Appendix D-3: Fire Modeling

CONTENTS

1. Introduction

The purpose of this Appendix is to provide additional guidance on the use of fire models. Fire modeling is the application of any type of mathematical analysis to quantify the effects of a fire in a plant. The use of fire models is discussed in section 2.4.1 (Engineering Analyses) and Appendix C of NFPA 805.

Fire modeling often involves the use of a combination of engineering calculations and computer-based modeling. Rarely can the desired analysis be performed through the application of any one method. The selection of a single model is therefore not nearly as important as utilizing the range of appropriate engineering tools and data available. In the context of NFPA 805, fire models take three broad forms, Engineering Calculations, Zone Type Computer Models and Field Type (CFD) Computer Models.

The type of model necessary to perform a given analysis is a function of the important physical processes in the problem, the capabilities of the particular model and to a lesser extent, the degree of accuracy required of a specific analysis. For certain types of problems, the use of engineering calculations in the form of correlations, closed form solutions, etc., may be more appropriate and more accurate than even the most sophisticated computer-based models available.

This appendix is organized in five major sections. Section 2 provides an introduction to the process of engineering analysis of fire protection issues using modeling. It describes the modeling approach used in NFPA 805 and provides some specific guidance on each process element. One of the key elements is the description of the maximum expected fire scenario (MEFS). Section 3 of the Appendix deals specifically with information and guidance on developing MEFS for various source fires including fires involving flammable and combustible liquids, electrical cables, cabinets and transient combustibles. Section 4 of the Appendix deals with calculation methods for types of calculations performed. These include flame radiation and plume calculations, target damage, detector actuation, flashover, etc. Section 5 provides a brief overview of the issue if validation. This Appendix attempts to summarize the state of the art and summarize adequate references and guidance for a user to apply fire-modeling techniques in a nuclear power plant in accordance with NFPA 805. Substantial additional material is available in the references provided. A useful primer on the subject with specific sample problems detailed is the EPRI Fire Modeling Guide for Nuclear Power Plant Application (EPRI, 2002). It should also be noted that while this Appendix and many of the references propose specific methods and/or data, neither should be construed as an indication that the method or data described excludes the use of other calculation methods, assumptions or data for any particular purpose.

2.0 Engineering Analysis Using Fire Models

This section describes the process of engineering analysis for fire related problems, with specific reference to the requirements of NFPA 805.

2.1 Introduction

The use of fire models arises in many different contexts, ranging from simple calculations, such as determining whether flashover can occur given the ventilation and fuel load in a compartment, to a detailed transient calculation such as determining the temperature and velocity field for a large turbine hall fire. The purpose of the calculation has an important bearing on the type of modeling and the approach used. For example, to estimate the heat flux required to damage two targets with a specified separation distance (assuming a large room with limited combustibles), a simple flame radiation/plume calculation can be used such as that contained in the FIVE methodology (EPRI, 1992) and updated spreadsheet versions of these calculations (EPRI, 2002) or NRC spreadsheet calculations (Salley and Iqbal, 2002), which are derived in large part from the SFPE Handbook of Fire Protection Engineering (SFPE, 2002). If the resulting fire size greatly exceeds any fixed or transient fire load expected then that is the only calculation that is required.

For this type of calculation multiple simple methods exist. The use of bounding assumptions along with adequate safety factors enables one to quickly answer the question or determine the need for additional analysis. This is termed a screening analysis.

At the opposite extreme are problems that involve complex geometries. These models require complex calculations with limited data, multiple phenomena with strong interactions and are very sensitive to changes in input data or fire growth assumptions. An example of this type of problem is a fire involving grouped electrical cables in multiple layers in a relatively small room (i.e. a room size such that the expected energy release rates result in substantial (>150°C) temperature rise in the hot gas layer.) Suppose that the problem involves calculation of the damage to a target located near the ceiling but at some radial distance from the source fire. In addition, assume that cables in a tray are ignited. The question is will and if so when the target will be damaged. This example involves predicting the flame spread rate along cable trays, the ignition of adjacent or proximate cable in trays, the effect of an increasing fire size on the hot gas layer temperature in the compartment, the effect of that hot gas layer temperature on the growth rate of the cable fire and the effects of the combination of the hot layer and ceiling jet temperature on the target being assessed. This type of problem is at the limits of current capability in fire modeling, primarily because no current models adequately address flame spread and fire growth along contiguous combustibles. Such an analysis would require the use of, at minimum, a zone model in conjunction with other calculations to make it even tractable.

These two examples taken from both ends of the spectrum in terms of level of detail, difficulty, and uncertainty, illustrate the difference between simple screening calculations and detailed calculations requiring the use of detailed computer-based codes.

The qualifications necessary of personnel involved in the fire modeling projects depends to a great extent on their role, and the nature of the analysis. In general, the individual

responsible for conducting quantitative engineering analysis related to fire hazard quantification should be an experienced engineer with formal training in fire dynamics and use of the methods or models being used. The user should also have knowledge of available data sources and validation studies for the method being used. In addition to modeling and analysis expertise, the successful application of modeling will involve an individual or team with experience in NPP systems and plant operations, all relevant regulations, plant configurations and QA/QC programs. For simple screening calculations where well defined and isolated fuel arrays are being evaluated, and less expertise is required, an engineer with training in the calculation methods being used is adequate.

2.2 Screening Calculations

Screening calculations may involve the use of hand or spreadsheet calculations or the use of zone-type computer fire models. They are intended to be done quickly, and yield results that either demonstrates with substantial safety factor (>2) that the situation under analysis is acceptable or demonstrates the need for additional analysis or some alternative solution.

Screening calculations share one or more of the following attributes.

1. Well-defined simple geometry
2. Time scale is not important
3. Well-defined source fires with bounding assumptions on fire size
4. Constant fire size, no compartment effects on fire size
5. No fire or flame spread
6. Calculated results exceed thresholds by substantial margins
7. Calculated results not necessarily sensitive to input parameters

Screening calculation methods such as FIVE (EPRI, 1992, 2002), or those developed by the NRC (Salley, Iqbal, etc.) are conservative in the assumptions made to simplify the calculations. Screening calculations are often done in support of PRA analyses. Application of screening calculations is discussed in section 8.3, Plant Change Evaluations.

2.3 Detailed Analysis

Detailed engineering calculations or analysis require substantial additional resources to successfully complete the screening analysis. The attributes of problems requiring detailed calculations include one or more of the following:

1. Complex geometry
2. Time dependent problem
3. Time dependent fire growth
4. Flame spread along contiguous combustibles
5. Interaction between compartment effects and fire size/growth

6. Multiple target heating mechanisms (e.g. connection from plume or ceiling jet and hot layer and radiation from hot layer and/or flame.
7. Room ventilation effects
8. Result with minimum safety factor (in the range of 2-3)

The successful use of fire modeling in such conditions is therefore highly sensitive to the problem under evaluation.

2.4 Engineering Analysis Process

This section describes a generic process for performing engineering analysis consistent with the requirements of NFPA 805. It involves the following steps, illustrated in Figure 2.4.1.

1. Describe Problem
2. Select Approach
3. Select Model/Calculation Procedure
4. Define Maximum Expected Fire Scenario
5. Perform Calculations
6. Evaluate Results
7. Define range of limiting fire scenario
8. Perform calculations
9. Evaluate results
10. Documentation

2.4.1 Problem Description

This first step in this problem requires describing the problem in enough detail to enable decisions regarding the approach to the problem. The following information is required at this stage:

1. Define Objective: What is the performance or regulatory issue under evaluation? Does it involve probabilistic elements? Is it an equivalency evaluation and if so, equivalent to what requirements? Is the analysis part of a PRA assessment? (See section 8.3)

2. Performance Criteria: Based on the objective(s) of the analysis, this step requires establishing the desired performance objective(s). The objective(s) should be stated in a quantitative form so that comparison with the analysis results can be made. For example, in evaluating damage potential to a redundant circuit, the performance objective may be that the heat flux at that target location cannot exceed some critical value.

3. Identify important physical and environmental parameters. Source fire: steady, growing, contiguous combustibles

Compartment effects: negligible layer temperature and position, ventilation, room height, enclosure construction

2.4.2 Select Approach

This step is intended to lead to a decision as to which technical approach (engineering calculation, zone modeling, CFD modeling or some combination) is to be used in the analysis. The primary determinants in this step are:

1. Nature of problem

   Target damage or ignition
   Detector/sprinkler activation
   Flashover potential
   Human tenability
   Fire resistance calculation

2. Source Term Variables

   These describe the types of fire situations to be modeled and can be characterized as:

   a. Physically separated, discrete steady state fire sources (e.g. oil spill in contained area)
   b. Fire involving time dependent or fire spread efforts (e.g. fire spread across a cable tray)
   c. Fire spread across contiguous combustible (such as across closely spaced cable trays in a cable spreading room)

3. Compartment Effects

   These variables determine whether or not compartment effects are important. These include primarily:

   - Fire size
   - Room volume
   - Room height
   - Ventilation rate
   - Enclosure construction (i.e. leakage)

   A quick room temperature calculation or zone model run may answer this question. If the temperature rise or oxygen depletion is low enough so as not to impact the results, compartment effects may be neglected.

4. Environmental Variables

These are environmental aspects of the compartment that may be important to the problem.

a. Elevated ambient temperature
b. Thermal stratification (for detector activation problems)
c. High localized ventilation (wind effects)

The process of selecting the approach involves comparing the requirements of the analysis, and the nature of the problem to the capability of the model or calculation procedure to calculate the important phenomena and interactions of phenomena to yield reasonable results.

In many cases a combination of calculations is required. For example, using a zone model to calculate hot gas layer temperatures and combining that with a flame radiation model to estimate the flux to a target.

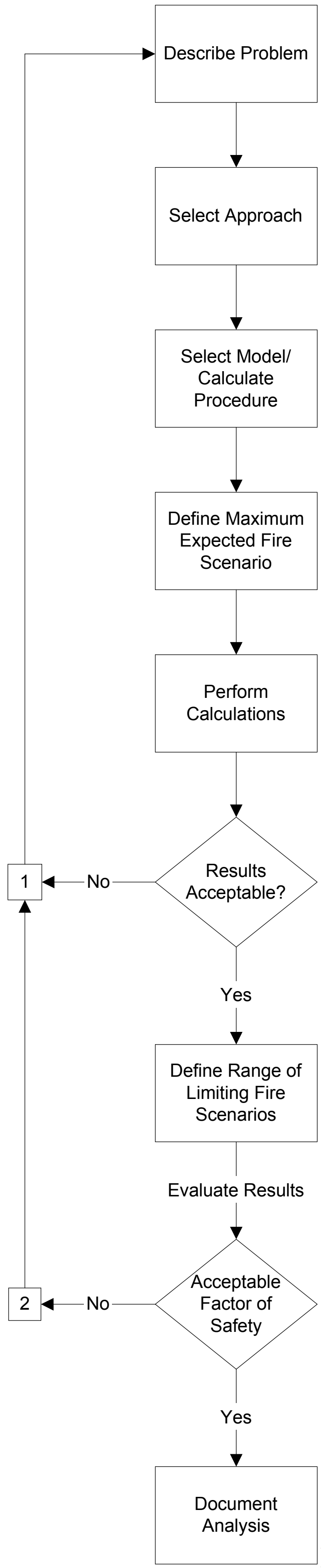


Figure 2.4.1 Simplified Analysis Procedure

Table 2.4.1 COMPARISON OF CALCULATION APPROACHES FOR TARGET DAMAGE PROBLEM

	Calculation	Zone Model	CFD
Source Term:	-Obtain from correlations	-Input data (from correlations) -May calculate interaction	-Input data (from correlations)
Compartment Effects:	-Limited use for screening calculations -Single compartment only	-Used to calculate layer temperature and position -Multiple rooms	-Can yield detailed spatially resolved temperature field
Problem Geometry:	-Can be used for complex geometries	-Simple geometries	-May be used for complex geometries, radiation calculations are sometimes weak
Environmental Effects:	-Can be used to estimate impact of wind and stratification	-Limited use	-Effective

An example of the combination of these variables in selecting the most appropriate approach is shown in Table 2.4.1 for a target heating/damage assessment problem. For example, if there are no compartment effects in a problem involving a complex geometry, hand or spreadsheet calculations may be used. For cases where compartment effects on hot layer temperature or oxygen depletion are important, zone or CFD models may be used. For complex geometries with compartment effects, a combination of zone modeling and engineering calculations may be appropriate.

