A Users Guide for the CFI Calculator and Fire Dynamics Equations

A publication by:

The International Association of Arson Investigators
and
The CFITrainer.net Steering Committee

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Users are warned that CFI Calculator and the CFI Calculator Users Guide is intended for use only by those competent in the field heat transfer, combustion and fire science, and is intended only to supplement the informed judgment of the qualified user. This calculator may or may not have predictive capability when applied to a specific set of factual circumstances. All results should be evaluated by an informed user.

This document has undergone extensive review but no warranty against errors or omissions is expressed or implied.

The IAAI would like to thank the following individuals for their review and contributions to this document:

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INTRODUCTION:

The CFITrainer.net CFI Calculator was developed as a part of a grant received by the International Association of Arson Investigators through the Federal Emergency Management Agency, Assistance to Firefighters Grant Program. The calculator is designed to assist field fire investigators in the development and testing of hypothesis while utilizing the scientific method, and to provide the investigator a tool that can be utilized to analyze fire behavior using fire dynamics equations.

The various formulae contained in the CFI calculator tool were derived from existing scientific publications and literature and have been subjected to continued assessment and peer review. The calculator is currently published in three formats, including a Palm OS application, a Pocket PC application and a desktop PC application.

While the look and feel of the three versions may differ slightly as a result of operating systems functionality and screen real estate issues, the calculated results are consistent. The tool has undergone extensive testing to ensure that the calculated results are consistent with calculated results derived utilizing alternative methods including long hand equation solving, solving utilizing programmable scientific calculators and solving utilizing other computer based tools.

The calculator currently contains seven equations including Flame Height, Heat Flux, Flashover, Fire Growth, Sprinkler Activation, Heat Release Rate and Time to Ignition. A number of these equations contain radio buttons, which are utilized to increase the functionality of the equation, allowing the user to solve for different unknown variables. Additionally, the tool employs drop down menus in a number of equations to serve as a reference guide for commonly utilized values.

While the equations stand alone in analyzing specific aspects of fire growth and behavior, there is an interrelationship between a number of the equations such as Heat Release Rate and Flame Height or Heat Release Rate and Heat Flux, etc.. This allows the equations to be utilized in conjunction with one another to analyze multiple aspects of a given scenario. While these equations can be very useful in hypothesis development and testing, it is important to recognize that these formulas do have limitations and are appropriately utilized to bound a problem, defining a “fence” around the realm of possibilities. These equations may provide support to a hypothesis or show that a particular hypothesis is less likely than others. However, no single formula or data will typically prove that an event could not have occurred; only that is was less likely given the parameters. For example, in estimating a time to Flashover the investigator may calculate a range of values from 1 to 4 minutes (depending on input). This should not be taken as proof that Flashover could not have occurred at 5 minutes, only that Flashover was feasible as soon as 1 to 4 minutes. This tool is designed to be utilized by those individuals that have a sound knowledge of fire dynamics and fire dynamics equations and the use of this tool may require referencing additional scientific literature or consulting outside experts.

DOWNLOADING:

The CFI Calculator is available for download to registered CFITrainer.net users at www.cfitrainer.net. All three versions (Palm, Pocket PC and Desktop) are available on this website and users are free to choose any or all of the applications. The desktop and Pocket PC versions require the installation of a .Net Framework version 2.0 application and directions for locating the download are available on the CFITrainer.net site.

Installation of updated versions may require the removal of older versions. Technical support is available if users have problems installing or running the applications. Additionally, the site hosts a frequently asked questions forum that addresses many of the common questions a user may have without the need for additional technical support. Users are also encouraged to provide feedback to the development team to ensure that the product is serving the needs of the fire investigation community, identify potential bugs that need correction, and provide insight on how the tool should be improved in future releases.

USER INTERFACE:

The application is typically launched by pressing a screen icon, similar to other computer applications. Upon opening, the home screen will appear, listing the various equations contained in the calculator tool. The equations are listed on "buttons" that are utilized to launch each specific equation tool. Additionally, a link to the general disclaimer is available on the home screen, warning users of the limitations of the tool. Once a button is clicked, the selected calculation will open and an input screen will appear allowing the input of the required variables necessary for solving the particular equation. The screen also includes a help button that opens additional information concerning the application of a particular formula and contains limited reference material. Additional navigation tools are available including a "Home" button that takes the user back to the opening screen containing all of the equations and a calculate button that will solve the equation and take the user to the output screen. The Pocket PC and Desktop version also contain a numeric and/or graphic input tool, which can be utilized for inputting the necessary data without the use of an external keyboard. As previously mentioned, a number of applications contain drop down menus, allowing the input of common values without the need of additional reference materials. In a number of applications, these drop down menus can be toggled on and off by depressing a button, allowing the user to manually input specific data, if available. Once transitioning to the output screen, the user will view the calculated results and additionally have a "Back" button navigation tool that returns the program to the input screen of the specific equation, allowing the user to run multiple iterations of the equation without difficulty. The program does not store or recall results so it is imperative that the user record the input variables and the output measures for later use.

EQUATIONS:

The next several sections relate to the various equations included in the CFI Calculator tool and are designed to break each formula down so the user understands what the requested input means, where to find the input data, and what the output measurements signify. By providing the user a better fundamental understanding of the equations, it is believed that the user will become better informed and better able to apply the tool to their fire scene hypotheses. The formulas and the CFI Calculator tool are designed to assist the field investigator in the analysis of fire behavior at fire event, analyze witness statements versus expected fire behavior, and predict results when conducting tests and experimentation. The formulas and the CFI Calculator tool are intended to be utilized as a part of and in furtherance of the proper application of the Scientific Method to a fire scene investigation. As some applications utilize more than one formula in calculating output data, each formula utilized will be discussed in the appropriate section to which it relates. The equations will not necessarily be discussed in the order in which they appear on the CFI Calculator tool. **It is important to note that all equations require input in metric values and conversions should be done prior to utilizing this tool.**

The most common measurements that need to be converted are feet to meters and ^{o}Fahrenheit to ^{o}Celsius. Simple formulas for these conversions are:

$$meters = feet / 3.2808 \text{ and } °Celsius = (°Fahrenheit - 32)/1.8$$

HEAT RELEASE RATE:

One of the fundamental properties of a fuel is its Heat Release Rate or Fire Power, which represents how much energy an item gives off over a period of time. It is represented by the symbol $\dot{Q}$, and is most accurately defined as “the energy produced by the fire per unit time or fire power.”[1] It takes into account a fuel’s effective heat of combustion (energy released by the fire per unit mass of burned fuels)[2], the mass loss rate per unit area (the mass of the fuel vaporized but not necessarily burned)[3], and the burning area.

The formula for determining the heat release rate or energy release rate[4] of a give fuel is:

$$\dot{Q} = \dot{m}'' A \Delta H_c$$

Where:

$\dot{Q}$ = Heat Release Rate in Kilowatts (kW)

$\dot{m}''$ = Mass Loss Rate of a given fuel in grams per unit area per second ($g/m^2 - s$). This value relates to how much “weight” a fuel loses over a given time (in seconds) and is usually a value derived from scientific reference material.

A = the area involved in the vaporization measured in square meters. (Note: When calculating the area of a pool fire, utilize the equation $A = \frac{\pi}{4} D^2$, where D = the diameter of the pool.)

ΔH_c = the effective heat of combustion measured in kilojoules per g (kJ/g). This value is usually derived from scientific reference material.

Utilizing this equation to calculate the estimated heat release rate of a pool fire of gasoline measuring approximately 1 meter across, with a Heat of Combustion (ΔH_c) value of 43.7 kJ/g and a Mass Loss Rate ($\dot{m}''$) value of 55 $g/m^2 - s$ (Average of range - 50-60 $g/m^2 - s$), the area of the fuel would first be calculated as follows:

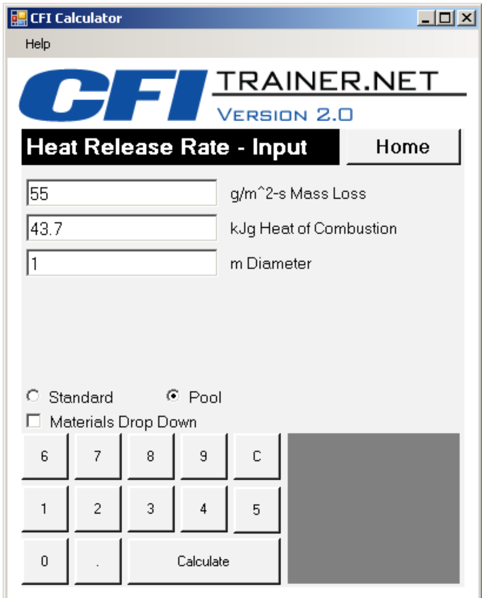
$$A = \frac{\pi}{4} D^2 = \frac{\pi}{4}(1m)^2 = 0.785\, m^2$$

The Heat Release Rate equation would then be utilized by inserting the data in the appropriate fields and the following results would be expected:

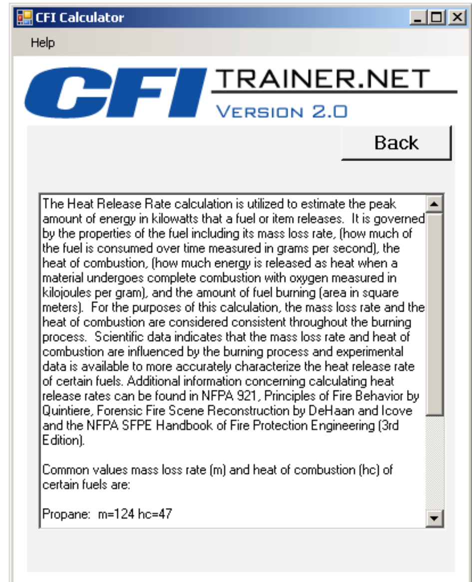
$$\dot{Q} = (55\, g/m^2 - s)(0.785\, m^2)(43.7\, kJ/g)$$

$$\dot{Q} = 1887\, kW$$

The expected input screen and output screen utilizing the CFI Calculator tool with the same values discussed previously are demonstrated below:



