July 12, 2001

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

THRU: John Hannon, Chief ***/RA/***
Plant Systems Branch
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Office of Nuclear Reactor Regulation

Eric Weiss, Section Chief ***/RA/***
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FROM: Naeem Iqbal and Mark Salley, Fire Protection Engineer ***/RA/***
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Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation

SUBJECT: REQUEST FOR APPROVAL TO PRESENT PAPER TITLED; "DEVELOPMENT OF A QUANTITATIVE FIRE SCENARIO ESTIMATING TOOL FOR THE U.S. NUCLEAR REGULATORY COMMISSION FIRE PROTECTION INSPECTION PROGRAM"

The purpose of this memorandum is to request approval to submit and present the subject paper at the Structural Mechanics in Reactor Technology (SMiRT) Post-Conference Fire Protection Seminar No. 1, on August 20-23, 2001, at the Millstone Nuclear Power Station Conference Facility in Waterford, Connecticut, USA.

Attachment 1 is NRC Form 390 for the Office Director approval. Attachment 2 is the final copy of the subject paper. The deadline for the paper submittal is July 15, 2001. This copy has been reviewed by the NRC Technical Editor.

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

Approved: ***/RA/*** on July 16, 2001
Gary M. Holahan, Director, DSSA/NRR

Attachments: As stated (2)

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DEVELOPMENT OF A QUANTITATIVE FIRE SCENARIO ESTIMATING TOOL FOR THE U.S. NUCLEAR REGULATORY COMMISSION FIRE PROTECTION INSPECTION PROGRAM*

Naeem Iqbal** and Mark Henry Salley, P.E.**
Office of Nuclear Reactor Regulation
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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 Program (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 the potential fire risks to the operating reactor. A key step in the SDP is determining whether a credible fire scenario is possible. Until now inspectors have done so by qualitative methods. This paper describes a simplified quantitative fire scenario estimating tool developed by the NRC Office of Nuclear Reactor Regulation (NRR) fire protection staff, for use by the regional fire protection inspectors to perform a fire hazard analysis (FHA) of a NPP. The FHA is intended to permit fire protection inspectors to conservatively evaluate the potential for credible fire scenarios to cause critical damage to essential fire safe-shutdown (FSSD) systems, components, or equipment. This quantitative tool was developed using Microsoft Excel® spreadsheets. We developed this tool by applying the principles of the state-of-the-art Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering (2nd Edition, 1995). An example of the methodology is presented in the Appendix.

*This paper was prepared by the employees of the U.S. Nuclear Regulatory Commission. The views presented do not represent an official staff position. The NRC has neither approved nor disapproved its technical content.

** Fire Protection Engineer

REGULATORY BACKGROUND

The primary objectives of the fire protection programs at operating U.S. nuclear power plants (NPPs) are to minimize the probability of occurrence of fire and to minimize the consequences of fire. To meet these objectives, the fire protection programs are designed to provide reasonable assurance, through defense in depth, that a fire will not prevent the performance of necessary safe-shutdown functions and that radioactive releases to the environment in the event of a fire will be minimized.

The NRC's regulatory framework for nuclear plant fire protection programs 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 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).

INTRODUCTION

One purpose of performing 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 thus prevent the release of radiation to the environment. Several methods are available for performing a FHA. In this paper we describe a method of quantitatively assessing fire hazards in NRC-licensed NPPs.

The 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. Our method is based on material fire property data being used in scientific calculations. The fire hazard calculations used in the worksheets are simple empirical correlations based on fire dynamics principles.

EFFECTS OF FIRE ON NPP OPERATIONS

Recent studies indicate that accidental fires pose a significant risk to the safe operation of a NPP. In addition to the local destruction, damage may occur far from the burning object through heat transfer and the spread of smoke. A toxic mixture of combustion products in the smoke hinders 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 when temperatures rise and smoke becomes more concentrated.