This table only applies to a target-heating problem. Other problems, such as detector activation, will yield different combinations of approaches.

2.4.3 Select Calculation Procedure

This step is intended to determine which calculation procedure or model should be used. In many analysis cases some combination of engineering calculations and zone or CFD modeling is appropriate. Selecting the calculation procedure is therefore a matter of determining which calculations and/or models will be used to calculate which variables. For purposes of PRA, the use of screening methods with appropriate factors of safety is described in Section 8.3 of this report.

2.4.3.1 Engineering Calculations

This type of calculation involves the use of correlations, closed form approximations or exact solutions which can be done by hand or in a spreadsheet. Typical examples include:

- Heat release rate of pool fires
- Temperature and velocity in a plume or ceiling jet.
- Radiative heat transfer between a flame and/or layer and a target
- Thermal detector response in unconfined space

These calculations are given in many reference texts, including handbooks. Some have recently been issued by the NRC as a series of spreadsheet calculations. Simplified screening versions of these correlations are the basis of the FIVE methodology. The NRC spreadsheet correlation contains the following calculation procedures.

- Compartment hot gas layer temperature and smoke layer height with natural ventilation
- Compartment hot gas layer temperature and smoke layer height with mechanical ventilation
- Burning Characteristics of Fire, Heat release rate, Flame height, and Burning duration
- Full-scale heat release rate of cable tray fire
- Burning duration of solid combustibles

- Flame heat flux from a fire to a target at ground level under wind free condition using point source radiation model
- Flame heat flux from a fire to a target at ground and above level under wind free condition using solid model
- Centerline temperature of a buoyant fire plume
- Sprinkler response time
- Smoke detector response time
- Heat detector response time
- Ignition time of target fuel exposed to a constant radiative heat flux
- Wall fire flame height
- Line fire flame height
- Corner fire flame height
- Compartment flashover calculation
- Pressure rise in a closed compartment due to fire
- Explosion calculation
- Fire resistance of structural members

These calculations are based largely on methods contained in the SFPE Handbook and Drysdale.

There are usually several generally accepted versions of any particular calculation. Calculations contained in the SFPE Handbook of Fire Protection Engineering are generally acceptable given they are used within a valid range.

2.4.3.2 Zone Models

There are approximately 20 different zone models in use in some form. The most widely used is CFAST (developed by NIST). COMPBURN IIIE has been widely used in nuclear power applications. COMPBRN IIIE is a combined probabilistic and zone type single compartment fire model. It has been used extensively in PRA applications for Nuclear Power Plants. It is not being further developed at this time. MAGIC is a zone model analogous to CFAST but with less capability but with specific additional features designed to aid calculations in NPP applications. Each zone model has its own relative strengths, weaknesses and features. A list of these models and some of their features is given in Appendix C of NFPA 805. The EPRI "Fire Modeling Guide for Nuclear Power Plant Applications" provides a good introduction to zone modeling and specific details on four models including FIVE, COMPBRN IIIE, CFAST and MAGIC (EPRI, 2002).

<u>Zone Model Features</u>

The following is a list of generic features and limitations of CFAST as a representative zone model. Most of the aspects are common to all zone models.

1. Model calculates a single hot gas layer temperature, layer height and layer composition for each room. Model has multiple room capability.

2. Model does not predict fire growth rates, heat release rates or generation of smoke and other products of combustion. These data are either required as input or are generated from engineering correlations. No effect of temperature or radiation on the fire growth is directly calculated.

3. The effects of hot gas layer temperature on radiation, fire growth and heat release rates are not calculated. The effect of oxygen depletion on energy release rate is estimated based on a correlation.

4. The model can treat natural and forced/mechanical ventilation.

5. Heat losses through walls are calculated via a simple transient heat conduction approximation with convective and radiative heating boundary conditions.

6. There is no coupling between the thermal or radiation conditions in the compartment and the burning fuel. Such effects must be accounted for in the specification of the source fire. This often involves an iterative process.

7. The effects of oxygen depletion are accounted for by reducing the heat release rate as a function of oxygen concentration. The energy release rate is reduced from the ambient value to zero when a limiting oxygen concentration (an input variable) is reached.

<u>Selection of Zone Model</u>

Selecting one zone model over another is largely a matter of balancing the validation and acceptability of a widely used, public domain, open source model such as CFAST, against particular features that another code such as MAGIC or COMPBURN may possess. There is, in general, no fundamental reason to select one code over another. All share the same inherent limitations of zone model codes.

Specific features such as target heating models that may exist in one code versus another can generally be incorporated or integrated with any other code by combining the results with independent engineering calculations. The use of CFAST within its range of validity and relevance to the problem under study has been well accepted. The use of other codes may require additional demonstrations of validity or acceptability. Validation efforts for several zone models are underway (Dey, 2002).

2.4.3.3 Field or Computational Fluid Dynamics (CFD) Models

Field or CFD models solve mass, energy and equation of motion for each volume element in a calculation grid. The grid size is determined by balancing the accuracy requirements of the analysis against the cost and computational time required to assess a finer grid. There are a range of CFD codes used in a wide variety of energy/fluid flow simulation problems. A few have been modified to deal more effectively with fire-related phenomena (plume entrainment, radiative transfer, etc.). The most important

public domain CFD code in the United States is FDS, or the Fire Dynamics Simulator, developed, maintained and distributed by NIST (McGrathan, et al, 2002). This code is a large eddy simulation (LES) of the plume and ceiling jet flows which has been demonstrated to be the most effective way of dealing with fire-induced flows.

The primary advantage of CFD models is their ability to handle the flow and mixing characteristics of fire–induced flows in complex geometries and their ability to spatially resolve the temperature and concentration fields throughout a compartment. This means that they do not have the inherent limitation of a two-zone/two temperature description of a zone model.

Like zone models, CFD models require that the fire source be provided as input data usually in the form of a gas evolution rate, which is analogous to mass loss rate of a fire. These codes do not predict fire growth across a fuel surface in a general way. Using a gas evolution rate, the model predicts the oxygen mixed with the fuel and calculates the energy release rate in that particular cell, based on a prescribed fuel release rate. FDS contains a solid fuel pyrolysis model which couples heat transfer from the flame to the burning surface. The use of this sub-model increases uncertainty in the results.

The primary disadvantage of CFD codes is the level of effort required for computation. Since most analysis in NPP applications require multiple calculations or computer runs to evaluate sensitivity and limiting cases this can be a substantial limitation. The use of CFD codes in conjunction with other methods can be highly effective where the CFD code is used to evaluate details or cases that are not adequately treated by other methods.

Selection of a CFD Code

The range and complexity of CFD codes makes selection of a specific code problematic. For most typical applications of fire modeling, FDS (Fire Dynamics Simulator) or an equivalent code possess the features necessary for successful application. Specific detailed problems may be better treated by more sophisticated codes, but these are currently not available to the typical user.

2.4.4 Develop Maximum Expected Fire Scenarios

A key concept of NFPA 805 as it relates to application of modeling is the maximum expected fire scenario (MEFS). A fire scenario is intended to describe all of the relevant variables in an analysis. The MEFS is intended to describe the most challenging scenarios that can reasonably be expected. It is not intended to describe worst case or limiting conditions nor does it define a mere average. The terms “reasonably be anticipated,” “realistic and conservative,” are used in Appendix C of 804 to describe the content of the MEFS. An introductory discussion of fire scenarios with examples for six important plant areas is given in the EPRI Fire Modeling Guide (EPRI, 2002).

The fire scenario is expected to capture all of the variables relevant or important to the analysis. For any given problem there may be several scenarios the require evaluation.

Establishing the scenario involves defining the problem in sufficient detail to perform calculations and to ensure that the input parameter set represents conditions that are "reasonable and conservative." Developing fire scenarios is intended to capture some elements of probabilistic inputs. For example, a self-ignited cable fire may not be considered as a scenario due to a low probability of occurrence. The integration of fire scenario development with probabilistic methods is a useful method to objectively develop the range of scenarios that are to be considered.

Section 8.3 discusses the use of modeling in PRA based evaluations. PRA assessments can also be used to screen potential fire scenarios, depending on the objective or purpose of the modeling.

The scenarios selected will to some extent depend on the problem being evaluated. The MEFS developed to evaluate detector or sprinkler response will be different from those needed to evaluate redundant shutdown circuit spacing. This is partially due to the fact that conservative assumptions for one analysis purpose are not necessarily conservative for another.

The scenario should include the following characteristics as described in NFPA 805.

1. Combustible Materials
2. Ignition Sources
3. Plant Area Configuration
4. Fire Protection Systems and Features
5. Ventilation Effects
6. Personnel

The combination of items 1 and 2 will define the fire sources on which the scenario is based. Plant configuration will establish the geometry of the problem including compartment size, relative position of fire sources and/or targets, and possible fire/smoke spread paths. If the objective of the analysis includes the evaluation of detection or suppression effects, details of fire protection systems in the area are required. Ventilation effects include mechanical and natural ventilation. For mechanical ventilation the supply exhaust, and re-circulation air flow rates, position of thermal or detector activated dampers, the location of the detectors which actuate the dampers, fan position (in order to evaluate thermal effects), position of supply and exhaust duct openings and depending on the analysis being performed, fan pressure/volume curves may be required. Fan shutdown due to automatic or manual means, the actuation of fire suppression systems or as a result of excessively high temperatures in the flow path may need to be addressed in the analysis. For natural ventilation openings, the size and location of each opening, the compartments to which they connect and ambient pressure differentials between these compartments may also be a required input to the analysis. Also, any changes in the configuration that may occur over the course of the scenario may need to be identified. These include door openings or closures, damper activations (closure), fan shutdown or other ventilation system reconfigurations.

Where personnel exposure or personnel actions are required the number and relative position of personnel is required.

2.4.4.1 Fire Source Variables

One of the most critical tasks in defining a fire scenario is the description of the fire source term. In general, all models are dependent on user specified or empirically derived fire source terms. This requires that the user specify a priori all of the details of the fire as a function of time. This involves specifying:

1. The heat release rate or mass loss rate as a function of time
2. Position of the fire using X, Y, and Z coordinates
3. Smoke and gas yields
4. Stoichiometry and limiting oxygen valves
5. Position of the source fire relative to a wall or corner

All of these values may not be required depending on the analysis method chosen and the problem being evaluated.

Compartment effects, if not treated adequately by the model used, must be accounted for by other calculations or demonstrated to be unimportant.

All five parameters must be considered in the context of the maximum expected conditions.

The selection of maximum expected source term parameters is sensitive to the type of analysis being performed. For example, maximizing a radiation fraction may pessimize the heat flux to a target in the lower layer but reduce the hot layer gas temperature. If the calculation is intended to evaluate detector response selection of a slower rate of fire growth or a smaller fire would be a more appropriate MEFS. Since there are often multiple objectives of a modeling assessment, multiple MEFS specifications are required to pessimize each objective for the intended initiating fire scenario.

Often it is not possible to identify the most reasonable conservative set of parameters. This often occurs when evaluating scenarios where oxygen depletion and mechanical ventilation are involved. Since the balance between fire size or fire growth rate and the ventilation rate are important, use of the largest expected fire size or fastest growth rate may not result in worse case conditions. In such cases it is often necessary to perform multiple modeling iterations to determine the maximum expected conditions for a fixed fire scenario.

All possible fire spread paths between objects must be evaluated prior to performing the calculation to ensure that either a) the model or calculation accounts for ignition, spread and subsequent contribution or b) the input fire source term contains the heat release rate contribution of remotely ignited or contiguous combustible materials.

Specific guidance on fire source terms is given in Section 3.

2.4.5 Perform Calculations

The next step in any engineering analysis is to perform the calculations based on the MEFS using the methods previously selected. The most important aspect of this step is to provide all necessary input data in the correct form for the model or calculation being utilized.