The tool is designed to allow the user to utilize the materials drop down menu (in this example we would select gasoline, and the stored data for the mass loss rate and effective heat of combustion would be utilized in the calculation. References for the values utilized in the drop down menu are also contained in the help file) or exact variables can be entered, if known to the user. When determining the area involved in vaporization, it is calculated by multiplying the length in meters by the width in meters. The area of a pool fire is calculated based on it's diameter in meters. For irregular shaped objects or irregular shaped pools, some approximations or estimates might have to be utilized. This calculator application has a radio button that allows the user to select if they are calculating the Heat Release Rate of a pool or a standard item. Examples of the drop down menu and reference help file are illustrated below:



An additional check with an Excel Spreadsheet tool (based on a spreadsheet tool developed by Dr. Fred Mowrer[5], with minor modifications) would yield the following output results:

Q dot = Heat Release Rate		
Input Parameters		
Heat of Combustion (ΔHc)	**43.7**	kJs/m2
Mass Loss ($\dot{m}''$)	**55**	kgs/m2
Area of Fuel Surface (A)	**0.785**	m2
Calculated Parameters		
Heat Release Rate ($\dot{Q}$)	**1886.7**	kW

These examples demonstrate that the calculated results are consistent with the manual calculation, the CFI Calculator Tool and the Excel Spreadsheet. Additional validation can be done by comparing the calculated/estimated results with data derived as a result of laboratory experimentation.

In 2005, an experiment involving a gasoline pool fire was conducted at the Bureau of Alcohol, Tobacco, Firearms and Explosives, Fire Research Laboratory as a part of a training session conducted for the International Association of Arson Investigators 56th Annual Training Conference. The experiment involved burning approximately 3.79 liters (1 gallon) of gasoline in a pan measuring approximately 0.55 meters (22 inches) in diameter. The pan was placed on a load cell to calculate the mass loss rate and the burn was conducted under a cone calorimeter to allow for the measurement of both peak heat release rate and total heat release rate. Thermocouples were set above the pool in 0.30 meter (1 foot) increments and heat flux gauges were set up approximately 0.50 meters and 1 meter from the axis of the pan.

With the given parameters of the experiment, the fuel properties and pan dimension can be utilized to calculate the estimated heat release rate. With the given values, the calculated peak heat release rate would yield the following results:

Area of Pool:

$$A = \frac{\pi}{4} D^2 = \frac{\pi}{4}(0.55\,m)^2 = \frac{\pi}{4}(.303\,m^2) = 0.238\,m^2$$

Heat Release Rate:

$$\dot{Q} = (55\,g/m^2 - s)(0.238m^2)(43.7\,kJ/g)$$

$$\dot{Q} = 572\ kW$$

The estimated peak heat release rate of the fire defined in these experiments is 572 kW. The experiment was run two times under the same set up parameters with the results listed below:

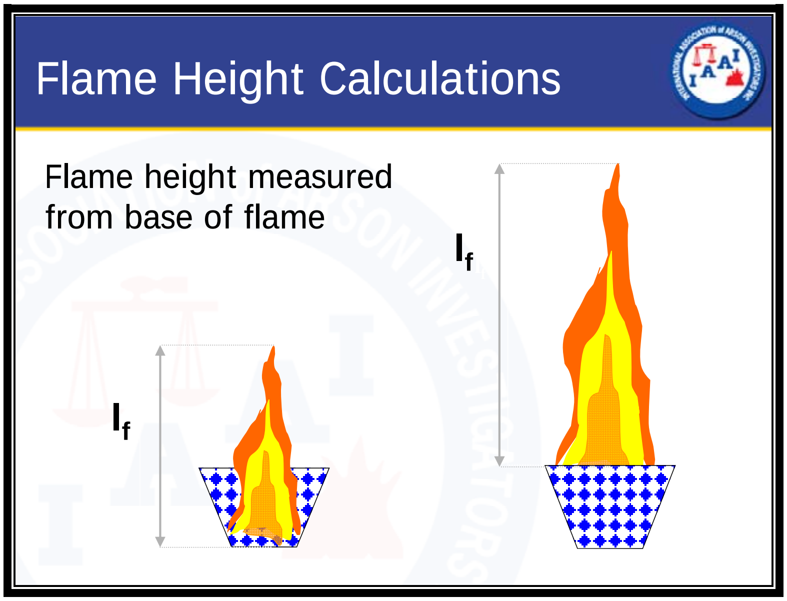
Peak (kW)	30 second maximum average (kW)	1 minute maximum average (kW)	5 minute maximum average (kW)	Total heat released (kJ)
326	**306**	**299**	**266**	**94607**
491	**457**	**442**	**309**	**96949**

As is demonstrated in this experiment, the measured results of actual peak heat release rate in the two experiments (326 kW and 491 kW respectively) utilizing the same parameters, fall below the calculated results of 572 kW. Utilizing the range of mass loss rate published for gasoline (50-60 $g/m^2 - s$) the peak heat release rate can be calculated at somewhere between 518 kW and 622 kW for the parameters defined in the experiment. These results are closer to the observed measurements at the lower end, and certainly help illustrate that these equations are appropriately utilized to bound a problem but cannot be expected to yield exact results. The number of variables that can influence experimental results including heat loss to the pan and heat loss to the floor are often too difficult to factor into equations and, therefore, experimentally derived results will vary not only from test to test but, often from the calculated results as well. These differences not withstanding, utilized appropriately, fire dynamics equations and calculations can serve an important role in the analysis of fire events.

The Heat Release Rate measurement is a common input value throughout most of the equations utilized in the CFI Calculator tool. In particular, it is closely associated with the flame height and heat flux calculations, as these properties are a function of, or greatly influenced by Heat Release Rate. While the Heat Release Rate equation can be utilized on it's own to help quantify the amount of energy a particular fuel or item will release, these other equations can also be utilized to help the investigator estimate this property of a burning item. The alternative uses of additional formulas will be discussed in the appropriate section.

FLAME HEIGHT

Flame height is closely associated with the amount of energy being released by a fuel (Heat Release Rate or $\dot{Q}$) with fuels with higher energy release rates expected to have higher flame heights as compared to those with lower heat release rates. Other factors, such as fuel configuration and fuel location, can also influence flame height and should be considered when utilizing these formulae. There are a number of calculations that have been developed that can be utilized to estimate the flame height based on the heat release rate and conversely, estimate the heat release rate based on an observed flame height. These formulas are useful in predictive analysis while conducting fire testing as well as analyzing witness statements. When calculating flame height, the measurement is taken from the base of the flame to the height above the flaming object, not from the base of the object.



The first formula to be discussed was developed by McCaffrey[6] and is expressed as follows:

$$Z_c = 0.08\dot{Q}^{2/5} \quad and \quad Z_i = 0.20\,\dot{Q}^{2/5}$$

Where:

Z_c = Consistent Height of Flame in Meters

Z_i = Intermittent Height of Flame in Meters

0.08 = Consistent Flame Variable in m/kW

0.20 = Intermittent Flame Variable in m/kW

$\dot{Q}$ = Heat Release Rate of Fire in Kilowatts

In this equation, McCaffrey utilizes the variables of 0.08 and 0.20 for the consistent flame height and intermittent flame height respectively. This formula describes the flame as varying between a relatively consistent height (the 0.08 value) and an intermittent, but higher level (0.20 value) that the flame reaches as it undulates or flickers at a periodic rate. These additional variables allow for additional estimations or calculations utilizing this methodology.

An example of the use of this formula calculating the consistent flame height of a 500 kW is as follows:

$$Z_c = 0.08\, m/kW\, (500\, kW)^{2/5}$$

$$Z_c = 0.08\, m/kW\, (12\, kW)$$

$$Z_c = 0.96\, m$$

The same example of this formula calculating the intermittent flame height would yield the following results:

$$Z_i = 0.20\, m/kW\; (500\, kW)^{2/5}$$

$$Z_i = 0.20\, m/kW\; (12\, kW)$$

$$Z_i = 2.4\, m$$

While McCaffrey's calculation does provide for estimating the consistent flame height and the intermittent flame height, the CFI Calculator utilizes the intermittent variable (0.20) as the observed results are more consistent with the methods of Heskestad and Alpert and Ward that incorporate an "average" variable, and compares more favorably to experimental data that will be discussed later.

These same input variables can be utilized to calculate the Heat Release Rate ($\dot{Q}$) of a fire where the flame height is know either through actual measurement or estimated from observation. The equation can be rebalanced algebraically to solve for the unknown, in this case $\dot{Q}$, as follows:

$$Z_i = 0.20\,(\dot{Q})^{2/5}$$

Divide each side by (0.20):

$$\left\{\frac{Z_i}{0.20} = \frac{0.20(\dot{Q})^{2/5}}{0.20}\right\} \quad = \quad \left\{\frac{Z_i}{0.20} = (\dot{Q})^{2/5}\right\}$$

Raise each side to a power of (5/2):

$$\left\{(\frac{Z_i}{0.20})^{5/2} = ((\dot{Q})^{2/5})^{5/2}\right\} \quad = \quad \left\{(\frac{Z_i}{0.20})^{5/2} = \dot{Q}\right\}$$

Utilizing the results of 2.4 meters, we obtained from calculating the flame height of a fire with a Heat Release Rate of 500 kW, we would estimate the heat release rate as follows:

$$(\frac{2.4\,m}{0.20\,m/kW})^{5/2} = \dot{Q}$$

$$(12\,kW)^{5/2} = \dot{Q}$$

$$498\,kW = \dot{Q}$$

This result compares favorably to the 500 kW fire in the example, with the differences attributed to the rounding properties assigned to the calculator.

