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The Fire Risk Analysis Methods

for the Savannah River Site (U)

September 30, 2000

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ABSTRACT

Fire is a significant hazard in most facilities that handle radioactive materials. Often it is the dominant risk. Thus, it is necessary to characterize the fire risk in such facilities. In 1993 the Savannah River Site (SRS), a Department of Energy facility, began an effort to enhance characterization of the fire risk at its nuclear facilities. This report consolidates the methods and techniques used to evaluate the industrial fire risk at SRS.

The fire risk characterization used at SRS is based on establishing representative fire consequences (i.e. classes), then predicting the frequency that these consequences would be exceeded. The analysis method readily accounts for building occupant intervention, limited controlled loading, automatic fire detection, sprinkler system performance, fire department intervention and fire barriers. A significant strength of the technique is the ready identification of the most significant protection features.

The risk assessment techniques, while developed to characterize nuclear facility risk, can readily be implemented for other occupancy types. The report contains recommended effectiveness (i.e. reliability and availability) predictions for a variety of fire protection systems and features. In many cases these values are applicable to both nuclear and non-nuclear facilities.

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INTRODUCTION

An uncontrolled fire in a nuclear facility can be a very energetic event. Severe smoke, excessive temperatures, and large thermal gradients are common. Such fires can readily breach containment barriers (glove box, ventilation ductwork and building envelope), and because of the significant thermal gradients, readily disperse radioactive material. Thus, uncontrolled fire can be a dominant risk in many nuclear facilities. This report consolidates efforts begun in 1993 to better characterize fire risk at Savannah River Site (SRS) Nuclear Facilities.

Recognition of fire as an important consideration in any safety analysis coincided with several different programs and activities. One such major event was the publication of DOE-STD-94-3009, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports* (Ref. 1). At the same time, the fire protection community was promoting the concept of risk based design (Ref. 2). These efforts have since resulted in several consensus guides (Ref. 3) that provide a basis for performance-based fire protection (i.e., risk-based). Thus, the emphasis on evaluating significant hazards such as fire and the tools necessary to evaluate such events were actively being implemented during the early and mid-1990s.

Prior to the issuance of DOE-STD-3009-94, it was common to assume that a facility that was compliant with fire protection, DOE orders, and national codes and standards was adequately protected. Thus, fires that propagated beyond the local region where the fire started were considered Beyond Design Basis and not analyzed. DOE Order 5480.23 (Ref. 4) and DOE-STD-3009-94, however, use 1.0E-6/yr conservatively calculated and 1.0E-7/yr realistically calculated as the threshold for incredibility. While this limit does not explicitly apply to in-facility accidents and thus to fire events, it established a criterion that has repeatedly been used to evaluate accident credibility. Since the frequency of multi-room fires in fully code compliant facilities commonly falls in the Extremely Unlikely range (1.0E-06 to 1.0E-04 per year) and sometimes higher, 3009-style safety documents began to address larger fires with correspondingly greater consequences.

The earliest effort to standardize a methodology to evaluate fire risk was issued in 1994 (Ref. 5). This method, which remains the basis for radiological fire risk work at SRS, presents fire risk results in terms of the frequency that a specific dose will be exceeded by a fire somewhere in the facility. Since this document was issued, the SRS generic fire risk methodology has been refined and has evolved into a technique that has significant credibility with DOE and the site's reviewers (Ref. 6).

The report is separated into three major topics: Hazards, Consequences and Frequency. A synopsis of the individual report sections is presented below.

Introduction. An overview of the information to be presented in the report.

Hazard and Accident Analysis Methodology. A discussion of how the fire risk analysis methods presented in this report fit in the context of the Safety Analysis Report (SAR) preparation process.

Fire Consequence Analysis. A discussion of methods to use in estimating fire severity and fire consequences.

Fire Frequency Analysis. A discussion of methods to use in estimating fire frequency.

Combining the Results. A discussion on how to combine the consequence and frequency results to quantify the overall facility risk.

Conclusions. A summary of the overall report.

Works Cited. A list of references cited in the report.

Appendix A, Definitions. A list of definitions useful in discussing fire risk.