Once the results are obtained they are checked against the performance criteria. These can be a simple evaluation of an actual calculated flux versus a critical flux or the results may require additional calculations depending on the problem.

If the calculated results are within 50 percent of the critical results, one should consider the use of more accurate or less conservative calculation procedures.

2.4.6 Limiting Fire Scenarios

NFPA 805 requires that the conditions under which failure occurs be identified. The set of input variables, which results in a failure condition, are termed limiting fire scenarios. The development of limiting fire scenarios is essentially a sensitivity analysis performed to identify which combinations of values of critical variables will result in failure.

The particular variables to be evaluated depend entirely on the specific problem. At a minimum one would expect to vary the following until failure conditions are identified.

1. Heat release rate per unit area and total heat release rate
2. Fire growth or flame spread rate
3. Flame radiative fraction or radiative power
4. Location of fuel package relative to target (if variable)

In some cases calculating the limiting fire scenario will necessitate postulating large fire sources. Once the limiting fire size exceeds the MEFS fire size by a factor of 3 or more there is no need to calculate the exact limiting fire size, merely indicating that it is "greater than 3 times" the MEFS should suffice.

Depending on the problem, many other input parameters may require evaluation. Once the range of limiting fire scenarios has been established and calculated, one can evaluate whether an adequate factor of safety exists.

2.4.7 Factor of Safety

At this point in the analysis the results of the MEFS case and the Limiting Fire Scenario(s) have been established. An evaluation of the factor of safety of the analysis can now be performed. The factor of safety is intended to ensure that the analysis reflects uncertainty in the MEFS, the evaluation method(s) used and the performance criterion.

There is no single recommended factor of safety or method for evaluation. A reasonable or appropriate factor of safety depends entirely on the situation under evaluation. Where very conservative assumptions are embedded in simple screening calculations the factor of safety can be less than one involving very detailed calculations or scenarios with significant uncertainty. This is illustrated in an example in section 4.1. For cases where the screening analyses are used in support of a Fire PRA a factor of safety of 2 relative to expected fire size is adequate (see section 8.4).

One design method with a recommended factor of safety is the "Engineering Guide for Assessing Flame Radiation to External Targets from Pool Fires," published by the Society of Fire Protection Engineers. [SFPE, 1999] This guide presents simplified methods for calculating radiation from a flame to an external target. This design guide recommends a factor of safety of two when using the screening methods described. That is, the calculated heat flux should be at 50% or less than the critical heat flux for the target. This factor of safety is based entirely on a comparison between various calculation methods and full-scale data. The factor of safety is intended to be applied to "design applications," further it states "where a realistic result is required, no safety factor should be applied."

In most fire engineering calculations the primary uncertainty is in the specification of the heat release rate of the fire. Uncertainty associated with the calculations varies widely. Some typical simple calculations, for example plume temperature, are effectively correlations of data and are reasonably accurate, in the range of 20%. For these types of calculations, the primary source of uncertainty is in the heat release rate of the fire. While no specific requirement has been established, it can be stated that a factor of safety of two on the critical heat release rate versus expected heat release rate is certainly adequate for most cases and may be unnecessarily high in others.

The required factor of safety also depends on the failure condition specified. For example, the use of steady state critical heat flux values for cable failure are very conservative in the sense that they ignore heat loss terms and assume that the exposure duration is long relative to the transient response of the target. In many cases this is a very conservative approximation. For short duration (<10 minute) exposures evaluated using steady state failure criteria, the factor of safety can be reduced. Alternatively, the analysis can be performed taking into account the other important processes to yield a more realistic result and hence, a more representative safety factor.

For certain problems the rate of change in the input heat release rate is important. For example, in calculating the time to flashover in a compartment fire, the growth rate of the fire will determine when or if flashover conditions will be reached. Responding on what the time to flashover result will be used for a factor of safety calculated on the basis of time to flashover or fire size at the time to flashover may be appropriate measures of the safety factor.

In summary, the appropriate factor of safety is a function of the problem being evaluated, the uncertainty in the calculation method used, the uncertainty in the definitions of the MEFS and the definition of the failure conditions or performance requirements.

In the event that the factor of safety is deemed inadequate two paths may be pursued. The first involves using more accurate calculation procedures with more representative failure conditions (e.g. cable temperature versus critical steady state heat flux). This generally requires more sophisticated calculation methods than those methods initially selected. It may, for example, involve the use of a live fire source for radiative heat transfer calculations in lieu of a simplified equivalent point source. The second path involves evaluating the initial conditions and input parameters to ensure they represent maximum expected versus worse case limiting conditions. Alternatively, the MEFS may be modified to reflect more restrictive conditions of operation or hardware solutions such as thermal radiation shields or additional insulation.

Since it is not unusual to perform screening or bounding calculations initially, subsequent refinement of both, the calculation method or model selected and the details used to determine the MEFS is expected.

2.4.8 Documentation

The assumptions, methods, input data and the results should be documented in sufficient detail to permit a reviewer to reconstruct the analysis and check all relevant calculations and results.

At a minimum the documentation should include:

1. Description of Problem

    - Objective of the analysis
    - Plant area or compartment
    - Plant configuration assumptions
    - Regulatory basis
    - Performance objectives

2. Calculation Method(s)

    - Description of calculation approach
    - Reference to equations used
    - Model(s) name and version number
    - Important assumptions made and rationale

3. Maximum Expected Fire Scenario Description

    - Scenario selection
    - Scenario description

- Source fire location and parameters
    - Rate of heat release as a F(t)
    - Data sources
- Failure criteria
- Ventilation configuration and size/flow rates
- Ambient environmental conditions

4. Input Data

    - Complete set of input data used for all calculations
    - Copies of input files used for computer models

5. Results

    - Complete set of all calculation results
    - Copies of output files from computer models
    - Relevant validation data if required

6. Limiting Fire Scenarios

    - Set of input conditions resulting in failure
    - Range of variables evaluated
    - Calculated safety factors
    - Discussion of uncertainty in the analysis

7. Conclusion Summary

    All documentation should meet the relevant quality assurance provisions. In some cases it will be advisable and/or necessary to include the model assumptions, data and results into the plant fire protection program.

3.0 Fire Source Terms for Maximum Expected Fire Scenarios

This section describes methods for developing Maximum Expected Fire Scenarios for selected types of fuel packages. Additional information and guidance is available in Appendix E of the EPRI Fire PRA Implementation Guide (EPRI, 1995) and the EPRI Fire Modeling Guide (EPRI, 2002) as well as references given in section 6 of this Appendix. Guidance presented in this section is not intended to be a complete discussion of a specific topic, nor is it intended to preclude the use of any other methods.

3.1 Pool Fires

Maximum Expected Fire Scenarios involving pool fires can be developed using the following guidance:

Pool Fire Size:

1. For confined spills, where curbs or equipment enclosures form the basis for the maximum pool area use this area as a maximum spill area.
2. For unconfined spills expected to be ignited, a steady state pool size can be calculated using data given by Gottuk and White, SFPE Handbook, these burning rates are much lower than these for confined spills. Unconfined spills have fuel depths in the range of 1 mm.
3. For unconfined spills where the fuel continues to flow it is reasonable to derive an equivalent steady state pool size that results in a burning rate equal to the spill flow rate.

Specific data and calculation methods on liquid fuel fires can be found in Gottuk and White (SFPE, 2002).

<u>Spray Fires</u>

The effect of pressurized liquid spray fires cannot presently be modeled using readily available tools. The overall impact of spray fires in a compartment can be approximate by treating the spray as a heat release rate term. This is a reasonable assumption if the spray is of sufficiently low momentum such that entrainment of into the spray is not significant <u>and</u> the size of the liquid jet is not a large fraction of the compartment floor area. Limited data on spray fires is given in Appendix E of the EPRI Fire PRA Implementation Guide (EPRI, 1995). Note that in many actual spray fires, energy is contributed from both the spray fire and a pool fire that forms under the spray. CFD methods are available for calculating the details of a spray flame, but these are not available for general design or analysis use. Limited data on radiation calculations from spray and jet flames is given by Beyler (2002). Target exposure calculations involving spray flame exposures require significant additional care.

3.2 Transient Combustibles

In most plant areas it is necessary to postulate a transient fuel fire source based on transient fuel loads. Transient fuel loads arise from normal operating conditions as well as maintenance or testing activities. Depending on the location in the plant and general area use, transient combustibles will comprise at a minimum, one or more trash or refuse bags. Large refuse bags have heat release rates in the range of 150 to 350 kw, depending on the nature of the contents, packaging density, size and weight. Other transient loads, including the use of lubricating oil and packaging material or furniture items as appropriate. Transient combustible materials should take into consideration transient loads allowed within the plant Fire Hazard Analysis and the combustible control program. Data on heat release rate characteristics of transient fuel loads is given in Babrauskas (SFPE Handbook, 2002) and “Heat Release in Fires” (Grayson, 2002). The EPRI Fire PRA Implementation Guide contains specific guidance for transient fuel loads in Appendix E (EPRI, 1995).

Transient loads are generally considered when computing the MEFS and Limiting Fire Scenarios as appropriate (postulating transient loads in addition to normal fuel loads.

3.3 Cabinet Fires

Heat release rates for electronics cabinets are developed using data from large-scale cabinet fire tests with similar ventilation and fuel loading. Two cabinet heat release rates have been recorded for use in Fire PRAs, derived from data from Chavez. Heat release rates of 65 and 200 kW are typically used, depending on fuel loading and cabinet ventilation. These values recommended for Fire PRA purposes are based on a set of cabinet tests conducted by Chavez. From these data two values are recommended, 65 Btu/sec and 190 Btu/sec. The value of 65 Btu/sec is recommended if the cables are IEEE-383 qualified and only one small cable "bundle" is expected to be involved. For other cases involving IEEE-383 qualified cables the higher value should be used. The heat release rate from electronics cabinets depends on the cabinet ventilation and the fuel loading and fuel distribution inside the cabinet. Fire testing was conducted by Chavez [1987] and Mangs and Keski-Rahkonen [1994, 1996] to evaluate the impact of these variables on the cabinet fire heat release rate. A summary of the test conditions is provided in Table 3.1. Additional data is available in the EPRI Fire PRA Implementation Guide (EPRI, 1995). This guide gives energy release rate data for cabinet fires as a function of cabinet fuel loading, cable type and ventilation opening.

Table 3.1. Electronic Cabinet Fire Test Conditions

Test No.	Ref.	Ventilation Area(m^2)			Fuel Load (kJ)	Peak HRR & Time (kW, min)	Fire Duration (min)
		Type	Lower	Upper			
VTT-I 1	[1]	Vent Grills, Door Ajar	0.050	0.11	924,700	385 @ 40	105
VTT-I 2	[1]	Vent Grills	0.040	0.079	456,200	50 @ 14	45
VTT-I 3-2	[1]	Vent Grills	0.040	0.079	1,358,100	180 @ 15	125
VTT-II 1	[2]	Vent Grills	0.0097	0.054	1,538,700	175 @ 36	105
VTT-II 2	[2]	Vent Grills	0.0097	0.054	1,597,400	110 @ 32	120
VTT-II 3	[2]	Vent Grills	0.0097	0.054	1,509,900	100 @ 13	120
ST #10	[3]	Vent Grills	0.14	0.14	611,530	280 @ 11	50
PCT #1	[3]	Vent Grills	0.14	0.14	784,000	185 @ 12	60
PCT #2	[3]	Open door	1.30	1.30	1,054,000	950 @ 11	40

1. Mangs and Keski-Rahkonen [1994]
2. Mangs and Keski-Rahkonen [1996]
3. Chavez [1987]

Heat release rate curves for various cabinet fires are given in Figure 3.1.

