FIELD APPLICATION OF FIRE DYNAMICS EQUATIONS:

The use of Scientific Calculators in Fire Scene Evaluations

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INTRODUCTION:

Since the inception of the ATF Certified Fire Investigation program, an emphasis has been placed on understanding the science of fire behavior and learning how to apply these concepts to field fire scene investigations. These efforts have included incorporating instruction and coursework on fire dynamics equations into our candidate training and re-certification programs and fostering working relationships with recognized experts in this field. These efforts have helped to further the development of our certified fire investigator program and have improved the investigator's ability to effectively utilize these concepts during field fire scene investigations. These relationships have also served to "bridge the gap" between the science and its field application and have resulted in recognized experts having a better working knowledge of how investigators utilize these fire dynamics theories and how the equations can be practically utilized outside of a laboratory environment. This paper will attempt to expand on this subject and clarify certain aspects that will allow for an increased understanding of the field application of fire dynamics equations.

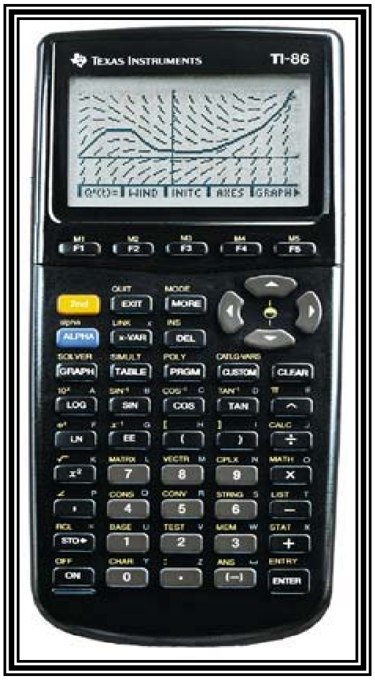
SCIENTIFIC CALCULATORS:

A valuable tool in the field application of fire dynamics equations is a programmable scientific calculator. This allows for the storage of equations and provides the ability to solve for any one of the variables in the equation. It is portable, easily maintained and provides the ability to conduct quick analysis in the field. The use of this tool has been common in the ATF CFI program for many years. The current calculator of choice is the Texas Instruments TI-86. This model is a slight upgrade from the TI-85 that was used earlier in the program. It is important to recognize that some of the formulas originally written for the TI-85 do not function properly when transferred or programmed into the TI-86, so minor variations in language may be present in this paper when compared to previous papers on this topic. Since the TI-86 is the calculator utilized by ATF CFIs, all formulas and programming issues discussed will be directly related to this model. This paper does not suggest that other programmable scientific calculators can not effectively serve the same purpose; it merely indicates that the formulae have not been tested in any other product.

BASIC OPERATION:

Before going into the programming of fire dynamics equations and discussion of the practical applications in field investigations, some basic operating features will be discussed. This will not cover every feature of the calculator, but will provide a short course on how the calculator operates. Other features and procedures can be researched in the user guide that accompanies the calculator. Most of the calculator's buttons have three functions including their base function (white), an alpha function (blue) and a secondary function (yellow). When utilizing the calculator, it is important to be familiar with how to access the auxiliary functions and their correct use. When programming the fire science equations, the factors (or variables) have been converted to text names. Accordingly, the "ALPHA" key is used to access letters A-Z enabling the input of text. Pressing the "ALPHA" key twice will lock the keyboard in the alpha mode and display upper case letters. Pressing the "2nd" key

Figure 1 - TI-86 Scientific Calculator



and then the “ALPHA” key accesses lowercase letters. Again, the keyboard can be locked in the lowercase mode by pressing the “2nd” key and the “ALPHA” key twice. The same exact name for a variable cannot be used in more than one equation, however since the variable meaning is case-specific utilizing upper and lower case letters allows for the same word to be utilized in different formulas. For example “QDOT”, “Qdot”, and “qdot” could all be used in separate equations and would have different meanings to the calculator. Multiple uses of the same letter combination in various formulas should probably be avoided to minimize the chance of confusion later.

Another feature that will be used commonly is the “2nd” key in combination with another key. For example, when entering a formula or solving a problem with the calculator, pressing the “2nd” key followed by the “π” key would access the “Pi”operation. You will note later when reviewing the formulas that some mathematical operations “Square Root” are usually typed out in text due to the limitations of the word processors utilized to prepare this document. When you see these mathematical functions typed out it indicates that you should enter the actual function into the equation on the calculator, not type out the word. The “2nd” key will be used with other keys such as “SOLVER”, “CONV”, and “CONST”, as well as others but these will be discussed later. Obviously pressing the “ON” key turns the calculator on and conversely, the unit is turned off by pressing the “2nd” key followed by the “OFF” key (secondary function of the “ON” key). When doing simple math problems outside of the equation feature, the “ENTER” key is utilized as the “=” or solve function. Another key that will be useful is the “CLEAR” key. This will clear the screen when you are outside of the equation solver and will clear fields when you are using the solver feature. “EXIT” will be utilized to end a secondary function, such as the equation solver (SOLVER) function and the conversion (CONV) function, and will return you to the base screen.

One final operation that may be useful is the contrast adjustment feature. This is used to adjust the screen's image, making it lighter or darker. It is accessed by pressing the "2nd" key, followed by pressing and holding the up cursor or down cursor until the desired level is reached. If you cannot see the values on the screen after turning on the calculator, adjusting the contrast may solve the problem. The TI manual indicates that once you have had to set the contrast to level "7" it is an indication that the batteries need to be replaced/recharged.