A second method of calculating flame height was developed by Heskestad[7,8,9]. This formula is typically utilized for calculating the flame height of pool fire and included a flame diameter variable. This formula compares well to the other formulas and can be used to calculate the flame height of other burning objects, in addition to pool fires. It is expressed as follows:

$$L_f = 0.23\dot{Q}^{2/5} - 1.02\,D$$

Where:

L_f = Height of Flame in Meters

$\dot{Q}$ = Heat Release Rate of Fire in Kilowatts

D = Diameter of Flame in Meters

0.23 = Flame constant expressed in m/kW

Utilizing the same example of a 500 kW fire that was discussed in the McCaffrey example and defining the diameter at 0.50 meters, the following results would be expected:

$$L_f = 0.23\,m/kW\,(500\,kW)^{2/5} - 1.02\,(0.50\,m)$$

$$L_f = 0.23\,m/kW\,(12\,kW) - (.51\,m)$$

$$L_f = (2.76\,m) - (.51\,m)$$

$$L_f = 2.25\,m$$

This result compares favorably to the McCaffrey Intermittent results of 2.4 meters. Again, this formula can be reconfigured algebraically to solve for the heat release rate as follows:

$$L_f = 0.23\dot{Q}^{2/5} - 1.02\,D$$

Add (1.02D) to each side:

$$\left\{L_f + 1.02D = (0.23\dot{Q}^{2/5} - 1.02D) + 1.02D\right\} = \left\{L_f + 1.02D = 0.23\dot{Q}^{2/5}\right\}$$

Divide each side by (0.23):

$$\left\{(\frac{L_f + 1.02D}{0.23}) = \frac{0.23\dot{Q}^{2/5}}{0.23}\right\} = \left\{(\frac{L_f + 1.02D}{0.23}) = \dot{Q}^{2/5}\right\}$$

Raise each side to the power of (5/2):

$$\left\{(\frac{L_f + 1.02D}{0.23})^{5/2} = (\dot{Q}^{2/5})^{5/2}\right\} = \left\{(\frac{L_f + 1.02D}{0.23})^{5/2} = \dot{Q}\right\}$$

Utilizing the example of a 2.25-meter flame height, (calculated from a given heat release rate of 500 kW) and a flame diameter of 0.50 meters, the results for an estimated heat release rate would be as follows:

$$(\frac{(2.25m) + 1.02(0.50m)}{0.23})^{5/2} = \dot{Q}$$

$$(\frac{(2.25m) + (.51m)}{0.23m/kW})^{5/2} = \dot{Q}$$

$$(\frac{2.76m}{0.23m/kW})^{5/2} = \dot{Q}$$

$$(12kW)^{5/2} = \dot{Q}$$

$$498kW = \dot{Q}$$

Again, this result compares favorably with what the expected results of 500 kW and the minor differences can be attributed to rounding.

The third formula included in the CFI Calculator and discussed in this paper, was developed by Alpert and Ward[10] and is included in the 2004 edition of NFPA 921[11]. Similar to the other equations discussed, this calculation is based predominately on the heat release rate. This equation includes a location factor, which is utilized to estimate the effects of entrainment on the flame height. Recent experimentation has indicated that the limiting effects of entrainment (factored at 50% for a wall configuration and 75% for a corner configuration) may not be as great as previously reported. Fuel shape does have some influence on this limiting effect, for example a square fuel against a wall or corner will reduce entrainment more than a round fuel in against a wall or corner. While the use of an entrainment-limiting factor is somewhat subjective, they can be utilized to establish a range of flame heights for use in scene analysis. The equation is expressed as follows:

$$H_f = 0.174(k\dot{Q})^{2/5}$$

Where:

H_f = Height of Flames in Meters

k = Location of Fire in Compartment with:

1= Center of Room
2= Against Wall
4= Corner of Room

$\dot{Q}$ = Heat Release Rate of Fire in Kilowatts

0.174 = Flame Constant in m/kW

Utilizing the same example of a 500 kW fire that was discussed in the other two equations, and giving it a center of the room value of (1) the following results would be expected:

$$H_f = 0.174 m/kW \,((1)\,(500 kW))^{2/5}$$

$$H_f = 0.174 m/kW \;(500 kW)^{2/5}$$

$$H_f = 0.174 m/kW \;(12 kW)$$

$$H_f = 2.09\, m$$

This result also compares favorably with the result obtained from the McCaffrey equation (2.4 meters) and the Heskestad equation (2.25 meters). The differences again, demonstrate that these formulas do have limitations and are appropriately utilized to bound a problem, defining a reasonable range of possibilities versus what scientifically could not happen.

Like the other flame height calculations, the Alpert and Ward formula can be reconfigured algebraically to solve for the heat release rate based on a known flame height. The formula would be configured as follows:

$$H_f = 0.174 (k\dot{Q})^{2/5}$$

Divide each side by (0.174):

$$\left\{ H_f / 0.174 = \frac{0.174 (k\dot{Q})^{2/5}}{0.174} \right\} = \left\{ H_f / 0.174 = (k\dot{Q})^{2/5} \right\}$$

Raise each side to the power of (5/2):

$$\left\{(H_f / 0.174)^{5/2} = ((k\dot{Q})^{2/5})^{5/2}\right\} = \left\{(H_f / 0.174)^{5/2} = (k\dot{Q})\right\}$$

Divide each side by (k):

$$\left\{\frac{(H_f / 0.174)^{5/2}}{k} = \frac{(k\dot{Q})}{k}\right\} = \left\{\frac{(H_f / 0.174)^{5/2}}{k} = \dot{Q}\right\}$$

Utilizing the example of a 2.09 meter flame height, (calculated from a given heat release rate of 500 kW) and a center of the room location factor of (1), the results for an estimated heat release rate would be as follows:

$$\frac{(2.09m / 0.174m / kW^{5/2}}{1} = \dot{Q}$$

$$\frac{(12kW)^{5/2}}{1} = \dot{Q}$$

$$\frac{498kW}{1} = \dot{Q}$$

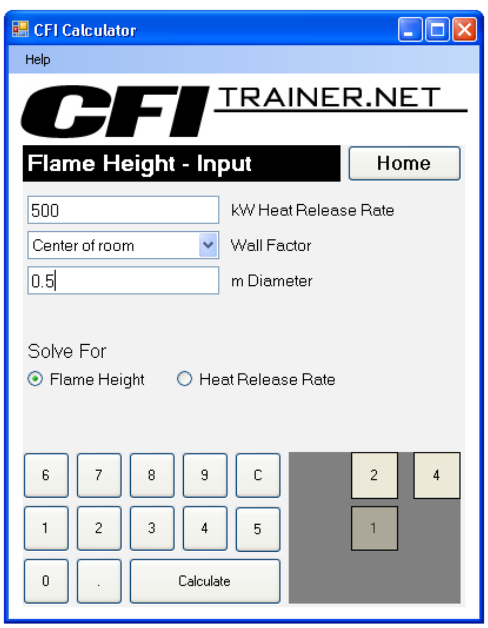
$$498\ kW = \dot{Q}$$

These results are consistent with the heat release rate results utilizing the other flame height calculations are consistent with our expected output of 500 kW. Again, the minor difference can be attributed to rounding issues.

A comparison of the calculated results with the Excel spreadsheet tool indicates very consistent results.

Estimate of Flame Heights			Calculated
Input Parameters			
Heat Release Rate	**500**	kW	
Wall Factor (kLF)	**1**		
Diameter (Pool Fires)(D)	**0.5**	m	
Calculated Parameters			
Persistent Flame Height	1.0	m	
Intermittent Flame Height	2.4	m	2.4
NFPA Flame Height	2.1	m	2.09
Pool Fire Flame Height	2.3	m	2.25

When utilizing the CFI Calculator tool, selecting the Flame Height button from the initial user interface will open the input screen. From the input screen, the user can toggle to calculate flame height based on heat release rate or heat release rate based on flame height as we have previously discussed. Samples of the input screen with the values utilized in earlier examples and the output screen revealing the calculated results are demonstrated below. These values are, again, consistent with the other tools utilized to make these calculations including hand calculating and the Excel spreadsheet.