Empirical data indicate that a nuclear facility experiences more event precursors (small fires that have little impact on nuclear safety) than actual fire events affecting nuclear safety equipment, such as the Browns Ferry Nuclear Power Plant (BFN), Unit 1 fire in 1975. Many argue that no fire in a NPP is without nuclear safety implications because every fire is a threat to safety through its effects on equipment or operating personnel. Nevertheless, statistically a NPP is expected to experience a fire that affects nuclear safety equipment every 6 to 10 years (Ramsey and Modarres, 1998). A recent probabilistic risk assessment (PRA) study of 70 U.S. NPPs (documented in the NUREG-1742 Volume 1, "Perspectives Gained from Individual Plant Examination of External Events (IPEEE) Program") showed that fire represented 75% of the core melt probability, primarily because a single fire and its effects can result in the loss of an otherwise highly reliable redundant safety capability. The loss of redundant safety capability defeats success paths and potentially leads to core melt damage.

FIRE DEVELOPMENT

Fire hazards to NPP equipment may result from thermal destruction, fouling, corrosivity, and other sources. Fire is essentially a chemical reaction of solids, liquids, and gases that ignite and undergo 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 extremely complex and difficult to describe completely.

A fire may start from the ignition of in situ or transient combustibles normally found in the NPP. These materials serve as fuel for combustion. For example, in the physical model a fire begins upon ignition when the fuel combusts and releases heat to the adjacent surroundings. This heat transfer may occur by conduction, convection, and/or radiation. In the fire compartment a rise in temperature 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 rise. The pressure differences across the compartment boundaries developed by the expanding gas typically depends on three factors: (1) the leakage area (including the ventilation system when applicable), (2) the volume of the fire compartment, and (3) the rate of temperature rise. 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 into service in a short time. Regional inspectors have diverse engineering backgrounds in electrical, mechanical, nuclear, chemical, civil engineering diciplines We had to present the fire dynamics correlations so they could be understood by engineers who have 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® spreadsheets with the complex equations and correlations pre-programmed and locked in. The spreadsheets would form the basis to be used to perform quick, easy, accurate calculations. The spreadsheets would also serve as a location to list the physical and thermal properties of materials commonly encountered in the NPP that would be needed in performing these evaluations.

QUANTITATIVE FIRE HAZARD ANALYSIS METHODS

To begin the process, we had to select a series of fire dynamics correlation methods. We decided to use state-of-the-art methods from the SFPE Handbook of Fire Protection Engineering, and if necessary to modify the equations for use in specific NPP application. The following section describes the basic fire dynamics methods selected to develop the fire series of spreadsheet templates.

METHOD OF ESTIMATING HEAT RELEASE RATE

Introduction

The single most important parameter in quantifying fire development is the heat release rate (HRR) of the material vs. time. The HRR history of a fire directly affects the hazard development potential of an enclosure fire. For a routine FHA a broad approximation of burning rates or HRRs is generally acceptable. This contrasts with a post-flashover structure analyses which is often based on the fire duration or fire severity associated with an aggregate fuel loading (combustible load per unit floor area). However, a more accurate determination of burning rate characteristics (i.e., HRR history) is necessary to estimate specific fire effects within an enclosure.

The HRR is not a fundamental property of a fuel and, therefore, cannot be calculated from the basic material properties. Estimates of fire source intensities (i.e., the HRR) can be based either on direct burning rate measurements of similar large fuel configurations or on extrapolations of small-scale test data obtained under simulated thermal conditions. In the absence of measured HRR data, the fire protection engineer must estimate the HRR history for a particular fuel. Although not as accurate as laboratory testing, information in the literature permits estimates of initial fire growth, peak burning rates, and fire duration for fuels and fuel geometries.

Representative unit HRR values for a number of fuels present in the NPP, (e.g., electrical cables, electrical cabinets, flammable/combustible liquids, and transient combustibles) have been measured and reported in various studies (Lee 1985; Nowlen 1986; Nowlen 1987; Chavez 1987; and Babrauskas 1991). Flammable/combustible liquid spill fires and trash fires are the most commonly postulated transient fuel exposure fires in NPPs. Electrical cable and electrical cabinet fires are the most commonly postulated fixed fuel fires.

Estimating HRR

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

Another common method of estimating the HRR is measuring the burning rate, or the mass loss rate. This is done by weighing the fuel package as it burns, using weighing devices or a load cell.

An estimate of the HRR requires that the effective heat of combustion be known. The HRR is calculated using the following equation:

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

where $\dot{Q}$ = heat release rate (kW)

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

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

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

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)

The average burning rate per unit per unit time, the heat of combustion, and fuel-specific properties have been tabulated for a number of different fuels (see SFPE Handbook 2nd Edition, Babrauskas 1995).