CONVERSION FUNCTION:

The conversion function (CONV) is used to change a value in one unit to an equivalent value in another unit. The conversion function of the TI-86 can be used inside or outside of an equation. Since most of the fire dynamics equations require entry in SI units (such as Celsius or meters), this feature will be utilized often. Pressing the "2nd" key followed by the "CONV" key accesses the conversion function. Typically you will enter the value you want converted followed by the "2nd" "CONV" keys. A menu will appear at the bottom of the screen that will allow the conversion of length, area, volume, time, temperature, mass force pressure, energy, power or speed. Since not all of these values can be displayed on the menu at the same time you can scroll through them by pressing the "MORE" key. This holds true on the sub-menu after the type of conversion is selected. When you get to the appropriate type and unit, press the corresponding key under the original unit followed by the corresponding key for the unit to be converted to. Press the "ENTER" key to run the conversion. For example, to convert 12 feet into equivalent meters, enter 12 followed by the “2nd” and “CONV” keys. Then select LNGTH by pressing the corresponding key (F1). Select “ft” (F5) and “m” (F3) and after pressing “ENTER”, the value of 3.6576 should appear as the answer. This value can then be recorded and entered into the appropriate field in the equation or to simplify things, you can run this conversion process on the appropriate line of the equation during the “SOLVER” function that will be discussed later.

FIRE DYNAMICS:

The formulas and equations that are going to be discussed in this paper are intended to be utilized by individuals that have a firm knowledge of the fire dynamics process and an understanding of the underlying principles each equation analyzes. It is important to understand concepts such as “Flashover”, “Heat Flux” and “Flame Height” and what they mean to the fire investigation before trying to effectively utilize the mathematical correlations. It is also important to understand the unit of measurement that the equation is expressed in to effectively apply them to a given situation. A firm understanding of the fire dynamics process of enclosure fires (compartments) is important to fire scene investigation and will, hopefully, allow the effective use of these calculations. For easy reference, the equations will be broken down into the particular aspect of fire behavior they are intended to analyze. As there may be more than one equation to describe certain fire phenomena (such as flashover), several different formulas may be presented and explained. An effort will also be made to explain what each variable in the formula relates to and how the input value is derived e.g. actual measurement or referenced materials. This paper is not meant to indicate that these are the only formulas that should be used or that these are the only formulas that will work in the calculator. These are simply equations that have been developed and effectively utilized in the calculator by field investigators.

PROGRAMMING EQUATIONS:

The equations discussed in this paper can be input into the calculator utilizing two different methods. The primary method is the text entry method where the designated equation is keyed in using the specified combination of alpha, numeric and mathematical functions. For entry purposes, each fire dynamics equation was converted to a word-type equation where the various factors or input variables have been changed to a designated text entry. Numeric entries and mathematical functions remain the same. It is important to enter the equation exactly as it appears in this paper. Entry is begun at a blank screen. If data is on the screen when the calculator is turned on, clear it by pressing the "CLEAR" if it is standard mathematical info or the "EXIT" key if an advanced function was previously utilized. After completing entry of the equation press the "ENTER" key. The word "Done" should appear at the bottom of the formula indicating it has been stored in the computer memory. If a syntax error is encountered, press "GOTO" and you will be returned to the entry screen. Review the input for errors and make corrections in the appropriate place by navigating with the cursor keys. When complete, place the cursor at the end of the input and press "ENTER" again to restore the equation. Again, remember that the input should be done as outlined in this paper as the same name for a variable cannot be utilized in more than one equation.

A second method of entering equations into the calculator is by linking it with a calculator that already has the formulas entered. This is accomplished with the cable that comes with the TI-86. After the two devices are connected, turn them on and press the

“2^{nd}”key, followed by pressing “LINK” key (secondary function of the x-VAR key). Press the corresponding “F Key” beneath “SEND” on the calculator that is already programmed and the corresponding “F Key” beneath “RECV” on the calculator that is to be programmed. On the sending calculator, you will then need to press the “F key’ beneath “ALL” and press the “F key” beneath “ALL+” (individual items can be selected or deselected navigating with the cursor keys and pressing the “F key beneath “SELCT”.) When all of the appropriate data is selected press the “F key beneath “XMIT” and the data transfer process will begin. If the formula or variable is already on the target calculator, it will ask whether it should replace the existing information.

HEAT RELEASE RATE:

Heat release rate or energy release rate is a critical factor in a number of the formulas that will be discussed in this paper. It is closely associated with flame height calculations and heat flux calculations and it is also a determining factor regarding a compartment’s potential to reach flashover. It is most accurately defined as “the energy produced by the fire per unit time or fire power.” [1] It takes into account the heat of combustion (energy released by the fire per unit mass of burned fuel)[2], the mass loss rate per unit area (the mass of fuel vaporized but not necessarily burned)[3] and the burning area. The formula for determining the heat release rate or energy release rate[4] is:

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

For input into the programmable scientific calculator this formula is expressed as:

QDOT = HEATCOMB * MDOT * SQM

Where:

A. QDOT = HEAT RELEASE RATE IN KILOWATTS
B. HEATCOMB = BOOK VALUE OF THE HEAT OF COMBUSTION OF THE GIVEN FUEL IN KILOJOULES PER SECOND/METERS^2 (ΔH_c factor)
C. MDOT = BOOK VALUE OF THE MASS LOSS OF THE GIVEN FUEL IN KILOGRAMS PER SECOND/METERS^2 (mdot'' factor)
D. SQM = AREA OF FUEL SURFACE IN METERS^2 (LENGTH IN METERS X WIDTH IN METERS)

Note: In a pool fire the meters squared (diameter squared) needs to be multiplied by pi/4 or (.785) before entering the number into the SQM factor.

