May 1, 2002

MEMORANDUM TO: Gary M. Holahan, Director
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation

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SUBJECT: REQUEST FOR APPROVAL TO PRESENT PAPER TITLED; "FIRST APPLICATIONS OF A QUANTITATIVE FIRE HAZARD ANALYSIS TOOL FOR INSPECTION IN THE U.S. COMMERCIAL NUCLEAR POWER PLANTS"

The purpose of this memorandum is to request approval to submit and present the subject paper at the 5th Meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plants Applications, to be held at the National Institute of Standards and Technology (NIST), Building and Fire Research Laboratory (BFRL), Gaithersburg, Maryland, May 2-3, 2002.

Attachment 1 is NRC Form 390 for the Office Director approval. Attachment 2 is the final copy of the subject paper. This paper has been reviewed by the NRC Technical Editor.

Please indicate your approval by signing above. Once you have given approved your approval, please forward the package to the Division Director for his approval.

Approved: _____**/RA/ S. Black for:**___________
Gary M. Holahan, Director, DSSA/NRR

Attachments: As stated (2)

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FIRST APPLICATIONS OF A QUANTITATIVE FIRE HAZARD ANALYSIS TOOL FOR INSPECTION IN THE U.S. COMMERCIAL NUCLEAR POWER PLANTS*

Naeem Iqbal and Mark Henry Salley, P.E.
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ABSTRACT

Fires in a nuclear power plant (NPP) are a significant safety concern. The U.S. Nuclear Regulatory Commission's (NRC's) new Reactor Oversight Process (ROP) uses a risk-informed approach to evaluate the safety significance of inspection findings. As a part of this approach, the inspectors use a significance determination process (SDP) to evaluate the significance of fire risks to the operating reactor, as required by the new NRC inspection manual. A key step in the SDP is determining whether a credible fire scenario is possible. The paper titled "Development of a Quantitative Fire Scenario Estimating Tool for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program" ** introduced the new quantitative analytical tools for performing fire hazard analyses (FHAs) being developed by the NRC Office of Nuclear Reactor Regulation (NRR) fire protection engineering staff. These tools are designed for use by the regional fire protection inspectors. The paper notes that a FHA is intended to permit fire protection inspectors to quickly evaluate the potential for credible fire scenarios to cause critical damage to essential fire safe-shutdown (FSSD) systems, components, or equipment. It also discusses the process of creating an analytical quantitative tool based on the fire dynamics equations and pre-programmed correlations using Microsoft Excel® worksheets. These worksheets form the basis to be used to perform quick, easy, accurate calculations. The first paper discussed how to estimate burning characteristics of fire (heat release rate, flame height and burning duration), and hot gas layer temperature. Since then a second series of computational worksheets with different concepts of fire dynamics have been developed and taught to the regional inspectors. Applications which are discussed in this paper include: flame heat flux from a fire source to a target fuel using a point source and solid flame radiation model, centerline temperature of a buoyant fire plume, sprinkler actuation time and heat release rate (HRR) required to cause flashover in a compartment. The NRR fire protection engineering staff is in the process of developing additional worksheets to promote greater application of fire science engineering in the field during inspection.

Key words: fire hazards analysis, nuclear power plant, fire protection inspection finding, credible fire scenario, fire dynamics, correlations, worksheet, quantitative methods

*** This paper was prepared by the NRC staff. The views presented do not represent an official staff position. The NRC has neither approved nor disapproved its technical content.**

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INTRODUCTION

One purpose of a fire hazard analysis (FHA) is to determine the effect of fires on the ability to operate the facility safely, that is, to protect the reactor and prevent the release of radiation to the environment. There are a variety of methods of performing a FHA. In this second paper we describe more analytical methods of quantitatively assessing fire hazards in NRC-licensed nuclear power plants (NPPs).

The NRC/NRR method uses simplified quantitative FHA calculation techniques to evaluate the potential for credible exposure fire sources to cause critical damage to essential fire safe-shutdown (FSSD) systems, components, or equipment, either directly or by igniting intervening combustibles, which in turn could cause critical damage. The NRC/NRR methods are based on material fire property data used in engineering and scientific calculations. The fire hazard calculations used in these worksheets are simple empirical correlations based on accepted fire dynamics principles.

REGULATORY BACKGROUND

The primary objective of the fire protection programs at U.S. NPPs is to minimize the probability and consequences of fires. Fire protection programs for operating NPPs are designed to provide reasonable assurance, through defense-in-depth (DID), that a fire will not prevent the performance of necessary safe-shutdown functions and that radioactive releases to the environment will be minimized. Regulatory Guide 1.189, "Fire Protection for Operating Nuclear Power Plants," April 2001, summarizes the multilevel approach to fire safety. The fire protection DID program has three objectives:

1. To prevent fires from starting.

2. To detect rapidly, control, and extinguish promptly those fires that do occur.

3. To provide protection for structures, systems, and components important to safety so that a fire that is not promptly extinguished by the fire suppression activities will not prevent the safe shutdown of the plant.

The NRC's regulatory framework for nuclear plant fire protection programs (FPPs) is described in a number of regulations and guidelines, including General Design Criterion 3 (GDC 3), 10 CFR 50.48, Appendix R to 10 CFR Part 50, Regulatory Guide 1.189, and other regulatory guides, generic communications (e.g., generic letters, bulletins, and information notices), NUREG reports, the Standard Review Plan (NUREG-0800) (SRP), and branch technical positions (BTPs).

FIRE HAZARD ANALYSIS FOR NPPs

NPPs achieve the required degree of DID for fire protection using echelons of administrative controls, fire protection systems and features, and safe-shutdown capabilities. A FHA should be performed to demonstrate that the plant will maintain the ability to perform safe-shutdown functions and minimize radioactive material releases to the environment in the event of a fire. Regulatory Guide 1.189 states that the objectives of a FHA are to,

1. Consider potential in-situ and transient fire hazards.

2. Determine the consequences of fire in any location in the plant according to the ability to safely shutdown the reactor and minimize and control the release of radioactivity to the environment.

3. Specify measures for fire prevention, fire detection, fire suppression, fire containment, and alternative shutdown capability for each fire area containing structure, systems, and components important to safety in accordance with NRC guidelines and regulations.

NPP FIRE SCENARIO DEVELOPMENT

A fire scenario can be thought of as a chain of events that begins with the ignition of combustibles and ends either with successful plant shutdown or core damage. A fire is postulated to occur at a specific location in a specific fuel package and to progress through various stages of growth. As the fire grows, it may damage plant equipment directly or indirectly (most often through electrical cables). For a given fire source, the FHA may postulate damage to different equipment, depending on how long the fire burns and the initial size of the fire. The postulated or predicted fire damage either directly or indirectly causes an initiating event such as a plant trip, or loss-of-offsite power.

When developing a fire scenario, the inspector should conservatively postulate a significant fire provided that the potential for a large fire is possible in the fire zone, area, or room. For example, in a large cabinet fire the initial fire damage extends beyond the cabinet where the fire started. A large cabinet fire in its initial stages may damage overhead cabling, an adjacent cabinet, or both. Assuming that electrical power is interrupted the initial size of a pump or motor fire may largely depend upon the size of the oil spill. If the configuration of the compartment, adjacent combustibles, etc., support the growth of a large fire, a large fire should be postulated. Since large-fire scenarios are normally expected to dominate the risk significance of an inspection finding, small-fires scenarios (for example a small electrical cabinet fire) are generally not analyzed when large-fire scenarios can be postulated. Suppression is not credited unless suppression could prevent the damage to the component. Automatic suppression, fire brigade, operator response, and fire frequencies are accounted for in other parts of the SDP.

FIRE PROTECTION INSPECTION FINDINGS

A fire protection inspection finding usually concerns a failure or partial failure in meeting one of the objectives of DID. If there are no DID-related findings against a fire protection feature or system, the fire protection feature and system is considered capable of performing its intended function and remaining in its normal (standby) operating state.