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

An example of estimating HRR using Microsoft Excel® spreadsheet has been presented in Appendix A, Figure 1.

METHOD OF ESTIMATING POOL FIRE FLAME HEIGHT

Introduction

A pool fire is a fire in a horizontal upward-facing combusting fuel. The name implies liquids but a pool fire includes certain flat slabs of solids that decompose approximately like liquids. For example Polymethylmethacrylate (PMMA), commonly referred to as “Plexiglass”, behaves in this manner. A liquid fuel can burn when stored in an open tank, or the combustion can take place when the liquid fuel is spilled on land or water. For a given fuel, a large spill of liquid fuel burns with a higher HRR for a short duration while a small spill burns with a lower HRR for a longer duration. When spilled a flammable/combustible liquid may form a pool of any shape and thickness. The shape of the pool may be controlled by the facility and storage geometries such as curbs or dikes. Once ignited, a pool fire spreads rapidly over the surface of the liquid spill. The burning rate of a given fuel can also be affected by the substrate in a spill (i.e., gravel and sand). For flammable/combustible liquids, flame spread rates typically range from approximately 10 cm/sec (4 in/sec) to 2 m/sec (6.6 ft/sec).

Estimating Flame Height

The height of a flame is a significant indicator of hazard since it directly relates to flame heat transfer and the propensity to impact surrounding objects. As a plume of hot gases rises above a flame the plume mixes with its surroundings and the temperature, velocity, and width of the plume changes.
The height and temperature of the flame are important in estimating the ignition of adjacent combustibles. Flames are characterized by a highly intermittent pulsing structure, particularly along the perimeter and near the top of the flame. The intermittency is driven largely by the turbulent mixing of air and subsequent combustion, the formation of new eddies of air and their mixing into the flame. The pulsing behavior affects the temperature of the flame. The temperature at a fixed position will fluctuate widely, particularly around the edges and near the top of the flame. Therefore flame temperature is usually reported in terms of the average flame temperature, or centerline flame temperature.

Flame height is a quantitative characteristic that is of practical importance in many fire situations. Flame height is normally defined as the height at which the flame is observed 50 % (or more) of the time. Above the fuel source, the flaming region is characterized by high temperature, and is generally luminous. Flames from pool fires fluctuate periodically so that the tip of the flame will be significantly different from the length of the continuous combustion or luminous region. Consequently, flame height has been defined by various criteria.

Flame height affects fire detection, fire suppression design, fire heating of building structures, smoke filling rates, fire venting and the ignition of adjacent combustibles. Flame height depends on whether the flame is laminar or turbulent. Short flames are generally laminar, while tall flames tend to be turbulent. The following correlation is widely used for determining the flame height of pool fires:

$$H_f = 0.235\dot{Q}^{\frac{2}{5}} - 1.02D \tag{3}$$

where H_f = flame height (m)

$\dot{Q}$ = heat release rate of the fire (kW)

D = diameter of the fire (m)

This correlation can be used for determining the length of the flame extension along the ceiling and for estimating radiative heat transfer to objects in the enclosure.

An example of estimating flame height using Microsoft Excel® spreadsheet has been presented in Appendix A, Figure 2.

METHOD FOR ESTIMATING BURNING DURATION

Introduction

The burning rate of a given fuel is controlled both by its chemistry and by its form. Fuel chemistry refers to composition, e.g., cellulosic vs. petrochemical. Wood, paper, and cotton are examples of cellulosic material. Petrochemical materials, in general, are plastics largely composed of petroleum or flammable/combustible liquids. The form of the material also has an effect on the burning rate. One way of looking at the form of the fuel is the surface area available to burn compared to the mass of the material. This relationship is called the surface-area-to-mass ratio.

Fire duration is a means of characterizing the hazard of a compartment fire by estimating how the compartment is expected to burn. This is based on the total amount of fuel available and often referred to as the fuel loading. Fuel loading then is the expected length of time a fire will burn,

once it is controlled by the amount of air available. A fire burning at a constant HRR burns fuel mass at a constant rate, as well. Given the mass of material being burned per second, and the amount of material available to be burned, it is possible to estimate the total burning duration of a fuel.