As indicated, a number of the factors in this formula (and others to be discussed later in this paper) including the mass loss rate and the change in heat of combustion can be obtained from various reference documents. A list of reference documents will be included at the end of this paper.

For example, the above formula can be utilized to calculate the anticipated heat release rate of an item such as 1 meter diameter pool of gasoline as follows:

QDOT = Unknown (Variable we will be solving for)

HEATCOMB = 43.7 kilojoules per second per meter squared[5]

MDOT = 50-60 grams per second per meter squared[6] (for this exercise we will use the median value of 55)

Area = 1 meter squared x $\pi/4$ (pool fire conversion) = .785 meters squared

QDOT = 43.7 kJ/g * 55 g/m^2-s *.785 m^2

QDOT = 1887 kW

SOLVER FUNCTION

After entering the QDOT formula it can be checked against the above example by accessing the “Solver” function mentioned earlier. The “SOLVER” function contains a menu of all of the formulas that are entered by the user. It is accessed by pressing the “2nd” key, followed by the “SOLVER” key (secondary function above the GRAPH key). The available formulas should then be listed alphabetically on the menu located at the bottom of the screen. Up to five formulas can be displayed and additional formulas in the menu can be accessed by pressing the “More” key. To access the desired formula press the corresponding function key located below the menu item. With only the QDOT formula entered it should appear above the “F1” key. After pressing the function key, the input fields should appear as follows with the meaning of each field in parenthesis:

exp = (Unknown value for QDOT which will be solved for in this example)
HEATCOMB = (Value to be entered) = 43.7
MDOT = (Value to be entered) = 55
SQM = (Value to be entered) = .785
bound = (-1e99, 1e99)

To calculate our gasoline example, you would scroll down to the desired input field using the cursor keys and enter the appropriate value. In this example you would enter 43.7 in the HEATCOMB field, 55 in the MDOT field and .785 in the SQM field. To solve the equation, scroll back up to the “exp” field and press the key below “Solve” (F5). The value that is displayed will be the heat release rate (QDOT) in kilowatts and should be 1886.7475 (when rounded this is comparable to our previous example answer of 1887). As previously mentioned, the equation solver can be utilized to solve for any one variable in the formula or equation if the others are known. For example if we know the

QDOT=2500, the HEATCOMB is 43.7 (gasoline) and the MDOT is 55 (gasoline) we could solve for the SQM of the burning area. In this case we would enter the values as follows:

exp = (Known value for QDOT to be entered for this example) 2500
HEATCOMB = (Value to be entered) = 43.7
MDOT = (Value to be entered) = 55
SQM = (Unknown Value that will be solved for in this example.)
bound = (-1e99, 1e99)

To solve for the SQM, position the cursor in this field and then press the “Solve” (F5) key. A value of 1.04 (rounded) should appear. The “bound” area is predefined in the calculator default and should not be adjusted unless you consult the TI 86 manual and determine the need to make adjustments. This bounds the parameters of the “solving” function and there should be no need to adjust it to properly employ the formulas that are being discussed. If an equation or formula function has been used previously it is advisable to select the formula, press the “Clear” key, and then select the formula again. This will clear the field next to the eng: dialog and ensure that you access the desired equation. This “SOLVER” process will be utilized to run all of the additional equations that are discussed in this paper and the input process is similar.

FLAME HEIGHT:

Flame height calculations can play an important role in the analysis of a fire scene and can be utilized during predictive analysis prior to conducting testing. Flame height is closely related to the heat release rate or energy release rate of the fuel with higher flame heights expected from items that release more energy. Several factors can influence the flame height, including the fuel configuration and the fuel location so these factors must be considered when doing this type of analysis. Several different formulas are available and have proven useful. Three different equations will be outlined. These formulas are utilized to calculate the flame height above the object burning (not from the floor or fuel base.) and can be utilized to evaluate expected patterns versus actual patterns. They also can be useful in analyzing potential fire size and energy level based on witness statements. The first formulas were developed by McCaffrey[7] and are expressed as follows:

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

In this equation, Z_c is equal to the consistent or persistent flame height and Z_i is equal to the intermittent flame height. For input into the scientific calculator the formula can be expressed as follows:

FLAMHIGH = FLTYPE(KW^.4)

Where:

A. FLAMHIGH = HEIGHT OF FLAME IN METERS
B. FLTYPE = TYPE OF FLAME HEIGHT
   1. PERSISTENT = .08
   2. INTERMITTENT = .20

C. KW = HEAT RELEASE RATE IN KILOWATTS

Note: This allows you to make two different calculations using this formula, analyzing the persistent or constant flame level and the intermittent or potential flame level based on the heat release rate of the item burning.

Another formula that can be successfully employed was developed by Heskestad[8, 9] and is expressed as:

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

For entry into the programmable calculator the equation is expressed as:

ZFLAME = (.23 * (QD^.4)) - (1.02 * DIAM)

Where:

A. ZFLAME = FLAME HEIGHT IN METERS OF A POOL OR SINGLE ITEM FIRE WITH NO WALL FACTORS
B. QD = HEAT RELEASE RATE IN KILOWATTS
C. DIAM = DIAMETER OF POOL OR SINGLE ITEM IN METERS

Note: This formula will calculate the intermittent flame of the pool fire.