Appendix B, Assumptions. A summary of the assumptions that may need to be addressed by the Functional Classification and Technical Safety Requirements.

Appendix C, Automatic Sprinkler System Reliability. A white paper that was prepared to support development of the Savannah River Technology Center SAR.

Appendix D, Sprinkler System Reliability and Performance. A white paper that was prepared to compare the SRS generic sprinkler system effectiveness probability with recently published data.

Appendix E, Fuel Package Modeling. Part of a fire risk training presentation that was prepared for DOE.

Appendix F, Fire Severity Estimates. Part of a fire risk training presentation that was prepared for DOE.

Appendix G, Dose Consequence Estimates. Part of a fire risk training presentation that was prepared for DOE.

Appendix H, Fire Department Response. Part of a fire risk training presentation that was prepared for DOE.

Appendix I, Fire Frequency Estimates. Part of a fire risk training presentation that was prepared for DOE.

Regulatory Basis for Fire Risk Analysis

At SRS, a fire risk evaluation is documented as a Fire Risk Analysis (FRA). Both the technical report and the calc-note format have been used in preparation of the FRA. The preferred format is the technical report. In preparing a 3009-style Safety Analysis Report (SAR), a multi-step analytical process is commonly used. The objective of the FRA is to fully support the SAR, a document which is the cornerstone of the Authorization Basis for most Hazard Category 1, 2 and 3 Nuclear Facilities in the DOE complex. The SAR is prepared to meet DOE Order 5480.23

(Ref. 4) using the methods described in DOE-STD-3009-94 (Ref. 1). When correctly implemented, the 3009-style format allows the Westinghouse Savannah River Company (WSRC) and DOE-SR to better understand the dominant risks.

The FRA starts with the acknowledgement that fire is a known hazard (i.e., hazard identification) in all SRS nuclear facilities and that the consequences are sufficiently high (i.e., hazard analysis result) to warrant a quantitative analysis. Thus, there is the need to estimate the radiological consequences of a fire and, if necessary, the frequency that these consequences might be exceeded.

The consequence estimate begins by establishing the operational range of combustible loading in the facility based on the building construction and the combustible controls program consistent with the Fire Hazards Analysis (FHA). A sufficiently bounding temperature curve for a fully involved room is then developed based on this range. For many SRS facilities, the curve is determined to have an average temperature based on ASTM E-119 (Ref. 7). Analysis cost is a significant consideration in defining the severity. The ASTM E-119 curve is a common qualification curve used in fire tests, thus it already includes a sufficiently bounding bias. Development of facility specific engineered temperature curves can increase the SAR preparation cost significantly without a corresponding reduction in the consequence estimate. Such detailed curves should only be developed when there is a significant need to demonstrate a lower fire severity (e.g., initial calculations do not meet site guidelines).

The frequency estimate is based on the premise that all severe fires begin as small fires. These small fires, if not extinguished, are assumed to propagate from incipient to fully involve the room of origin. Fires then grow in size from single room, to two-room, multi-room and multi-area fires. Each is more severe in terms of involvement. The frequency of these various severity levels is then estimated. The frequency estimates typically credit combustible controls, operator intervention, automatic detection, automatic suppression, fire barriers and the fire department.

Comparisons between anecdotal field results and the frequency estimates are possible. Fires that burn out because of limited or discontinuous combustibles are accounted for in the combustible controls credit. Historic instances where the event appears to start as a "large fire" can usually be traced to the ignition of one item followed by very rapid fire propagation. Such rapid fire propagation, which overwhelms the defense-in-depth, is accounted for as individual failures of each protection feature.

Where different fires have similar consequences, their frequencies are combined. These resulting frequency and consequence combinations are then compared to the SRS Evaluation Criteria. Fire consequences that occur less often than 1.0E-6/yr are deemed Beyond Extremely Unlikely and the consequences are not specifically analyzed.

In most cases, the FRA and SAR are considered to present a median estimate of on-site risk and a conservative estimate of offsite fire risk (95th dose quantile level). Usually the consequence estimates are characterized as sufficiently bounding (i.e., conservative) while the frequency estimates are median (i.e., best-estimate). The intent is to provide a realistic but conservative estimate of facility risk.