Estimate of Burning Duration of Pool Fire

When a spilled liquid fuel is ignited, a pool fire develops. The diameter of the pool fire depends upon the release mode, the release quantity (or rate), and the burning rate. The surface area of a burning pool fire depends on the configuration of the spill. In some cases, the pool burn area is the area within confined boundaries. Other spills are unrestricted and form a random pattern. The analyst will often have to postulate the expected diameter of the spill. For a fixed mass or volume of flammable/combustible liquid the burning duration t_b, for the pool fire is estimated using the following equation:

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

where t_b = burning duration (seconds or minutes)
V = volume of liquid (gallons or m^3)
D = pool diameter (m)
ν = regression rate (m/sec)

The rate of burning as a pool of liquid burns away and its depth decreases is called the regression rate. This is defined as volumetric loss of liquid per unit surface area of the pool in per unit time. The regression rate can be expressed as:

$$\nu = \frac{\dot{m}''}{\rho} \qquad (5)$$

where ν = regression rate (m/sec)
$\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)
ρ = liquid fuel density (kg/m^3)

An example of estimating burning duration using Microsoft Excel® spreadsheet has been presented in Appendix A, Figure 3.

METHOD OF PREDICTING TEMPERATURE IN A ROOM FIRE WITH NATURAL VENTILATION

Introduction

Estimating the temperature of the hot fire gases is of central importance to evaluating the environmental conditions due to a fire in an enclosure. The temperature change directly affects NPP safety. An estimate of temperature is necessary for predicting mass flow rates in and out through openings, thermal feedback to the fuel and other combustible objects, and thermal influence on detection and suppression systems. Heat from a fire poses a significant threat to the operation of the NPP, both when the component and equipment come in contact with fire gases (mostly CO_2 and H_2O) and when heat is radiated from a distance.

Compartment Fire Growth

A compartment or enclosure fire is a fire that is confined to a single compartment in a structure. Ventilation is through open doors (and other openings) or by heating, ventilation, and air-conditioning (HVAC) systems. The fuel is located in the compartment and typically progresses through several stages.

Stages of Compartment Fires

Initially, fire in a compartment can be treated as a freely burning unconfined fire. This treatment is usually valid until thermal feedback or oxygen depletion in the compartment becomes significant. In many ventilated spaces, ventilation is stopped automatically under fire conditions, either by shutting down fan units or automatic closing of fire doors and dampers. In other spaces, however, ventilation systems may continue to operate or unprotected openings may remain open.

Compartment fires have four stages: a plume/ceiling jet period, an unventilated enclosure smoke filling stage, a pre-flashover vented stage, and a post-flashover vented stage. The course of enclosure fires and the resulting conditions depend on a number of variables, including:

- the fire heat release rate (HRR)
- the enclosure size
- the enclosure construction
- the enclosure ventilation

Method of McCaffrey, Quintiere, and Harkleroad (MQH)

Calculating or predicting the temperatures in an enclosure fire requires, a quantitative relationship of the fire phenomena (i.e., ignition, flame spread, and burning rate). This relationship describes the fire in terms of equations for fire chemistry, physics, fluid mechanics and heat and mass transfer. The equations can be solved to predict the temperature in the compartment. Such a relationship is, therefore, an idealization of the compartment fire phenomena.

The method presented in this section to predict temperature of the hot gas layer in an enclosure fire is the most widely accepted in the fire protection engineering literature. The inspectors are trained to understand assumptions and limitations of the method before employing it.

The temperatures in an enclosure in which a fire is burning are affected by how much air is supplied to the fire and where the air enters the enclosure. Under-ventilated fires in an enclosure have different temperature profiles than well-ventilated fires.

An enclosure with a single rectangular wall opening such as a door (or window) is commonly used for room fire experiments. Such enclosures are commonly involved in real fire scenarios, where a single door (or window) opening serves as the only path for fire-induced natural ventilation to the enclosure. The hot gas layer that forms in compartment fires descends within the opening until a quasi-steady balance is established between the rate of mass inflow to the layer and the rate of mass outflow from the layer.