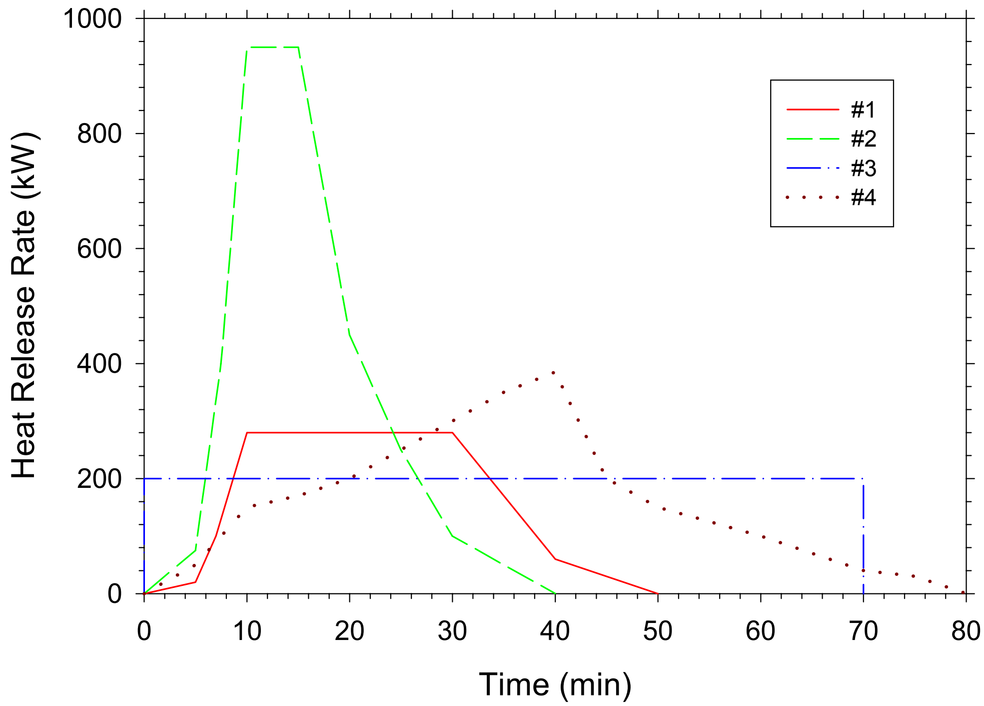


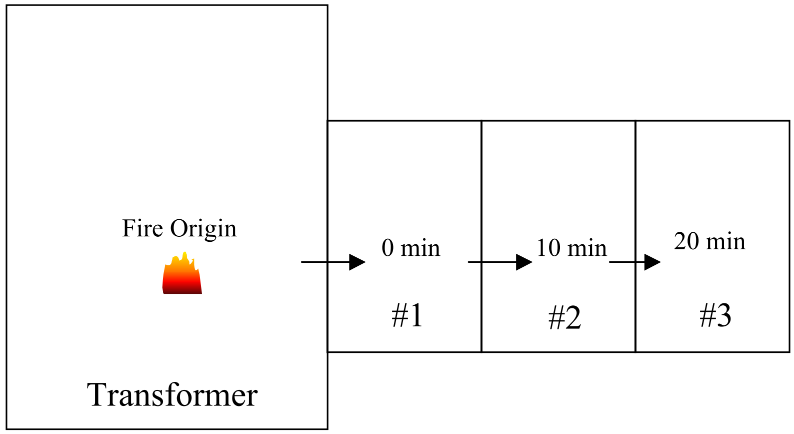
Figure 3.1. Heat release rate of individual electronic cabinets in the cable spreading room. Curve #1 from ST#2 and PCT#1 [Chavez, 1987], Curve #2 from PCT#2 [Chavez, 1987], Curve #3 [Najafi et al.,1999], and Curve #4 from Test 1 [Mangs and Keski-Rahkonen, 1994].

Often cabinets are located adjacent to or close to other cabinets. The potential for fire spread to adjacent cabinets can be based on experimental data from tests conducted by Chavez [1987] and Mangs and Keski-Rahkonen [1994, 1996]. Chavez [1987] found that electronic cabinets that are not separated by an air gap can transmit sufficient heat to allow auto-ignition of cables in the adjacent cabinet. Wall temperature data obtained from by Mangs and Keski-Rahkonen [1994, 1996] indicate that fires will spread to adjacent cabinets approximately 10 minutes after ignition of a burning cabinet.

A heat release rate curve that combines the contribution of individual cabinets based on an ignition delay is shown in Figure 3.2 for an example curve of fire spread from a transformer to three adjacent cabinets.

<u>High Voltage Faults</u>

None of the cabinet fire data currently available are relevant to the case of a high voltage arcing failure (NRC, 2002). No existing fire modeling calculation method can deal directly with these types of events. An approach to treating such scenarios is to account for the initial electrical energy release as a zero oxygen consumption heat release rate and them assume ignition of all combustibles within a certain radius (1-2 m). Fire spread beyond this initial ignition zone could then be treated by existing methods as appropriate. Since the energy release rate for all models is given as input data, such an approach would enable the user to evaluate compartment-wide effects of such initiating events.



Top view showing fire spread to adjacent cabinets.

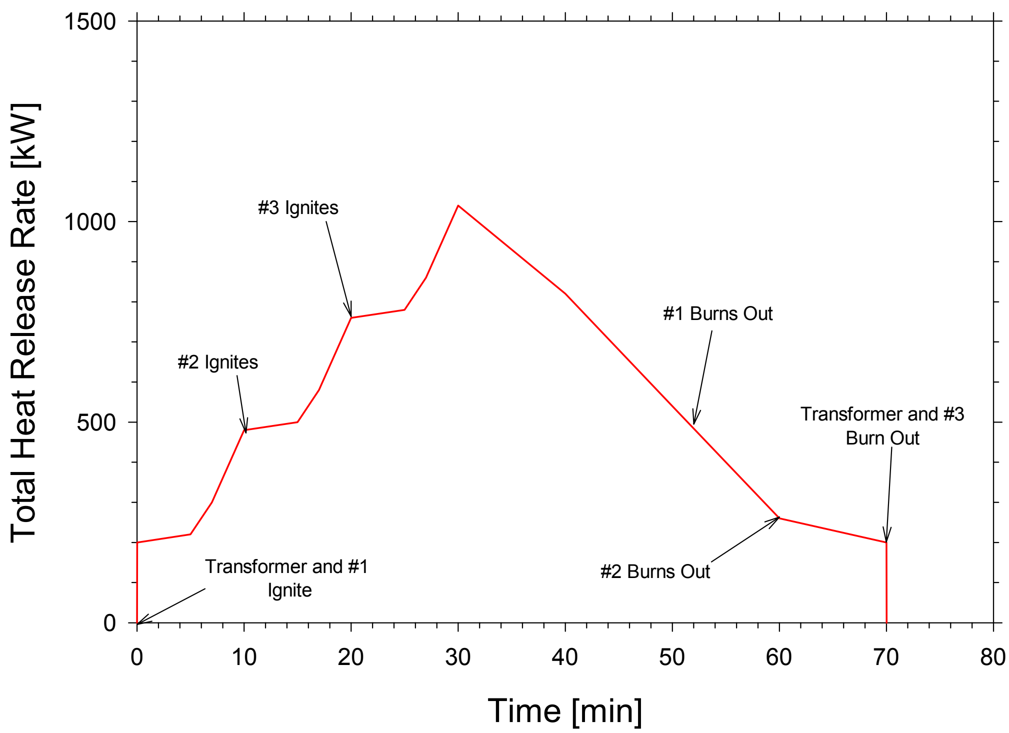


Figure 3.2. Heat Release Rate Profile and Depiction of Fire from a Transformer to Adjacent Cabinets.

3.4 Cable Fires

Cable fire growth rates are approximated by empirical correlations relating bench scale heat release rate data to full scale fire spread and heat release rate curves. The heat release rate and fire spread characteristics are strongly dependent on the following variables.

1. Jacket and insulation material
2. Conductor size
3. Cable construction
4. Cable density and arrangement
5. Orientation (vertical/horizontal)

Empirical data is only available for a small fraction of all cables current in use, so approximations are necessary. The range of heat release rate data for a given type of insulation and jacket material varies widely. For example, heat release rate data for PE/PVC cable construction can vary between 200 kW/m^2 and 600 kW/m^2 for IEEE 383 qualified cables.

The correlation between small or bench scale heat release rate data and full scale cable arrays is given by Babrauskas [SFPE, 2002). This correlation is specifically for a large-scale test array described in Lee (1985).

A sample method for calculating the growth of a fire along a cable tray is given below. The cable tray fire is treated as a line fire that spreads in two directions along a tray.

The heat release rate per unit length of the cable tray system is a function of the plan area of the cables as follows:

$$\dot{q}'_{tot} = \dot{q}''_{fs} \cdot W_{p,c} \qquad (1)$$

where $\dot{q}''_{fs}$ is the full-scale single cable tray heat release rate (kW/m^2) and $W_{p,c}$ is the maximum plan width of the cables (m). The plan width is equal to the sum of all individual cable outer diameters or the actual cable tray width, which ever is smaller.

The full-scale heat release rate per unit area is determined using the equation [Lee, 1985]:

$$\dot{q}''_{fs} = 0.45 \cdot \dot{q}''_{bs} \qquad (2)$$

where $\dot{q}''_{bs}$ is the heat release rate per unit area measured at an incident heat flux of 60 kW/m^2 in a bench-scale (Cone Calorimeter) apparatus.

Burning Duration

The burning duration at a single point is in direct proportion to the quantity of combustible material available and the burning rate. The following equation is used to determine the burning duration:

$$t_d = \frac{Q'}{\dot{q}'_{tot}} \quad (3)$$

where t_d is the fire duration at a specific location (s), and Q' is the energy load of the cable tray system (kJ/m).

Spread Rate

Evidence suggests the spread rate in cable tray fires is a function of the bench-scale heat release rate [Lee, 1985]. Lee [1985] correlated bench-scale data to moderate-scale tests in terms of an *area* spread rate for a single cable tray *array*. The cable tray array contained six tiers or two cable trays. Each individual tray within the array was 0.46 m wide [Sumitra, 1982].

As noted by Lee [1985], the correlated area spread rate is valid "…only to [for] cable tray arrangements, cable packing densities, and exposure fires similar to those tested by Sumitra."

The arrangement of the cable tray system is typically smaller than those that were tested. Consequently, some modification to the Lee [1985] methods is required before the test results can be applied to the configuration at hand.

The correlation derived by Lee can be modified using the actual test observations by Sumitra [1982]. Sumitra noted the number of trays involved before the onset of suppression for each test. This information, along with the burn area at the time suppression as determined by Lee [1985] was used to calculate the actual flame spread rate. Figure 3.4.1 shows the flame-spread rate versus bench-scale heat release rate along with a linear curve fit. The following correlation was obtained from the linear curve fit:

$$v_s = (7.55E-3) \cdot \dot{q}''_{bs} - 1.25 \quad (4)$$

where v_s is the area spread rate (mm/s).

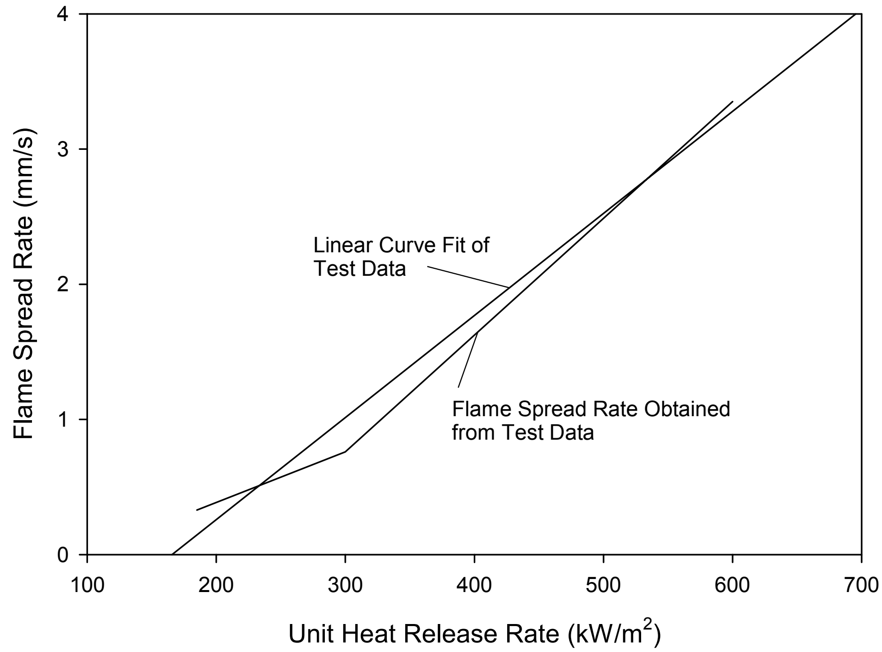


Figure 3.4.1. – Flame spread rate as a function of unit heat release rate

The flame spread velocity as calculated using Equation 4 was compared to other test data on cable trays and cable fires for validity. Factory Mutual researcher's observations indicate that the horizontal spread velocity in a communications cables is about 0.63 mm/s for a three-tiered cable tray arrangement [Tewarson *et al*., 1993]. Investigations of a power cable fault fire [FTIC, 1989] concluded that the spread velocity in these cables was about 2 mm/s. Vertical cable trays with various types of cables have been shown to have a flame spread rate between 2 mm/s and 7 mm/s [Tewarson and Kahn, 1988]. Thus, the flame-spread rate is expected to lie between 0.63 mm/s and 7-mm/s, which is nearly the case for Equation 5.