EFFECTS OF FIRE ON NPP OPERATIONS

Recent studies indicate that fires are a significant risk to the safe operation of an NPP (NUREG-1742). In addition to local damage, heat transfer and the spread of smoke may cause damage far from the burning object. A toxic mixture of combustion products in the smoke can hinder work in the area by reducing visibility and creating a potentially lethal environment for plant personnel. Furthermore, the probability of failures in electrical components increases as temperatures rise and smoke becomes more concentrated.

Empirical data indicates that a nuclear power facility experiences more event precursors (small fires that have little impact on nuclear safety) than actual fire events such as the Browns Ferry Nuclear Power Plant (BFN) Unit 1 fire (NRC Bulletin 75-04, March 1975). Many fire protection experts argue that no fire in an NPP is without nuclear safety implications because every fire is a threat to safety through its effects on equipment or operating personnel. Statistically however, a NPP is expected to experience a fire that affects nuclear safety equipment every 6 to 10 years (Ramsey and Modarres 1998). The NUREG-1742 review of individual plant examinations of external events [including some detailed fire probabilistic risk assessments (PRAs)] showed that fire can be a significant contributor to a given plant's core damage frequency because a single fire and its effects can result in the loss of an otherwise highly reliable redundant safety capability. The loss of a redundant safety capability reduces possible success paths and may lead to core melt damage accidents

FIRE DEVELOPMENT

Fire hazards to NPP equipment may result from thermal destruction, fouling, corrosivity, and other sources. Fire is essentially a rapid self-sustaining oxidation process, producing heat and light of varying intensities. The chemical and physical reactions that take place during a fire are very complex and difficult to describe completely.

A fire starts when in-situ or transient combustibles ignite and then release heat to the surroundings by conduction, convection, and/or radiation. The rise in temperature in the fire compartment increases the volume of gas and forces it out of the compartment. The flow of expanding gas out of the compartment continues as the temperature rises. The pressure differential of the expanding gas across the compartment boundary depends on a number of factors including (1) the leakage area (including the ventilation system if applicable), (2) the volume of the fire compartment, (3) the rate of temperature rise, and (4) the rate of gas generation from the combustion process. When the fire temperature reaches a steady-state value, the gases in the fire compartment cease to expand. A balance is established as smoke moves out of the compartment (primarily by buoyancy) and air moves in to replace the smoke.

DEVELOPMENT OF THE FIRE DYNAMICS WORKSHEETS

Our challenge was to develop a method that could be taught to regional inspectors and put to use in a short time. Regional inspectors have diverse backgrounds typically in electrical, mechanical, nuclear, chemical, and civil engineering. We had to present the fire dynamics correlations so they could be understood by engineers who had little or no formal education in the field of heat and mass transfer. We also had to present the fire dynamics equations and correlations in a user-friendly format. After discussions with the fire protection engineers from the U.S. Bureau of Alcohol, Tobacco and Firearms (ATF) we decided to develop a series of Microsoft Excel® worksheets similar to ATFs' with the equations and correlations pre-programmed and locked in. The worksheets would allow quick, easy, accurate calculations. The worksheets would also list the physical and thermal properties of materials commonly encountered in the NPP. To begin the process, we had to select a series of fire dynamics correlation methods. We decided to base our program on state-of-the-art methods from the SFPE Handbook of Fire Protection Engineering, NFPA Fire Protection Handbook, and if necessary to modify the equations for use in specific NPP application. The paper titled, "Development of a Quantitative Fire Scenario Estimating Tool for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program," presented at the Structural Mechanics in Reactor Technology (SMiRT) Post-Conference Seminar No.1, 2001, discussed the first set of worksheets that were put into use by the regional inspectors.

The following section describes the second addition of fire dynamics worksheets recently developed to complement the first series.

METHODS OF PREDICTING HEAT FLUX FROM FIRE TO A TARGET FUEL

Introduction

The McCaffrey, Quintiere, and Harkleroad (MQH) and Foote, Pagni, and Alvares (FPA) temperature correlations are not valid for analyzing a fire scenario in a large open compartment. Very large spaces such as the reactor building in a boiling-water reactor (BWR) or the turbine building have too large of a volume for a uniform hot gas layer to build up. In these scenarios, we must look at other forms of heat transfer such as radiation. This section addresses radiation heat transfer when the target is at floor level.

Thermal radiation can be the significant mode of heat transfer for situations where a target is located laterally from the exposure fire source. An example is a floor-based fire adjacent to an electrical cabinet or a vertical cable tray in a large compartment.

Fire normally grows and spreads by direct burning, which results from impingement of the flame on combustible materials or by heat transfer to other combustibles. The three modes of heat transfer are, conduction, convection, and radiation. All these modes may be significant in heat transfer from fires. For example, conduction is particularly important in allowing heat to pass through a metallic object in a solid barrier and ignite material on the other side. Most of the focus on heat transfer in fires involves convection and radiation. It is estimated that in most fires some 75% of the heat emanates by convection. The hot products of combustion rising from a fire typically have a temperature in the range of 800 -1200 °C (1472 -2192 °F) and a density a quarter that of air. However, in an open industrial facility much of the convective heat is dissipated into the atmosphere. Conversely, in a smaller building compartment the heat is contained by the ceiling and walls. Radiation usually accounts for a smaller proportion of the heat generated from the fire. Radiated heat is transferred directly to nearby objects. However, in large open spaces where a hot gas layer is not established, radiation may be the most significant mode of heat transfer to evaluate. Thermal radiation is electromagnetic radiation of wavelengths from 2 to 16 μm (infrared). It is the net result of radiation from substances such as H_2O, CO_2, and soot (often dominant in pool fires).

Critical Heat Flux to a Target

Radiation from a flame or any other hot gas, depends on the temperature and emissivity of the gas. Emissivity is a measure of how well the hot gas emits thermal radiation. Emissivity is a value between 0 to 1, where 1 is a perfect radiator. The radiation that an observer feels depends on the emissivity and height of the flame.

The incident heat flux required to raise the surface of a target to a critical temperature is termed the critical heat flux. Measured critical heat flux levels for representative electrical cable samples typically range from 15 to 25 kW/m^2 (1.32 to 2.2 Btu/ft^2-sec). To account for inaccuracies, critical heat fluxes should be established for screening purposes with values of 10 kW/m^2 (0.88 $Btu/ft^2/sec$) for IEEE-383 qualified cable and 5 kW/m^2 (0.44 $Btu/ft^2/sec$) for non-IEEE-383 qualified cable. These values are consistent with selected damage temperatures for both types of cables as referenced in EPRI's Fire-Induced Vulnerability Evaluation (FIVE) methodology.

Numerous methods have been developed to calculate the heat flux from a flame to a target located outside the flame. Flames have been represented as cylinders, cones, planes and point sources to evaluate the effective configuration factor or view factor between the flame and the target. The configuration or view factor is a purely geometric quantity. It gives the fraction of the radiation leaving one surface that strikes another surface directly. The predictive methods range from very simple to very complex methods. The more complex methods involve correlations and detailed solutions to the equations of radiative heat transfer and computational fluid mechanics. Routine FHAs are usually based on simple correlations because of the macroscopic goals of the analyses and the limited resources available for routine evaluation. As a result of the widespread use of these methods, a great deal of effort has gone into their development. Burning rates, flame heights, and radiative heat fluxes can be predicted by these methods.

POINT SOURCE RADIATION MODEL

A point source estimate of radiant heat flux is the simplest and the most widely used flame representation. To predict the thermal radiation field of a flame, the flame is modeled as a point source at the center of a flame. More realistic radiator shapes entail very complex configuration factor equations. With the point source model radiant heat flux varies as the inverse square of the distance to the target, R. With an actual point or spherical source of thermal radiation, the distance R is simply the distance from the point, or from the center of the sphere, to the target (Drysdale 1998 and SFPE Engineering Guide 1999).