A complete solution of the mass flow rate in this scenario requires equating and solving two nonlinear equations describing the vent flow rate and the plume entrainment rate as functions of the layer interface height, i.e., the height at which the smoke layer and the non-smoke layer interface. If the smoke layer is not vented the smoke layer gradually increases as the fire grows. This lowers the layer interface and smoke may eventually fill the compartment. McCaffrey, Quintiere, and Harkleroad (MQH) have developed a simple equation for correlating fire growth in a naturally ventilated compartment with the hot gas layer temperature.

Their statistical correlation is based on 100 experimental fires (from eight series of tests involving several types of fuel) in conventionally sized rooms with openings. The temperature differences varied from ΔT = 20 °C (68 °F) to 600 °C (1112 °F). The data were obtained from fires set in the center of the compartment away from the walls. The larger the HRR and the smaller the vent, the higher the temperature of the upper layer gas is expected to rise. The formula for the approximate hot gas layer temperature rise ($\Delta T_g = T_g - T_0$) is:

$$\Delta T_g = 6.85\left[\frac{\dot{Q}^2}{\left(A_0\sqrt{h_v}\right)\left(A_T h_k\right)}\right]^{\frac{1}{3}} \qquad (6)$$

where ΔT_g = upper layer gas temperature rise above ambient ($T_g - T_0$) (K)

$\dot{Q}$ = heat release rate of the fire (kW)

A_0 = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

h_k = heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surfaces excluding area of vent opening (m^2)

This equation can be used for multiple vents by summing the $A_0 (h_v)^{1/2}$ values and can be used for different construction materials by summing the A_T values for the various wall, ceiling, and floor elements.

An example of estimating hot gas layer in a compartment fire with natural ventilation using Microsoft Excel® spreadsheet has been presented in Appendix A, Figure 4.

METHOD OF PREDICTING TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION

Introduction

Forced-ventilation compartments fire scenarios may also be encountered in NPP structures. A fire in a forced-ventilation compartment is very different than in a compartment with natural ventilation. More important the stratified thermal hot gas layer produced by the fire may be unstable. Normally a ventilating system recirculates most of the exhaust air. Continued normal operation of the ventilating system during a fire could mix smoke and combustion products with the supply air and deliver the contaminated mixture throughout the ventilation zone. To prevent this, fire/smoke dampers are often placed in the system. Upon fire detection, the damper positions are changed (closed) so that all exhaust from the fire zone is confined or removed and make-up air is drawn from another area.

Mechanically ventilated spaces are generally easier to analyze than naturally ventilated spaces because the ventilation rate is known with more precision. The volumetric flow rate depends on the pressure-flow characteristics of the fan units serving the space and on the operating control procedures followed under fire conditions. There are four general types of mechanical ventilation systems encountered: (1) push systems, (2) pull systems, (3) push-pull systems, and (4) recirculation systems.

Method of Foote, Pagni, and Alvares (FPA)

This method follows the basic correlations of MQH and adds data for forced-ventilation compartment fire scenarios. Temperature data were obtained from a series of tests conducted at the Lawrence Livermore National Laboratory (LLNL) in the 1983. Fresh air was introduced at the floor and pulled out the ceiling by an axial fan. The approximate constant HRR and ventilation rates were chosen to be representative of possible fires in ventilation-controlled rooms with seven room air changes per hour.

The upper layer gas temperature rise above ambient is given as a function of the fire HRR, the compartment ventilation flow rate, the gas specific heat capacity, the compartment surface area, and an effective heat transfer coefficient. The non-dimensional form of the resulting temperature correlation is:

$$\frac{\Delta T_g}{T_0} = 0.63\left(\frac{\dot{Q}}{\dot{m}c_p T_0}\right)^{0.72}\left(\frac{h_k A_T}{\dot{m}c_p}\right)^{-0.36} \qquad (7)$$

where ΔT_g = hot gas layer temperature rise above ambient, $(T_g - T_0)$ (K)

T_0 = ambient air temperature (K)

$\dot{Q}$ = HRR of the fire (kW)

$\dot{m}$ = compartment mass ventilation flow rate (kg/sec or cfm)

c_p = specific heat of air (kJ/kg-K)

h_k = heat transfer coefficient (kW/m^2-K)

A_T = total area of compartment enclosing surfaces excluding area of vent opening (m^2)

This correlation for forced-ventilation fires can be used for different construction materials by summing the A_T values for the various wall, ceiling, and floor elements.

