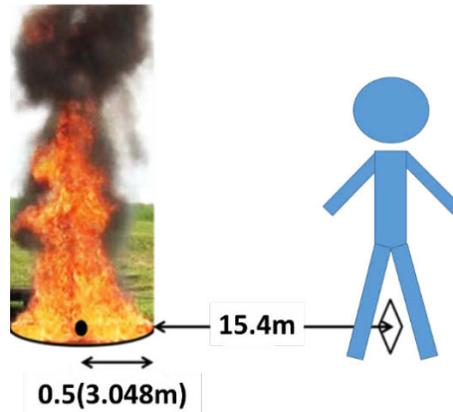


Figure 13: Diagram for Radiative heat flux using Shokri and Byler Radiation Calculations

Solution:

$$d_t = 15.4m$$

$$D_p = 3.048m$$

$$\dot{q}_{rad}'' = 15.4 \left(\frac{15.4 + 0.5(3.048m)}{3.048m} \right)^{-1.59} = 1.02kW / m^2$$

Using a safety factor of 2 as recommended by the equation developers produces a calculated heat flux of 2.04 kW/m^2 which would be a potentially hazard for causing pain to exposed skin. This can also be solved using the “Radiation – Shokri&Beyler” tab of the excel spreadsheet provided with the course as shown below:

This spreadsheet calculates the radiative heat flux to a target from a pool fire corresponding with Equation 9 in the course material.		
Shokri and Beyler		
D_p	3.048	m
d_t	15.24	m
\dot{q}''	1.02	kW/m^2
Safety factor of 2	2.05	kW/m^2



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5.2 Point source model for heat flux

It is logical to continue from the empirical equation to a generic a point source model, also known as a spherical approximation. At the simplest level, this calculation is accomplished by dividing the radiative output of the fire by the surface area of a sphere with a radius equal to the distance from the average flame height at the center of the fire to the target [2] as shown in figure 14. To simplify the calculation for the students, the angle from the point source to the target is assumed to be 90° which is typically the worst case scenario. The point source method is meant for use with objects relatively far from the fire where the angle approaches 90° as the distance increases. A literature backing for this form of the equation is found in the “Fire Dynamics” textbook [21] and in the Nuclear Regulatory Commission’s (NRC) Fire Dynamic Tool (FDT) spreadsheet calculating radiant heat flux with no wind [22].

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi(d_t + 0.5D_p)^2}$$

d_t - distance from the edge of the fire to the target [m]
 D_p - diameter of pool of burning fuel [m] (10)
 \dot{q}_{rad}'' - radiative heat flux [kW/m²]
 \dot{Q} - heat release rate of fire [kW]
 χ_r - radiative fraction [-]

The radiative fraction of a fire is often assumed to be 30% but in reality it typically varies from approximately 10%-40% and is a function of the fuel and the ventilation conditions. Specifically for pool fires, it has been shown that the radiative fraction is also a function of the diameter of the fire and can be calculated using equation 11 [9].

$$\chi_r = 0.21 - (0.0034)D_p \quad (11)$$

This can be incorporated into the point source model specifically for pool fires to give equation 12.

$$\dot{q}'' = \frac{(0.21 - (0.0034)D_p) \dot{Q}}{4\pi(d_t + 0.5D_p)^2} \quad (12)$$



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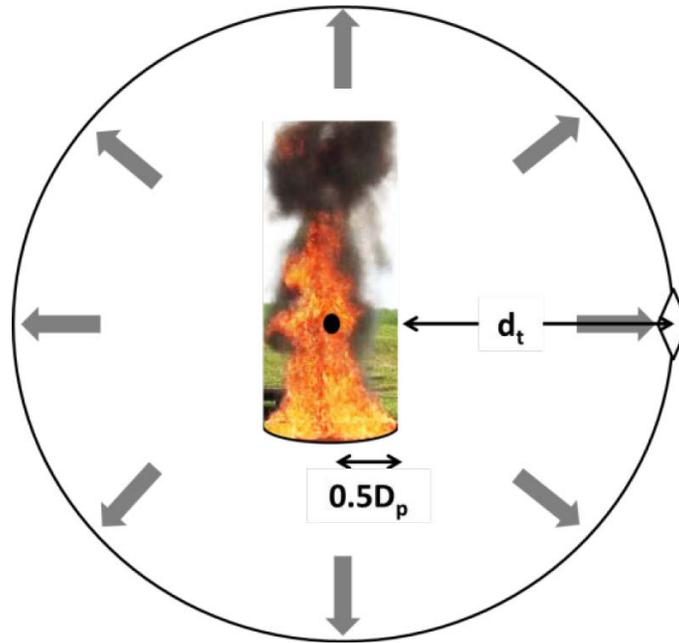


Figure 14: Diagram of point source model

It is important to note the limitations of this equations. Not only does this formulation assume a 90° angle, which maximizes the heat flux at a given distance, but there are also limitations on where the model itself is valid. The point source model is most accurate when the ratio of the diameter of the fire to the distance to the target is: $(d_t + 0.5D_p) / D_p > 2.5$ [23] and this method under predicts incident fluxes at small distances from the fire. The point source model is not recommended for use at heat flux levels above 5 kW/m^2 , and a factor of safety of 2 is recommended when used for design purposes [3]. Due to this limitation this is not a good method to determine the heat flux for ignition purposes (as that typically requires $10\text{-}20 \text{ kW/m}^2$ as mentioned earlier) but it can be used for analyzing the risk of a burn to unprotected human skin. Example 7 provides sample calculations for using the point source model. Equations 10 has been programmed into the Excel fire provided with this course in the tab titled "Radiation – Point Source."



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Example 7: Point Source Model

A 3.048m (10ft) diameter storage tank is burning 15.24m from a group of people, according to research the pain tenability limit for bare human skin is 1.7 kW/m². If the heat release rate is 8600 kW, and it is assumed 30% of the fire's heat release rate is given off as radiation, using the point source model, will the exposure rate in the crowd be above the tenability limit for pain?

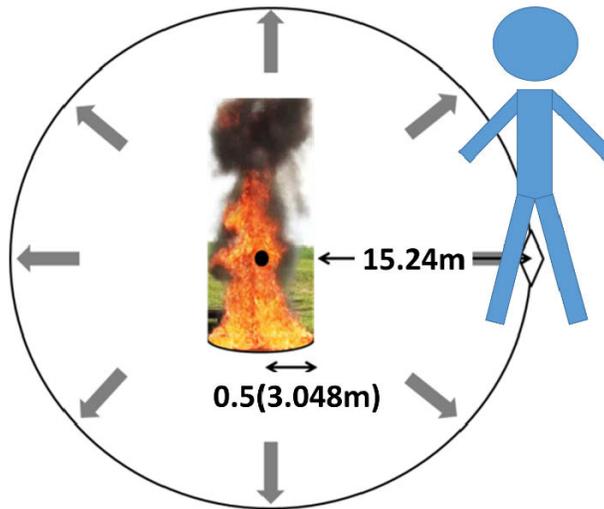


Figure 15: Diagram for Example of Point Source Model

Solution:

$$d_t = 15.4\text{m}$$

$$D_p = 3.048\text{m}$$

$$\dot{Q} = 8600\text{kW}$$

$$\chi_r = 0.3$$

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi(d_t + 0.5D_p)^2} = \frac{(0.3)(8600\text{kW})}{4\pi(15.4\text{m} + 0.5(3.048\text{m}))^2} = 0.73\text{kW} / \text{m}^2$$

Using a safety factor of 2 as recommended by the method developers produces a calculated heat flux of 1.46 kW/m² which would likely not be a hazard for causing pain but it is above the threshold allowed by the US Department of Housing and Urban Development.