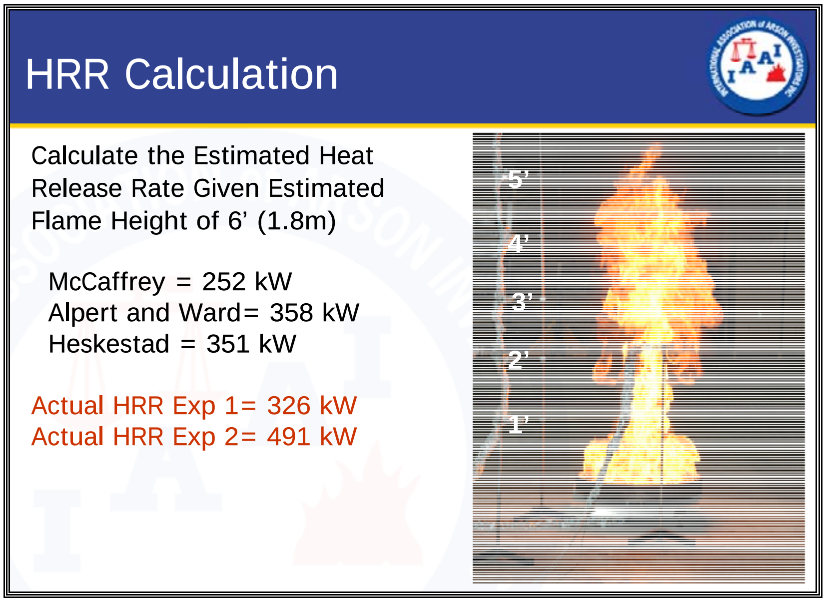


For an example of the practical application of the flame height calculation, the 2005 experiment at the Fire Research Laboratory can be utilized. Recall that the experiment involved burning approximately 3.79 liters (1 gallon) of gasoline in a pan measuring approximately 0.55 meters (22 inches) in diameter. The pan was placed on a load cell to calculate the mass loss rate and additionally the burn was conducted under a cone calorimeter to allow for the measurement of the peak heat release rate and total heat release rate. Thermocouples were set above the pool in 0.30 meter (1 foot) increments and heat flux gauges were set up approximately 0.50 meters and 1 meter from the axis of the pan. The calculated heat release rate with the given parameters was 572 kW and the measured results from the two experiments were 326 kW and 491 kW respectively. Utilizing these figures in the flame height equations, the calculated flame height would be as follows:

Method	HRR	McCaffrey	Heskestad	Alpert and Ward
Calculated	572 kW	2.54 m	2.35 m	2.21 m
Exp 1	326 kW	2.02 m	1.77 m	1.76 m
Exp 2	491 kW	2.38 m	2.18 m	2.07 m

Observational evidence derived from photographs indicates a flame height in the range of 1.8 meters (6 feet) above the pool. This compares most closely to the calculated results of experiment 1. In comparing the observed results to the range of calculated results, there are some differences noted, however they are fairly accurate for this type of application. Again, we are establishing a range of possibilities versus developing an exact result.

If we utilize the observed flame height of 1.8 meters to calculate an estimated heat release rate we would observe the following:



Again, minor differences are observed, but it is clear that the calculated results are reasonably reliable and are within the "fence of reality" established by the measured results. These results help indicate that the calculations can be reliable within the scope of their intended use and can be effectively utilized in analytical analysis.

HEAT FLUX

The heat flux equation utilized in the CFI Calculator measures the radiant heat flux utilizing a point-source method. This methodology is based on the assumption that all of the energy is received uniformly a sphere radius from the flame.[12] The tool is set up similar to the flame height calculation, in that the formula can be utilized to calculate heat flux based on a known heat release rate (calculated utilizing the heat release rate equation or the flame height equation or obtained from published literature) or utilized to calculate the heat release rate if a heat flux value is known. Radiation is heat energy that is transferred through electromagnetic waves and unlike conduction and convection, this form of energy transfer does not need any intervening medium. Heat flux can be defined as the heat flow per unit area of flow path[13] and is generally expressed in kilowatts per meter squared (kW/m^2). As a fire transitions through the development stages, radiation becomes the dominant form of energy transfer and greatly influences fire progression as it preheats and ignites additional fuels. The heat flux equation is based on a number of factors including the heat release rate, how efficiently the fuel radiates energy (radiation fraction) and the distance between the fuel and the target. The equation is stated as follows:

$$\dot{q}'' = \frac{X_r \dot{Q}}{4\pi c^2}$$

Where:

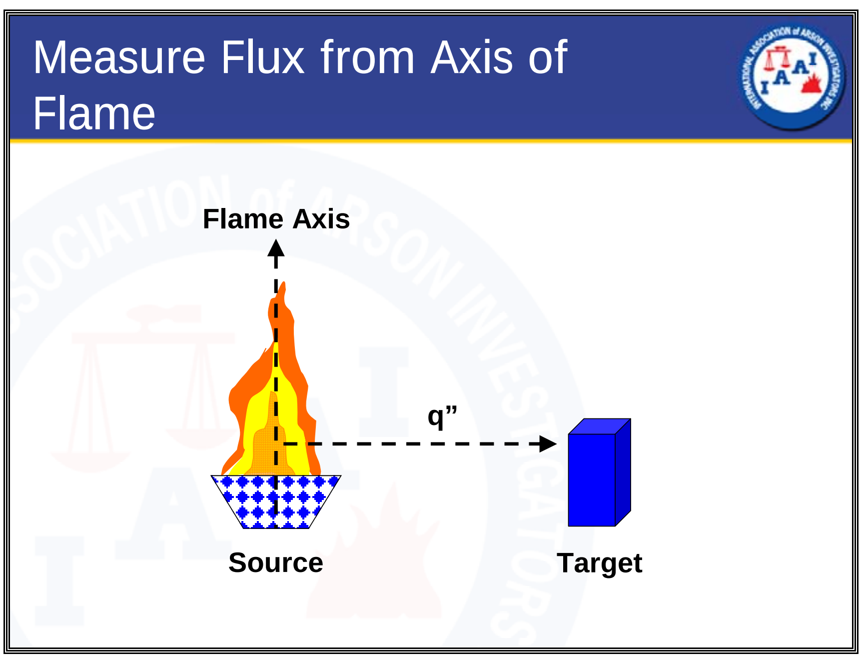
> $\dot{q}''$ = Heat Flux in kilowatts per meter squared (kW/m^2)
>
> X_r = Fraction (percentage of Combustion Energy lost by the flame as Radiation (Value generally acquired from reference material)
>
> $\dot{Q}$ = Rate of Heat Release measured in kilowatts. (usually estimated based on published reference material or calculated utilizing other formulas such as Heat Release Rate or Flame Height (in Heat Release Rate mode)
>
> c =distance between the axis of the flame and the target receiving the radiation in meters.

The Radiation Fraction (X_r) factor relates to how efficiently a given fuel radiates energy and is expressed as a fraction of energy radiated relative to the total energy released. It is not a constant for a given fuel but will vary between 0.15 for low soot fuels such as methane to 0.60 for high soot fuels such as polystyrene.[14] This value can generally be estimated based on values in published literature, and the CFI Calculator includes a drop down menu with the values of methane, wood, and gasoline being:

GAS=0.45 (Average Radiation Fraction for Gasoline)
WOOD=0.35 (Average Radiation Fraction for Wood)
METH=0.17 (Average Radiation Fraction for Methanol and methane)

It is advisable to run multiple iterations of the equation utilizing the range of values so a more accurate and useful estimation can be made. It should also be note that as the diameter of a fire increases the Radiation Fraction (X_r) decreases.

The equation is generally accurate when applied to a target that is more than two flame diameters from the axis of the flame. The potential for ignition caused by radiation for thermally thin materials increases at 10 kW/m^2 and above and at 20 kW/m^2 for thermally thick materials.[15] Floor-level heat flux at the onset of flashover is typically measured in excess of 20-25 kW/m^2 and this can typically be achieved when the upper smoke layer temperature reaches the 500°-600° Celsius range.[16]



A typical application of the formula to estimate the heat flux received by an object 1 meter away from the flame axis, utilizing a heat release rate of 500 kW, the radiation fraction of wood (0.35) would appear as follows:

$$\dot{q}'' = \frac{(0.35)(500\,kW)}{4\pi(1m)^2}$$

$$\dot{q}'' = \frac{175\,kW}{12.56\,m^2}$$

$$\dot{q}'' = 13.9\ kW/m^2$$

It is important to note that the heat flux formula follows the inverse square rule, meaning that the flux is inversely proportional to the square of the distance between the flame and the target. This means that doubling the distance between the flame and the target (for example from 1 meter to 2 meters) reduces the flux by 75%, not simply 50% that one might think. An example utilizing the 2-meter value would appear as follows:

$$\dot{q}'' = \frac{(0.35)(500\,kW)}{4\pi(2\,m)^2}$$

$$\dot{q}'' = \frac{175\,kW}{4\pi(4\,m^2)}$$

$$\dot{q}'' = \frac{175\,kW}{50.24m^2}$$

$$\dot{q}'' = 3.48\ kW/m^2$$

Comparing the results of the two calculations, it is observed that the value of 3.48 kW/m^2 measured at 2 meters away is approximately 75% of the value of 13.93 kW/m^2 measured at 1 meter away.