The thermal radiation hazard of fires depends on the composition of the fuel, the size and the shape of the fire, the duration of the fire, its proximity to the object at risk, and the thermal characteristics of the object exposed to the fire. A point source exposure fire may start from either fixed or transient combustibles (e.g., electrical cabinet, pump, liquid spill, switchgear or motor control center (MCC), or intervening combustible some distance above the floor). For example, the top of a electrical cabinet is the point source we use for a postulated switchgear fire. The point source of a transient combustible liquid spill or pump fire is located on the floor.

The point source model assumes that radiant energy is released from the center of the fire. The radiant heat flux is inversely related to the horizontal distance of the target from the fire. This is expressed mathematically, in the following equation:

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

where:

- $\dot{q}''$ = radiative heat flux (kW/m^2 [Btu/sec/ft^2)]
- $\dot{Q}$ = heat release rate of the fire [kW (Btu/sec)]
- R = radial distance from the center of the flame from edge of source fire [m (ft)]
- χ_r = fraction of total energy radiated

In general, χ_r depends on the fuel, flame height, and configuration. It varies from approximately 0.15 for low-sooting fuels, such as most alcohols, to 0.60 for high-sooting fuels. In very large fires (several meters in diameter), cold soot can envelop the luminous flames and reduce χ_r considerably. (See Figure 1.)

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

$$\dot{Q} = \dot{m}''\Delta H_{c,eff} A_f \qquad (2)$$

where:

- $\dot{Q}$ = heat release rate (kW)
- $\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)
- A_f = horizontal burning area of the fuel (m^2)

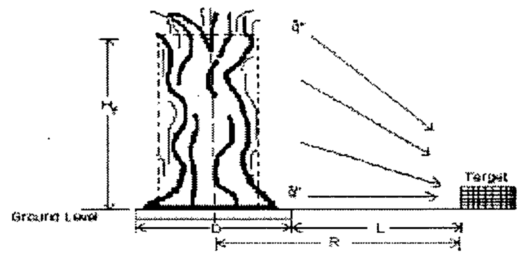


Figure 1 - Illustration of Radiant Heat Flux From a Point Source Fire to a Target Fuel

Appendix A gives an example of the use of a Microsoft Excel® worksheet to estimate flame heat flux to a target fuel using point source radiation model.

SOLID-FLAME RADIATION MODEL WITH TARGET LOCATED ABOVE GROUND LEVEL

This worksheet provides a method for assessing the impact of radiation from pool fires to potential targets using view or configuration factor algebra. The method included in this worksheet contains a range of detailed calculations. Some methods are most appropriate for first order, initial hazard assessments, while greater engineering effort is required for more detailed methods which are capable of better predictions.

The method presented in this section has been included in the Society of Fire Protection Engineering (SFPE) Engineering Guide on Thermal Radiation. The accuracy of this method has been examined in the SFPE Engineering Guide through comparisons of the method with available experimental data (SFPE Engineering Guide 1999).

The solid-flame model assumes that the fire can be represented by a solid body of a simple geometrical shape, with thermal radiation emitted from its surface, and that non-visible gases do not emit much radiation. (See Figure 2.) The geometries of the fire, target, and their relative positions must be taken into account since part of the fire may be obscured as viewed from the target thus changing the effective volume of the fire. The thermal radiation intensity to an element outside the flame envelope is calculate by the following equation:

$$\dot{q}'' = EF_{12} \qquad (3)$$

where:

$\dot{q}''$ = incident radiative heat flux (kW/m^2)
E = average emissive power at flame surface (kW/m^2)
$F_{1\to2}$ = configuration or view factor

<u>Emissive Power</u>

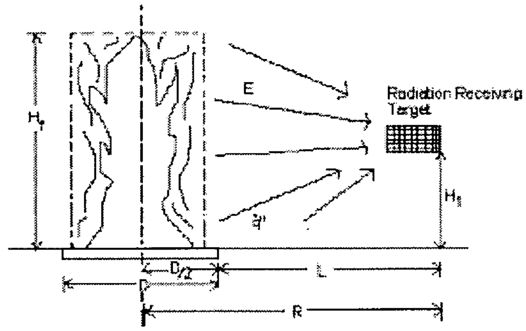
Emissive power is the total radiative power leaving the surface of the fire per unit area per unit time. Emissive power can be calculated by the use of Stefan's law, which gives the radiation of a black body in relation to its temperature. Because fire is not a perfect black body, the emissive power is a fraction (ε) of the black body radiation:

$$E = \varepsilon\sigma T^4 \qquad (4)$$

where:

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

Figure 2 - Solid Flame Radiation Model With No Wind and Target Above Ground Level



To use Stefan-Boltzmann's law to calculate radiation the inspector must estimate the fire's temperature and emissivity. Turbulent mixing causes the fire temperature to vary. Therefore, it can be useful to calculate radiation from data on the fraction of heat liberated as radiation, or to rely on measured radiation values.

Shokri and Beyler (1989) correlated experimental data on flame radiation to external targets in terms of the "average emissive power" of the flame. The flame is assumed to be a cylindrical, black-body, homogeneous radiator with an average emissive power. The effective power of the pool fire in terms of effective diameter is given by the following correlation:

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

where:

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

The effective power is the average emissive power over the whole flame and is significantly less than local emissive power level. The emissive power decreases with increasing pool diameter because black smoke outside the flame dims the radiation of the luminous flame.

For noncircular pools, the effective diameter is the diameter of a circular pool with an area equal to the actual pool area. The effective diameter is obtained by the following equation:

$$D = \sqrt{\frac{4A_f}{\pi}} \qquad (6)$$

where:

A_f = surface area of the noncircular pool
D = diameter of pool fire (m)

Configuration Factor, View Factor or Shape Factor, $F_{1\to2}$

The configuration factor is a purely geometric quantity. It is the fraction of the radiation leaving one surface that strikes another surface directly. In other words, it is the fraction of hemispherical surface area (or solid angle) viewed by the differential element when looking at another differential element on the hemisphere.

The configuration factor is a function of target location, flame height, and fire diameter. Its value is between 0 and 1. When the target is very close to the flame, the configuration factor approaches 1 since the target views only the flame. The flame is modeled as a cylinder with a diameter equal to the pool diameter, D, and a height equal to the flame height, H_f. If the pool has a length-to-width ratio near 1, a circular source of equivalent area can be used to determine the flame height, H_f for non-circular pools. (See Figure 3.)

The flame height of the pool fire is obtained by the following correlation (Heskestad 1995):

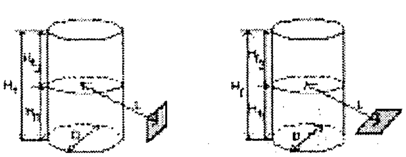
$$H_f = 0.235\dot{Q}^{\frac{2}{5}} - 1.02D \qquad (7)$$

where:

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

Figure 3 - Two-Cylinder Representation of the Configuration Factor for Target Located Above Ground Level

As previously discussed, HRR of the fire can be determined by laboratory or field testing. In the absence of experimental data, the maximum HRR for the fire, $\dot{Q}$, is estimated by Equation 2. The radiation exchange factor between a fire and an element outside the fire depends on the flame's shape, the distance between the fire and the receiving element, and the orientation of the element to the fire. The turbulent diffusion flame is approximated by a cylinder. Under wind-free conditions, the cylinder is vertical (Figure 2).



Given the diameter and height of the flame, Equations 9 is used to obtain the view or configuration factor, $F_{1\to2}$, for a cylindrical radiation source whose target is above the ground . Two cylinders are used to represent the flame for a target above the floor. One cylinder represents the flame below the height of the target, and the other represents the flame above the height of the target (Figure 3).