This can also be solved using the “Radiation – Point Source” tab of the excel spreadsheet provided with the course as shown below:



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This spreadsheet calculates the radiative heat flux to a target from a fire using the point source model corresponding with Equation 10 in the course material.		
Point Source		
D_p	3.048	m
d_t	15.24	m
χ_r	0.3	[-]
\dot{Q}	8600	kW
\dot{q}''	0.73	kW/m ²
Safety factor of 2	1.46	kW/m ²

5.3 Cylindrical View factor model for Radiative heat flux for pool fires

Due to the limitations associated with the empirical and point source models, other models more representative of the physics of the situation can be utilized. These are known as view factor models and approximates the flame as a geometric shape. Then an average emissive power of the geometric object to estimate the heat flux to a target. A view factor is defined as the fraction of radiation leaving one surface, which is intercepted by the other surface [3]. The cylindrical view factor approximation is the next simplest approach after the point source model and is recommended by Shokri and Beyler in their paper for calculating the heat flux from a pool fire [12]. In the cylindrical view factor method, average flame height is the cylinder height, and the pool fire diameter is the diameter of the cylinder as shown in figure 16. The distance to the target is measured from the center of the cylinder base to the edge of the target, which can once again be written as half the pool diameter plus the distance from the fire edge to the target. The target must be at the same level as the bottom or top of the cylinder; if the target is not at ground level, multiple cylinders can be used and added together.

The basic radiative heat flux equation utilizing a view factor (also known as a configuration factor) multiplies the emissive power of the flame (E) by a relevant view factor (F_{12}), and an assumed transmissivity (τ) of whatever medium the radiation is passing through as shown in Eq. 13. Particles in the air such as smoke or water droplets will reduce the transmissivity but for clear air calculations this is often assumed to be 1.



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$$\dot{q}_{rad}'' = EF_{12}\tau$$

\dot{q}_{rad}'' - radiative heat flux [kW/m²]
 E - emissive power of the flame [kW/m²]
 F_{12} - view factor [-]
 τ - transmissivity [-]

(13)

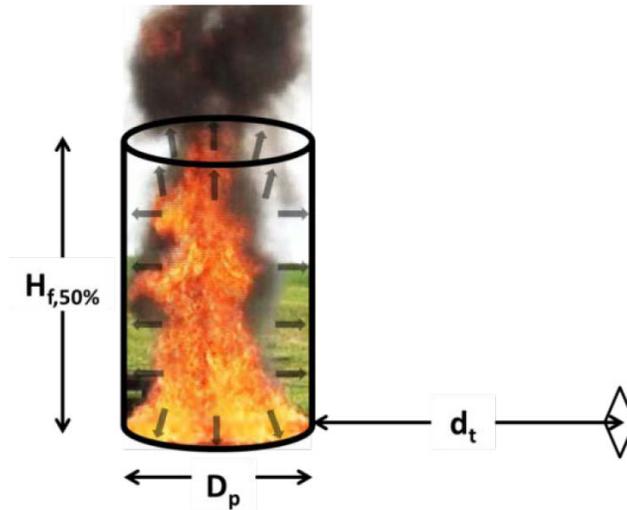


Figure 16: Naming convention shown for cylindrical view factor approximation

Calculating the view factor (F_{12}) is a long and involved equation that I believe is easiest to do when broken down into eight subparts. The first four parts are non-dimensional parameters (C_1 - C_4) shown in the Eq. 14 line. These non-dimensional parameters are then used in four calculations for part₁-part₄. Parts 1-4 are then used to calculate the final view factor shown in equation 16.

$$C_1 = \frac{d_t + 0.5D_p}{0.5D_p}, C_2 = \frac{H_{f,50\%}}{0.5D_p}, C_3 = (C_1 + 1)^2 + C_2^2, C_4 = (C_1 - 1)^2 + C_2^2$$
(14)

$$\text{part 1} = \frac{1}{\pi C_1} \tan^{-1} \left(\frac{C_2}{\sqrt{C_1^2 - 1}} \right), \text{part 2} = \frac{C_3 - 2C_1}{C_1 \sqrt{C_3 C_4}}$$
(15)

$$\text{part 3} = \tan^{-1} \sqrt{\frac{C_3(C_1 - 1)}{C_4(C_1 + 1)}}, \text{part 4} = \frac{1}{C_1} \tan^{-1} \sqrt{\frac{C_1 - 1}{C_1 + 1}}$$

$$F_{12} = \text{part 1} + \frac{C_2}{\pi} [\text{part 2} * \text{part 3} - \text{part 4}]$$
(16)



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This representation makes a number of simplifying assumptions. The flame is assumed to be in the shape of a solid object, usually in a uniform, simple geometric shape. It is assumed that there is an even distribution of power emitted over the surface of the chosen shape, and the transmissivity of the medium between the view factor and object is assumed to be 1. The cylindrical approach is reasonable for circular pool fires with no wind, fuels with typical flame heights, and all the limitations associated with the equations used to calculate the cylinder dimensions are included as-well. The view factor method is also limited to the accuracy of the emissive power of the flame calculation with all its associated limitations.

5.4 Emissive power of flame

The simplest method to determine the emissive power of a pool fire is the empirical equation by Shokri and Beyler [12] shown as equation 17.

$$E = 58 \left(10^{-0.00823(D_p)} \right)$$

E - emissive power of flame [kW/m²] (17)
 D_p - Diameter of pool of burning fuel [m]

For this equation, wind is assumed to be negligible. This equation is based on experimental observations of mostly luminous flames from typical fuels, such as kerosene, from 0-50m in diameter and should have use limited to fires with ratios of fire diameter vs distance to the target of $0.7 < (d_t + 0.5D_p) / D_p < 15$ [9]. The cylindrical view factor method' set of equations (Eqs. 13-17) can be programmed into a spreadsheet program like Microsoft Excel as shown in table 1. This is included in the excel file provided with the course in the tab named "Radiation – Cyln View Factor".