Fire Behavior Overview

The consequences of a fire (e.g., release of radioactive material, explosion of a package) are strongly dependent on the building and package response to fire. Typically, the consequence

values are based on mechanistic models that assume specific fire protection features fail to function as designed. The reasonably bounding responses of a building are fairly predictable. Some of the expectations are:

- Smoke migrates through a significant portion of the structure hampering emergency response and personnel evacuation.
- Intermediate walls (both rated and unrated) delay fire spread, but do not prevent it. Multiple room involvement occurs.
- Metal panel exterior walls open, venting smoke directly to the outside.
- Exposed structural steel fails, allowing additional venting.

The general sequence of a fire is predictable. With favorable geometry, adequate combustibles and no intervention, most fires will proceed through the phases shown in Figure 1. Ignition will occur when a kindling material is brought in contact with an ignition source. A fire is considered to exist when "the physical and chemical processes involved in reaching a point of self-perpetuation of fire [exist] whether or not there is an open flame" (Ref. 8). When sufficient combustible materials are present, the fire will grow exponentially until fully developed. Full development occurs when fire growth stops because of limited oxygen, fuel, or chemical kinetics. When the combustibles are exhausted, the room temperature will start to decrease (decay) as heat escapes the fire compartment.

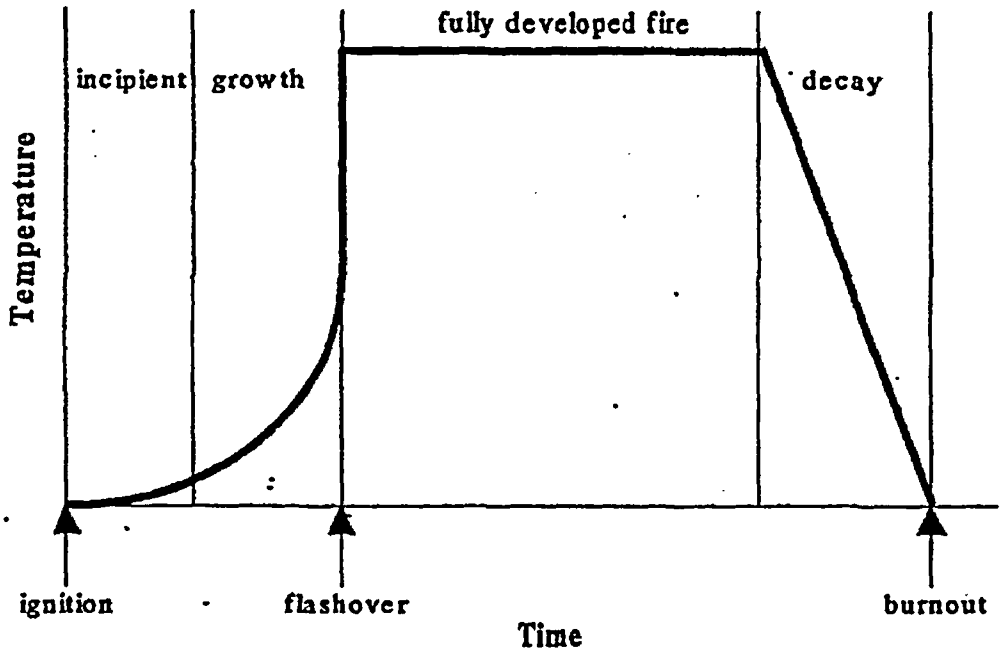

Figure 1--Typical compartment fire curve

Overheat Phase. When a heat source is brought in contact with a combustible material, overheating of the combustible material may occur. This is apparent by the destruction of material "without self-sustained combustion [where] removal of the heat source will stop the

destruction. Overheat is the stage before ignition" occurs (Ref. 8). This stage is not shown in Figure 1.