For targets above ground level, Equations 8 and 9 are used to estimate the two configuration factors for Equation 9:

$$F_{1\to2,V_1} = \begin{pmatrix} \frac{1}{\pi S}.\tan^{-1}\left(\frac{h_1}{\sqrt{S^2-1}}\right) - \frac{h_1}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \\ \frac{A_1 h_1}{\pi S\sqrt{A_1^{\ 2}-1}}.\tan^{-1}\sqrt{\frac{(A_1+1)(S-1)}{(A_1-1)(S+1)}} \end{pmatrix} \qquad (8)$$

where:

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

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

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

$$F_{1\to2,V_2} = \begin{pmatrix} \frac{1}{\pi S}.\tan^{-1}\left(\frac{h_2}{\sqrt{S^2-1}}\right) - \frac{h_2}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \\ \frac{A_2 h_2}{\pi S\sqrt{A_2^{\ 2}-1}}.\tan^{-1}\sqrt{\frac{(A_2+1)(S-1)}{(A_2-1)(S+1)}} \end{pmatrix} \qquad (9)$$

where:

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

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

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

and:

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

The total view or configuration factor at a point is the sum of two configuration factors:

$$F_{1\to 2,\,V} = F_{1\to 2,\,V1} + F_{1\to 2,\,V2} \qquad (10)$$

Appendix A provides an example of the use of a Microsoft Excel® worksheet to estimate flame heat flux to a target fuel above ground level using solid flame radiation model with no wind.

A METHOD FOR ESTIMATING THE CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

Introduction

A fire plume is a buoyant rising column of combustion products, not-yet-burned fuel vapor, and entrained air. The plume of a fire in a building impinges on the ceiling unless the fire is very small or the ceiling very high. A fire plume usually contains smoke particles. Surrounding air mixes into the plume and dilutes the smoke which reduces the temperature. This mixing is called entrainment. To predict the course of a fire, it is necessary to know the rate at which air is entrainmed into the plume. There are correlations for calculating the rate of entrainment, but the results are not entirely reliable because small disturbances in the air near the plume can have large effects on the entrainment rate. If combustion occurs only in the lower part of the plume, there is approximately an order of magnitude more entrained air above the combustion zone than the stoichiometric requirement.

A fire plume has two zones: the flaming (reacting) zone and the nonflaming (nonreacting) zone. The flaming zone is just above the fire source; the fuel vapors released by the combustibles burn in this zone. The air for the reaction is entrained by the upward movement of the reactants. Above the flaming zone of the column of hot combustion products is called the nonflaming zone since no reactions take place there.

Fire Plume Characteristics

Fire plumes are characterized in various ways depending on the scenario. The most common plume for fire protection engineering applications is the point source thermal plume or buoyant axisymmetric plume, which is caused by a diffusion flame just above the burning fuel. An axis of symmetry is assumed along the vertical centerline of this plume. Another type of fire plume is the line plume. This is a diffusion flame formed above a long narrow burner. Air is entrained from both sides of the burner as the hot gases rise. Some examples of line fires are flames spreading over flammable wall linings, a balcony spill plume, a burning long-sofa, a burning row of townhouses, and the advancing front of a forest fire.

Plume Temperature

The highest temperature is at the plume centerline. The temperature decreases toward the edge of the plume, where more ambient air is entrained, thus cooling the plume. The centerline temperature, $T_{p(centerline)}$, varies with height. It is roughly constant in the continuous-flame region and represents the mean flame temperature. The temperature decreases sharply above the flames as more ambient air is entrained into the plume. The symbol $\Delta T_{p(centerline)}$ represents the difference between the centerline plume temperature and the ambient temperature, T_0. Thus $\Delta T_{p(centerline)} = T_{p(centerline)} - T_0$.

There are numerous ways of correlating the height above the fire source and HRR to estimate the plume centerline temperature. For example, consider a region of a ceiling jet at a radial distance from the fire axis equal to the vertical distance from the fire source to the ceiling. In this region, the maximum velocity in the jet drops to half the value near the fire axis, and the temperature (relative to the ambient temperature) drops about 60 percent near the fire axis. The maximum velocity and temperature occur at a distance below the ceiling equal to about 1 percent of the distance from the fire source to the ceiling. If the walls are very far away, the temperature and velocity of the ceiling jet decay to negligibly low values before the jet reflects when it reaches the wall. If the wall is close, the jet reaches the wall. The reflected jet goes back toward the fire axis, just under the original jet. Thus the hot layer under the ceiling becomes thicker.

If the compartment has an open door or window and fire continues, the hot layer ultimately becomes thick enough to reach the top of the opening, at which point the hot smoke-laden gases start to exit the compartment. If the fire is next to a wall (or a corner), the behavior of the ceiling jet can be predicted provided the fire is assumed to be twice (for wall) or four times (for corner) as large as the actual size.

Heskestad 1995, provided a simple correlation for estimating the maximum centerline temperature of a fire plume as a function of ceiling height and HRR:

$$T_{p(centerline)} - T_0 = \frac{9.1\left(\frac{T_0}{g c_p^2 \rho_0^2}\right)^{\frac{1}{3}} \dot{Q}_c^{\frac{2}{3}}}{(z - z_0)^{\frac{5}{3}}} \qquad (11)$$

where:

$T_{p(centerline)}$ = plume centerline temperature (K)
T_0 = ambient air temperature (K)
$\dot{Q}_c$ = convective HRR (kW)
g =acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/Kg-K)
ρ_0 = ambient air density (kg/m^3)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fire (m)

The virtual origin is the equivalent point source height of a finite area fire. The location of the virtual origin is needed to calculate the thermal plume temperature for fires that originate in an area heat source. The thermal plume calculations assume that the plume originates in a point heat source. Examples of area heat sources are pool fires and burning three-dimensional objects such as electrical cabinets and cable trays. A point heat source model is made for an area source by calculating the thermal plume parameters at the virtual point source elevation rather than the actual area source elevation.

The virtual origin, z_0, depends on the diameter of the fire source and the total energy released. The virtual origin is given by:

$$\frac{z_0}{D} = -1.02 + 0.083\frac{\dot{Q}^{\frac{2}{5}}}{D} \qquad (12)$$

where:

z_0 = virtual origin (m)
D = diameter of fuel source (m)
$\dot{Q}$ = total HRR (kW)

For noncircular pools, the effective diameter is the diameter of a circular pool with an area equal to the actual area (Equation 5).

Total HRR, ($\dot{Q}$), is used when calculating the mean flame height and the position of the virtual origin. In estimating other plume properties the convective HRR, ($\dot{Q}_c$), is used since this is the part of the energy release rate that causes buoyancy. The energy losses due to radiation from the flame are generally about 20% to 40% of the total HRR, ($\dot{Q}$). Sootier and more luminous flames, often from fuels that burn inefficiently, will have higher energy losses. The convective HRR is therefore often in the range $\dot{Q}_c$ = 0.6 to $0.8\dot{Q}$, where $\dot{Q}$ is the total HRR and $\dot{Q}_c$ is the convective heat release from the fire.

Appendix A provides an example of the use of a Microsoft Excel® worksheet to estimate the centerline temperature of a buoyant fire plume.

A METHOD FOR ESTIMATING SPRINKLER ACTUATION TIME

Introduction

It is often useful for an inspector to be able to determine if, or when automatic suppression will activate for a postulated fire scenario.

Automatic sprinklers are thermosensitive devices designed to react at predetermined temperatures by automatically releasing streams of water and distributing them in specified patterns and quantities over designated areas. The automatic distribution of water is intended to extinguish a fire or control its spread. A closed-element sprinkler is only activated when it absorbs a sufficient quantity of heat.

The effectiveness of a sprinkler installation depends upon the characteristics of the system itself (e.g., the thermal rating and spacing of the sprinklers, how far the sprinklers are mounted below the ceiling, and their pressure/flow characteristics), the characteristics of the building in which the system is installed (e.g., the height of the ceiling, the volume of the compartment, the presence of openings, joists, or ventilation currents at ceiling level), which can affect the flow of hot gases from a fire to the sprinklers, the type of combustibles, and their closeness to the ceiling.

Sprinkler Activation

In a fire protection analysis, it is often important to estimate the burning characteristics of selected fuels and their effects in enclosures including when fire protection devices such as automatic sprinklers, and thermal and smoke detectors will activate for specific fire conditions. There are equations available based primarily on experimental correlations, for estimating these effects.