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Table 1: Programming Cylindrical View Factor Model into Computer Spreadsheet

	A	B	C
1	H _f	(Average flame height in meters)	m
2	D _p	(Diameter of the fire in meters)	m
3	d _t	(Distance to the target in meters)	m
4	C1	= $(B3+0.5*B2)/(0.5*B2)$	[-]
5	C2	= $B1/(0.5*B2)$	[-]
6	C3	= $(B4+1)^2+B5^2$	[-]
7	C4	= $(B4-1)^2+B5^2$	[-]
8	Part1	= $1/(PI()*B4)*ATAN(B5/SQRT(B4^2-1))$	[-]
9	Part2	= $(B6-2*B4)/(B4*SQRT(B6*B7))$	[-]
10	Part3	= $ATAN(SQRT((B6*(B4-1))/(B7*(B4+1))))$	[-]
11	Part4	= $1/B4*ATAN(SQRT((B4-1)/(B4+1)))$	[-]
12	F ₁₂	= $B8+B5/PI()*(B9*B10-B11)$	[-]
13	tau	1	[-]
14	E	= $58*(10^{(-0.00823*B2)})$	kW/m ²
15	q̇''	= $B14*B12*B13$	kW/m ²



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Example 8: Radiative Heat Flux Calculation using Cylindrical View Factor Method

What would be the heat flux to person 10m from a 1.22m (4 ft.) diameter kerosene fire with a heat release rate of 1360 kW and the average flame height of 2.97 m and would the person be at risk of pain from thermal radiation? Assuming:

$$\chi_c = 0.85, \Delta H_c = 43200[kJ / kg], \dot{m}_\infty = 0.039[kg / (m^2 s)], k\beta = 3.5[1 / m]$$

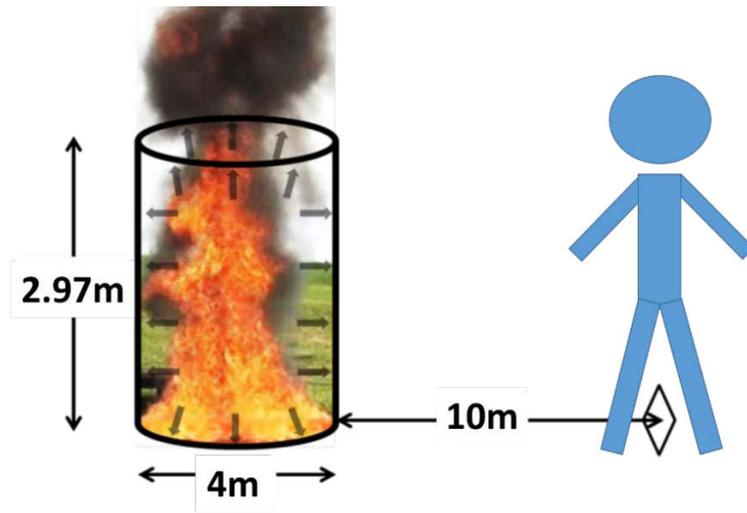


Figure17: Diagram for Cylindrical View Factor Example

Solution:

Rather than working this set of equations out by hand, the excel spread sheet is used to complete the calculation. Using the Excel spreadsheet provided with the course the answer is found to be approximately 0.6 kW/m² as shown in the figure below, therefore the person is at risk of pain on exposed skin from thermal radiation.



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This spreadsheet calculates the radiative heat flux to a target from a fire using the cylindrical view factor model corresponding with Equations 13-16 in the course material.		
H_f	2.97	m
D_p	1.22	m
d_t	10	m
C1	17.39344262	[-]
C2	4.868852459	[-]
C3	362.0244558	[-]
C4	292.4506853	[-]
Part1	0.005002805	[-]
Part2	0.057820565	[-]
Part3	0.809964	[-]
Part4	0.043501212	[-]
F_{12}	0.010165766	[-]
tau	1	[-]
E	56.67446036	kW/m ²
\dot{q}''	0.6	kW/m ²

Figure 18: Using spreadsheet to solve example problem

Since the minimum heat flux to cause pain on an average person is 1.7 kW/m² as discussed earlier in this course, the person in this example would not be in danger of having pain from the radiative heat flux.

There are a variety of different view factors (also called “configuration factors”) which can be used in different situations. These are available online at websites such as <http://www.thermalradiation.net/> which is run by a professor at the University of Texas at Austin or in general reference texts such as the SFPE Handbook of Fire Protection Engineering.



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5.5 Parallel Plane View factor method

A parallel plane view factor method has been used in some training materials to calculate the heat flux to firefighters from the smoke layer as they move down a hallway along the floor. This is being used to explain the dangers of flameover/rollover to firefighters due to the rapid increase in the temperature of the area above the firefighters as they move down a hallway. The view factor calculation is shown in Eq. 18 and the diagram to understand what each represents is shown in figure 19. Sample calculations which involve utilize equations 8, 13, and 18 are shown in example 9. These equations were also programmed into the Excel file provided with this course in the tab named “Radiation - Parallel View Factor.”

$$F_{12} = \frac{2}{\pi} \left[\frac{X}{\sqrt{1+X^2}} \tan^{-1} \left(\frac{Y}{\sqrt{1+X^2}} \right) + \frac{Y}{\sqrt{1+Y^2}} \tan^{-1} \left(\frac{X}{\sqrt{1+Y^2}} \right) \right]$$
$$X = \frac{a}{c}$$
$$Y = \frac{b}{c}$$

(18)

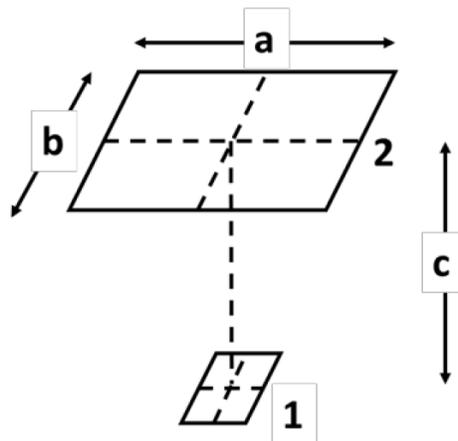


Figure 19: Parallel view factor diagram



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Example 9: Parallel View Factor Radiation Calculation

What is the radiative heat flux to a firefighter crawling 2m below a heated upper gas layer with a temperature of 700K versus the radiative heat flux to a firefighter crawling under a flame rollover with a temperature of 1400K? Assume the upper layer has a width of 3m and a length of 4m.

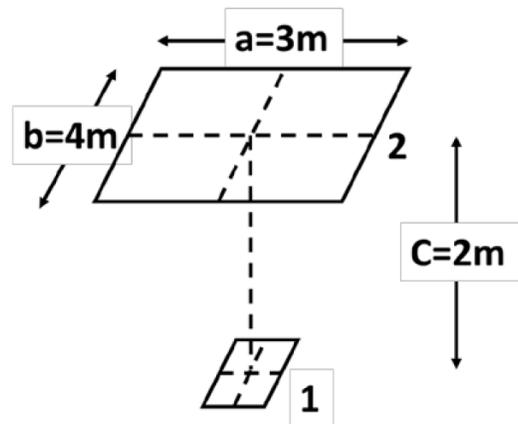


Figure 20: Diagram for Parallel View Factor Example

Solution:

$$X = \frac{3m}{2m} = 1.5$$

$$Y = \frac{4m}{2m} = 2$$

$$F_{12} = \frac{2}{\pi} \left[\frac{1.5}{\sqrt{1+1.5^2}} \tan^{-1} \left(\frac{2}{\sqrt{1+1.5^2}} \right) + \frac{2}{\sqrt{1+2^2}} \tan^{-1} \left(\frac{1.5}{\sqrt{1+2^2}} \right) \right] = 0.7799$$

$$E_{700K} = \varepsilon \sigma (T_L^4 - T_\infty^4) = (1) \left(5.67 \times 10^{-11} \frac{kW}{m^2 K^4} \right) (700^4 - 298^4) = 13.2 kW / m^2$$

$$E_{1400K} = \varepsilon \sigma (T_L^4 - T_\infty^4) = (1) \left(5.67 \times 10^{-11} \frac{kW}{m^2 K^4} \right) (1400^4 - 298^4) = 217.4 kW / m^2$$

$$\dot{q}_{rad,700K}'' = E F_{12} \tau = (13.2 kW / m^2)(0.7799)(1) = 10.3 kW / m^2$$

$$\dot{q}_{rad,1400K}'' = E F_{12} \tau = (217.4 kW / m^2)(0.7799)(1) = 169.5 kW / m^2$$



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Assuming the fighters crawling along the floor are 2m below a smoke layer at 700K the heat flux is approximately 10.6kW/m², while this would rapidly damage unprotected skin, a firefighter’s typical turnout gear is designed to withstand this level of heat flux. In the event of a rollover where the temperature of the upper layer doubles to 1400K the radiative heat flux increases to 170 kW/m² which is well beyond the design criterion for a standard set of turnout gear.