Heat Transfer Coefficient, h_k

Heat transfer coefficient, h_k, is a quantity that represents the ability of heat to be transformed from a moving fluid to a solid surface expressed in terms of heat flux per unit temperature difference. Warmer, less dense fluid rises and is replaced by a cooler fluid. Convection currents rise during a fire event due to heat transfer to the surrounding air, causing it to rise and allow cooler air to enter the fire environment at the base of the fire. The heat transfer coefficient is known to be a function of fluid properties (thermal conductivity, density, and viscosity), the flow parameters (velocity and nature of the flow), and the geometry of the surface, dimensions and angle of the flow.

For very thin solids (thermally thin material), heated for a long time, conduction becomes stationary (i.e., steady state). The heat transfer coefficient, h_k, after long heating times, can be written as:

$$h_k = \frac{k}{\delta} \qquad (8)$$

where h_k = heat transfer coefficient (kW/m^2-K)
k = interior lining thermal conductivity (kW/m-K)
δ = interior lining thickness (m)

This equation is useful for steady state applications where the fire burns longer than the time required for the heat to be transferred through the material and heat begins to be lost out the back side. This time is referred to as the thermal penetration time, t_p, which can be calculated by:

$$t_p = \left(\frac{\rho\, c_p}{k}\right)\left(\frac{\delta}{2}\right)^2 \qquad (9)$$

where t_b = thermal penetration time (seconds or minutes)
δ = interior lining thickness (m)
ρ = interior lining density (kg/m^3)
c_p = interior lining thermal capacity (kJ/kg-K)
k = interior lining thermal conductivity (kW/m-K)

However, if the burning time is less than the thermal penetration time, t_p, (thermally thick material) the boundary material retains most of the heat transferred to it and little heat is lost out the back side. The heat transfer coefficient in this case h_k is estimated using the following equation for $t < t_p$:

$$h_k = \sqrt{\frac{k\rho c}{t}} \qquad (10)$$

where h_k = heat transfer coefficient (kW/m^2-K)
$k\rho c$ = interior construction thermal inertia ((kW/m^2-K)^2-sec)
t = time after ignition (sec) (characteristic burning time)

For cases where $t < t_p$, Equation (10) applies;

$$h_k = \sqrt{\frac{k\rho c}{t}}$$

Alternately for cases where $t \geq t_p$, Equation (8) applies;

$$h_k = \frac{k}{\delta}$$

The parameter $k\rho c$ is material thermal property responsible for the rate of temperature rise. This is the product of the material thermal conductivity, k, the material density, ρ, and the heat capacity, c. Collectively, $k\rho c$ is known as the material thermal inertia. For most materials, c does not vary significantly, and the thermal conductivity is largely a function of the material density. This means that density is often the most important material property. Low-density materials tend to be excellent thermal insulators. Since heat does not pass through the material, the surface of the material heats more rapidly and, as a result, combustible materials are ignited more quickly. For this reason foamed plastics are often so dangerous in fires. The thermal response property, ($k\rho c$) has been reported in the literature for a variety of generic materials. These values are derived from measurements in the small-scale lateral ignition and flame spread test (LIFT) apparatus.

Area of the Compartment Enclosing Surfaces, A_T

Most compartments will be in a rectangular shape with two larger and two smaller walls and the ceiling and floor surface areas equal.

Based on the assumption, the compartment interior surface area, A_T, can be calculated as follows:

A_T = ceiling + floor $2\,(w_c \times l_c)$
2 large walls $2\,(h_c \times w_c)$
2 small walls $2\,(h_c \times l_c)$

$$A_T = [2\,(w_c \times l_c) + 2\,(h_c \times w_c) + 2\,(h_c \times l_c)] - A_0 \qquad (11)$$

where A_T = total compartment interior surface area (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_0 = area of ventilation opening (m^2)

As with all forms of calculated approximations, there are a number of assumptions and limitations. The assumptions and limitations are taught to the inspectors in class room exercises. The following are a list of the major assumptions and limitations.