Test data on vertical cable tray tests indicates that the flame-spread rate in cables is sensitive to the packing density [Hasegawa *et al*., 1983]. Hasegawa *et al*. [1983] found that cable trays with a packing density of 25 percent had a 50 percent or greater reduction in the flame spread rate.

Alternative (and lower) flame spread rates for cable arrays are given in the FIVE method documentation (EPRI, 1992), and discussed in the EPRI Fire Modeling Guide for Nuclear Power Plant Application (EPRI, 2002).

<u>Spread Distance</u>

The maximum flame spread distance from the point of origin in one direction is

$$X_s = t_d v_s \tag{5}$$

where X_s is the distance the flame spreads from the origin before the onset of burnout (m). Note that the total spread distance is *twice* this value because it is assumed that flame spread occurs in two directions.

The method described above is applicable for single horizontal cable tray arrays. Vertical arrays spread flame much more quickly. No generic method exists for calculating or estimating this spread rate. For many problems vertical flow spread may be assumed to happen instantaneously.

For complex horizontal cable array geometries (such as those which typically occur in cable spreading areas), a bench to full-scale spread correlation can be used to approximate a slow or medium growth rate fire. Note that none of those methods account for the change to flame spread rates that occur as the compartment heats up. As cables become immersed in hot gases the spread rate increases. Methods for approximating the increase in flame spread rate can be derived from methods used to calculate flame spread on combustible surfaces (SFPE Handbook reference).

It is not presently possible to directly account for the effects of coating on electrical cables without additional full- or bench-scale data. Reference to full-scale cable tray test data may provide some guidance in establishing source fire characteristics of coated cables, provided data beyond IEEE-383 results for the coating used (Klamerus, 1978). At a minimum, coated cables passing IEEE-383 can be reasonably expected to equal the performance of IEEE-383 qualified cables from the standpoint of damageability.

4.0 Guidance on Application of Engineering Methods

This section provides guidance and reference material on the use of engineering methods and models for specific applications.

4.1 Damage or Ignition of a Target

This category of problems is widely encountered in NPP's, due to its relationship with prescribed minimum separation distance requirements between certain systems and circuits. The general problem can be subdivided into two cases, one where the room size is large and the source fire relatively small such that compartment effects are negligible, and the case where compartment heating and/or oxygen depletion effects are expected to be significant.

4.1.1 No Compartment Effects

Plumes and Ceiling Jets

This case is illustrated schematically in Figure 4.1. Three sample target positions are indicated T1, T2 and T3. Position T1 is the case where the target is immersed in the plume at some elevation above the flame. The plume temperature may be calculated using methods found in Iqbal and Salley (2002), FIVE, (EPRI, 1992), Lattimer (SFPE, 2002) or Heskestead (SFPE, 2002). For line type flames and plumes, different correlations are required. For cases involving targets in ceiling jets (location T2), refer to Iqbal and Salley (2002), Alpert (SFPE, 2002) or FIVE (EPRI,1992). These cases can also be evaluated using computer codes used for detector/sprinkler activation, for example, DETACT and LAVENT.

Where plumes or ceiling jets are flowing through highly obstructed paths (e.g. near the ceiling of a cable spreading room), the use of the methods described above will over-predict temperatures. However, a target located outside of the path of an unobstructed plume or ceiling jet may become immersed in that flow path. Where detailed calculations are necessary in this case a CFD code such as FDS (NIST, 2002) must be invoked, and the relevant flow path obstructions identified as input.

The temperatures calculated for both plume and ceiling jets are maximum temperatures that occur at the centerline of the plume or ceiling jets. Where the target is not on the centerline, the temperature at a radial distance from the centerline can be estimated. For plumes the assumed temperature profile is gaussian. By applying a gaussian profile for the plume radius r and elevation z a more accurate representation of the actual temperature at the target can be obtained. Heskestead (2002) gives the necessary correlations to perform this calculation. In most applications (particularly for low ceiling heights), use of maximum plume temperature is more appropriate.

Flame Radiation

In the situation noted by the target location T3, the primary exposure is flame radiation. This problem can be readily solved if the flame is approximated as a circular source with a simple target-flame geometry using a number of techniques including Beyler (SFPE, 2002), the SFPE Engineering Guide for Assessing Flame Radiation to External Targets from Pool Fires (SFPE, 1999) or calculations by Iqbal and Salley (2002).

More complex geometries involving non-circular source fires (e.g. line fires), or complicated flame target positions, flame shields, etc., require more complex methods as given in Beyler (SFPE, 2002) or Heshestead (SFPE, 2002).

For cases where non-circular flames or alternative target geometries are required, the general process for calculating flame radiation effects is as follows.

1. Estimate heat release rate
2. Establish base dimensions of the flame
3. Calculate flame height
4. Estimate emissive power at flame
   a. use radiative fraction of the total heat release rate divided by the flame area or
   b. use average flame temperature and emissivity
5. Calculate view factor from flame to the target, accounting for shields on line of sight obstructions
6. Apply any corrections for transmittivity or absorption by intervening gas (can be neglected for most cases)
7. Calculate radiant flux at target

This procedure can be used for any flame and flame/target geometry. The application of the flame radiation calculation is given for three different methods. The examples illustrate the relationship between methods used and the appropriate safety factor.

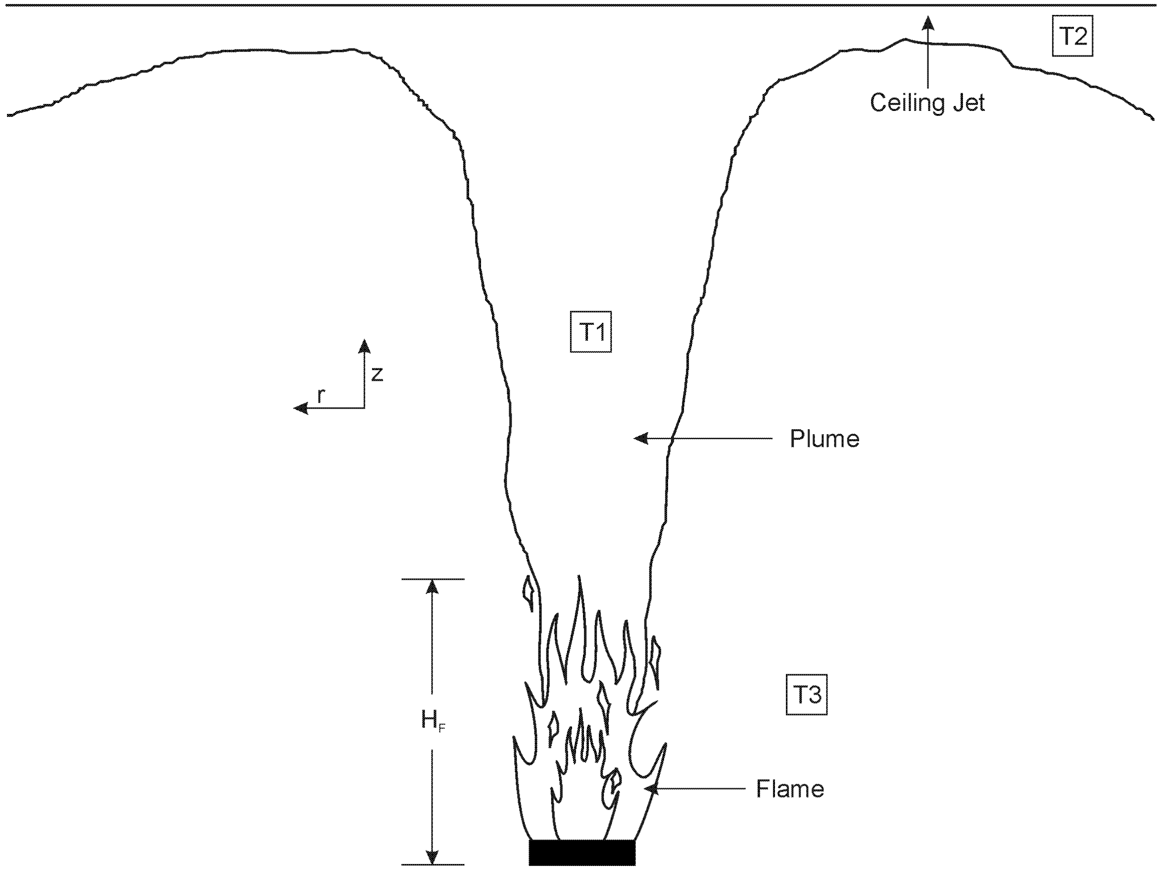


Figure 4.1: Schematic of Target Exposure, No Compartment Effects

Comparison of Flame Reduction Calculation Methods

The classical point source model was used in this analysis because it is simple to apply and it is the only method that does not require a determination of the diameter of the fire. The point source model assumes that the radiant energy is released at a point located at the center of the fire. The heat flux is inversely related to the separation from a source fire the following equation [Drysdale, 1999]:

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

where $\dot{q}''$ is the heat flux (kW/m^2 (Btu/s-ft^2)) at a distance R (m (ft)) from the center of the flame, P_r is the energy fraction released as thermal radiation, and $\dot{Q}_p$ is the peak heat release rate (kW (Btu/s)). As can be seen in Equation 4-1, only the peak heat release rate and separation distance are required to calculate the heat flux to a target.

In most instances, the fraction of energy released as radiation varies between 0.1 and 0.3 [SFPE, 1999]. A value of 0.35 is conservatively assumed in the following analysis. It is

also assumed that the separation distance *R* is equal to the horizontal distance between the edge of the source fire and the edge of the target. Because the horizontal separation distance will always be less than the distance to the center of the flame, the heat flux values predicted by Equation 4-1 will be more conservative using the horizontal separation distance. Equation 4-1 has been compared to actual test data from pool fires with diameters of less than 3.1 m (10 ft). The test data for pool fires greater than 3 m (10 ft) was not considered because none of the source fires in the bay and cell spaces are expected to be on this order of magnitude. Table 4-1 summarizes the experimental data sets that were used in this comparison. Figure 4-1 shows a plot of the measured versus predicted heat flux values Equation 4-1 using a radiative fraction of 0.35 and a separation equal to the horizontal distance from the edge of the source fire.

Although most of the target heat fluxes are conservatively over-predicted, there are still enough data points that are under-predicted to warrant the use of a safety factor.