This can also be solved using the “Radiation – Parallel View Factor” tab of the excel spreadsheet provided with the course as shown below:

This spreadsheet calculates the radiative heat flux to a target below a hot upper layer using the Parallel factor model corresponding with Equations 8,13, and 18 in the course material.		
width	a	3 m
length	b	4 m
distance from upper layer to firefighter	c	2 m
	X	1.5 [-]
	Y	2 [-]
View factor	F_12	0.779921 [-]
upper layer smoke temperature	T_layer	700 K
flaming upper layer temperature	T_flame	1400 K
Ambient temperature	T_inf	298 K
stefan-Boltzmann's constant	sigma	5.67E-11 kW/(m ² K ⁴)
epsilon		1
smoke layer heat flux	q_smoke	13.2 kW/m ²
flame layer heat flux	q_flame	217.4 kW/m ²
heat flux to crawling firefighter - smoke		10.3 kW/m²
heat flux to crawling firefighter - flame		169.5 kW/m²



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Part 6: Ignition of solid fuels

When dealing with ignition of solids, in terms of heat transfer there generally considered to be two types, “thermally thick” and “thermally thin”. The majority of materials are considered to be “Thermally thick” which means there is a temperature gradient throughout the material. In other words, the surface of the material will heat up faster than the interior. The second and less common type of material is known as “thermally thin” and are described as having no temperature gradient throughout the thickness. Thermally thin materials are typically less than 1mm thick and have an insulate backing. An example of a thermally thin material would be the paper covering on fiberglass insulation. Since the vast majority of materials are thermally thick we will focus on the ignition criterion for these kinds of materials. The following equation can be used to estimate the ignition time for a material. Besides the material properties such as density and specific heat, the main criterion needed are the ignition temperature and critical heat flux which can be found in resources such as the Ignition Handbook by Babrauskas [24]. Equation 19 can be used to calculate the ignition time for a thermally thick solid [3]. The (2/3) term incorporates some assumed heat loss to the system and it is important to note that for the equation to be valid the incident heat flux must be higher than the critical heat flux for the material in question. The critical heat flux represents the minimum heat flux which would ignite the material in an infinite amount of time. Example 10 shows sample calculations using this equations. This equation has been programmed into the Excel file provided with the course in the “Ignition Time” tab.

$$t_{ig} = \left(\frac{2}{3}\right)(k\rho c_p) \left[\frac{(T_{ignition} - T_{initial})^2}{\dot{q}''} \right]$$

t_{ig} - time to ignition [s]
 ρ - density [kg]
 c_p - specific heat [kJ/kg K] (19)
 k - thermal conductivity [kW/(m K)]
 T_{ig} - ignition temperature [K]
 T_{∞} - initial temperature [K]
 \dot{q}'' - heat flux (must be larger than critical heat flux)



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Example 10: Ignition of thermally thick solid

How long would it take for a solid pine wall support member to ignite if it is 1ft thick and the wall is being heated by a bedside radiant heater at a flux of 25kW/m²? Assume that pine has a critical heat flux of 16 kW/m², an ignition temperature of 663K, a conduction coefficient of 1.4x10⁻⁴ kW/(m K), a density of 640kg/m³, and a specific heat of 2.85 kJ/(kg K).

Solution:

$$\rho = 640 \text{ kg}, c_p = 2.85 \text{ kJ/kg K}, k = 1.4 \times 10^{-4} \text{ kW/(m K)}$$

$$T_{ig} = 663\text{K}, T_{\infty} = 298\text{K}$$

$$\dot{q}'' = 25\text{kW/m}^2$$

$$t_{ig} = \left(\frac{2}{3}\right) \left((1.4 \times 10^{-4} \text{ kW/(m K)}) (640 \text{ kg}) (2.85 \text{ kJ/kg K}) \right) \left[\frac{(663\text{K} - 298\text{K})}{25\text{kW/m}^2} \right]^2 = 36.3\text{s}$$

This can also be solved using the “Ignition Time” tab of the excel spreadsheet provided with the course as shown below:

This spreadsheet calculates the ignition time for a thermally thick material corresponding with Equation 19 in the course material.		
k	0.0001400	kW/(m ² K)
rho	640	kg/m ³
c _p	2.85	kJ/(kg K)
T _{ign}	663	K
T _{initial}	298	K
q̇''	25	kW/m ²
q̇'' _{critical}	16	kW/m ²
is q̇'' > q̇'' _{critical}		yes
Thermally thick		
t _{ign}	36.3	s



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Part 7: Smoke Detector and Sprinkler activation

There are two main types of smoke detector sensors, ionization and photoelectric. Both types of sensors attempt to use the smoke from a fire to signal the alarm. Determining amount and type of smoke generated by the multitude of different kinds of fires and ventilation conditions is outside the scope of this course but it has been shown that ionization smoke detectors activate when there is an associated temperature increase at the detector of approximately 5K in both small and large compartments [25]. The activation of sprinkler heads in a structure fire is an interesting heat transfer problem. Most sprinkler systems are pressurized with water which is released when a sprinkler head is activated (unlike what is typically portrayed in movies, where pulling a fire alarm immediately initiates the water based sprinkler system). Having sprinkler heads activate when heated allows the sprinkler system to release water specifically where the fire is which reduces the amount of water needed and used. This saves significant cost in the design of the sprinkler system. Most sprinkler heads either have a sealed glass bulb filled with a liquid that expands when heated or a fusible link. In sprinkler heads with glass bulbs, the expansion of this liquid shatters the glass at a specific temperature which then releases the water. Fusible link sprinkler heads have a bimetallic link that melts at a specific temperature based on the alloy used, when the link melts it releases the pressurized water in a typical sprinkler system. Figure 21 shows a picture of a variety of different sprinkler heads using glass bulbs and fusible links. Videos of sprinkler system tests by FM Global can be found on YouTube <https://www.youtube.com/user/FMGlobalVideos/videos> and high speed video of sprinkler head activation can be found on various YouTube channels if students are interested in seeing the activation process.