A third formula for calculating flame height is contained in NFPA 921[10] and is expressed as follows:

$$H_f = 0.174\left(k\dot{Q}\right)^{0.4}$$

For entry into the programmable calculator the equation is expressed as:

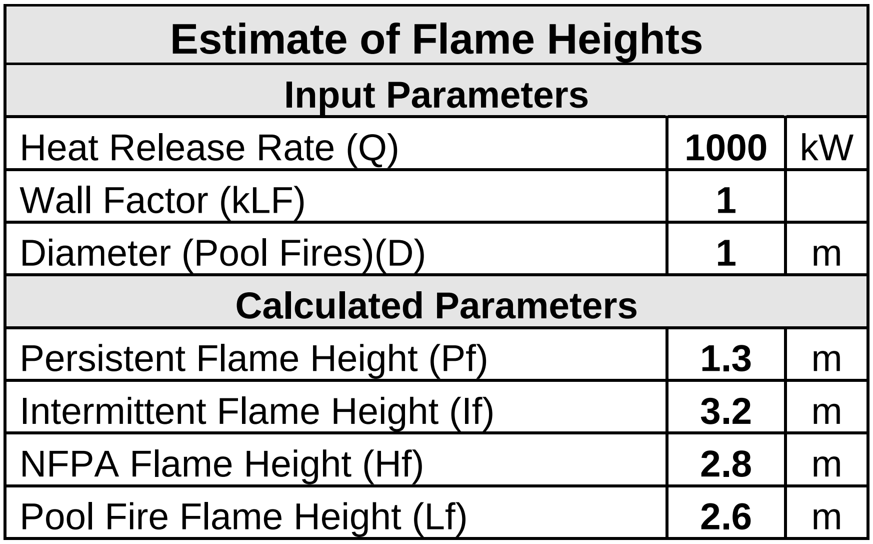
NFPAFLAM = .174 (WALL * QWATTS)^.4

Where:

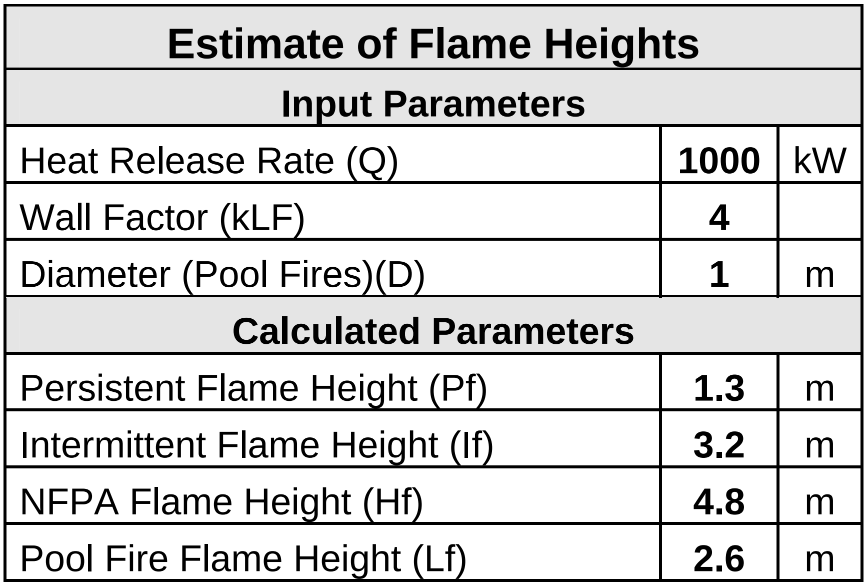
A. NFPAFLAME = FLAME HEIGHT IN METERS
B. WALL = LOCATION OF FIRE IN RELATIONSHIP TO THE ROOM WALLS
    1. WALL FACTOR 1 = NO WALLS / CENTER ROOM FIRE
    2. WALL FACTOR 2 = 1 WALL OR FIRE NEAR ONE WALL
    3. WALL FACTOR 4 = 2 WALL OR CORNER FIRE
C. QWATTS = HEAT RELEASE RATE IN KILOWATTS

Note: This formula was taken from NFPA 921 and includes a wall factor in calculating flame height.

A comparison of the anticipated results of the three formulas can be observed in the following charts. Note that the only difference between the results is observed in the calculation obtained from NFPA 921 and this can be attributed to the use of the location factor.



Estimate of Flame Heights		
Input Parameters		
Heat Release Rate (Q)	**1000**	kW
Wall Factor (kLF)	**1**	
Diameter (Pool Fires)(D)	**1**	m
Calculated Parameters		
Persistent Flame Height (Pf)	**1.3**	m
Intermittent Flame Height (If)	**3.2**	m
NFPA Flame Height (Hf)	**2.8**	m
Pool Fire Flame Height (Lf)	**2.6**	m



Estimate of Flame Heights		
Input Parameters		
Heat Release Rate (Q)	**1000**	kW
Wall Factor (kLF)	**4**	
Diameter (Pool Fires)(D)	**1**	m
Calculated Parameters		
Persistent Flame Height (Pf)	**1.3**	m
Intermittent Flame Height (If)	**3.2**	m
NFPA Flame Height (Hf)	**4.8**	m
Pool Fire Flame Height (Lf)	**2.6**	m

HEAT FLUX:

Heat Flux and related formulas such as Time to Ignition can be useful to the field investigator while conducting fire scene examinations, conducting fire testing and while analyzing witness statements. Heat Flux is radiant energy and can be defined as the heat flow rate per unit area of flow path[11] and is generally expressed in kilowatts per meter squared. Radiant energy becomes the dominant form of heat transfer as a fire moves through the development stages and can be responsible for the preheating and ignition of fuels. The potential for ignition of thermally thin objects increases at 10 kW/m^2 and above and at 20 kW/m^2 and above for thermally thick materials.[12] Additionally, upper layer smoke temperatures in the 500^o to 600^o Celsius range can generate heat flux to the floor in the 20-25 kW/m^2 range and is commonly associated with the onset of flashover.[13] A formula for determining "point-source" heat flux is expressed as:

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

This formula is relatively accurate if applied more than two flame diameters from the flame and is based on the assumption that all of the energy is received uniformly over a sphere radius from the flame.[14]

For entry into the scientific calculator the equation is expressed as:

FLUX = RADFRA * RHR/(4π(DIST^2))

Where:

A. FLUX = RADIANT HEAT FLUX IN KILOWATTS PER METER SQUARED
B. RADFRA = FRACTION OF COMBUSTION ENERGY LOST BY FLAME AS RADIATION (X_r Factor)
C. RHR = RATE OF HEAT RELEASE IN KILOWATTS (Q DOT)
D. DIST = DISTANCE BETWEEN CENTER OF THE FLAME AND TARGET

Note: RADFRA relates to how efficiently a fuel radiates energy and can be 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 .15 for low soot fuels such as methane to .60 for high soot fuels such as polystyrene.[15] It should also be noted that the distance from the source to the target is measured from the axis line of the flame, not from the flame edge.

It is also important to note that Heat Flux is inversely proportional to the square of the distance, meaning that doubling the distance between the source and the target (e.g. 1 meter increased to 2 meters) reduces the flux by approximately 75% not simply by 50%. An example of the anticipated results for this formula are contained in the charts below and illustrate the reduction factor discussed above.

Estimate of Heat Flux on Target		
Input Parameters		
Radiation Fraction (Xr)	**0.5**	
Heat Release Rate (Q)	**1000**	kW
Distance between Radiator and Target (D)	**2**	m
Calculated Parameter		
Radiant Heat Flux (q)	**9.95**	kW/m2

Estimate of Heat Flux on Target		
Input Parameters		
Radiation Fraction (Xr)	**0.5**	
Heat Release Rate (Q)	**1000**	kW
Distance between Radiator and Target (D)	**1**	m
Calculated Parameter		
Radiant Heat Flux (q)	**39.81**	kW/m2

TIME TO IGNITION:

An associated formula that incorporates heat flux is Time to Ignition. The Time to Ignition formula[16] is a useful tool if you are trying to analyze how long it would take for a fire to progress from one fuel to another. While there is a differentiation between the ignition times of thin fuels (thermally thin) and the ignition time of thick fuels (thermally thick), we will only discuss the formula for thermally thick fuels. The formula takes into account the thermal inertia of the fuel which is defined as "a thermal property responsible for temperature rise"[17] and the ignition temperature of the fuel. More simply, thermal inertia is a property related to how easy or difficult it is to get a fuel involved in the fire process. Fuels with low thermal inertia values are more readily ignited while fuels with higher thermal inertia values are more difficult to ignite. The formula is expressed as follows:

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

For input into the programmable calculator the formula is expressed as:

IGNTIME=(.785 * KRHOC)((IGNTEMP - ORIGTEMP)/HEATFLUX)^2

Where:

A. IGNTIME = TIME TO IGNITION IN SECONDS
B. KRHOC = THERMAL INERTIA OF PRODUCT (BOOK VALUE)
C. IGNTEMP = TEMPERATURE NECESSARY TO IGNITE A GIVEN PRODUCT (BOOK VALUE) (IN DEGREES CELSIUS)
D. ORIGTEMP = AMBIENT TEMPERATURE IN ROOM (IN DEGREES CELSIUS)
E. HEATFLUX = HEAT FLUX BEING APPLIED TO PRODUCT IN kWw/M^2

NOTE: The KRHOC ($k\rho c$) value can typically be obtained in appropriate reference sources.

The charts below illustrates the anticipated results of this formula and compares two fuels (3/4 inch (19mm) plywood and 1 inch)(25mm flexible foam) that have similar ignition temperatures but different $k\rho c$ values.

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/m2-K)2/s
Ignition Temperature (Tig)	**390**	C
Ambient Temperature (To)	**29**	C
Exposure Heat Flux (q")	**15**	kW/m2
Calculated Parameters		
Ignition Time (tig)	**246**	S
Energy Input for Ignition (E")	**3685**	kJ/m2

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")	**15**	kW/m2
Calculated Parameters		
Ignition Time (tig)	**146**	S
Energy Input for Ignition (E")	**2184**	kJ/m2

FLASHOVER:

Flashover is the transition phase of the fire development process in which all available fuels in a compartment become involved in the fire dynamics 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 to 600^{O} C.”[18] It is important to understand that it is a phase or a series of occurrences, not one specific point in time. Three formulas can be utilized to analyze the anticipated minimum energy release rate or heat release rate (in kilowatts) required in order drive a compartment to flashover. These formulas vary slightly, but all include a basic ventilation factor. All three formulas require the dimensions to be specified in meters so it is recommended that you either convert the measurements prior to starting the equation or utilize the method discussed earlier to convert the measurement within the formula field. The first formula was developed by McCaffery, Quintiere and Harkleroad[19] and is referred to as the MQH method of determining flashover. This method has the most input variables including the thickness of the bounder surface and the thermal conductivity of the boundary surface. The formula is expressed as follows:

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

For input into the programmable calculator the formula is expressed as follows:

MQHFLASH = 610 * SQUARE ROOT ((WALLCOND/WALLTHCK) (2 * ((RMLNGTH * RMWDTH) + (RMLNGTH * RMHIGH) + (RMWDTH * RMHIGH)) - (OPENWDTH * OPENHIGH)) (OPENWDTH * OPENHIGH) (SQUARE ROOT (OPENHIGH))

Where:

A. MQHFLASH = KILOWATT OUTPUT TO PRODUCE FLASHOVER
B. WALLCOND = CONDUCTIVITY OF WALL (h_k Factor)
C. WALLTHCK = THICKNESS OF WALL IN METERS (h_k Factor)
D. RMLNGTH = LENGTH OF ROOM IN METERS (A_t Factor)
E. RMWDTH = WIDTH OF ROOM IN METERS (A_t Factor)
F. RMHIGH = HEIGHT OF ROOM IN METERS (A_t Factor)
G. OPENWDTH = WIDTH OF OPENING IN METERS (A_o Factor)
H. OPENHIGH = HEIGHT OF OPENING IN METERS (A_o and H_o Factor)

The next formula that can be utilized was developed by Thomas.[20,21] Again it contains the ventilation factor and also includes a total surface area variable (boundary surface area minus vent openings). The formula is expressed as follows:

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

For input into the programmable calculator the formula is expressed as follows:

THOMAS=7.8(2*((L*W)+(L*H)+(H*W))-
(VH*VW))+378*((VW*VH)(SQUAREROOT VH))

Where:

A. THOMAS= KILOWATT OUTPUT TO PRODUCE FLASHOVER
B. L = LENGTH OF COMPARTMENT IN METERS
C. W = WIDTH OF COMPARMENT IN METERS
D. H = HEIGHT OF COMPARTMENT IN METERS
E. VH = HEIGHT OF VENT OPENING IN METERS
F. VW = WIDTH OF VENT OPENING IN METERS

The third formula that will be discussed was developed by Babrauskas.[22, 23] It relies on the ventilation factor as its input variable. The formula is expressed as follows:

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

For input into the programmable calculator the formula can be expressed as follows:

BABFLASH =750(HO*WO)(HO)^.5

Where:

A. BABFLASH=KILOWATT OUTPUT TO PRODUCE FLASHOVER
B. HO = HEIGHT OF VENT OPENING METERS
C. WO = WIDTH OF VENT OPENING IN METERS

All three formulas are useful but each will yield different results. It is important to recognize this fact and it is recommended that the three formulas be used in companion with each other to develop anticipated parameters of what amount of energy is necessary to achieve flashover. The chart below illustrates the anticipated results of the three formulas utilizing the same input parameters as appropriate. It also highlights the slight differences that can be achieved. For the purposes of this comparison a compartment of 3 meters wide x 3 meters long x 3 meters high and a ventilation opening of 0.6 meters wide x 2.4 meters high will be utilized.

Estimates of HRR Needed to Reach Flashover (F/O)		
Input Parameters		
Room Length (L)	**3**	m
Room Width (W)	**3**	m
Room Height (H)	**3**	m
Opening Width (Wo)	**0.6**	m
Opening Height (Ho)	**2.4**	m
Boundary Conductivity (k)	**0.00048**	kW/m^2-k
Boundary Thickness (d)	**0.02**	m
Calculated Parameters		
Boundary Surface Area (At)	**52.56**	m^2
Ventilation Factor	**2.23**	m$^{5/2}$
Area of Opening	**1.44**	m^2
h sub k Factor	**0.0240**	
Babrauskas F/O Prediction	**1673**	kW
MQH F/O Prediction	**1023**	kW
Thomas F/O Prediction	**1253**	kW

TIME TO FLASHOVER:

Another formula that is very important in fire scene analysis and predictive analysis during fire testing is Time to Flashover. This formula is utilized to determine how long it is anticipated that a fire will take to reach a given Heat Release Rate based on a given fire growth factor. It utilizes a T^2 analysis method where the fire growth is proportional to time squared. The formula is expressed as follows:

$$\dot{Q} = at^2$$

For use in the programmable calculator the formula is expressed as follows:

TFIRE = GROWTH * TIME^2

Where:

A. TFIRE = (T SQUARED FIRE) HEAT RELEASE RATE NEEDED TO PRODUCE FLASHOVER IN KILOWATTS
B. GROWTH = GROWTH FACTOR
    1. SLOW =.00293
    2. MODERATE = .01172
    3. FAST = .0469
    4. ULTRA FAST= .1876 (.400 - MOWRER RATE)
C. TIME = ELAPSED TIME OF FIRE TO FLASHOVER (LENGTH OF TIME NEEDED TO PRODUCE ENOUGH KILOWATTS TO CAUSE FLASHOVER)

This formula is useful in determining an estimate of how long it will take a fire to reach a critical point based on an estimated growth factor. It is very useful in assessing witness statements and in developing a timeline. In some instances it is more useful than determining the potential for a room to go to flashover based on available fuel because in most modern homes, the amount of fuel and synthetic products is more than adequate to drive a compartment to flashover given the proper ventilation factor. When utilizing this formula you will solve for time and utilize the heat release rate calculated by one of the three methods above as the TFIRE variable. You can accomplish this by first running one of the flashover equations and then writing down the answer for input into the TFIRE equation or you can carry the flashover figure over to the TFIRE formula by solving the flashover correlation and then pressing “2nd”, “SOLVER” and selecting TFIRE from the menu. The heat release rate required for flashover will then be in the “exp=” field. You would then enter the desired fire growth factor and move the cursor to the Time= field and press solve. This will solve for time in seconds to reach a specified Heat Release Rate using a specified fire growth rate. Again, it is recommended that you utilize several growth rates (or combinations thereof) and draw a boundary around the anticipated amount of time to reach a specific point. The charts below will illustrate the different heat release rate anticipated at a given time interval based on the various growth factors.