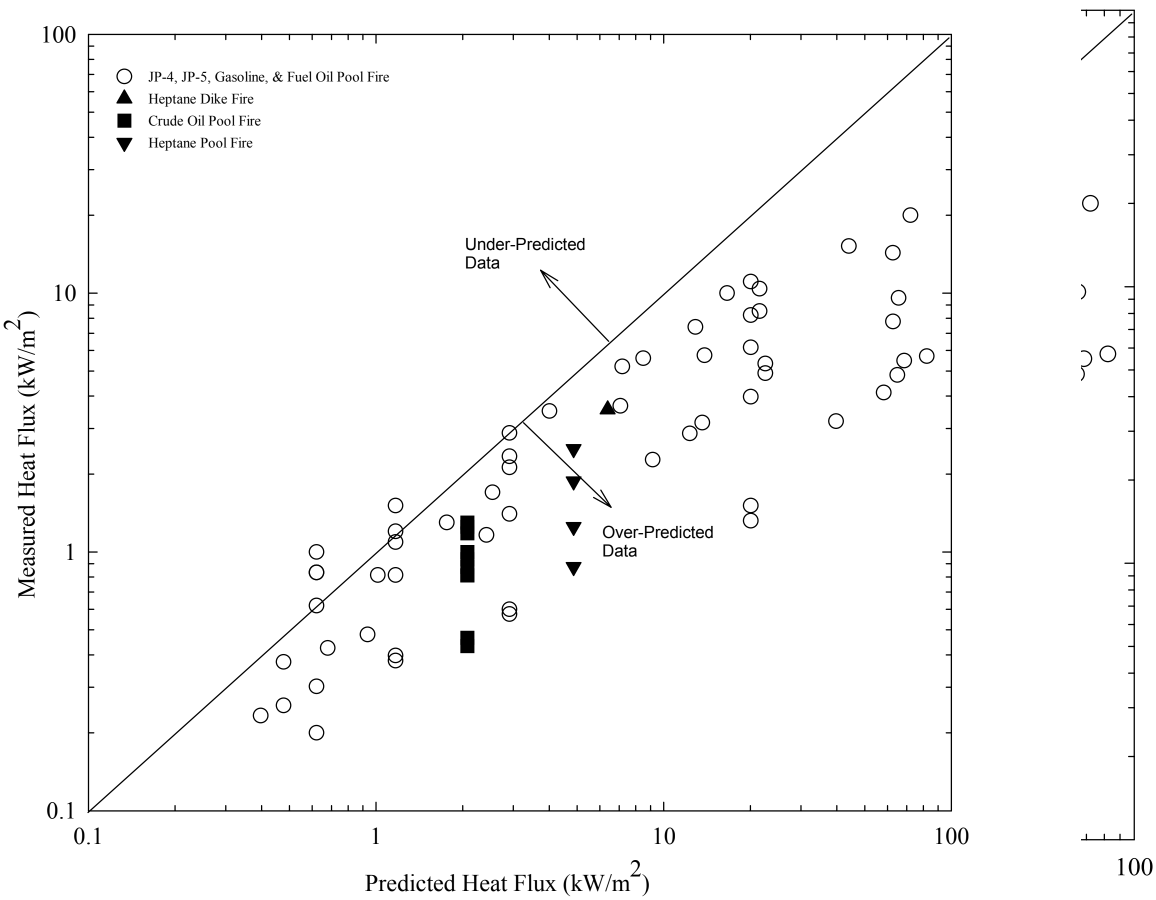


Figure 4-1. Predicted Versus Measured Target Heat Fluxes Using the Classical Point Source Model. Although Most of the Target Heat Fluxes Are Over-predicted, there Are Still Enough Under-predicted Data Points to Warrant the Use of a Safety Factor

Table 4-1. Summary of Experimental Data Used to Validate Heat Flux Model

Data Reference	Type of Fuel	Fire Diameter (m (ft))	Number of Data Points
Seeger [1974]	Fuel Oil	1.6 (5.2)	4
Yumoto [1977]	Gasoline	1.0 (3.3) to 1.5 (5.0)	11
Dayan and Tien [1974]	JP-4	1.2 (4.0)	4
Dayan and Tien [1974]	JP-5	2.4 (8.0) to 3.1 (10.0)	8
Hagglund and Persson [1976]	JP-4	1.1 (3.6) to 2.3 (7.4)	11
Koseki and Mulholland [1991]	Crude Oil	1.0 (3.3) to 3.1 (10.0)	5
Koseki and Yumoto [1988]	Heptane	1.0 (3.3) to 2.0 (6.6)	2
Koseki and Yumoto [1989]	Heptane	3.1 (10.0)	1

Figure 4-2 shows point source model predictions using a safety factor of 1.5, a radiative fraction of 0.35, and a separation distance equal to the horizontal distance from the edge of the source fire. As can be seen, all of the data is either accurately predicted or conservatively over-predicted. In some instances the heat flux is over-predicted by a considerable amount. Nevertheless, Figure 4-2 shows that the model will result in conservative predictions for a wide range of fuels and fire sizes without the need for evaluating fire specific parameters such as the diameter and flame height.

The SPFE Engineering Guide [SFPE, 1999] uses an energy release fraction of 0.21 or less. The separation distance is also determined using the middle of the flame as the point of radiant origin. The application in this analysis is more conservative, hence more of the data is over predicted in Figure 4-2 than is in the Engineering Guide application of the point source model.

<u>Comparison of Heat Flux Models</u>

An example of applying various calculation procedures and the effect it has on the appropriate safety factor is given in this section. Three methods for calculating flame radiation are described and compared with experimental data. The classical point source model can be compared to the other three methods cited above for calculating the incident heat flux to a target and shown to be conservative. The predictions will be compared by comparing the calculated heat flux for each method against the data set used in Section 3.1.1 to validate the point source model.

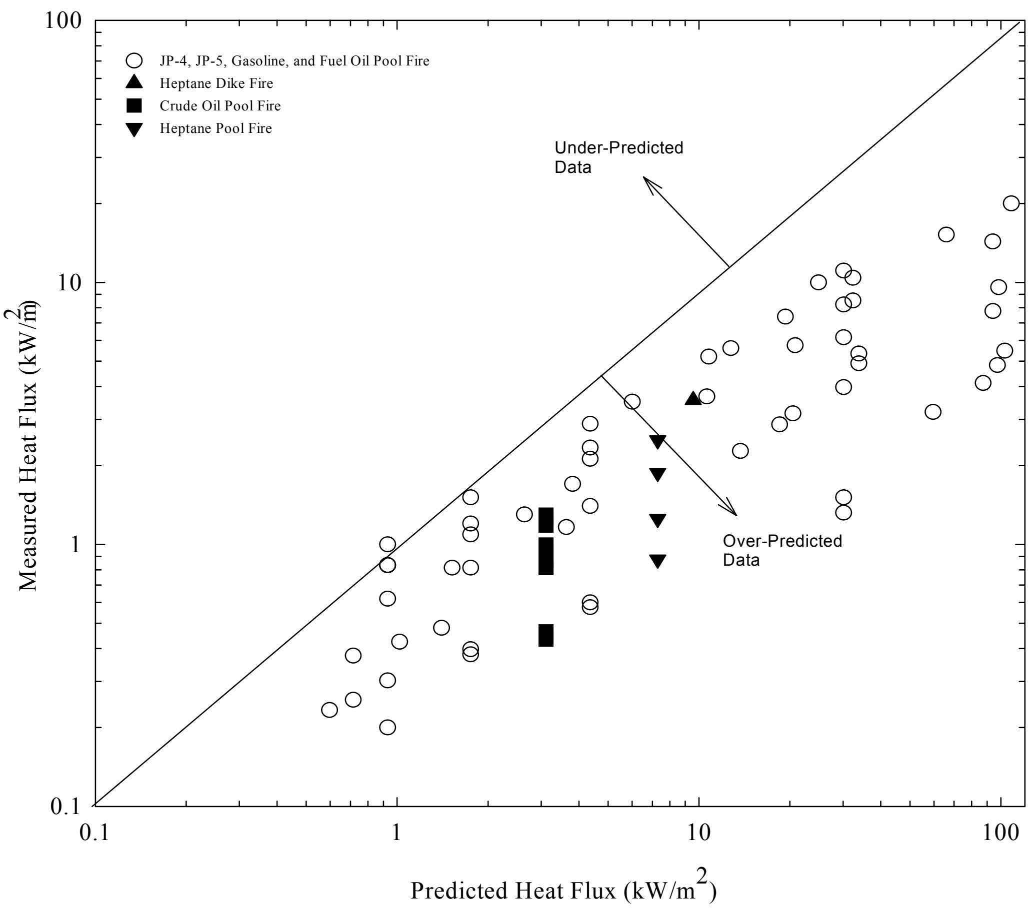


Figure 4-2. Predicted Versus Measured Target Heat Fluxes Using the Classical Point Source Model with a Safety Factor of 1.5 This Figure Illustrates That the Point Source Model Will Result in Conservative Predictions for a Wide Range of Fuels And Fire Sizes

The Shokri and Beyler correlation requires the determination of the fire diameter. The following equation is used in this method to calculate the heat flux to a target (Shokri and Beyler, 1989):

$$\dot{q}'' = 15.4\left(\frac{R}{D}\right)^{-1.57} \qquad (4)$$

where *D* is the source fire diameter (m). The radial separation *R* is the distance between the center of the source fire and the edge of the target. Figure 3-4 shows the predicted heat flux versus the measured heat flux at a target for the same data set used to validate the point source model. Figure 3-4 shows that the Shokri and Beyler correlation under estimates about half of the data points and over estimates the other half. This is the basis for a recommended factor of safety of 2 in the SFPE Engineering Guide.

The Shokri and Beyler procedure is more detailed than the Shokri and Beyler correlation and the results are improved. The heat flux to a target is calculated using the following equation:

$$\dot{q}'' = EF \qquad (4)$$

where *E* is the emissive power of the fire flame (kW/m^2 ($Btu/s\text{-}ft^2$)) and *F* is the radiation configuration factor between the target and the flame. The emissive power of the flame is determined using the following equation [Shokri and Beyler, 1989]:

$$E = 58 \cdot 10^{-0.00823D} \qquad (4)$$

where *E* is in kW/m^2 and *D* is in meters. The configuration factor between the target and the flame is a function of the flame height, the fire diameter, the shape of the flame, and the orientation of the target. Shokri and Beyler assume that the flame can be approximated as a cylinder with a diameter equal to the diameter of the source fire and a height equal to that of the flame. The equations for this radiation configuration factor geometry are summarized in Shokri and Beyler [1989]. Figure 4-4 shows the predicted versus measured target heat fluxes for the same data set used to validate the point source model. The figure indicates that this method is much better than the Shokri and Beyler correlation, though some data is still under estimated, hence a lower factor of safety may be warranted.

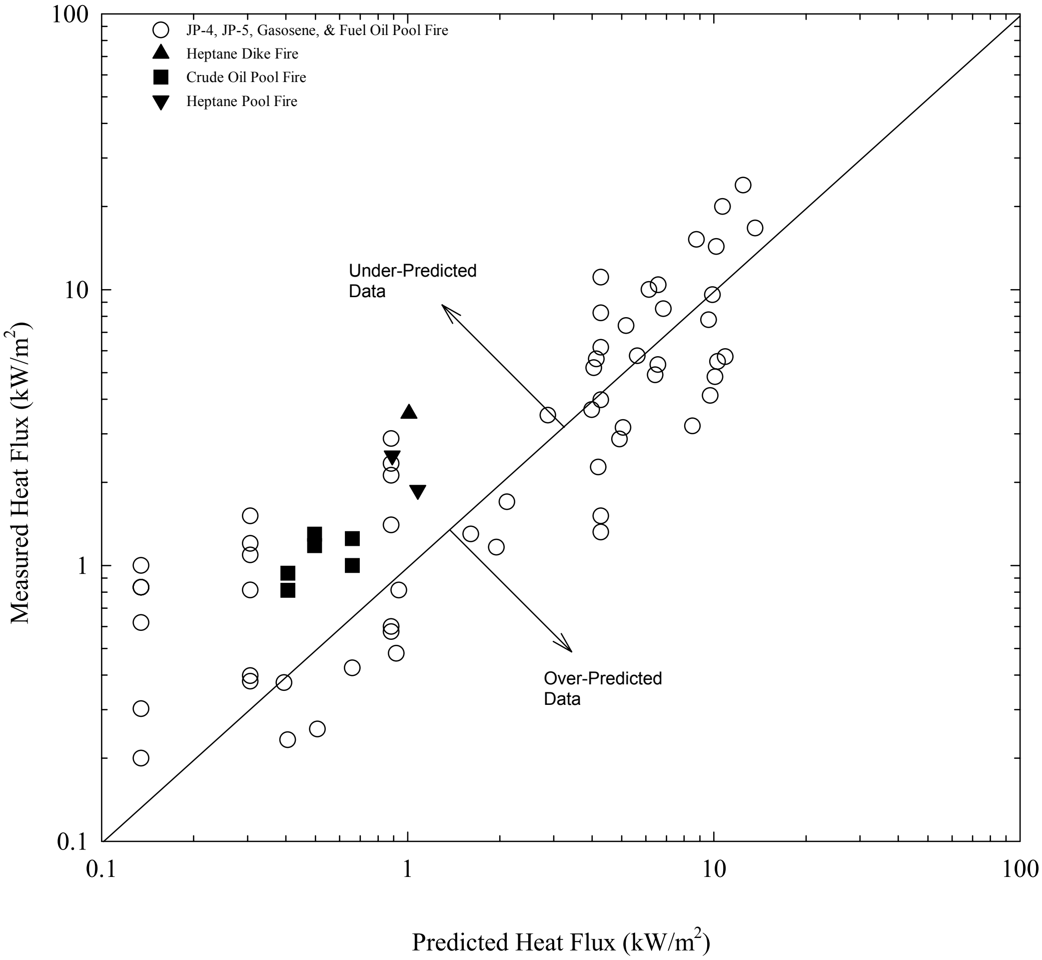


Figure 4-3. Predicted Versus Measured Target Heat Fluxes Using the Shokri and Beyler Correlation.