Sprinklers are primarily activated by the convective heat transfer from the fire. Convection transfers heat through a circulating medium, typically, air. The air heated by the fire rises in a plume, entraining additional room air. When the plume strikes the ceiling, it spreads to produce a ceiling jet, in a shallow layer beneath the ceiling surface, driven by the buoyancy of the hot combustion products. The thickness of the ceiling jet flow is 5 to 12 percent of the height of the ceiling above the fire source, with the highest temperature and velocity at 1 percent of the distance from the ceiling to the fire source. Heat-sensing elements of sprinklers and thermal detectors are activated by the ceiling jet.

Computer programs have been developed to calculate the response time of sprinklers installed below the ceilings of large compartments. These programs estimate the time to operation for a set-specified fire HRR history. They are convenient because they avoid the tedious repetitive calculations needed to analyze a growing fire. The same calculations can be easily done with a scientific hand calculator for stead-state fires that have a constant HRR. If cases where a more detailed analysis of a fire that has important changes in HRR over time is required, the fire may be represented as a series of steady-state fires one after another.

The following equation gives the time needed to heat the sensing element of a suppression device, from room temperature to operation temperature, in a steady-state fire:

$$t_{activation} = \frac{RTI}{u_{jet}} \ln\left(\frac{T_{jet} - T_0}{T_{jet} - T_{activation}}\right) \qquad (13)$$

where:

$t_{activation}$ = sprinkler head activation time (sec)
RTI = Response Time Index $(\text{m-sec})^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_0 = ambient air temperature (°C)
$T_{activation}$ = activation temperature of sprinkler head (°C)

RTI is the fundamental measure of the thermal sensitivity of sprinklers. The RTI is determined using plunge tests in which the sprinkler is exposed to a uniform gas flow of constant temperature and velocity. The test results can be used to predict the activation time of sprinklers in any fire environment. The RTI assumes that conductive heat exchange between the sensing element and supports is negligible. The RTI is a function of the time constant, τ, of the sprinkler head which is related to the mass and surface area of the sensing element. Faster sprinklers have lower RTI and smaller time constants. Sprinklers with low time constants typically have low ratios of mass to surface area. This is the basis of quick response sprinklers. The RTI concept was developed by Factory Mutual Research Corporation (FMRC). It is given by the following equation:

$$RTI = \frac{m_e c_{p(e)}}{h_e A_e}\sqrt{u_{jet}} \qquad (14)$$

where:

m_e = mass of element (kg)
$c_{p(e)}$ = specific heat of element (kJ/kg-K)
h_e = convective heat transfer coefficient (kW/m^2-K)
A_e = surface area of element (m^2)
u_{jet} = velocity of gas moving past the sprinkler (m/sec)

The expressions for estimating the maximum ceiling jet temperature and velocity as a function of ceiling height, radial position, and HRR were developed by analyzing of experimental data on large-scale fires having HRRs between 668 kW to 98,000 kW. The expressions are given for two regions: where the plume directly hits the ceiling and the surrounding region and, where the flow is horizontal.

The ceiling jet temperature and velocity correlations are given by the following equations (Alpert 1972, and Budnick et al.,1997):

$$T_{jet} - T_0 = \frac{16.9\dot{Q}^{\frac{2}{3}}}{H^{\frac{5}{3}}} \quad \text{for} \frac{r}{H} \le 0.18 \qquad (15)$$

$$T_{jet} - T_0 = \frac{5.38\left(\frac{\dot{Q}}{r}\right)^{\frac{2}{3}}}{H} \quad \text{for} \frac{r}{H} > 0.18 \qquad (16)$$

$$u_{jet} = 0.96\left(\frac{\dot{Q}}{H}\right)^{\frac{1}{3}} \quad \text{for} \frac{r}{H} \le 0.15 \qquad (17)$$

$$u_{jet} = \frac{0.195\dot{Q}^{\frac{1}{3}}H^{\frac{1}{2}}}{r^{\frac{5}{6}}} \quad \text{for} \frac{r}{H} > 0.15 \qquad (18)$$

where:

T_{jet} = ceiling jet temperature (°C)
T_0 = ambient air temperature (°C)
$\dot{Q}$ = heat release rate of the fire (kW)
r = radial distance from the plume centerline to the sprinkler head (m)
H = distance from the top of the fuel package to the ceiling level (m)
u_{jet} = ceiling jet velocity (m/sec)

These correlations are widely used to calculate the maximum temperature and velocity in the ceiling jet at any distance, r, from the fire axis. Note, the regions where each expression is valid are given as a function of the ratio of the radial distance, r, to the ceiling height, H. As the ratio of r to H increases with distance from the centerline of the plume jet, r/H increases. For example, regions where r/H>18, use Equation 16. Equation 15 is used for a small radial distance where the hot gases have just begun to spread under the ceiling.

As with the temperatures there are two velocity regions in the ceiling jet flow, u_{jet}: (1) one close to the impingement point where velocities are nearly constant and (2) the other farther away where velocities vary with radial position.

The ceiling jet temperature is important in fire safety analysis because sprinklers are usually on the ceiling. Knowing the temperature and velocity of the ceiling jet as a function of radial distance enables inspectors to estimate the response times of sprinklers.

The temperature and velocity of a ceiling jet also vary with the depth of the jet. Near the ceiling, the temperature is at a maximum, then decreases downward. The temperature profile of a ceiling jet is not symmetric like the temperature profile of a plume, where the maximum temperature is along the plume centerline.

Knowing the ceiling jet temperature and velocity, the actuation time of a sprinkler can be estimated if the spacing of the sprinkler and the RTI is known.

Appendix A provides an example of the use of a Microsoft Excel® worksheet to estimate the sprinkler actuation time.

A METHOD FOR PREDICTING COMPARTMENT FLASHOVER

Introduction

The likelihood of flashover can be estimated by determinating the temperature within a compartment during a fire. Flashover occurs when the surface temperatures of combustibles rise, producing pyrolysis gases, and the compartment heat flux ignites the gases. Flashover is assumed if the temperature of the smoke layer exceeds 450 °C (842 °F). Flashover generally occurs when the smoke layer reaches temperatures between 500 °C (932 °F) and 600 °C (1112 °F). The hot-smoke layer is considered almost a black-body radiator. At 450 °C (842 °F) the radiation from the smoke would be approximately 15 kW/m^2 (1.32 Btu/ft^2-sec). Fuel burning above 450 °C (842 °F) has a higher incident heat flux if the fire is in the open.

The International Standards Organization (ISO), defines flashover as "the rapid transition to a state of total surface involvement in a fire of combustion material within an enclosure and the relatively abrupt change from a localized fire to the complete involvement of all combustibles within a compartment" ("Glossary of Fire Terms and Definitions," ISO/CD 13943, International Standards Organization, Geneva, 1996).

NFPA 555 "Guide on Methods for Evaluating Potential for Room Flashover," defines room flashover in terms of temperature rise and heat flux at floor level. The NFPA guide gives a gas temperature rise at flashover of 600 °C (1112 °F) and a floor-level heat flux at flashover of 20 kW/m^2.

Heat Release Required to Cause Flashover

The minimum HRR necessary to cause flashover in a compartment has been widely studied. The minimum rate increases with the size of the compartment, and depends, on the ventilation in the compartment. If there is too little ventilation, flashover cannot occur. If there is too much excess air flow, it dilutes and cools the smoke, requiring a higher HRR to reach the critical temperature for flashover. The materials of construction and the thickness of the ceiling and upper walls are also important factors in determining whether flashover will occur and, if so, how soon.

There are several methods of estimating the onset of flashover in a compartment. The methods are usually based on simplified mass and energy balances for single-compartment fires and correlations with experimental data on fires.

Observations from full-scale fire tests and fire fighter experience describe flashover as a discrete event. Numerous variables affect the transition of a compartment fire to flashover. Thermal influences are clearly important when radiative and convective heat flux are assumed to be predominate. Ventilation, compartment volume, and the chemistry of the hot-gas layer can also influence the occurrence of flashover. Although the speed of the transition to flashover increases the uncertainties, the onset of flashover can still be estimated by correlating with the considerable body of full-scale test data on flashover.