As indicated earlier, this equation can be rearranged algebraically to solve for heat release rate if the heat flux is known (or given if estimating what the heat release rate would need to be to yield a flux value at a given distance). The formula is rearranges as follows:

$$\dot{q}'' = \frac{X_r \dot{Q}}{4\pi c^2}$$

Multiply each side by $4\pi c^2$:

$$\left\{\dot{q}'' 4\pi c^2 = \left(\frac{X_r \dot{Q}}{4\pi c^2}\right) 4\pi c^2\right\} = \left\{\dot{q}'' 4\pi c^2 = X_r \dot{Q}\right\}$$

Divide each side by X_r:

$$\left\{\frac{\dot{q}'' 4\pi c^2}{X_r} = \frac{X_r \dot{Q}}{X_r}\right\} = \left\{\frac{\dot{q}'' 4\pi c^2}{X_r} = \dot{Q}\right\}$$

Utilizing the results of 13.93 kW/m^2, we obtained from calculating the heat flux 1 meter away from a wood fire with a radiation fraction of 0.35 a fire, we would estimate the heat release rate as follows:

$$\frac{(13.93kW/m^2)(4\pi(1m)^2)}{0.35} = \dot{Q}$$

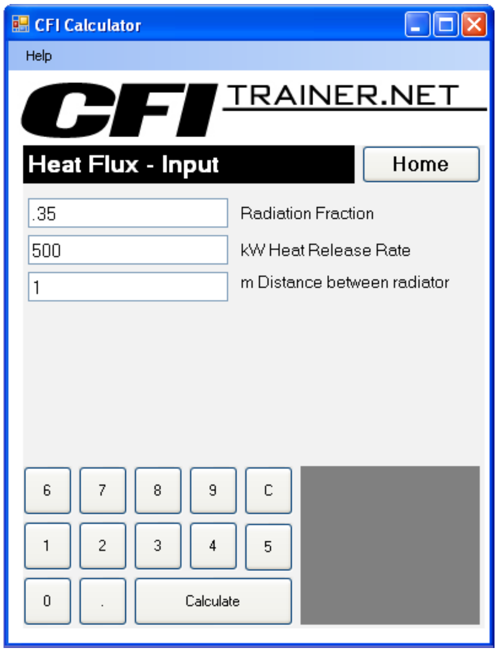
$$\frac{(13.93kW/m^2)(12.56\,m^2))}{0.35} = \dot{Q}$$

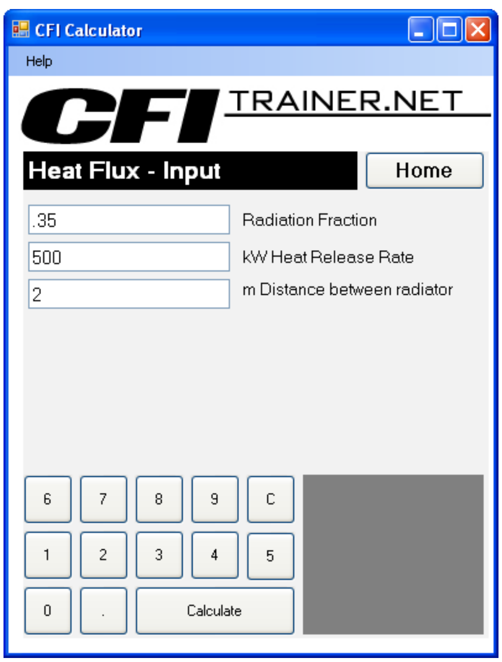
$$\frac{174.96\,kW}{0.35} = \dot{Q}$$

$$499.98\,kW = \dot{Q}$$

This value compares favorably to the heat release rate of 500 kW utilized in the original examples, with the minor differences attributed to rounding.

When utilizing the CFI Calculator tool, selecting the Heat Flux button from the initial user interface will open the input screen. From the input screen, the user can toggle to calculate heat flux based on heat release rate or heat release rate based on heat flux as we have previously discussed. Samples of the input screen with the values utilized in earlier examples and the output screen revealing the calculated results are demonstrated below.





The 2005 Fire Research Laboratory experiment can again, be utilized as an example of the practical application of the heat flux calculation. Recall that the experiment involved burning approximately 3.79 liters (1 gallon) of gasoline in a pan measuring approximately 0.55 meters (22 inches) in diameter and heat flux gauges were placed 0.50 meters and 1 meter from the axis of the pan. The pan was placed on a load cell to calculate the mass loss rate and additionally the burn was conducted under a cone calorimeter to allow for the measurement of the peak heat release rate and total heat release rate. The calculated heat release rate with the given parameters was 572 kW and the measured results from the two experiments were 326 kW and 491 kW respectively. Utilizing these figures in the heat flux equation, the heat flux would be calculated with the following results:

Heat Flux Calculations

Calculate the Heat Flux at .5 meter and 1 meter Given the Estimated Heat Release Rates based on Flame Height

Method	HRR	.5 meter	1 meter
McCaffrey	252	36	9
NFPA	358	50	12
Heskestad	351	51	12
Actual (calc 1)	326	46	11
Actual (calc 2)	491	78	19.5
Actual (Exp 1)	326	27	9.7
Actual (Exp 2)	491	29.2	11.5

From the above results, it is observed that the 1-meter values are consistent and compare favorably to the actual measured values. The 0.50 results do not show as much accuracy and this can be attributed to the fact that the calculated results and measured results are less than a flame diameter away from the flame axis. The equation can be effectively utilized with the values derived from other equations, such as Heat Release

Rate or Flame Height (Heat Release Rate Option). Used within its limits, the equation can be utilized effectively to assist in fire progression and analyzing witness statements.

TIME TO IGNITION:

The Time to Ignition formula has a close inter-relationship to the heat flux values. The Time to Ignition formula[17] is useful in analyzing fire progression and determining how long a secondary fuel would take to ignite (progress from one fuel to another). There is a differentiation between calculating ignition times of thin fuels (thermally thin) and thick fuels (thermally thick). The calculator only utilizes the methodology for calculating ignition of thermally thick fuels and this will be the only process discussed. The formula utilizes certain properties of the fuel including the ignition temperature and the thermal inertia ($k\rho c$), as well as the heat flux being applied to the fuels and the ambient temperature in the environment. The thermal inertia is defined as "a thermal property responsible for temperature rise."[18] More simply, thermal inertia is a property related to how easy or difficult a fuel it is to get a fuel involved in the fire process. Fuels with low thermal inertia are more readily ignited, while fuels with high thermal inertia are more difficult to ignite. The formula is expressed at follows:

$$t_{ig} = \frac{\pi}{4}\kappa\rho c\left[\frac{T_{ig}-T_s}{\dot{q}''}\right]^2$$

Where:

t_{ig} = Time to ignition in seconds

$k\rho c$ = Thermal inertia of fuel (typically obtained from appropriate reference material) measured in $\frac{(kW/m^2K)^2}{s}$ (where k = thermal conductivity, ρ = density and c = specific heat capacity)

T_{ig} = Auto Ignition temperature of fuel item in degrees Celsius (typically obtained from appropriate reference material)
T_s = Ambient temperature of compartment in degrees Celsius

$\dot{q}''$ = Heat flux being applied to fuel in kW/m^2 (can be estimated or calculated using other methods as heat flux formula)

Utilizing the reference values for ¾-inch plywood (19mm) of a thermal inertia 0.54 and an ignition temperature of 390° Celsius, along with a measured ambient temperature of 29° Celsius and heat flux of 20 kW/m^2, the equation would be worked as follows:

$$t_{ig} = \frac{\pi}{4}(0.54\frac{(kW/m^2K)^2}{s})\left[\frac{390\,s - 29\,s}{20\,kW/m^2}\right]^2$$

$$t_{ig} = (.785)(0.54\frac{(kW/m^2\,K)^2}{s})\left[\frac{361\,s}{20\,kW/m^2}\right]^2$$

$$t_{ig} = (0.42\frac{(kW/m^2K)^2}{s})\left[18\frac{s}{kW/m^2}\right]^2$$

$$t_{ig} = (0.42\frac{(kW/m^2K)^2}{s})\left[324\frac{s}{kW/m^2}\right]$$

$$t_{ig} = 136 \quad s$$

For comparison purposes, the charts below illustrate the anticipated results of this formula and compares two fuels having similar ignition temperatures but different thermal inertia values. Included in this example are 3/4 inch (19mm) plywood which has an ignition temperature of 390° Celsius and a thermal inertia of 0.54 $\frac{(kW/m^2K)^2}{s}$ and 1 inch (25mm) flexible foam, which also has an ignition temperature of 390° Celsius and a thermal inertia of 0.32 $\frac{(kW/m^2K)^2}{s}$. This example utilizes a heat flux value of 20 kW/m^2 and an ambient temperature of 29° Celsius.

Estimate of the Time to Ignite a Thermally Thick Solid Exposed to a Constant Heat Flux		
Input Parameters – Plywood ¾ inch (19 mm)		
Thermal Inertia of Material ($k\rho c$)	**0.54**	(kW/m^2-K)2/s
Ignition Temperature (T_{ig})	**390**	C
Ambient Temperature (Ts)	**29**	C
Exposure Heat Flux (q")	**20**	kW/m2
Calculated Parameters		
Ignition Time (tig)	**138**	S

Estimate of the Time to Ignite a Thermally Thick Solid Exposed to a Constant Heat Flux		
Input Parameters – Rigid Foam 1 inch (25.4mm)		
Thermal Inertia of Material ($k\rho c$)	**0.32**	(kW/m2-K)2/s
Ignition Temperature (Tig)	**390**	C
Ambient Temperature (To)	**29**	C
Exposure Heat Flux (q")	**20**	kW/m2
Calculated Parameters		
Ignition Time (tig)	**82**	S

The results indicated for the plywood (138 s) compare favorably with the calculated results (136 s) the Excel sheet indicates, with the minor difference attributed to rounding. The 52 s difference between the plywood (138 s) and the rigid foam (86 s) helps illustrate the effect of thermal inertia. An additional factor that needs to be considered is that this formula is only effective when the heat flux value utilized is at or above the published critical heat flux value. This is the minimum flux, determined experimentally, that must be present for the given fuel to ignite.

When utilizing the CFI Calculator tool, selecting the Time to Ignition button from the initial user interface will open the input screen. Samples of the input screen utilizing the values for Acrylic Carpet with an ignition temperature of 300° Celsius and a thermal inertia of $0.24\frac{(kW/m^2K)^2}{s}$ and an ambient temperature of 20° Celsius, and a heat flux of 15 kW/m^2 the output screens would appear as below:

The user can also utilize the stored values for ignition temperature and thermal inertia by toggling the Materials Drop Down radio button. The user input screen would allow the drop down menu to appear in lieu of these fields and the user can scroll and select the appropriate material. The help file also includes published critical heat flux values (10 kW/m^2 value for the Acrylic Carpet utilized in the above example) for the materials contained in the drop down menu and can be utilized as a reference tool. The drop down menu would appear as follows:

While there are other variations of the Time to Ignition calculations, including an alternative formula for thin fuels and an alternative variable that account for heat loss by the target fuel[19], this calculation and the CFI Calculator tool can appropriately be utilized to give a reasonable estimation for use by the field investigator.