ASSUMPTIONS AND LIMITATIONS FOR PREDICTING TEMPERATURE IN A ROOM FIRE WITH NATURAL AND FORCED-VENTILATION

1. These temperature correlations hold for compartment upper layer gas temperatures up to approximately 600 °C (1112 °F) in naturally ventilated spaces where a quasi-steady balance develops between the rates of mass inflow and outflow from the hot gas layer.
2. Compartment geometry assumes that a given space can be analyzed as a rectangular space with no beam pockets. This assumption the affects smoke filling rate within a space if the space has beam pockets. For compartments with irregular shapes, an equivalent compartment dimensions length, width and height must be calculated.

3. The method applies to both transient and steady-state fire growth; the HRR must be known. These correlations assume fire is located in the center of the compartment or away from the center. If the fire is flush with a wall or in a corner configuration in a compartment, the MQH and FPA correlations are not valid.

4. The method predicts average temperatures and cannot be used to predict local temperatures. For example, it should not be used to predict detector or sprinkler actuation or the temperatures of materials as a result of direct flame impingement.

5. The method assumes heat is lost as mass flows out through openings. It is therefore not applicable to situations where significant delay time passes before hot gases start leaving the compartment through openings.

6. The above methods to predict temperature in a room fire does not include an overhead with cables trays and conducts.

SUMMARY

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

1. The use of the simple fire dynamics correlations will enable the regional fire protection inspectors to transition from purely qualitative fire risk evaluations to evaluation based on both qualitative and quantitative methods. This will decrease reliance on opinion and bases the evaluation more in physical fire dynamics correlations. This serves to help reduce the level of uncertainly in fire risk evaluations.

2. The use the spreadsheet templates with locked-in equations and correlations will allow regional inspectors to quickly perform the analyses more quickly and will reduce the potential for mathematical errors and the misapplication of the SFPE Handbook of Fire Protection Engineering equations.

3. The regional inspectors gain insight to the fire risk associated with different hazardous scenarios by having a tool that can rapidly be changed and recalculate the potential fire dynamics effects on the area of concern.

CONCLUSION

By taking a commonly available computer spreadsheet software (like Microsoft Excel®), and creating a series of computational worksheets, different concepts like fire dynamics can be taught to, and put into reliable field application by inspectors. The use of the spreadsheet templates further reduces mathematical complexities and errors, and promotes greater application of fire science and engineering in field use.

The NRR fire protection staff is in the process of developing additional worksheets for regional inspector application in the area of fire risk evaluation. The worksheets discussed in this paper are the first once completed and put into use. A complete suite of spreadsheets is expected to be completed in approximately 3 years.

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APPENDIX A

SAMPLE PROBLEM

We illustrate the application of the equations presented in this paper by an example of a fire in a NPP compartment. This example shows how to do an engineering FHA using the fire dynamics spreadsheets.

PROBLEM STATEMENT

It is important to determine whether a fire involving an 8 gallon, 3.5 ft diameter spill of lubricating oil from the auxiliary feed water (AFW) pump could damage the safety-related cable trays. There are safety-related cable trays located 8 ft above the AFW pump. The pump room has a floor area of 15 x 15 ft and a ceiling height of 10 ft. The pump room has a single unprotected vent opening of 4 x 6 ft. The construction is 1 ft thick concrete. Compute the fire hazard to the safety-related cable trays.

ANALYSIS

Accidental spills of flammable/combustible liquid fuels and resulting fires depend on a number of parameters, including 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.

The summary results of the calculations are given in Table 1.
See Figures 1, 2, 3, and 4, Microsoft Excel® worksheets for details of the calculations.

Table 1
Fire Hazard Calculation for AWF Lubricating Oil Spill

HRR $\dot{Q}$ (kW) Figure 1	Pool Fire Flame Height H_f (m) Figure 2	Burning Duration t_b (minutes) Figure 3	Compartment Hot Gas Layer Temperature T_g (°C) Figure 4
1603	3.4 (11 ft)	11	353 (667 °F) at 5 minutes

It should be noted that exposure to direct flame impingement or high plume temperatures could cause the unprotected safety-related cable trays to fail.

The flame height of 3.4 m (11 ft) is greater than the height of the cable trays 2.44 m (8 ft) so the fuel spill could result in a flame high enough to directly flame impinge on the safety-related cable trays.

The results of the calculation demonstrate that a 3.5 ft diameter pool fire in AFW pump room has the potential to cause failure of unprotected safety-related cable trays.