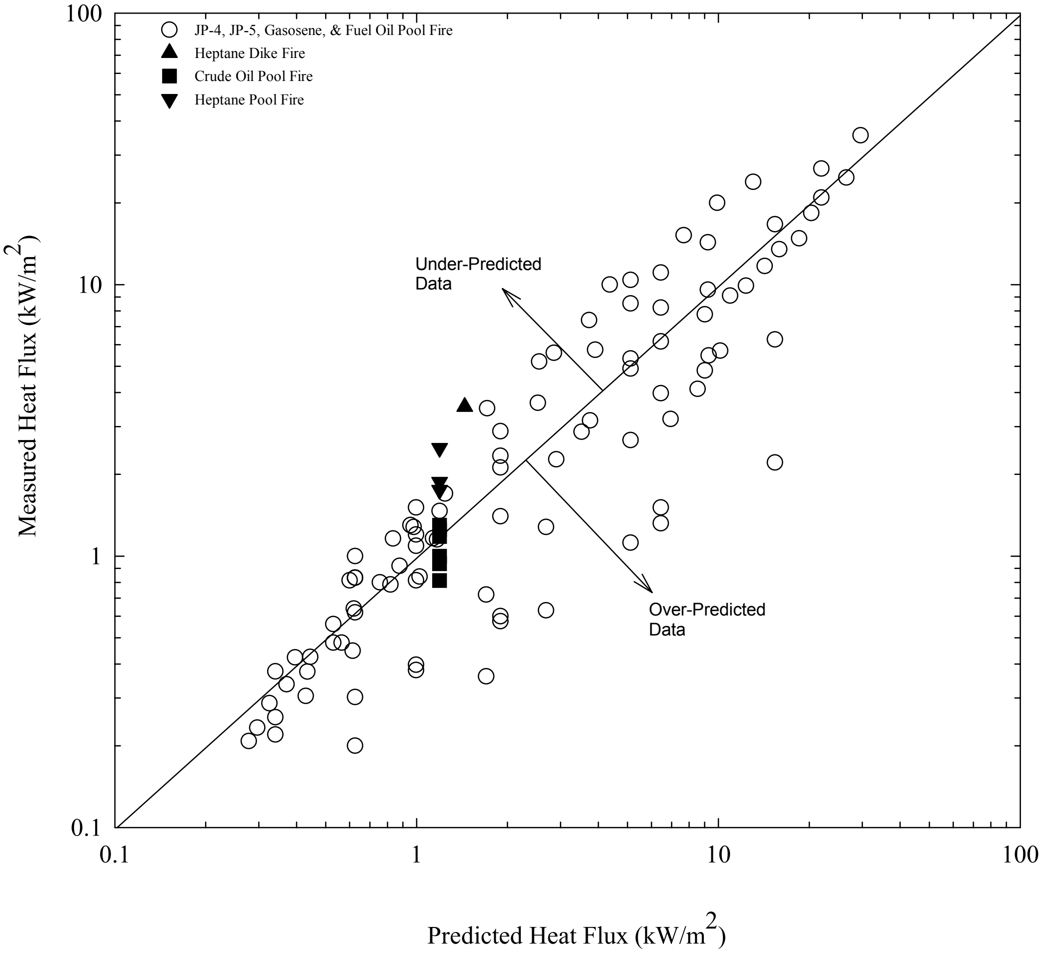


Figure 4-4. Predicted versus Measured Target Heat Fluxes Using the Shokri and Beyler Procedure.

<u>Sample Application Comparing the Heat Flux Models</u>

This section presents an application that compares the calculated predictions of each heat flux model. The fuel package is characterized as a 1.5 m (4.9 ft) diameter combustible material fire. The assumed heat release rate per unit area is 400 kW/m^2 (35 Btu/s-ft^2), which represents an upper bound estimate for miscellaneous bags of combustible materials [NFPA 72, 1996]. The peak heat release rate is the heat release rate per unit area times the area of the combustible materials, or 700 kW (660 Btu/s). The incident target heat flux at several distances was calculated using each of the four methods discussed above. Table 4-2 summarizes the predictions of each method. The results of the method used in this analysis are shown in bold italic font. The point source model yields the most conservative results near the source fire and is the next most conservative method at distances away from the fire.

Table 4-2. Comparison of Heat Flux Predictions for Miscellaneous Fire Example

Method	Heat Flux (kW/m^2 (Btu/s-ft^2))				
	at 0.5 m (1.6 ft)	at 1.0 m (3.3 ft)	at 1.5 m (4.9 ft)	at 2.0 m (6.6 ft)	at 2.5 m (8.2 ft)
Point Source Model 1 (Recommended Model)	**117 (10.3)**	**29.2 (2.57)**	**13.0 (1.14)**	**7.3 (0.64)**	**4.7 (0.41)**
Shokri/Beyler Correlation	**20.6 (1.81)**	**12.1 (1.07)**	**8.1 (0.71)**	**5.9 (0.52)**	**4.5 (0.4)**
Shokri/Beyler Procedure	**30.6 (2.69)**	**17.2 (1.5)**	**10.4 (0.92)**	**6.9 (0.61)**	**4.9 (0.43)**
Mudan/Croce Procedure	**67.0 (5.9)**	**39.3 (3.46)**	**24.6 (2.17)**	**16.6 (1.46)**	**11.8 (1.0)**

[1]Point source model with a safety factor of 1.5 and a radiant fraction of 0.35.

4.1.2 Compartment Effects

Compartment effects are critically important fire engineering calculations. These effects manifest themselves in several ways. It is important to ensure that any analysis captures these effects where important. These effects include:

1. The formation of a hot gas layer that thermally exposes all elements located within that layer. At relatively low temperatures, this exposure is primarily convective, and as this temperature approaches 500°C radiative heat transfer dominates. In many cases both heat transfer mechanisms should be accounted for.

2. The hot gas layer causes an increase in plume and ceiling jet temperatures since the plume and jet are entraining hot air. Any calculations involving direct exposure from a plume or ceiling jet must be performed with this effect in mind.

3. The hot gas layer has a reduced oxygen concentration. This has two primary effects. The first is that when the flame zone is immersed in the hot gas layer, the flame entrains gases and air at reduced oxygen concentrations. This results in lengthening of the flame and a decrease in heat release rate/unit length of the flame (energy release rate). This same effect will cause an increase in soot production and in the yield of CO.

4. At elevated hot gas layer temperatures, radiation from the hot gas layer will cause an increase in the burning rate of objects located within the layer and eventually radiation from the hot gas layer will increase the burning rate of objects located below it. In the limiting case, flashover, objects below the hot layer will ignite and the compartment fire will transition to a post-flashover state.

In any given analysis some of these effects may not be important or can be readily treated.

Cases where compartment effects are or may be important are given schematically in Figure 4.5. There are two basic approaches to these types of problems. The first involves using engineering calculations to calculate plume and ceiling jet exposures (T1, T2) as if there were no hot layer. Then estimate the hot gas layer temperature using either engineering calculations, (Iqbal and Salley (2002), Walton (SFPE, 2002)), Zone models (e.g. CFAST (2002), MAGIC (2002)) or field models (e.g. FDS (NIST 2002)). The average hot gas layer temperature rise due to compartment heating is added to the temperature increase due to the plume or ceiling jet. This will result in slightly over-predicted temperatures. This approach has the advantage of exploiting a range of conditions for plumes and ceiling jets and allows easy calculations of a range of target positions.

For targets located outside of the plume or ceiling jet, the target temperature can be calculated directly from the hot gas layer temperature. An alternative approach is to use a zone model to calculate the heating of a target in the hot gas layer and exposed to flame and hot gas layer radiation. Both CFAST (NIST, 2002) and MAGIC (EPRI, 2002) are sufficient for this purpose. MAGIC will also calculate exposure to a target in a ceiling jet (within the hot gas layer). MAGIC also calculates the exposure to a target in a compartment with radiation screens.

A third approach is to use a CFD or zone model (e.g. FDS) to calculate the temperature and velocity field at a target location. CFD codes can be used to great advantage where resolution in a complex flow field or geometry is required. FDS should not be used where detailed flame radiation calculations are important.

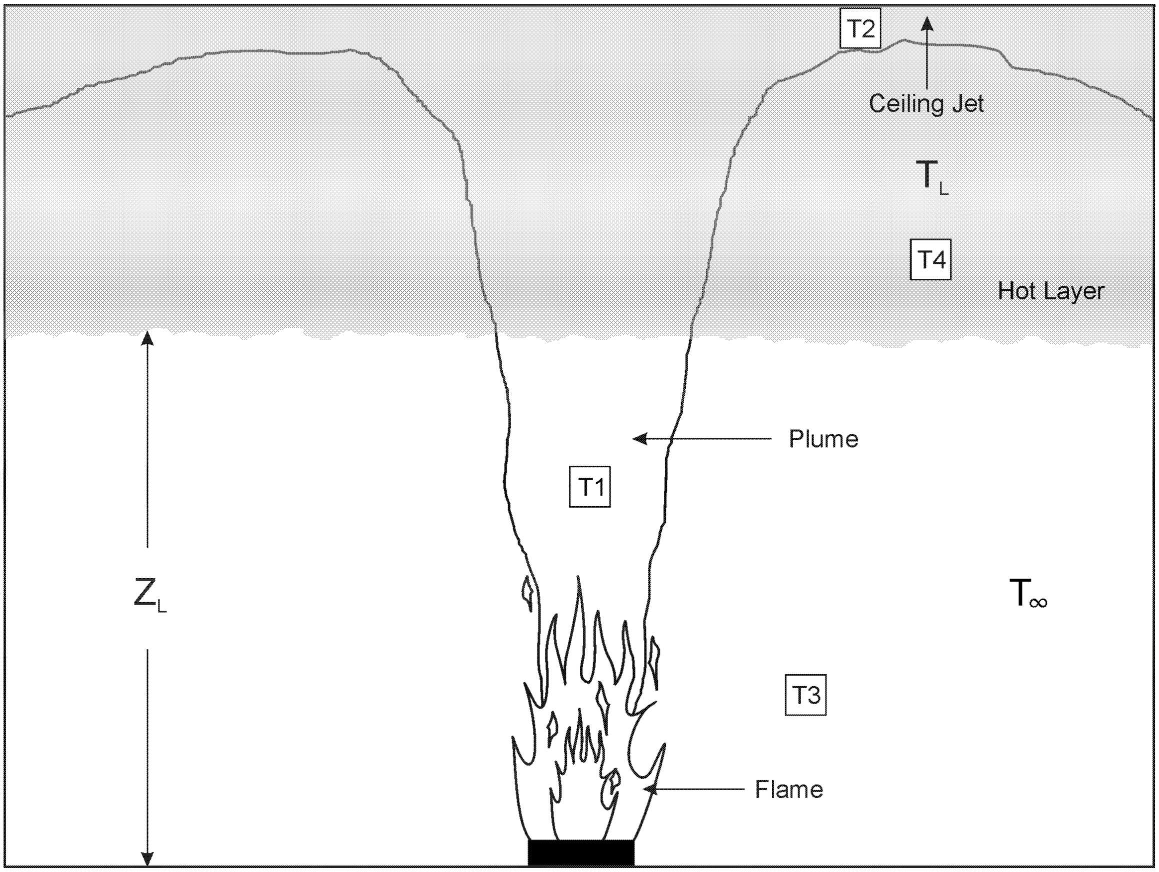


Figure 4.5: Schematic of Target Exposure Problem with Compartment Effects

4.1.3. Target Response Calculations

Damage to or ignition of target items is generally handled in two ways. In the simplest case a threshold gas temperature or critical heat flux value is used based on some empirical data. For example, IEEE 383 qualified cables are often assumed to fail when the heat flux exceeds 1.0 Btu/ft^2 –sec or 11.4 kW/m^2. Similar gas temperature criteria are also available. The second approach involves calculating heat transfer to the target and subsequent transient heating of the target until some failure criteria is met.