FLASHOVER:

Flashover is the transition phase of the fire development process in which all available fuels in a compartment become involved in the fire process. It is defined as " a dramatic event in a room fire that rapidly leads to full room involvement and an event that can occur at a smoke temperature of 500° - 600° Celsius."[20] The flashover process is a transition phase and series of events and is not one specific moment in time. There are three primary equations utilized for calculating the energy release rate required for flashover (including the Thomas method, the Babrauskas method and the McCaffery, Quintiere, Harkleroad method) and all three are included in the CFI Calculator tool. While each includes slightly different variables, the process is influenced by the available ventilation and each equation includes a ventilation factor based on the area of the openings and the height of the openings ($A_0\sqrt{H_0}$). Methods for calculating or factoring multiple openings will be discussed later in this paper.

The first equation to be discussed is the McCaffery, Quintiere, Harkleroad (MQH) method[21] which is expressed as:

$$\dot{Q}_{fo} = 610(h_k A_t A_o \sqrt{H_o})^{1/2}$$

Or

$$\dot{Q}_{fo} = 610\sqrt{h_k A_t A_o \sqrt{H_o}}$$

Where:

Q_{fo} = Energy Release Rate necessary to achieve flashover in kilowatts

h_k = Wall conductivity factor divided by wall thickness (in meters) expressed in kW/m^2K. Although these values change with time of fire, typical conductivity factors are referenced as:[22]

Drywall = 0.00048
Brick = 0.00069
Wood = 0.00018
Concrete = 0.0011

A_t = Total area of boundary surfaces less ventilation openings in m^2 (typically (2 *((L x W) + (L x H) + (W x H)) – (Vent Width x Vent Height)) but should include all compartment surfaces)

A_o = Total area of ventilation opening(s) in m^2 (Vent Width x Vent Height)

H_o = Height of the opening in meters

The MQH equation is based on an approximation or estimation that an upper layer temperature change of 500° Celsius is a criterion for the transition to flashover.[23] An example of this equation being utilized to calculate the energy required to cause a compartment lined by 0.012 meter sheetrock/drywall (equivalent of ½ inch) measuring 3 meters long by 4 meters wide by 2.4 meters wide with a door opening measuring 0.91 meters wide by 1.98 meters from the floor to reach flashover is as follows:

$$\dot{Q}_{fo} = 610((0.00048/0.012)(55.8)(1.8)(\sqrt{1.98}))^{1/2}$$

$$\dot{Q}_{fo} = 610((4.02)(1.41))^{1/2}$$

$$\dot{Q}_{fo} = 610(5.67)^{1/2}$$

$$\dot{Q}_{fo} = 610\,(2.38)$$

$$\dot{Q}_{fo} = 1452\, kW$$

A second commonly utilized flashover correlation was developed by Thomas[24,25] and is expressed as follows:

$$\dot{Q}_{fo} = 7.8 A_t + 378 A_o \sqrt{H_o}$$

Where:

Q_{fo} = Energy Release Rate necessary to achieve flashover in kilowatts

A_t = Total area of boundary surfaces less ventilation openings in m^2 (typically (2 *((L x W) + (L x H) + (W x H)) – (Vent Width x Vent Height)) but should include area of all compartment surfaces)

A_o = Total area of ventilation opening(s) in m^2 (Vent Width x Vent Height)

H_o = Height of the opening in meters

Utilizing the same input variables utilized in the MQH example above (compartment measuring 3 meters long by 4 meters wide by 2.4 meters wide with a door opening measuring 0.91 meters wide by 1.98 meters from the floor) we would calculate energy required for flashover as follows:

$$\dot{Q}_{fo} = 7.8(55.8) + 378\,(1.8)\sqrt{1.98}$$

$$\dot{Q}_{fo} = (435.24) + (680.4)(1.41)$$

$$\dot{Q}_{fo} = (435.24) + (959.36)$$

$$\dot{Q}_{fo} = 1395\,kW$$

The third method utilized in the CFI Calculator to calculate the heat release rate necessary to cause flashover was developed by Babrauskas.[26,27] Unlike the other correlations that include room dimensions; this formula relies on the ventilation factor as its primary input variable. The equation is expressed as follows:

$$\dot{Q}_{fo} = 750\,A_o\sqrt{H_o}$$

Where:

A_o = Total area of ventilation opening(s) in m^2 (Vent Width x Vent Height)

H_o = Height of the opening in meters

Utilizing the same input variables utilized in the MQH and Thomas examples above (compartment measuring 3 meters long by 4 meters wide by 2.4 meters wide with a door opening measuring 0.91 meters wide by 1.98 meters from the floor) we would calculate energy required for flashover as follows:

$$\dot{Q}_{fo} = 750(1.80)\sqrt{1.98}$$

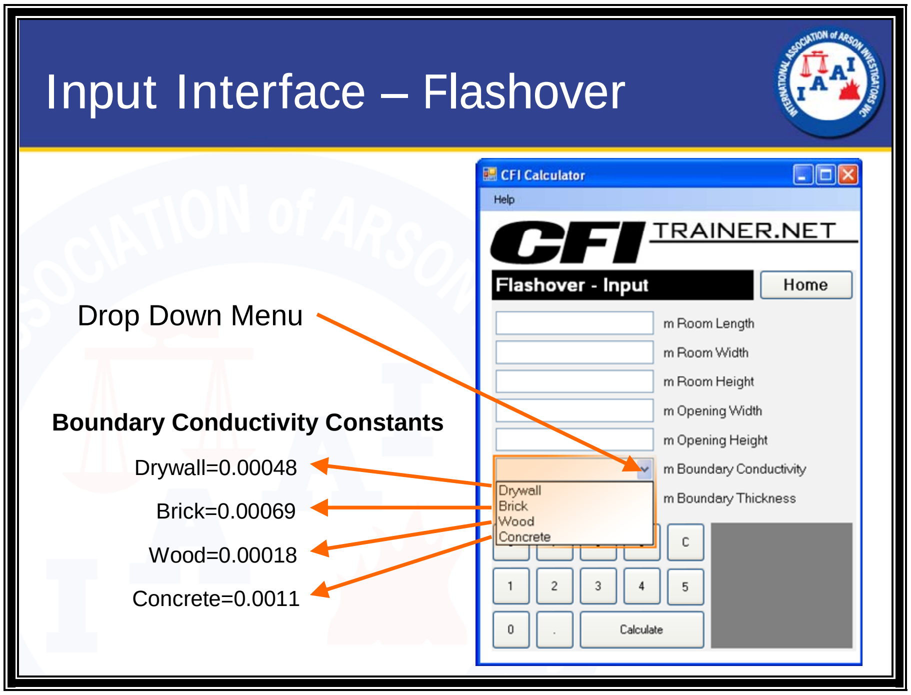
$$\dot{Q}_{fo} = 750(1.80)(1.41)$$

$$\dot{Q}_{fo} = 750(2.54)$$

$$\dot{Q}_{fo} = 1905kW$$

When utilizing the CFI Calculator, all three formulas can be calculated from the data entered on the input interface. The Thomas and Babrauskas methods require input of the room dimensions and ventilation dimensions (even though the Babrauskas method does not technically factor in the room dimensions) and the MQH method requires the additional entry of the boundary conductivity factor and the boundary thickness variables (which account for heat loss to the boundary surfaces.) Samples of the input screen with the values utilized in the earlier examples and the output screen revealing the calculated results are demonstrated below:

The results calculated utilizing the CFI Calculator compare favorably to the results from the above examples, with minor differences attributed to rounding. As in other calculations contained in CFI Calculator tool, the Flashover Calculation includes a built in drop down menu for the Boundary Conductivity variable. An example of the menu with the associated values appears below.



An additional check with the Excel spreadsheet tool yields the results listed below, which again compare favorably to the previous examples.