Thomas (1981), developed a semi-empirical correlation of the HRR necessary to cause flashover in a compartment. He used a simple model of flashover in a compartment to study the effect of wall-lining materials and thermal feed-back to the burning objects. He predicted a temperature rise of 520 °C (968 °F) and a black-body radiation of 22 kW/m^2 to a surface distant from burning wood fuel at the predicted critical HRR necessary to cause flashover. According to the NFPA 555, room flashover potential is best estimated by using Thomas's flashover correlation (Equation 18).

Thomas' flashover correlation simplifies the energy balance of a compartment fire. The correlation gives the minimum HRR for flashover (Thomas 1981, Walton, and Thomas 1995, and NFPA 555 2000 Edition):

$$\dot{Q}_{FO} = 7.8A_T + 378A_v\sqrt{H_v} \tag{19}$$

where:

$\dot{Q}_{FO}$ = heat release rate to cause flashovber (kW)
A_T = total area of the enclosing compartment surfaces (m^2), excluding the area of the vent opening(s)
A_v = area of the ventilation opening(s) (m^2)
H_v = height of the ventilation opening(s) (m)

The constants in Equation 18 represent values correlated to experiments producing flashover.

This equation requires that the duration of the fire be known or that the fire has been burning for a long period of time and the heat conduction has become steady-state.

Typically a few minutes up to around 30 minutes is a reasonable range of time for estimating the likelihood of flashover. Firefighter response time is also usually within this range (Karlsson and Quintiere 2000).

Appendix A provides an example of the use of a Microsoft Excel® worksheet to estimate the HRR necessary to cause flashover.

SUMMARY

The additional fire scenario estimating tools described in this paper will advance the NRC risk-informed inspection process in several ways:

1. The use of simple fire dynamics correlations will enable regional fire protection inspectors to transition from purely qualitative fire risk evaluations to evaluations based on both qualitative and quantitative methods. The correlations will decrease the reliance on opinion and reduce the uncertainties in fire risk evaluations.

2. The worksheets with locked-in equations and correlations will allow regional inspectors to more easily perform fire hazard analyses, reduce the potential for mathematical errors and the misapplication of the SFPE Handbook of Fire Protection Engineering and NFPA Fire Protection Handbook equations.

3. Regional inspectors gain insights into the fire risk scenarios by having tools that can rapidly be changed to calculate potential fire dynamics effects.

LESSONS LEARNED AND IMPROVEMENTS

Lessons learned and improvements have come about primarily during training of the inspectors in the quarterly NRC regional fire protection inspectors workshops and the inspector's applications of the worksheets in actual NPP inspections. There are three major areas where lessons learned/improvements have been made to date.

1. One advantage of worksheets is the tabular listing of material fire property data. Collecting the input to the fire dynamics equations and correlations for this is a project in itself. There were three lessons learned identified. First, when there are several values in the literature for the same material, which value should be used? This was a problem with HRRs for cable jackets. The solution was to pick the "best" value and use only that value in the worksheet. If the licensee has a more precise value the inspector can input that value. The second problem is unavailable or incomplete data. This problem was discussed in training workshop sessions. Much of the HRR data currently available was funded and developed for a specific end-user. For example, the General Services Administration (GSA) (which deal mostly with office environments) HRR values

may not be applicable to NPPs. At times inspectors have to correlate the scenario they are developing with known data that may not, at first, seem applicable to NPPs. Third, some of the existing data does not fully describe the potential hazard. A good example of this is the HRR for electrical cabinets. The published data focus on combustibles in the cabinet (typically cable insulation) and neglect possible large energy release [amperes squared multiplied by time (I^2t)]. The fire at San Onofre Nuclear Generating Station, Unit 3, on February 3, 2001, showed that heat from an electrical fault in a cabinet can vaporize copper conductors and destroy surrounding metal cabinets. For medium- and high-voltage applications, preliminary NRC research indicates that these HRR values may be under predicting by a factor of 1000. Inspectors are aware of this and are instructed to use higher values to include the electrical energy when they can justify the higher values. Additionally, the inspector are trained in the fundamentals of fire dynamics and the use of the engineering correlations to recognize those configurations where the correlations are appropriate and where they should not be used. The NRC/NRR staff fire protection engineers are always available for inspector consultation to ensure the proper application of these analysis tools.

2. Most of the equations and correlations in the worksheets are simple mathematical expressions. The mathematical expressions are not limited and sometimes give physically impossible values. To prevent such errors, the worksheets have red warning flags added. If a value exceeds known limits, a red flag appears. For example a red flag appears when an equation increases room temperature values well beyond those physically possible.

3. For convenience the new worksheets use pull-down menus and dialog boxes. This enhancement will allow the users to select the single input, instead of entering all the parameters associated with the input. For example, an inspector can simply click on "concrete" in the menu and the correct parameters appear in the equation. This enhancement will also eliminate manual errors in entering the table values in the equations.

CONCLUSION

Using commercial available spreadsheet software (like Microsoft Excel®) to create a series of computational worksheets, the techniques of fire dynamics analysis can be taught to and reliably applied by inspectors. The worksheets also reduce mathematical complexities and errors.

The NRR fire protection staff is continuing to develop additional worksheets for regional inspector application in the area of fire risk evaluation. The worksheets discussed in this paper are the second set completed and put into use. The NRC/NRR fire protection engineering staff expects to complete the full suite of fire dynamics worksheets in about 3 years.

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APPENDIX A

SAMPLE PROBLEM

This is an example of how to do an engineering FHA using the NRC/NRR fire dynamics Microsoft Excel® worksheets.

STATEMENT OF PROBLEM

During a routine fire protection inspection, a NRC inspector discovers a significant oil leak in a station air compressor. It is important to determine whether a fire involving 20 gallon spill of lubricating oil from a compressor could damage the safety-related cable tray and electrical cabinet in an access corridor in the fuel building. The compressor is on a pedestal approximately 1.0 foot above floor level and has a 12 ft^2 (1.12 m^2) oil retention dike. The safety-related cable trays are located 8 ft (2.45 m) above the corridor floor with a horizontal distance of 4 ft (1.2 m) from edge of the compressor's dike. The horizontal distance between the compressor dike and the electrical cabinet is 5 ft (1.52 m).

The access corridor has a floor area of 20 x 15 ft (6 x 4.6 m), a ceiling height of 10 ft (3 m), and has a single unprotected vent opening (door) of 4 x 6 ft (1.22 x 1.4 m). The compartment has no forced ventilation. The compartment construction is 1 ft thick concrete. The corridor has a detection system and a wet pipe sprinkler system. The nearest sprinkler is rated at 165 °F (74 °C) with a RTI of 235 $(m\text{-}sec)^{1/2}$) and located 9.8 ft (2.98 m) from the center of the dike. Determine if there is a credible fire hazard to the safety-related cable trays and electrical cabinet.

Use the following worksheets to evaluate fire scenario.

1. Heat flux to the target (electrical cabinet) using point source model, $\dot{q}''_{cabinet}$
2. Heat flux to the target (cable trays) using the solid-flame radiation model, $\dot{q}''_{cable}$
3. Centerline plume temperature, $T_{P(centerline)}$
4. Sprinkler activation time, $t_{activation}$
5. HRR necessary to cause flashover, $\dot{Q}_{FO}$

ANALYSIS

Accidental spills of flammable and combustible liquid fuels and resulting fires depend on the composition of the fuel, the size and shape of the fire, the duration of the fire, its proximity to the object at risk, and the thermal characteristics of the object exposed to the fire. Liquids with relatively high flash points (like lube oil or diesel fuel) require localized heating to ignite. However, once started, a pool fire spreads rapidly over the surface of the liquid spill. To perform a conservative FHA, it will be assumed that the 20 gallons of lubricating oil will be spilled into the diked area and the over heated compressor ignites the oil.

The summary results of the calculations are given in table. See Microsoft Excel® worksheets for details of the calculations.