Incipient Phase. The incipient stage begins with ignition. This is defined in NFPA 901 (Ref. 8) as "The physical and chemical processes involved in reaching a point of self-perpetuation of fire whether or not there is an open flame." It is during the incipient stage that successful intervention by facility personnel is considered likely. To facilitate the formation of the event tree the incipient stage description has been quantified as:

1. Involves only a single object within a room,
2. Limited to 300 kW peak heat release, (This value is the maximum expected for two bags of paper trash (Ref. 9).
3. Can be extinguished with a hand held fire extinguisher (by limiting the fire's size and geometry).
4. Will not activate a correctly designed, operational automatic sprinkler system (by limiting the fire's size and geometry).

This description limits the size of an incipient fire to that considered reasonable for facility personnel with rudimentary training to effectively fight the fire with a hand-held fire extinguisher.

Growth Phase. The growth stage of a fire is the most dramatic. This stage is characterized by rapid fire growth. The end of the growth stage will commonly conclude with flashover, a phenomena that results in the simultaneous ignition of all items in the room. Where airflow is restricted, flashover may not occur, thus the growth stage is considered to conclude when the room temperature stabilizes.

Fully Developed Phase. Once a fire reaches the fully developed stage, it exhibits little variation in energy production, and room temperature with time and may last for several hours. It is possible that the room temperature will continue to increase during this stage, however the rate of increase will be fairly slow in comparison to the exponential increase in the growth phase. The combustion rate may be limited by several mechanisms: fuel surface area limited, local convection limited, or room ventilation limited (Ref. 9).

Decay Phase. As the available fuel is exhausted, the rate of combustion will slow. Energy release will decrease and the room temperature will start to drop. This stage of the fire timeline is referred to as the decay phase.

HAZARD AND ACCIDENT ANALYSIS METHODOLOGY

DOE-STD-3009-94 (Ref. 1) suggests that Chapter 3 of the Safety Analysis Report (SAR) present two analysis sections. These are the Hazard Analysis and the Accident Analysis. Each section accomplishes specific objectives. The sequence for preparation of the these sections is shown in Figure 2. The hazard analysis is required to systematically identify facility hazards and accident potentials. It must evaluate the complete spectrum of hazards and accidents and becomes the basis for the entire safety analysis effort. In addition, the HA identifies a limited subset of accidents to be carried forward to the Accident Analysis.

While the HA evaluates the complete spectrum of accidents, the Accident Analysis presents a limited subset of accidents, that bound "the envelope of accident conditions to which the operation could be subjected." The presentation is typically more quantitative and formal. Detailed computations are summarized with all assumptions identified and justified.

The overall intent of the SAR Chapter 3 Hazard and Accident Analysis effort is to provide a basis for selecting and categorizing the controls that ensure that a facility does not present an undue risk to the public and workers. Thus, throughout the evaluation process, preventive and mitigative SSCs and pertinent elements of programmatic controls are identified. The SSCs and controls are then evaluated through the Functional Classification process to identify the functions that must be defined as Safety Class, Safety Significant and Defense-in-Depth (i.e., Chapter 4 of the SAR). Their identification also facilitates the development of the Technical Safety Requirements (i.e., Chapter 5 of the SAR).

The development of the Hazard and Accident Analysis Chapter in a Safety Analysis document (i.e., Chapter 3) is a multi-discipline process. This is most apparent for the fire events where the disciplines commonly include fire protection, structural mechanics, source term modeling, meteorological receptor dose modeling and frequency analysis. In addition, since fire events are usually a major (if not the most significant) facility risk. Excessive conservatism may lead to misleading conclusions about overall facility risk and/or the types and numbers of needed controls (i. e., accident prevention and mitigation features and programs). Thus, the development of the fire events usually requires an iterative analysis approach that balances conservatism, funding and facility safety basis needs. Usually, by balancing frequency and consequence results it is possible to demonstrate an acceptable level of facility fire risk.

The facility fire risk estimates must be developed in the context of the other SAR Chapter 3 development efforts. This paper describes how the fire risk estimates are prepared for Chapter 3.