Estimates of HRR Needed to Reach Flashover (F/O)		
Input Parameters		
Room Length (L)	**3**	m
Room Width (W)	**4**	m
Room Height (H)	**2.4**	m
Opening Width (Wo)	**0.91**	m
Opening Height (Ho)	**1.98**	m
Boundary Conductivity (k)	**0.00048**	kW/m^2-k
Boundary Thickness (d)	**0.012**	m
Calculated Parameters		
Boundary Surface Area (At)	**55.80**	m^2
Ventilation Factor	**2.54**	$m^{5/2}$
Area of Opening	**1.80**	m^2
Babrauskas F/O Prediction	**1902**	kW
MQH F/O Prediction	**1451**	kW
Thomas F/O Prediction	**1394**	kW

While the calculator tool is not designed to factor in abnormal geometries such as irregular shaped rooms, irregular shaped ceilings or multiple ventilation openings, the equations themselves can be utilized to analyze these types of problems. For example, given the room dimensions previous examples (width of 3 meters, length of 4 meters, wall height of 2.4 meters, 0.91 opening width, 1.98 opening height) but changing to a cathedral ceiling with a peak height of 4.24 meters, we could calculate the estimated heat release rate for flashover by utilizing the sum of all planes less the ventilation opening as the A_t factor. To do so, we would have to calculate the area of all seven planes including: two equal square wall planes along the length (A and C), two equal gable end wall planes along the width (B and D), two equal ceiling planes (E and F) and one floor plane (G). In this example, the area of each plane would be as follows:

Plane A = 7.2 m^2 (3m x 2.4m)

Plane B = 12.06 m^2 (4m x 2.4m) + (area of gable triangle = 2.46 m)

Plane C = 7.2 m^2 (3m x 2.4m)

Plane D = 12.06 m^2 (4m x 2.4m) + (area of gable triangle = 2.46 m)

Plane E = 7.02 m^2 (3m x 2.34m)

Plane F = 7.02 m^2 (3m x 2.34m)

Plane G = 12 m^2 (3m x 4m)

For purposes of calculating the area of the various planes, the additional area created by the gable ends was measured by finding the area of the gable “triangle” utilizing (A = ½ B * H) and adding it to the area calculated by multiplying the height of plane A or C by the Width of Plane B or D. Additionally the distance from the top of plane A or C to the peak of the ceiling was determined by calculating the hypotenuse of a triangle utilizing the formula $C = \sqrt{A^2 + B^2}$ (Where C = the unknown distance). Utilizing 1.23m as distance A (increase height along gable wall above height of plane A or C) and 2m as distance B (1/2 of length of plane B or D), distance C is calculated to be 2.34 m. The sum of the areas of all planes results in a total surface area calculation of 64.56 meters. This figure can then be utilized in the Thomas equation as follows:

$$\dot{Q}_{fo} = 7.8\,(63.48) + 378\,(1.8)\sqrt{1.98}$$

$$\dot{Q}_{fo} = 495.14 + (680.4)(1.41)$$

$$\dot{Q}_{fo} = 495.14 + 959.36$$

$$\dot{Q}_{fo} = 1460\ kW$$

Utilizing the properties of ½ inch sheetrock/drywall (thickness of 0.012 m, conductivity of 0.00048), the estimated Heat Release Rate required for flashover utilizing the MQH method can be calculated as follows:

$$\dot{Q}_{fo} = 610((0.04)(63.48)(1.8)(\sqrt{1.98}))^{1/2}$$

$$\dot{Q}_{fo} = 610\,(6.44)^{1/2}$$

$$\dot{Q}_{fo} = 610\,(2.54)$$

$$\dot{Q}_{fo} = 1550\ kW$$

As illustrated, calculating the irregular ceiling resulted in an increased estimated Heat Release Rate required for flashover in both the Thomas and MQH methods. The Babrauskas method was not illustrated, as it is primarily dependant on the ventilation openings and not influenced by room geometry.

Similar methodologies can be utilized for determining a weighted value for ventilation openings.[28] Utilizing the dimensions from our standard compartment discussed in a number of exercises above (length 3 m, width 4 m, height 2.4 m, opening width 0.91 m, opening height 1.98 m) and adding additional ventilation openings including another door with a width of 0.91 and a height of 1.98 and a window with a width of 1 m and a height of 1 m. In this example, the weighted area of the openings would be found by adding (0.91 x 1.98) + (0.91 x 1.98) + (1 x 1) resulting in an A_o factor of $4.60m^2$. The weighted H_o factor can be calculated by adding the area of the opening x, the height of the opening for the three vents and dividing the total by the A_o factor. In this example Ho = ((1.80 x 1.98) + (1.80 x 1.98) + (1 x 1))/4.40 or 1.84 m.

In this example a slightly different definition of A_t is utilized in which the area of the openings is not removed from the enclosures total surface area.[29] This factor can now be utilized in the various formulas in place of the standard ventilation factor. An example of this procedure for each equation (Thomas, MQH and Babrauskas) is as follows:

Thomas:

$$\dot{Q}_{fo} = 7.8(64.56) + 378\,(4.40)(\sqrt{1.84})$$

$$\dot{Q}_{fo} = 7.8(64.56) + 378\,(5.98)$$

$$\dot{Q}_{fo} = 503.57 + 2260.44$$

$$\dot{Q}_{fo} = 2760\ kW$$

MQH:

$$\dot{Q}_{fo} = 610((0.04)(64.56)(4.40)(\sqrt{1.84}))^{1/2}$$

$$\dot{Q}_{fo} = 610(15.45)^{1/2}$$

$$\dot{Q}_{fo} = 610(3.93)$$

$$\dot{Q}_{fo} = 2400\ kW$$

Babrauskas:

$$\dot{Q}_{fo} = 750\ (4.40\sqrt{1.84)}$$

$$\dot{Q}_{fo} = 750\ (5.98)$$

$$\dot{Q}_{fo} = 4490\ kW$$

As illustrated, increased ventilation openings result in an increase in the amount of energy estimated to reach flashover. Caution must be utilized when using this approach as the location of the vent is not necessarily factored into the calculations.

FIRE GROWTH:

The Fire Growth calculation[30] is utilized to estimate how long it will take a fire to progress to a given heat release rate based on certain fuel properties. It is useful in analyzing fire development and estimating a timeline of events, and is useful when utilized with other formulas such as Flashover, Flame Height or Heat Release Rate. The calculator is designed to allow the user to determine how much energy a fire would produce at a given time based on the various growth factors (solve for heat release rate), and conversely, an estimate of how long it would take a fire to reach a given heat release rate based on the various growth factors (solve for time). This calculation is based on the estimate or assumption that growth is in proportion to time squared (t^2) and is based on flame spread velocity[31]. If the growth rate is dependent on the fire itself, than the fire would be classified as an exponential and would require a different calculation.[32] The formula for estimating fire growth is expressed as follows:

$$\dot{Q} = \alpha t^2$$

Where:

$\dot{Q}$ = Heat Release Rate or Energy Release Rate in kilowatts

α = Growth Factor or Growth Variable where Slow = 0.00293, Moderate = 0.01172, Fast = 0.0469, and Ultra Fast = 0.1876 (0.400- Mowrer Rate)

t = Time in seconds

Note: This equation is only valid to $\dot{Q}_{max}$

Utilizing a moderate fire growth rate of 0.01177 and a time of 60 seconds we would calculate as follows:

$$\dot{Q} = (0.01172)(60)^2$$

$$\dot{Q} = (0.01172)(3600)$$

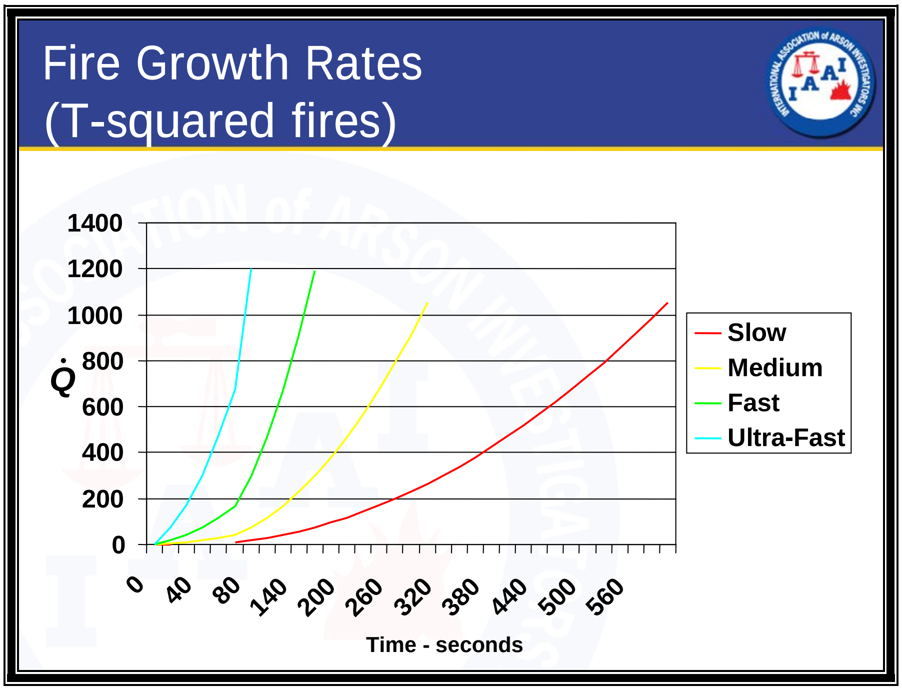
$$\dot{Q} = 42.19\ kW$$

When utilizing the calculator to solve for Heat Release Rate based on a given time, the input screen and output screen would appear as follows:

When solving for Heat Release rate, the user does not have to select a specific growth variable, as the calculator will provide estimated Heat Release rates for all of the growth rates. When comparing the results from the equation and the calculator with results from the excel spreadsheet, the outputs compare favorably.

Estimates of HRR In T squared Fire		
Input Parameters		
Time	**60**	s
Calculated Parameters		
HRR (Slow)	**10.55**	kW
HRR (Moderate)	**42.19**	kW
HRR (Fast)	**168.84**	kW
HRR (Ultra Fast)	**675.36**	kW
HRR (Mowrer Ultra Fast)	**1440**	kW

Growth rates have been determined or estimated based on the properties of the fuel and are generally classified into the growth factors identified above. The following chart helps illustrate the standard growth curves for the various classifications.



While fuels generally can be classified broadly into one of the growth areas, the fuel configuration may have some effect on the growth curve. For example, the fire growth in a mattress arranged horizontally might be somewhat slower than a similar mattress arranged in a vertical configuration. When utilizing this calculation it is best to run multiple iterations utilizing a combination of growth factors. This will allow you to bracket the problem and come to some reasonable conclusions regarding the fire growth.