Fire Hazard Calculation for Compressor Lubricating Oil Spill in Access Corridor

Heat flux to target (electrical cabinet) $\dot{q}''$ (kW/m^2)	Heat flux to target (cable trays) $\dot{q}''$ (kW/m^2)	Centerline plume temperature $T_{P(centerline)}$ [°C (°F)]	Sprinkler activation time $t_{activation}$ (min)	HRR necessary to cause flashover $\dot{Q}_{FO}$ (kW)
12.50	17	689 (1272)	2	2100

It should be noted that exposure to high plume temperatures could potentially cause the unprotected safety-related cable trays to fail. The flame heat fluxes to the electrical cabinet and the cable trays are high enough to damage them.

The results of the calculation demonstrate that a pool fire with a 12 ft^2 dike area in an access corridor could damage unprotected safety-related cable trays and electrical cabinets. The analysis also suggests that for the postulated oil fire, the sprinkler system, if operable, should activate and should provide some protection to the safety-related cables and equipment.

METHOD OF ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET LIQUID FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION POINT SOURCE RADIATION MODEL

The following calculations estimate the radiative heat flux from liquid pool fire to a target fuel. The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

All subsequent values are calculated by the spreadsheet, and based on values specified in the input parameters.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Net Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Spill Area or Dike Area (A_{dike})	12.00	ft^2	1.11
Distance between Pool Fire and Target (L)	5.00	feet	1.52
Radiative Fraction (χ_r)	0.35		

THERMAL PROPERTIES FOR

Lube Oil

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Effective Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)
Methanol	0.017	20,000	796
Ethanol	0.015	26,800	794
Butane	0.078	45,700	573
Benzene	0.085	40,100	874
Hexane	0.074	44,700	650
Heptane	0.101	44,600	675
Xylene	0.09	40,800	870
Acetone	0.041	25,800	791
Dioxane	0.018	26,200	1035
Diethy Ether	0.085	34,200	714
Benzine	0.048	44,700	740
Gasoline	0.055	43,700	740
Kerosine	0.039	43,200	820
Diesel	0.045	44,400	918
JP-4	0.051	43,500	760
JP-5	0.054	43,000	810
Transformer Oil, Hydroc	0.039	46,000	760
Fuel Oil, Heavy	0.035	39,700	970
Crude Oil	0.0335	42,600	855
Lube Oil	0.039	46,000	760

Reference SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-2)

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference SFPE Handbook of Fire Protection Engineering 2nd Edition (Page -3-206)

POINT SOURCE RADIATION MODEL

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

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

Pool Fire Diameter Calculation

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

$D = (4\ A_{dike}/\pi)^{1/2}$

D = **1.19** m

Heat Release Rate Calculation

$Q = m''\Delta H_c A_{dike}$

Where
- Q = pool fire heat release rate (kW)
- m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ΔH_c = net heat of combustion of fuel (kJ/kg)
- A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)

Q = **2000.02** kW

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

R = L+D/2

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

R = **2.12** m

Radiative Heat Flux Calculation

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

q'' = 12.40 kW/m^2 1.09 BTU/ft^2-sec ANSWER

FAILURE CRITICAL HEAT FLUX FOR CABLES

Cable Type	Damage Threshold Damage Threshold Heat Flux (kW/m^2)
IEEE-383 qualified	10
IEEE-383 unqualified	5

Reference Fire-Induced Vulnerability Evaluation (FIVE), page 6-14

NOTE

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METHOD OF ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET LIQUID FUEL ABOVE GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

The following calculations estimate the radiative heat flux from liquid pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire above ground level to determine if secondary ignitions are likely with no wind.

Parameters should be specified ONLY IN THE RED INPUT PARAMETER BOXES.
All subsequent values are calculated by the spreadsheet, and based on values specified in the input parameters.

INPUT PARAMETERS

Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Net Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Spill Area or Dike Area (A_{dike})	12.00	ft^2	1.11 m^2
Distance between Pool Fire and Target (L)	4.00	feet	1.219 m
Vertical Distance of Target from Ground ($H_1 = H_{f1}$)	7.00	feet	2.134 m

THERMAL PROPERTIES FOR

Lube Oil

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Effective Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)
Methanol	0.017	20,000	796
Ethanol	0.015	26,800	794
Butane	0.078	45,700	573
Benzene	0.085	40,100	874
Hexane	0.074	44,700	650
Heptane	0.101	44,600	675
Xylene	0.09	40,800	870
Acetone	0.041	25,800	791
Dioxane	0.018	26,200	1035
Diethy Ether	0.085	34,200	714
Benzine	0.048	44,700	740
Gasoline	0.055	43,700	740
Kerosine	0.039	43,200	820
Diesel	0.045	44,400	918
JP-4	0.051	43,500	760
JP-5	0.054	43,000	810
Transformer Oil, Hydroc	0.039	46,000	760
Fuel Oil, Heavy	0.035	39,700	970
Crude Oil	0.0335	42,600	855
Lube Oil	0.039	46,000	760

Reference SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-2)

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference SFPE Handbook of Fire Protection Engineering 3rd Edition (Page -3-272)

SOLID FLAME RADIATION MODEL

$q'' = EF_{12}$

Where q'' = incident radiative heat flux on the target (kW/m^2)
E = emissive power of the pool fire flame (kW/m^2)
F_{12} = view factor between target and the flame

Pool Fire Diameter Calculation

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

$D = (4\, A_{dike}/\pi)^{1/2}$

D = **1.19** m

Emissive Power Calculation

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

E = **56.71** (kW/m^2)

View Factor Calculation

$F_{12,V1} =$ $1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2})-(h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_1h_1/\pi S(A_1^2-1)^{1/2}\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$

$F_{12,V2} =$ $1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2})-(h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_2h_2/\pi S(A_2^2-1)^{1/2}\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$

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

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

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

$S = 2R/D$

$h_1 = 2H_{f1}/D$

$h_2 = 2H_{f2}/D$

$F_{12,V} = F_{12,V1} + F_{12,V2}$

Where $F_{12,V}$ = total vertical view factor
R = distance from center of the pool fire to edge of the target (m)
H_f = height of the pool fire flame (m)
D = pool fire diameter (m)

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

R = L+D/2 = **1.815** m

Heat Release Rate Calculation

$Q = m''\Delta H_c A_f$

Q = **2000.02** kW

Pool Fire Flame Height Calculation

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

H_f = **3.699** m

$S = 2R/D =$	**3.047**						
$h_1 = 2H_{f1}/D =$	**3.582**						
$h_2 = 2H_{f2}/D =$ $2(H_f-H_{f1})/D =$	**2.628**						
$A_1 = (h_1^2+S^2+1)/2S =$	**3.793**						
$A_2 = (h_2^2+S^2+1)/2S =$	**2.821**						
$B = (1+S^2)/2S =$	**1.687**						
$F_{12,H} =$	**0.153**	0.093	0.231	0.388	0.750	**0.153**	$F_{12,V1}$
$F_{12,V} =$	**0.143**	0.077	0.170	0.294	0.800	**0.143**	$F_{12,V2}$
$F_{12,V} =$	**0.296**						

Radiative Heat Flux Calculation

$q'' = EF_{12}$

q"= **16.76 kW/m²** **1.48 BTU/ft²-sec** **ANSWER**

FAILURE CRITICAL HEAT FLUX FOR CABLES

Cable Type	Damage Threshold Damage Threshold Heat Flux (kW/m²)
IEEE-383 qualified	11.4
IEEE-383 unqualified	5.7

Reference Fire-Induced Vulnerability Evaluation (FIVE), page 6-14

NOTE

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METHOD OF ESTIMATING TEMPERATURE OF A BUOYANT FIRE PLUME

The following calculations estimate the centerline plume temperature in a compartment fire.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
All subsequent values are calculated by the spreadsheet, and based on values specified in the input parameters.