Estimates of HRR In T squared Fire		
Input Parameters		
Time	**100**	s
Calculated Parameters		
HRR (Slow)	**29.30**	kW
HRR (Moderate)	**117.20**	kW
HRR (Fast)	**469.00**	kW
HRR (Ultra Fast)	**1876.00**	kW
HRR (Mowrer Ultra Fast)	**4000**	kW

MISCELLANEOUS FORMULAS:

As mentioned earlier, the formulas outlined in this paper are not all-inclusive and are not the only formulas that can be utilized to analyze fire growth and development, nor are they the only formulas that will work in scientific programmable calculators. It is a mere snapshot of how these formulas can be successfully employed and outlines the potential benefit of utilizing the programmable calculator. Several other formulas that have successfully been developed and entered into the TI 86 calculators include formulas for calculating the Ceiling Jet Temperature, Layer Temperature and the Fire Plume Temperature:

The Ceiling Jet Formula can be expressed as follows for entry into the programmable calculator:

JETTEMP = (5.3(QDOTSS/DISTAWAY)^.66 / CEILHIGH) – AMTEMP

Where:

A. JETTEMP = TEMPERATURE OF CEILING JET AT A GIVEN DISTANCE FROM THE FLAME AXIS (CENTERLINE) IN DEGREES CELSIUS
B. QDOTSS = HEAT RELEASE RATE IN KILOWATTS
C. DISTAWAY = DISTANCE FROM FLAME AXIS IN METERS WHERE TEMPERATURE MEASUREMENT IS DESIRED
D. CEILHIGH = ROOM HEIGHT IN METERS
E. AMTEMP = AMBIENT TEMPERATURE OF ROOM IN DEGREES CELSIUS

Note: This formula is utilized to determine the temperature of the ceiling jet (JETTEMP) at a given point away from the flame axis.

The Plume Temperature Formula can be expressed as follows for entry into the programmable calculator:

PLUMTEMP = AMBTEMP + (21.6 * (QDOTS^(.666) * HIGHABV^(-5/3))

Where:

A. PLUMTEMP = TEMPERATURE OF GAS PLUME IN DEGREES CELSIUS AT A GIVEN HEIGHT ABOVE THE FIRE
B. QDOTS = HEAT RELEASE RATE IN KILOWATTS
C. HIGHABV = HEIGHT ABOVE FIRE IN METERS WHERE TEMPERATURE MEASUREMENT IS DESIRED

Note: This formula is utilized to determine the temperature of the fire plume (PLUMTEMP) at a given point above the fire.

The Layer Temperature Formula can be expressed as follows for entry into the programmable calculator

LAYERTMP = (((((QDOTSSS)^2 / ((VENTHIGH X VENTWDTH) (SQUARE ROOT VENTHIGH) (HEATCOFF) (2((AREAHIGH * AREALGTH) + (AREALGTH *AREADPTH) + (AREAHIGH * AREADPTH))))))^(1/3))6.85

Where:

A. LAYERTEMP = UPPER GAS LAYER TEMPERATURE IN DEGREES CELSIUS
B. QDOTSSS = HEAT RELEASE RATE IN KILOWATTS
C. VENTHIGH = HEIGHT OF VENTILATION OPENING IN METERS
D. VENTWDTH = WIDTH OF VENTILATION OPENING IN METERS
E. HEATCOFF = EFFICIENCY OF HEAT TRANSFER (0.1 least to 0.6 most)
F. AREAHIGH = ROOM HEIGHT IN METERS
G. AREALGTH = LENGTH OF ROOM IN METERS
H. AREADPTH= WIDTH OF ROOM IN METERS

NOTE: This formula is utilized to determine the temperature of the upper gas layer in degrees Celsius based on the heat release rate of the fire and the dimensions of the compartment.

CONSTANTS:

Another useful feature of the programmable calculator is its ability to store constants or values that will be utilized in the various formulas such as fire growth rate values, radiation factors (X_r), and boundary surface thickness dimensions. This list is not all inclusive and other values, such as ignition temperature could easily be stored in the constants memory section. To enter a constant value, access the constant menu by pressing “2nd”, the “CONS” (#4 key). Press the Edit key and the following menu should appear with a notation of what the field is utilized for in parenthesis:

CONSTANT
Name= (Name of Constant to Be Stored)
Value= (Numeric Value of Constant)

You can then enter the name of the constant you are entering (this field is already in “alpha mode”). After completing the name entry, move to the Value field by moving the cursor down. Enter the appropriate value and press “Next”. You will then be able to enter all of the desired values. When running an equation, the constant values can be accessed within the formula similar to the “CONV” feature. In the appropriate field, access the Constant Menu and press “User.” This will bring up a list of the constant names that you entered. You can access additional names by pressing “More.” When you get to the desired value, press the corresponding “F” key beneath the appropriate name. When you move the cursor to another field or the field to be solved for, the constant value will appear. Please not that when you have two features open (such as SOLVER and convert (CONV), or SOLVER and constant (CONS), the solver menu will move to the top and will be accessed by pressing the “2nd” key prior to the appropriate “F” key (e.g. “2nd”, “F5” to solve an equation.)

The following is a partial list of useful constants that can be stored. Again, it is not all inclusive and other values that you deem appropriate or useful can easily be stored.