Figure 21: Different kinds of sprinkler heads (the top row has fusible links, the bottom row has glass bulbs)



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When dealing with the activation time of a sprinkler system, once again, fire scientists have made calculations simpler than a traditional heat transfer calculation. Sprinkler heads are designed with a parameter called a “Response Time Index” (RTI) which represents the thermal properties of the glass bulb or fusible link that will release the water in the system when sufficiently heated. Equation 20 can be used to calculate the time it will take for a sprinkler to activate at a given gas temperature and velocity [3]. This equation can be programmed into a spreadsheet program such as Microsoft Excel. This is included in the Excel file provided with the course in the “Sprinkler Activation” tab. Example 11 provides sample calculation using this equation in a theoretical application.

$$t = \frac{RTI}{u^{1/2}} \ln \left(\frac{T_g - T_\infty}{T_g - T_r} \right)$$

RTI - response time index $[m^{1/2} s^{1/2}]$
 T_r - sprinkler response/activation temperature [K] (20)
 T_g - temperature of heated flow [K]
 T_∞ - ambient temperature [K]
 t - time for sprinkler activation [s]
 u - flow velocity $[m/s]$

Example 11: Sprinkler activation

How long would it take for a sprinkler head with an RTI of $110m^{1/2}s^{1/2}$ and an activation temperature of 348K (75°C) activate in a fire plume with a temperature of 500K and a velocity of 1.5 m/s? Assuming an ambient temperature of 298K.

$$RTI = 110m^{1/2}s^{1/2}$$

$$T_r = 348K$$

$$T_g = 500K$$

$$T_\infty = 298K$$

$$u = 1.5m/s$$

$$t = \frac{RTI}{u^{1/2}} \ln \left(\frac{T_g - T_\infty}{T_g - T_r} \right) = \frac{110m^{1/2}s^{1/2}}{(1.5m/s)^{1/2}} \ln \left(\frac{500K - 298K}{500K - 348K} \right) = 25.5s$$

This can also be solved using the “Sprinkler Activation” tab of the excel spreadsheet provided with the course as shown below:



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This spreadsheet calculates the activation time for a sprinkler head corresponding with Equation 20 in the course material.

RTI	110	$m^{1/2}s^{1/2}$
T_r	348	K
T_g	500	K
T_{inf}	298	K
u	1.5	m/s
t	25.5	s

You may have noticed that the above equation requires the temperature and velocity of the heated air around the sprinkler head to calculate the activation time. The temperature and velocity of the buoyant smoke and combustion products created by a fire as they traveling along a ceiling, also known as a ceiling jet, can be calculated using a set of equations known as Alpert's correlations [26]. These equations are shown as equations 21-24. This is a set of four equations, two for velocity and two for temperature. The decision of which in each pair to use is based on the ratio of r/H where r is the horizontal distance from the centerline of the fire to the detector and H is the height from the base of the fire to the ceiling as shown in figure 22. Alpert's equations assume a steady state fire and an infinite flat ceiling. Once an upper layer starts to develop these equations should no longer be used. Example 12 provides a set of sample calculations using these equations. Alpert's correlation equation can be programmed into an excel spreadsheet using built in logic that automatically evaluates the correct equation based on the r/H value as shown in table 2. This is included in the excel file provided with this course in the "Alpert's Correlations" tab.



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$$\left[\frac{r}{H} \leq 0.15 \right] \Rightarrow u = 0.95 \left[\frac{\dot{Q}}{H} \right]^{1/3} \quad (21)$$

$$\left[\frac{r}{H} > 0.15 \right] \Rightarrow u = 0.197 \frac{\left(\frac{\dot{Q}}{H} \right)^{1/3}}{\left(\frac{r}{H} \right)^{5/6}} \quad (22)$$

$$\left[\frac{r}{H} \leq 0.18 \right] \Rightarrow T = T_{\infty} + \frac{16.9 \dot{Q}^{2/3}}{H^{5/3}} \quad (23)$$

$$\left[\frac{r}{H} > 0.18 \right] \Rightarrow T = T_{\infty} + \frac{5.38 \left(\frac{\dot{Q}}{r} \right)^{2/3}}{H} \quad (24)$$

T - temperature at sprinkler location [K]

T_{∞} - ambient temperature in compartment [K]

\dot{Q} - heat release rate of fire [kW]

r - horizontal distance from centerline of fire to sprinkler [m]

H - distance from the base of the fire to the ceiling [m]

u - flow velocity [m/s]

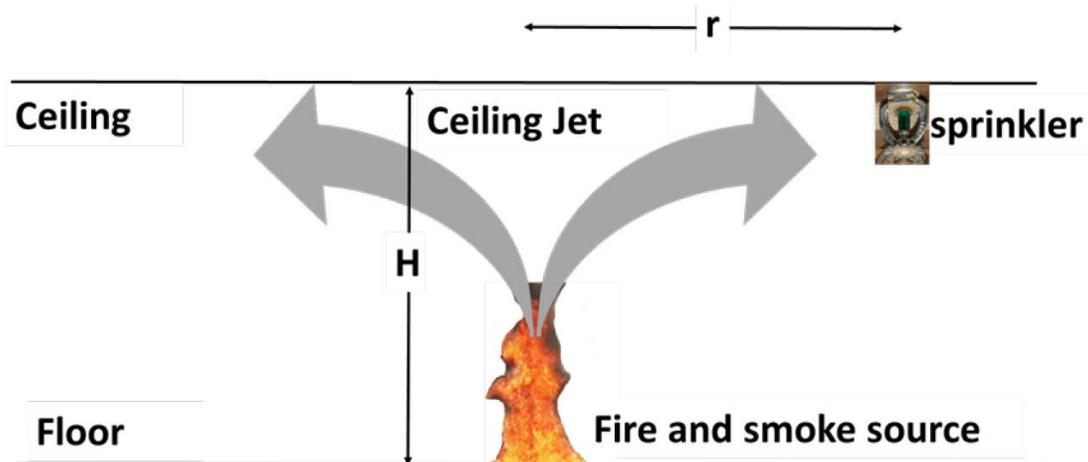


Figure 22: Idealized room configuration for use with Alpert's correlation Equations



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Table 2: Programming Alpert's Correlations in a Spreadsheet using built in logic

	A	B	C
1	r	(distance of detector from center line of fire)	m
2	H	(height of the ceiling)	m
3	\dot{Q}	(heat release rate)	kW
4	T_∞	(ambient air temperature in compartment)	K
5	r/H	=B1/B2	[]
6	u	=IF(B5>0.15,0.197*(B3/B2)^(1/3)/(B1/B2)^(5/6),0.95*(B3/B2)^(1/3))	m/s
7	T	=IF(B5>0.18,B4+5.38*(B3/B1)^(2/3)/B2,B4+16.9*B3^(2/3)/B2^(5/3))	K

Example 12: Sprinkler activation time

What is the temperature and velocity at a location 4m from the centerline of a fire with a steady state heat release rate of 300 kW in a compartment with a ceiling height of 5m as shown below? (Assume the base of the fire is on the floor.)