The second method of utilizing this equation involves solving for time based on a known or estimated heat release rate. To do this, the equation can be rearranged algebraically to solve for time instead of heat release rate. This would be done as follows:

$$\dot{Q} = \alpha t^2$$

Divide each side by α:

$$\left\{ \dot{Q}/\alpha = \alpha t^2/\alpha \right\} = \left\{ \dot{Q}/\alpha = t^2 \right\}$$

Find the Square Root of each side:

$$\left\{ \sqrt{\dot{Q}/\alpha} = \sqrt{t^2} \right\} = \left\{ \sqrt{\dot{Q}/\alpha} = t \right\}$$

Or

$$t = \sqrt{\dot{Q}/\alpha}$$

Utilizing a heat release rate of 1395 kW and a moderate growth rate of 0.01172 the results would be calculated as follows:

$$t = \sqrt{1395 / 0.01172}$$

$$t = \sqrt{119027}$$

$$t = 345 \quad s$$

By utilizing the Solve for Time radio button contained within this equation and utilizing the same variables outlined above (1395 heat release rate, moderate growth rate value (0.01172) selected from the drop down menu within the calculator), the input and output screens would appear as follows:

These results are consistent with the calculated results obtained utilizing the long hand method and the results can be recalculated utilizing a number of growth rates to provide a range for use in analyzing the fire scene.

SPRINKLER ACTIVATION:

The Sprinkler Activation equation[33] contained within the CFI Calculator is intended to estimate how long it would take a given sprinkler device to respond to a fire of given parameters. The equation is expressed as follows:

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

Where:

$t_{activation}$ = Time for Sprinkler to Activate in Seconds

RTI = Response Time Index (A property of a specific device identified by the manufacturer in comparison to established parameters)

U_{jet} = Velocity of the Ceiling Jet in Meters per Second (Calculated)

ln = logarithmic number

T_{jet} = Temperature of the Ceiling Jet in Degrees Celsius (Calculated)

$T_{ambient}$ = Ambient Temperature in Degrees Celsius

$T_{activation}$ = Sprinkler Activation Temperature in Degrees Celsius

The Response Time Index and the Sprinkler Activation Temperature vary among the different sprinkler types and sprinkler manufactures but specific data should be available on the specific device, or published and available for a specific device.

In general, sprinklers fall into the following RTI categories:

Standard Response Bulb=235
Standard Response Link=130
Quick Response Bulb=42
Quick Response link=34

Sprinklers can generally be categorized in the following Sprinkler Activation Temperature categories:

Ordinary = 74 (range 57-77)
Intermediate = 100 (range 80-107)
High = 135 (range 121-149)
Extra High = 172 (range 162-190)
Very Extra High = 232 (range 204-246)
Ultra High = 288 (range 260-301)

As indicated above the Ceiling Jet Velocity[34] (U_{jet}) is calculated for inclusion in the Sprinkler Activation Equations. There are two different calculations for determining ceiling jet velocity and the radial distance between the detector and the centerline of the plume divided by the height of the detector above the fire (r/H) determine which equation is utilized. The equations are as follows:

$$U_{jet} = 0.96\,(\dot{Q}_c)^{2/3} / H^{5/3} \quad if\ r/H \le 0.15$$

And

$$U_{jet} = (0.195\,\dot{Q}^{1/3} H^{1/2}) / r^{5/6} \quad if\ r/H \ge 0.15$$

Where:

U_{jet} = Ceiling Jet Velocity in Meters per Second

$\dot{Q}$ = Heat Release Rate in Kilowatts

H = Height of Sprinkler Above Fire in Meters

R = Radial Distance Between Centerline of Fire and Sprinkler in Meters.

The ceiling jet temperature[35] (T_{jet}) is also calculated based on the radial distance between the detector and the centerline of the plume divided by the height of the detector above the fire (r/H). To calculate ceiling temperature the following equations are utilized:

$$T_{jet} = 16.9(\dot{Q}_c)^{2/3} / H^{5/3} + T_{ambient} \quad if\ r/H \leq 0.18$$

And

$$T_{jet} = 5.38(\dot{Q}_c / r)^{2/3} / H + T_{ambient} \quad if\ r/H \geq 0.18$$

Where:

T_{jet} = Temperature of the Ceiling Jet in Degrees Celsius

$\dot{Q}_c$ = Convective Portion of Heat Release Rate in Kilowatts (Determined by utilizing the equation $\dot{Q}_c = X_c \dot{Q}$, where X_c is the convective heat release fraction with an assigned value of 0.70[36])

r = Radial Distance Between Plume Centerline and Sprinkler Head

H = Height of Sprinkler Above Fuel Package

$T_{ambient}$ = Ambient Air Temperature in Degrees Celsius.

Given an example of a sprinkler head located on the ceiling of a compartment located approximately 1.0 meters from the centerline of the fire plume and located approximately 2.0 meters above a burning fuel and a fire burning with a heat release rate of 700 kW, the first step in solving the Sprinkler Response Equation would be to divide radius r (1.0 m) by the height H (2.0m). The dividend of 1.0/2.0 = 0.50 identifies which equation to utilize for calculating the ceiling jet velocity and the ceiling jet temperature.

Since $0.50 \geq 0.15$, the ceiling jet velocity would be calculated as follows:

$$U_{jet} = (0.195\,(700)^{1/3}(2.0)^{1/2})/(1.0)^{5/6}$$

$$U_{jet} = (0.195\,(8.9)(1.41))/(1.0)$$

$$U_{jet} = 2.45/1.0$$

$$U_{jet} = 2.45\,m/s$$

The ceiling jet temperature would be calculated utilizing the formula indicated by $0.50 \geq 0.18$. To utilize this equation, the value for $\dot{Q}_c$ by utilizing the following formula:

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

Where:

$\dot{Q}_c$ = Convective Portion Heat Release Rate in Kilowatts

X_c = Convective Heat Release Fraction (0.70 utilized in the CFI Calculator based on reference material[37])

$\dot{Q}$ =Heat Release Rate in Kilowatts

In this example $\dot{Q}_c = (0.70)(700)$ or 490 kW. This adjustment is made as most existing formulas calculate sprinkler response based purely on the convective portion of heat being released.[38]

Utilizing the above information, and given an ambient compartment temperature of 20 degrees Celsius, the ceiling Jet temperature is calculated as follows:

$$T_{jet} = 5.38(490/1)^{2/3}/2 + 20$$

$$T_{jet} = 5.38(62.2)/2 + 20$$

$$T_{jet} = 5.38\,(31.07) + 20$$

$$T_{jet} = 167.19 + 20$$

$$T_{jet} = 187.19\ kW$$

With the calculated ceiling jet velocity and ceiling jet temperature and the given ambient temperature of 20 degrees Celsius, the estimated sprinkler response of a device with an RTI of 42 (quick response bulb) and an activation temperature of 100 degrees Celsius (intermediate range), the equation would be calculated as follows:

$$t_{activation} = (42/\sqrt{2.45})\,(\ln(187.19 - 20/187.19 - 100))$$

$$t_{activation} = (42/1.57)\,(\ln(167.19/87.19))$$

$$t_{activation} = (26.75)\,(\ln(1.91))$$

$$t_{activation} = (26.75)\,(.65)$$

$$t_{activation} = 17.06\ \sec onds$$

When utilizing the above data to calculate Sprinkler Activation within the CFI Calculator, the input and output would appear as follows:

As is illustrated above, the ceiling jet temperature and the ceiling jet velocity are calculated based on the input given and the calculated results are utilized to solve for the time to activation. The results compare fairly well to the results previously obtained, with the minor differences attributed rounding and other minor deviations in the calculation methods. If the calculated results for time to activation are less than zero, a warning will appear indicating that the sprinkler will not activate. This warning appears as follows:

The Sprinkler Activation calculation also includes two drop down menus for RTI and activation temperature. These menus utilize the published references above and can be toggled on and off by utilizing the radio buttons. The user input screen with drop down menus would appear as follows:

While it is best to utilize this calculation with the specific information on the sprinkler device in question, estimated results can be obtained utilizing the drop down menus and the input data contained within the program. As with the other calculations contained in the CFI Calculator, it is advisable to run multiple iterations of the Sprinkler Activation calculation to derive results that define a reasonable analysis of what might have occurred and allow you to "bind" the problem.

END NOTES:

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[4] Ibid, (108)

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[8] Quintiere, *Principals of Fire Behavior*, (138)

[9] Icove, *Forensic Fire Scene Reconstruction*, (82)

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[12] Quintiere, *Principles of Fire Behavior*, (58)

[13] Ibid, (252)

[14] Ibid, (58)

[15] Ibid, (61)

[16] Ibid, (61)

[17] Ibid, (87)

[18] Ibid, (254)

[19] Ibid, (69-72)

[20] Ibid, (252)

[21] Icove, *Forensic Fire Scene Reconstruction*, (63)

[22] Quintiere, *Principles of Fire Behavior,* (51)

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[24] Icove, *Forensic Fire Scene Reconstruction*, (62)

[25] NFPA 921 (2004), (27)

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[27] NFPA 921 (2004), (27)

[28] Karlsson, *Enclosure Fire Dynamics*, (129)

[29] Ibid, (128)

[30] Quintiere, *Principles of Fire Behavior,* (123)

[31] Ibid, (122)

[32] Ibid, (122)

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[34] Hurley, Morgan J. and Quiter, J.R. (2003), "Simplified Fire Hazard Calculations," *NFPA Fire Protection Handbook 19th Edition*: 3-155

[35] Ibid, (3-155)

[36] *Fire Dynamics Tools (FDT) Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program*, NUREG-1805, Volume 1 (2003), available at: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/final-report/10_Detector_Activation_Time.xls, accessed December 19, 2007

[37] Ibid

[38] Budnick, "Simplified Fire Growth Calculations," (3-141)