INPUT PARAMETERS

Heat Rlease Rate of the Fire (Q)	2000.00	(kW)		
Distance from the Top of the Fuel to the Ceiling (z)	9.00	ft	2.74	m
Area of Combustible Fuel (A_c)	12.00	ft^2	1.11	m^2

AMBIENT CONDITIONS

Ambient Air Temperature (T_0)	77.00	°F	25.00	°C
			298.00	K
Specific Heat of Air (c_p)	1.00	kJ/kg-K		
Ambient Air Density (ρ_0)	1.20	kg/m^3		
Acceleration of Gravity (g)	9.81	m/sec^2		
Convective Heat Release Fraction (χ_c)	0.50			

ESTIMATING PLUME CENTERLINE TEMPERATURE

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 2-9)

$T_{p(centerline)} - T_0 = 9.1\ (T_0/g\ c_p^2\ \rho_0^2)^{1/3}\ Q_c^{2/3}\ (z - z_0)^{-5/3}$

Where
- Q_c = Convective portion of the heat release rate (kW)
- T_0 = ambient air temperature (K)
- g = acceleration of gravity (m/sec^2)
- c_p = specific heat of air (kJ/kg-K)
- ρ_0 = ambient air density (kg/m^3)
- z = distance from the top of the fuel package to the ceiling (m)
- z_0 = hypothetical virtual origin of the fire (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\ Q$

Where
- Q = heat release rate of the fire (kW)
- χ_c = convective heat release fraction

Q_c = 1000 kW

Pool Fire Diameter Calculation

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

$D = (4\ A_{dike}/\pi)^{1/2}$

D = 1.19 m

Hypothetical Virtual Origin Calculation

$z_0/D = -1.02 + 0.083\ (Q^{2/5})/D$

Where
- z_0 = virtual origin of the fire (m)
- Q = heat release rate of fire (kW)
- D = diameter of pool fire (m)

z_0/D = 0.44

z_0 = 0.52 m

Centerline Plume Temperature Calculation

$T_{p(centerline)} - T_0 = 9.1\ (T_0/g\ c_p^2\ \rho_0^2)^{1/3}\ Q_c^{2/3}\ (z - z_0)^{-5/3}$

$T_{p(centerline)} - T_0$ = 664.22

$T_{p(centerline)}$ = 962.22 K

$T_{p(centerline)}$ = 689.22 °C   1272.59 °F   ANSWER

NOTE

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METHOD OF ESTIMATING SPRINKLER RESPONSE TIME

The following calculations estimate the sprinkler head activation time with no forced ventilation.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
All subsequent values are calculated by the spreadsheet, and based on values specified in the input parameters.

INPUT PARAMETERS

Heat Release Rate of the Fire (Q)	2000.00	(kW)		
Sprinkler Response Time Index (RTI)	235	$(m\text{-}sec)^{1/2}$		
Activation Temperature of the Sprinkler Head ($T_{activation}$)	165	(°F)	73.89	°C
Distance from the Top of the Fuel Package to the Ceiling Level (H)	9.00	(ft)	2.74	m
Radial Distance from the Plume Centerline to nearest Sprinkler Head (r)	9.80	(ft)	2.99	m
Ambient Air Temperature (T_0)	68.00	(°F)	20.00	°C
			293.00	K

Convective Heat Release Fraction (χ_c) 0.70

r/H = 1.09

GENERIC SPRINKLER RESPONSE TIME INDEX (RTI)* FOR Standard response bulb

Common Sprinkler Type	Generic Response Time Index RTI $(m\text{-}sec)^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34

Reference: Madrzykowski, D., "Evaluation of Sprinkler Activation Prediction Methods" ASIAFLAM'95, International Conference on Fire Science and Engineering, 1st Proceeding, March 15-16, 1995, Kowloon, Hong Kong, pp. 211-218.

***Note: The actual RTI should be used when the value is available.**

GENERIC SPRINKLER TEMPERATURE RATING ($T_{activation}$)* FOR Ordinary

Temperature Classification	Range of Temperature Ratings (°F)	Generic Temperature Ratings (°F)
Ordinary	135 to 170	165
Intermediate	175 to 225	212
High	250 to 300	275
Extra high	325 to 375	350
Very extra high	400 to 475	450
Ultra high	500 to 575	550
Ultra high	650	550

Reference: Automatic Sprinkler Systems Handbook, 6th Edition, Natrional Fire Protection Association, Quincy, Massachusetts, 1994, p. 67.

***Note: The actual temperature rating should be used when the value is available.**

ESTIMATING SPRINKLER RESPONSE TIME

Reference: NFPA Fire Protection Handbook 18th Edition (Page 11-97)

$t_{activation} = (RTI)/u_{jet}^{1/2} \ln (T_{jet} - T_0)/T_{jet} - T_{activation})$

Where $t_{activation}$ = sprinkler activation response time (sec)

RTI = sprinkler Response Time Index $(m\text{-}sec)^{1/2}$

u_{jet} = ceiling jet velocity (m/sec)

T_{jet} = ceiling jet temperature (°C)

T_0 = ambient air temperature (°C)

$T_{activation}$ = activation temperature of sprinkler head (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_0 = 16.9\,(Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_0 = 5.38\,(Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)
T_0 = ambient air temperature (°C)
Q_c = convective portion of the heat release rate (kW)
H = distance from the top of the fuel package to the ceiling level (m)
r = radial distance from the plume centerline to the sprinkler head (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\,Q$

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

Q_c = 1400 kW

Radial Dstance to Ceiling Height Ratio Calculation

r/H = 1.09 r/H > 0.18

$T_{jet} - T_0 = 5.38\,(Q_c/r)^{2/3}/H$

$T_{jet} - T_0$ = 118.34

T_{jet} = 138.34 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\,(Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\,Q^{1/3}\,H^{1/2})/r^{5/6}$ for r/H > 0.15

u_{jet} = ceiling jet velocity (m/sec)
Q = heat release rate of the fire (kW)
H = distance from the top of the fuel package to the ceiling level (m)
r = radial distance from the plume centerline to the sprinkler head (m)

Radial Dstance to Ceiling Height Ratio Calculation

r/H = 1.09 r/H > 0.15

$u_{jet} = (0.195\,Q^{1/3}\,H^{1/2})/r^{5/6}$

u_{jet} = 1.635 m/sec

Sprinkler Activation Time Calculation

$t_{activation} = (RTI)/u_{jet}^{1/2}\ \ln\,(T_{jet} - T_0)/T_{jet} - T_{activation})$

$t_{activation}$ = 111.69 sec

The sprinkler will respond in approximately **1.86 minutes** **ANSWER**

NOTE: If $t_{activation}$ = "NUM" Sprinkler is not activate

NOTE

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METHOD OF PREDICTING VENTED COMPARTMENT FLASHOVER
NO FORCED VENTILATION

The following calculations estimate the minimum heat release rate required to cause compartment flashover.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
All subsequent values are calculated by the spreadsheet, and based on values specified in the input parameters.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	feet	6.096	m
Compartment Length (l_c)	15.00	feet	4.572	m
Compartment Height (h_c)	10.00	feet	3.048	m
Vent Width (W_v)	4.00	feet	1.219	m
Vent Height (H_v)	6.00	feet	1.829	m

METHOD OF THOMAS

Reference: SFPE Handbook of Fire Protection Engineering 2nd Edition (Page 3-146)

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (H_v)^{1/2}$

Where Q_{FO} = heat release rate of the fire (kW)
A_T = total area of the compartment enclosing surface boundaries (m^2)
A_v = area of ventilation opening (m^2)
H_v = height of ventilation opening (m)

Area of Ventilation Opening Calculation

$A_v = (W_v)(H_v)$

$A_v =$ **2.23** m^2

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c x l_c) + 2(h_c x w_c) + 2(h_c x lc)] - A_v$

$A_T =$ **118.54** m^2

Minimum Rate of Heat Release for Flashover

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (H_v)^{1/2}$

$Q_{FO} =$ **2064.41** kW **ANSWER**

NOTE

The above calculations are based on principles developed in the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering, 2nd Edition 1995. Calculations are based on certain assumptions and has inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.