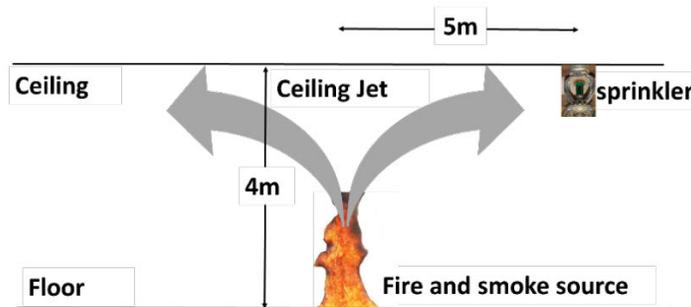


Figure 23: Diagram of Sprinkler Activation Time Example

Solution:

$$r = 5m, H = 4m, \dot{Q} = 300kW, T_\infty = 298K$$

$$\frac{r}{H} = \left[\frac{5}{4} \right] = 1.25 > 0.15 \Rightarrow u = 0.197 \frac{\left(\frac{\dot{Q}}{H} \right)^{1/3}}{\left(\frac{r}{H} \right)^{5/6}} = 0.197 \frac{\left(\frac{300}{4} \right)^{1/3}}{\left(\frac{5}{4} \right)^{5/6}} = 0.689m/s$$

$$\frac{r}{H} = \left[\frac{5}{4} \right] = 1.25 > 0.18 \Rightarrow T = T_\infty + \frac{5.38 \left(\frac{\dot{Q}}{r} \right)^{2/3}}{H} = 298 + \frac{5.38 \left(\frac{300}{5} \right)^{2/3}}{4} = 318.6K$$



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When doing this type of problem we once again want to ask ourselves if the answer is reasonable. Typically compartment fire flows driven by buoyancy are on the order of 1m/s so this velocity result seems reasonable. Temperatures in compartment fires can vary over a wide range but we can see that the calculated temperature is above the ambient temperature. If we had forgotten to add the ambient temperature the result would have been 20.6K which would not make sense. The result is lower than the boiling point of water (373K) which is what we would expect for a fire of this size and distance from the sprinkler location. If we had left out the $2/3$'s exponential in the numerator the result would have been 378K which, while not out of the range of possibility would cause me to double check my calculations.

This can also be solved using the “Alpert’s Correlations” tab of the excel spreadsheet provided with the course as shown below:

This spreadsheet calculates the temperature and velocity of the smoke at ceiling level in a steady state compartment fire corresponding with Equations 21-24 in the course material. There is built in logic to automatically select the correct value between Eqs. 21 vs. 22 and 23 vs. 24		
r		5 m
H		4 m
\dot{Q}		300 kW
T_{∞}		298 K
r/H		1.25 [-]
u		0.69 m/s
T_det		318.61 K

Typical compartment fires grow as a function of time squared. Since fires typically do not burn in a steady state fashion the equations empirical equations used for hand calculations are rough approximations since they use an assumption of a steady state fire. These hand calculations are useful to get an idea of what is going on in a compartment but to get a more accurate idea of the heat transfer occurring in a compartment computer fire models can be used these are discussed in the next section.



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Part 8: Computer Fire Models

There are multiple types of computer fire models, but the three most common types are spreadsheet models, zone models, and field models. Spreadsheet models can be considered the simplest type of computer fire model. One of the key concepts for computer models is verification and validation of the program. Verification is the process of making sure that the mathematical equations are coded into the program correctly. Validation is the process of making sure that the math that the program is solving is actually representative of the real world physics the program is modeling. These issues will be briefly discussed in the zone and field modeling sections below.

8.1 Spreadsheet Models

An example of a set of spreadsheet models are the *Fire Dynamic Tools (FDT) Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program (NUREG-1805, Supplement 1, Volumes 1 & 2)* [27] created by the US Nuclear Regulatory Commission (NRC). These are Microsoft Excel files with built-in macro programming that provide calculations such as heat flux to an object from a fire, compartment upper layer temperature, burn duration of a confined liquid fire, and others depending on which file is used. A select list of the excel spread sheets is provided in table 3 and the spreadsheets are freely available at the following link: <http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/s1/>. These spreadsheets are available in both English and SI units. The spreadsheets have built in material properties for walls such as concrete or drywall. The spreadsheets involving heat release rate have built in properties for fuel such as kerosene or JP-4. The excel files are set up in a format that can easily be printed as a report which the users can sign and include notes. The report includes the equations being solved and references for where the equations came from in the scientific literature. As a demonstration a screen shot of the upper portion a sample spreadsheet for calculating heat flux to a target is shown in figure 24, due to size limitations a copy of the entire spreadsheet is not included in this text of this course. The green cells are automatically filled in from the material properties drop down menu. Currently the macros for the drop down menu to select property data do not work for Mac users but the input parameters can be manually typed into the green cells and the calculations will function.



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Table 3: Selected list of NRC Fire Dynamic Tools

Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire with Natural Ventilation
Predicting Hot Gas Layer Temperature in a Room Fire with Door Closed
Estimating Radiant Heat Flux from Fire to a Target Fuel at Ground Level in Presence of Wind (Tilted Flame) Solid Flame Radiation Model
Estimating Thermal Radiation from Hydrocarbon Fireballs
Estimating Sprinkler Response Time
Estimating Fire Resistance Time of Steel Beams Protected by Fire Protection Insulation (Quasi-Steady-State Approach)
Estimating Fire Resistance Time of Unprotected Steel Beams (Quasi-steady-state Approach)



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

Version 1805.1
 (SI Units)

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

Project / Inspection Title:

INPUT PARAMETERS

Mass Burning Rate of Fuel (m'')	<input type="text" value="0.101"/> kg/m ² -sec
Effective Heat of Combustion of Fuel (ΔH_{eff})	<input type="text" value="44600"/> kJ/kg
Empirical Constant (k_p)	<input type="text" value="1.1"/> m ⁻¹
Heat Release Rate (Q)	<input type="text" value="527713.12"/> kW
Fuel Area or Dike Area (A_{fuel})	<input type="text" value="117.15"/> m ²
Distance between Fire and Target (L)	<input type="text" value="29.87"/> m
Radiative Fraction (α_r)	<input type="text" value="0.30"/>

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

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m ² -sec)	Heat of Combustion ΔH_{eff} (kJ/kg)	Constant k_p (m ⁻¹)	Select Fuel Type
Methanol	0.017	20,000	100	Heptane
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	25,900	1.9	
Dioxane	0.018	26,200	5.4	
Diethyl 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	

Scroll to desired fuel type then Click on selection

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 2-26.

Figure 24 Screen shot of NRC FDT for estimating radiant heat flux from a fire



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8.2 Zone Models

A more complex method for calculating fire effects is the “zone model”. This type of model typically divides a compartment into two layers, a hot layer and a cold layer, and solves conservation of mass and conservation of energy equations for each zone to determine the conditions in the room for a specified fire. This process is described in the CFAST Technical Reference Guide. This type of model does not calculate fire growth or spread and a specified heat release rate curve has to be supplied by the user for the situation they are trying to model. In these calculations the fire basically acts like a pump and pushes hot air into the upper layer which then allows more cool air to be brought into the lower layer from outside of the compartment. An example of a popular zone modeling program is the Consolidated Model of Fire and Smoke Transport (CFAST) [28] created by the National Institute of Standards and Technology (NIST). A screen shot of a CFAST model of the Eastern Kentucky University (EKU) burn building is shown in Fig. 25. As a general overview, besides the visual output, this model calculates upper layer temperature, height, and species concentration. Heat flux to targets and walls. The program can calculate smoke detector and sprinkler activation times. The user can build a model with over 30 compartments connected by horizontal vents, vertical vents and mechanical flow vents which can be opened and closed in the model. For a more in-depth description of the program’s capabilities users are directed to the CFAST user’s manual. The equations solved by the program are available in the Technical reference guide which is provided with the program installation files. A validation guide is also provided with the installation, CFAST has validated internally by NIST and a variety of other research organizations. Some of the parameters that have been studied include Model sensitivity, fire plumes, multiple compartments, large compartments, and comparison to full scale fires. CFAST is freely available and can be downloaded from the NIST website: <https://www.nist.gov/el/fire-research-division-73300/product-services/consolidated-fire-and-smoke-transport-model-cfast>. One reason CFAST is a popular program is because it has a graphical user interface and has built in default heat release rate curves based on tests done at NIST for various items such as a chest of drawers or a kiosk, as shown in Fig. 26. Since these test burns were done in the open and compartment fires potentially have limited ventilation, the default fires are not necessarily good to use in actual models but they are a nice place to start. There is a variety of other zone models that have been created by various institutions, some of these include COMPBRN III, CONTAM, CSTBZ1, BRANZFIRE, FPETOOL, LAVENT, and WPI/FIRE among others. These, and others, are each briefly described in the Section 3, chapter 7 of the SFPE Handbook of Fire Protection Engineers [3]. Unlike CFAST some of these models are no longer being worked on and do not have support. CFAST currently has an online discussion group (<https://groups.google.com/forum/#!forum/cfast>) and users can ask questions and get help from the developers at NIST.