FIRE GROWTH RATE CONSTANTS:[24]

GRSLOW=0.00293
GRMOD=0.01172
GRMFST=0.02345 (Average of Moderate Growth and Fast Growth Rate)
GRFAST=0.0469
GRULTRA=0.1876
GRMOWR=0.4

RADIATION FRACTION CONSTANTS:[25]

RADGAS=0.45 (Average Radiation Fraction for Gasoline)
RADWOOD=0.35 (Average Radiation Fraction for Wood)
RADMETH=0.17 (Average Radiation Fraction for Methanol and methane)

BOUNDRY CONDUCTIVITY CONSTANTS:[26]

BCGYPM=0.00048 (Drywall)
BCBRICK=0.00069
BCWOOD=0.00018
BCCONC=0.0011 (Average for Concrete)

BOUNDRY THICKNESS CONSTANTS:

BTHALF=0.0127 (1/2 inch converted to meters)
BTFIVE8=0.015875 (5/8 inch converted to meters)
BTQRTR=0.00635 (1/4 inch converted to meters)

Note: For users outside of the United States, the name can be changed to something more representative of the materials you will encounter.

FLAME HEIGHT CONSTANTS:[27]

FLPERST=0.08
FLINTRM=0.20

MASS LOSS RATE CONSTANTS:[28]

MDOTGAS=55
MDOTPMMA=28
MDOTPUFM=25 (Polyurethane Foam)
MDOTPVC=16
MDOTPAPR=14 (Paper)
MDOTJET=60 (JP 4 Jet Fuel)
MDOTHEP=70 (Heptane)
MDOTACET=40 (Acetone)
MDOTPOLS=36 (Polystyrene)

Note: Some values are averages for different forms of similar products. These values are useful for quick calculations but it is recommended that the requested value be obtained from a reference publication for use in final calculations.

THERMAL INERTIA CONSTANTS:[29]

KRCPMMA=1.0
KRCHGYP=0.45 (Half inch (12.7mm) gypsum board)
KRCCARP=0.20 (Average of wool type carpets)
KRCPINE=0.25
KRCOAK=0.32
KRCPFOAM=0.00095
KRCHPLY=0.54 (Half inch (12.7mm) plywood)

Note: Some values are averages for different forms of similar products. These values are useful for quick calculations but it is recommended that the requested value be obtained from a reference publication for use in final calculations.

TEMPERATURE OF IGNITION CONSTANTS:[30],[31]

TIGGAS= 456 (Gasoline)
TIGKERO=210 (Kerosene)
TIGPROP=450 (Propane)
TIGACET=465 (Acetone)
TIGNATG=550 (Average for Natural Gas)
TIGPLYW= 390 (Plywood)
TIGWCARP=450 (Average of wool type carpets)
TIGPARTB=412 (Particle board)
TIGPMMA=380 (Cast type)
TIGHGYP=565 (Half inch (12.7mm) Gypsum)

Note: Some values are averages for different forms of similar products. These values are useful for quick calculations but it is recommended that the requested value be obtained from a reference publication for use in final calculations.

HEAT OF COMBUSTION CONSTANTS:[32]

HCMETH=50 (Methane)
HCPROP=46.5 (Propane)
HCHEPT=44.6 (Heptane)
HCGAS=43.7 (Gasoline)
HCKERO=43.2 (Kerosene)
HCACET=30.8 (Acetone)
HCPOLYS=39.8 (Polystyrene)
HCPMMA=24.9
HCPVC=16.4
HCCELLU=16.1 (Cellulosic Materials)
HCWOOD=14

Note: Some values are averages for different forms of similar products. These values are useful for quick calculations but it is recommended that the requested value be obtained from a reference publication for use in final calculations.

End Notes and Source Documents

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[1] Quintiere, James (1997). *Principles of Fire Behavior*. Albany, NY.: Delmar Publishing (252)

[2] Ibid, (252)

[3] Ibid, (253)

[4] Ibid, (108)

[5] Ibid, (111)

[6] Ibid, (109)

[7] Icove, David J. and DeHaan, John D. (2004). *Forensic Fire Scene Reconstruction*. Upper Saddle River, NJ.: Prentice Hall (81)

[8] Quintiere, (138)

[9] Icove, (82)

[10] NFPA (2004) *NFPA 921: Guide for Fire and Explosion Investigations 2004Edition.* Quincy, MA.: National Fire Protection Association (29)

[11] Quintiere, (252)

[12] Ibid, (61)

[13] Ibid, (61)

[14] Ibid, (58)

[15] Ibid, (58)

[16] Ibid, (87)

[17] Ibid, (254)

[18] Ibid, (252)

[19] Icove, (63)

[20] Ibid, (61)

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[21] NFPA 921, (27)

[22] Icove, (62)

[23] NFPA 921, (27)

[24] Icove, (57)

[25] Quintiere, (59)

[26] Ibid (51)

[27] Icove (81)

[28] Quintiere (109)

[29] Ibid (67, 79, 90)

[30] Ibid (67, 79, 90)

[31] NFPA 921 (21)

[32] Quintiere (111)

Additional Recommended Reference Documents and Resource Tools:

Babrauskas, Vytneis (2003). *Ignition Handbook*, Issaquah, WA: Fire Science Publishers

National Fire Protection Association et al (1995). *SFPE Handbook of Fire Protection Engineering, 2nd Edition*. Quincy, MA: National Fire Protection Association.

Drysdale, Dougal (1998). *An Introduction to Fire Dynamics, 2nd Edition*. West Sussex, UK: John Wiley and Sons, Ltd.

National Fire Protection Association (2003). *Fire Protection Handbook, 19th Edition (Volumes I and II)*. Quincy, MA: National Fire Protection Association

FIRE TOOLS Website – accessed June 9, 2005
http://users.wpi.edu/~ierardi/FireTools/#firetoolsandresources

Nuclear Regulatory Commission Tools – accessed June 9, 2005
http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/final-report/index.html
(Reports and Excel Spreadsheets can be viewed and downloaded from this site)

Other editions of the FPE Handbook are also useful