The use of steady state heat flux or gas temperature failure criteria is conservative and simple. Depending on the problem under evaluation, such methods may result in excessively conservative values. The calculation of the transient heating of the target will in general result in much longer times to failure and in many cases no failure as compared to simple threshold gas temperature values. These transient calculations are, however, subject to increased uncertainty.

For cases where a threshold gas temperature or critical flux are used and the calculated factor of safety is not considered adequate, additional calculations involving transient heating of the target will provide a quantitative improvement in the factor of safety.

Target heating calculations can be performed using several methods. The first broad category involves exact solutions of thermally thin and semi-infinite solid surface heating problems. These are standard engineering calculations that can be applied in special cases. These calculations are embedded as target heating models in some zone models, notably MAGIC and to a lesser extent, CFAST. The second type of heating calculation involves the use of finite difference or finite element heat transfer computer codes. There are many such codes available. HEATING, as an example, has been used for this purpose.

4.2 Fire Spread on Contiguous Combustibles

This class of problems relates to fire between fuel packages that are continuous or close enough that direct flame spread mechanisms are important. No validated model exists to calculate flame spread directly, with the possible exception of combustible wall and ceiling surfaces, therefore any problem involving direct flame spread must be estimated using some combination of empirical data and calculations. Flame spread on cable fires is an example of this class of problem. Methods for estimating fire growth and flame spread rate for cables are given in section 3 of this Appendix.

A related issue often arises when modeling electronic cabinet fires. For cases where more fire-stopped exposed cables penetrate the top of the cabinet a direct contiguous flame spread path to cable trays located above the cabinet exists and must be calculated. Any modeling or calculations done to evaluate the impact of cabinet fires should include as part of the source fire term flame spread to the cables above.

4.3 Thermal Detector Activation Time

This problem, in effect, is a calculation of the thermal response of a lumped heat capacity thermal element to a temperature and velocity field in a plume or ceiling jet. It is analogous to the target damage problem, except in this case the target has very high conductivity and low mass (e.g. a sprinkler fusible link).

The calculation of sprinkler or heat detector response time requires two steps.

1. Calculate the temperature and velocity at the detector position in the plume or ceiling jet.
2. Solve the transient heating equation for the thermal link or detector using the Response Time Index (RTI) of the thermal element.

Evaluation of the plume and ceiling jet temperatures and velocities as a function of position are done using correlations. The transient heating of the thermal element is performed using a lumped heat capacity model. The RTI is a sprinkler specific constant that is generally determined by the manufacturers. The lower the RTI value, the quicker the sprinkler will respond to a temperature increase. Generally, standard response sprinklers have RTI values that are between 150 and 200 $ft^{0.5}$-$s^{0.5}$ [Budnick, 1984; Solomon, 1989]. Quick response sprinklers can have RTI values between 40 and 60 $ft^{0.5}$-

$s^{0.5}$ [Budnick, 1984; Solomon, 1989]. The actuation temperature for ordinary sprinklers is normally between 155 °F and 165 °F. Sprinkler models are available with ratings as low as 135 °F and greater than 300 °F. Only ordinary sprinklers are considered in this analysis. Closed form approximations for t^2 fires are given by Schifiliti (SFPE Handbook).

Sprinkler and thermal detector actuation models are for flat open ceiling configurations, most notably DETACT-QS [Evans and Stroup, 1985; Portier, 1996]. DETACT-QS calculations have been compared to experimental data in several studies. These studies include Madryzykowski [1993], Walton and Notarianni [1993], and Notarianni and Davis [1993]. In general, the DETACT-QS model performs well considering the inherent uncertainty in the some of the input parameters, such as the sprinkler RTI value and the actual source fire heat release rate. In some instances, the effects of a hot layer were found to be significant [Madrzykowski, 1993].

The activation of smoke detectors can be treated in an analogous way. Schifiliti (SFPE, 2002) gives a method for treating smoke detector activation, based on both a calculated temperature rise and optical density. Such calculations can be performed using closed form equations as well as zone or CFD models.

4.4 Tenability Calculations

These calculations refer to calculating the conditions under which personnel would be threatened. They arise from these primary effects, reduction in visibility due to smoke, effects of temperature or heat flux and the effects of toxic gases.

Visibility is based on the optical density of the smoke in a hot layer. It is a function of the mass of material burned and the soot properties of the material. It is either directly calculated in the model or can be readily calculated from the results of either zone or modeling. It requires the specification of accurate soot yield and soot optical properties as input data. Methods for calculating visibility are given by Mulholland (SFPE, 2002) and Jin (SFPE, 2002).

Temperature effects are based on time/temperature relationships for human exposure. Data on limiting thermal radiation and temperature conditions for human exposure can be found in Beyler (SFPE, 2002) and Purser (SFPE, 2002). These data indicate tolerance levels of 110°C for between 10-25 minutes in dry air.

Toxicity assessments are normally not required in NPP applications. Calculation methods are available to estimate time to incapacitation for combination of fire products including CO, CO_2, HCl, acrolein and formaldehyde, using a Fractional Effective Dose, or FED approach. These methods can be readily applied using the results of zone and CFD models. Purser (2002) provides a methodology for estimating time to incapacitation.

4.5 Suppression Effects

The effects of fire suppression systems on fire growth rate, room temperature conditions, etc. can only be crudely accounted for using existing zone and CFD models. CFAST uses completely empirical measured room temperature and heat release rate reductions values based on a limited set of sprinkler tests. This method cannot be used in general. CFD codes have been used in special applications to calculate the effects of sprinkler and water spray systems. The use of models for routine design or analysis purposes is currently not possible.

To account for suppression effects one is forced to rely on full-scale test data from tests that approximate the conditions being evaluated. A very crude but conservative approximation would be to hold the heat release rate constant at the time of sprinkler operation. Alternatively, one could specify a cooling rate based on relevant full-scale test data.

4.6 Flashover Calculations

These calculations are used to quickly determine the minimum heat release rate necessary to cause flashover. Flashover occurs when the hot layer temperature exceeds 500-600°C, and effectively marks the location in a fire development history where the heat release rate of the fire is limited. This limit is due to primarily to the amount of air available or for very low fuel load areas where the burning rate is limited by the total exposed fuel surface area.

The minimum fire size to cause flashover is a function of the room size, bounding surface area, thermal properties of the bounding surfaces and the ventilation available, both natural and mechanical.

These methods are summarized by Walton (SFPE, 2002). Methods described by Iqbal and Salley based on spreadsheet calculations can also be readily used.

4.7 Post Flashover Temperature Calculations

These calculations are a special case of compartment fire temperature calculations. They are done for cases assuming flashover occurs where the primary variable of interest is the room temperature, and usually for purposes of evaluating the fire resistance of structural elements. In general, the calculations assume that the energy release rate of these fires is limited by the air inflow available. While zone and CFD models can be used for calculating post flashover temperatures, time/temperature relationships have already been calculated and are available in table and graphical form (Milke, SFPE, 2002). In addition, zone models often significantly over-predict layer temperatures in post flashover conditions.

In addition to those data, post flashover temperature calculations can also be estimated using methods given by Walton (SFPE, 2002) and Iqbal and Salley (2002).

5.0 Validation of Engineering Methods

Limitation of the various types of models has been described throughout this Appendix and in the context of specific applications in section 4. They are discussed further along with validation in the following sections.

There are no fire-related engineering methods or models that have been validated over the entire range of applications for which they might reasonably be used. There have been and are substantial and ongoing efforts directed at performing validation studies on calculation methods and models. ASTM E-1355 gives general guidance on evaluating the predictive capability of fire models.

Engineering Calculations

Most calculation procedures are based on correlations of data. These include, for example, relationships for flame radiation, plume and ceiling jet temperature and velocity, flashover calculations, etc. These correlations are based on full-scale test data and can be expected to give reasonable results within the limits of the mathematical model on which they are based. They can be reasonably applied to most NPP applications and are primarily limited by uncertainty of the correlations beyond the range of the data set on which they are based. In NPP calculations this is often manifested for very large ceiling height spaces (>30-40 ft), highly obstructed flow paths and very large fires in large spaces (e.g. turbine halls).

Zone Models

Zone type fire models have been extensively "validated" or compared to experimental data for a range of applications, including NPP's. An ongoing project on Evaluation of Fire Models for Nuclear Power Plants, (Dey, 2002) supported by the NRC has conducted an international set of validation studies for a range of zone and CFD codes using typical NPP applications. These validation data sets include room size up to 1300 m^3, fire sizes from 100 kW to 2.5 MW and a range of fire sources. In general, the results are reasonable for many of the models evaluated including CFAST and MAGIC. CFAST has been subject to many varied validation studies primarily due to its wide application, non-proprietary nature and long history of development.

Zone models capture in an approximate way the important physical processes related to energy and mass transfer from a two-layer compartment fire. For cases where a two-layer approximation does not give the resolution required for the result it may be necessary to use CFD modeling. An example where the average layer temperature is used to calculate the exposure to a target located relatively close to the fire source. For cases where an average temperature is acceptable, zone models, properly applied, will yield adequate results, subject to physical limitations of the model.

CFD Models

CFD models including FDS have been subjected to validation studies. The most applicable to fire applications, FDS, JASMINE, and VULCAN are included in the NRC-supported international model evaluation project. The major advantage of CFD codes relative to validation is that they, as a group, are inherently less dependent on empirical data or approximations. The codes utilizing large eddy simulation LES (e.g. FDS) methods predict the turbulent flow behavior of fire-induced flows without the need for manipulation of turbulence characteristics. The implementation of certain physical phenomena, notably radiation, is a weak point in these codes, particularly flame radiation in the case of FDS.

Summary

Calculation methods and models have been validated to an adequate level for most NPP-related problems. Subject to the overall caveat that the fire source term can be specified a priori. Cases where insufficient validation and substantial uncertainty list are primarily for large spaces (>2000 m^3) with large (>10 mw) fire sources. There have been no validation studies that would approximate a large multi-level fire in a turbine hall. There is no theoretical reason that models should not adequately treat these cases, and larger scale validation tests are planned. Adequate validation of calculation methods and models largely remains one of balancing the uncertainty in the calculations with adequate factors of safety applies to the results.

6.0 Sources of Input Data

Summarized below are particularly useful references for input data sources related to heat release rate, thermal property data and methods, ignition and damage criteria and flame spread.

6.1 Data Sources for Input Data for Heat Release Rates

Heat release rate data may be based on full or small-scale experiments or it may be deduced using methods or models previously described. Sources of data, including experimental heat release rate measurement and parameters used to calculate the heat release rate are included below.

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Thermal properties that are used to calculate the temperature rise of solid materials include the thermal conductivity, the heat capacity, and the density. Boundary condition information, such as the convection heat transfer coefficient and the radiation absorption and emission properties are also included this input category. Properties for specific materials that are not available in the references listed below may be obtained from the manufacturer or retailer.

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6.3 Input Sources for Ignition/Damage Thresholds

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