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The screenshot displays the CFAST software interface. At the top, a menu bar includes 'File', 'Run!', 'Tools', 'View', and 'Help'. Below the menu is a navigation bar with tabs for 'Simulation Environment', 'Compartment Geometry', 'Horizontal Flow Vents', 'Vertical Flow Vents', 'Mechanical Flow Vents', 'Fires', 'Detection / Suppression', 'Targets', and 'Surface Connections'. The main window features a table of compartments and a detailed configuration panel for 'Compartment 5 (of 10)'. The table lists compartments A1, B1, 1B-C, A2, and B2 with their respective dimensions and material properties. The configuration panel for compartment B2 shows geometry (Width: 3.66 m, Depth: 4.8768 m, Height: 2.9 m), materials (Gypsum Board for ceiling and walls, Off for floor), and advanced flow characteristics (Normal (Standard two-zone model)).

Compartment	Num	Width	Depth	Height	K	Position X	Position Y	Position Z	Ceiling	Walls	Floor	F	H	V	M	D	T
A1	1	4.8768	4.2696	2.9	0	0	0	0	gypsum	gypsum	off	0	4	0	0	0	0
B1	2	3.66	4.8768	2.9	0	4.2696	0	0	gypsum	gypsum	off	0	2	0	0	0	0
1B-C	3	1.2168	4.8768	2.9	3.66	4.2696	0	0	gypsum	gypsum	off	0	4	0	0	0	0
A2	4	4.8768	4.2696	2.9	4.8768	0	0	0	gypsum	gypsum	off	0	3	0	0	0	0
B2	5	3.66	4.8768	2.9	4.8768	4.2696	0	0	gypsum	gypsum	off	0	3	0	0	0	0

Compartment 5 (of 10)
Compartment Name: B2

Geometry
Width (X): 3.66 m
Depth (Y): 4.8768 m
Height (Z): 2.9 m
Position, X: 4.8768 m
Y: 4.2696 m
Z: 0 m

Advanced
Flow Characteristics: Normal (Standard two-zone model)
Variable Cross-sectional Area:
Height | Area

Materials
Ceiling: Gypsum Board (5/8 in)
Walls: Gypsum Board (5/8 in)
Floor: Off
Conductivity: 0.00016 kW/(m °C)
Specific Heat: 0.9 kJ/(kg °C)
Density: 790 kg/m³
Thickness: 0.016 m

Buttons: Open, Save, Geometry, Run, View

Figure 26: Screen Shot of CFAST graphical user interface



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8.3 Field Models (computational Fluid Dynamic models)

Field models also known as computational fluid dynamic (CFD) models are pointedly more complicated than zone models. Instead of breaking the compartment into two zones, field models calculate the conservation equations in thousands or millions of separate small control volumes. The smaller the control volume the more accurate the model can theoretically be but the more computationally expensive and longer the model takes to run. While multi room zone models can run in a matter of seconds, CFD models may take weeks or months to complete. Besides the conservation equations, CFD codes can also include turbulence modeling using a direct numerical simulation (DNS) or a large eddy simulation (LES) approach. A discussion of the mathematics of how these types of equations are solved is outside the scope of this course but a description can be found in a numerical methods for solving partial differential equations text among others. One of the most popular field models for use in structure fires is Fire Dynamic Simulator (FDS) [29] also created and supported by NIST. Figures 27 and 28 show a simulation of one of the rooms in the EKU burn building in FDS. This type of model breaks up the simulation environment into a multitude of cells (shown in Fig. 27b) and solves conservation equations on each cell to determine the conditions in the simulation environment. Figure 28a shows a rendering of buoyancy driven smoke generated by a fire coming out of the compartment doors and windows. Figure 28b shows temperature profiles along the plane of the middle of the door and the side window of the room with a simulated fire. FDS is freely available on the NIST website: <https://pages.nist.gov/fds-smv/>. The program has a wide and continuously expanding list of capabilities besides the general buoyancy driven flow mechanics such as particle and droplet tracking, surface wetting, HVAC duct, simple vents, fans, and heaters, a pyrolysis model, etc. Furniture other objects inside of a compartment can be modeled. For a full list of capabilities see the FDS Users guide. How the equations are solved is described in the FDS technical reference guide and the FDS installation programs also include validation and verification guides for FDS itself and a verification guide for Smokeview which is the software used to display the model (figures 27 and 28). FDS uses a text based input system rather than a graphical user interface (GUI) which can make building models time consuming. As an example, figure 29 shows a simple compartment with 2 windows and a door, each wall is color coded and represents a single line of text. Figure 30 shows the 8 lines of code required to create the compartment shown in Fig. 29 and an arrow for which line represents which part of the model. Besides the typical coding syntax, each wall and window is represented in three dimensional space by six numbers which give the coordinates of the object. In the x, y, z Cartesian coordinate system, these numbers are in the order of x_{min} , x_{max} , y_{min} , y_{max} , z_{min} , and z_{max} . As you can imagine, modeling a complicated structure with multiple room, floors, and items inside each compartment potentially requiring thousands of lines of code would take an extended amount of time. Due to this issue, there are commercial third party software packages



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available such as Pyrosim created by Thunderhead Engineering (<http://www.thunderheadeng.com/pyrosim/>) that can make it easier to program more complicated geometries.

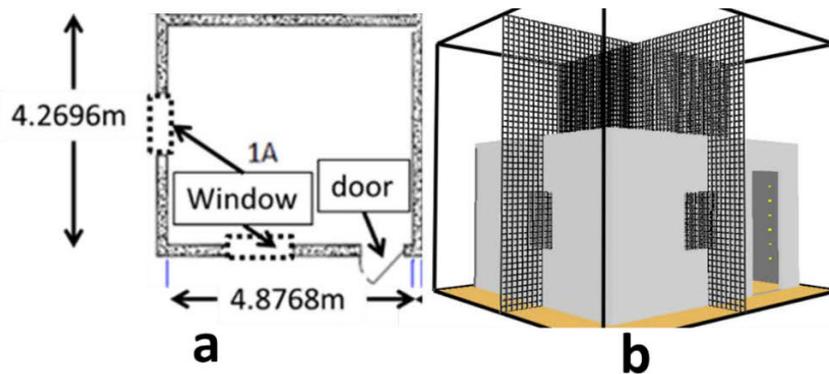


Figure 27: Fire Dynamics simulator model of a compartment. a) Room dimensions
b) FDS simulation showing grid cell size in xy planes.

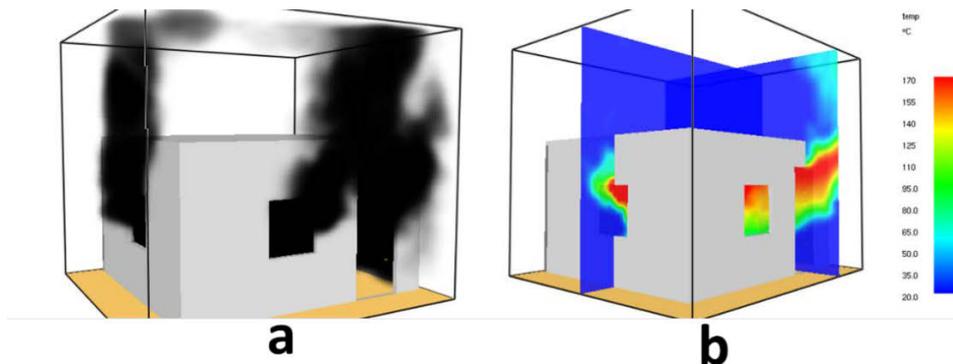


Figure 28: FDS simulation of a fire in a compartment a) Rendering of smoke coming out of compartment containing a fire. b) Temperature profile in door and side window caused by a fire in the compartment.



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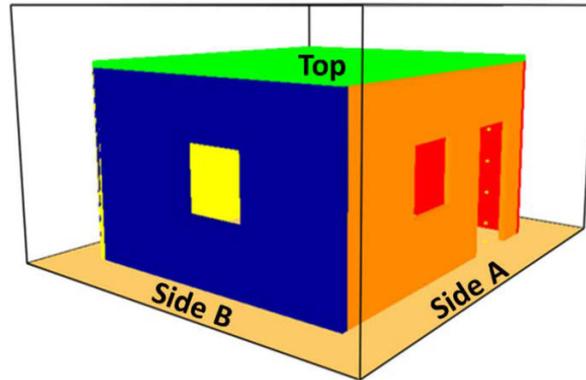


Figure 29: Simple geometry



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Simulate Cell A1 of burn building in FDS

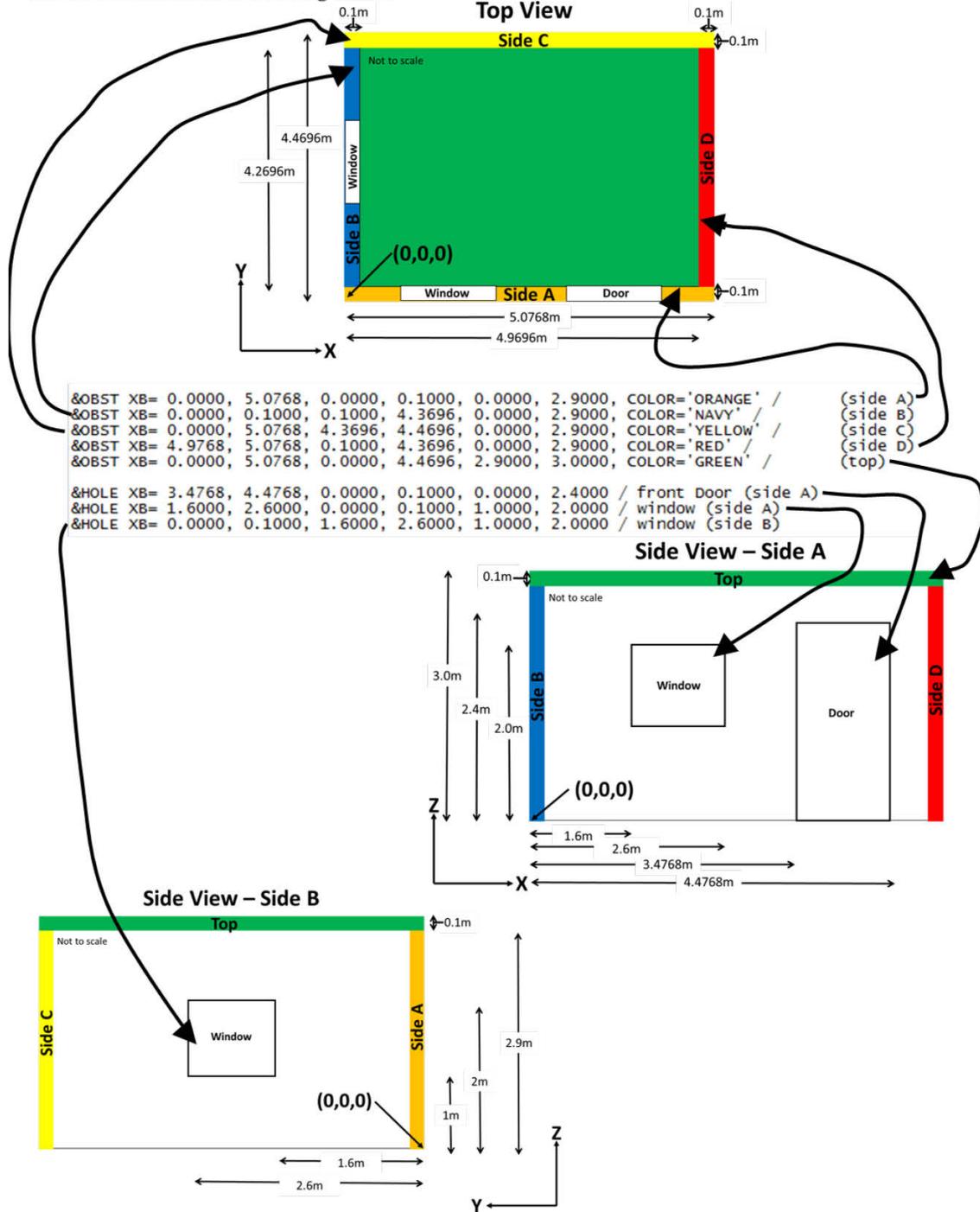


Figure 30: FDS Input Code for Simple Geometry



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Besides the typical fire and structural models, there are also a wide variety of other models that can be used in the evaluation of fire effects on an industrial facility. There are models to simulate how people will move throughout a structure such as EXODUS. There are other combustion models such as FireFOAM, which is an open course computational fluid dynamics (CFD) model created by FM Global. There are explosion modeling programs such as FLACS-DustEx sold by Gexcon. These are outside the scope of this course but I wanted to make a mention of them.



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Part 9: Other resources

There are a wide variety of resources dealing with structure fires available on the internet. For instance the National Institute of Standards and Technology (NIST) has posted fire related resources on the internet: <https://www.nist.gov/el/fire-research-division-73300/fire-web> and the International Association of Arson Investigators (IAAI) has free courses involving fire dynamics and fire investigation at the following website: <https://www.cfitrainer.net/>. Table 4 provides a select list of websites and their general topics.

Table 4: Websites Containing Fire Science Information

Websites	General Topics
http://www.firesciencetools.com	Tools for teaching fire science
http://www.koverholt.com/	Fire Science and modeling tools
http://www.fire.nist.gov/	NIST fire demonstration videos and data
http://www.nist.gov/fire/	Instructional topics have videos at bottom of page
http://www.cfitrainer.net/	Free fire investigation video programs
http://www.khanacademy.org/	Math and Science tutorials
www.engineeringtoolbox.com	Material properties
https://www.doctorfire.com/	Fire Science Information and Publications
http://www.thermalradiation.net/	View Factor Equations



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