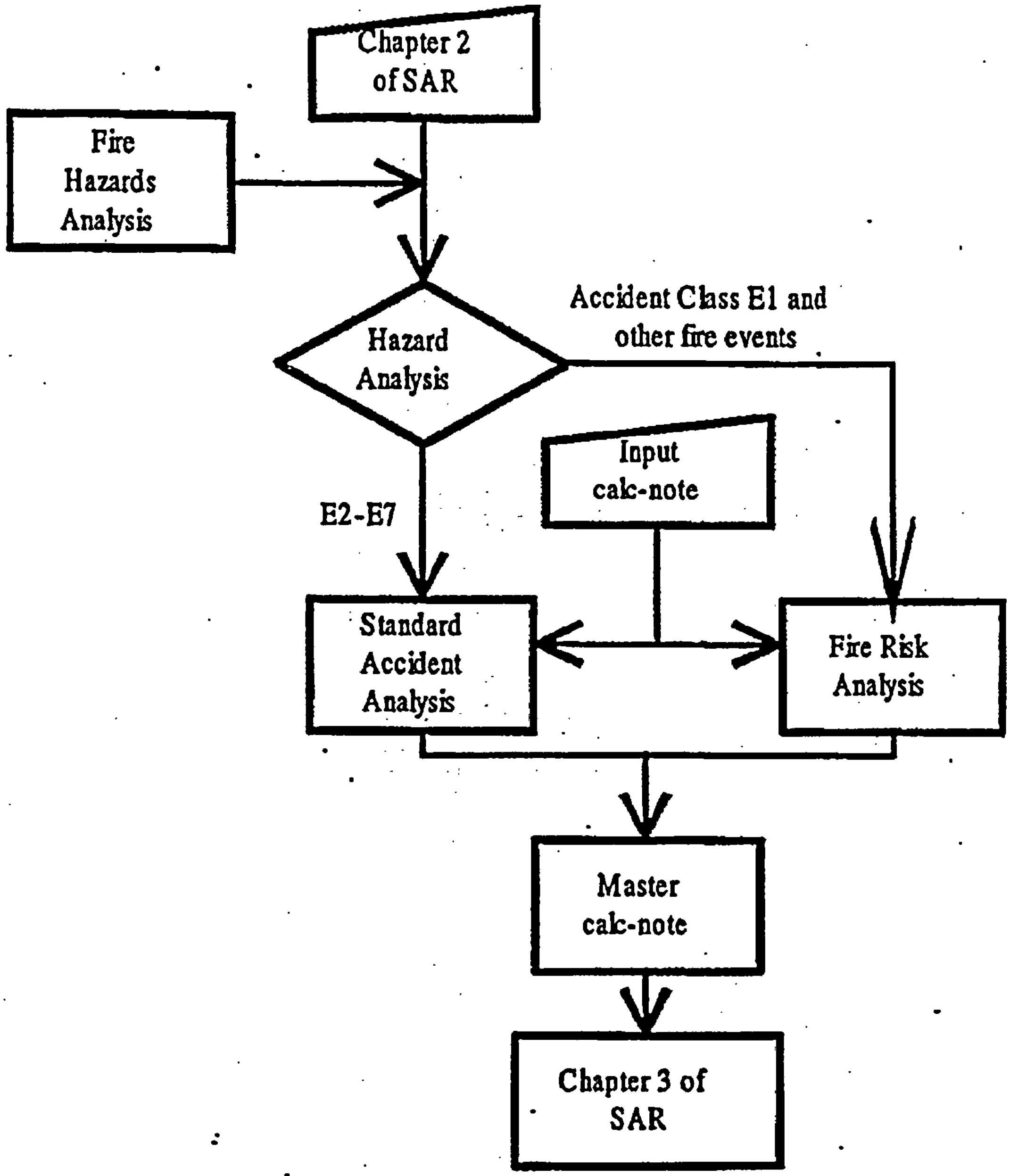

Figure 2--SAR Chapter 3 Development Flow Chart

Basic Inputs

The basic inputs for Chapter 3 analysis are documented in SAR Chapter 2, Facility Description. Other inputs that are used in developing SAR Chapter 3 are:

- facility description document (including process and activity descriptions)
- a comprehensive inventory document listing radiological and chemical hazards (includes form, type, location, quantity, and associated system or subsystem).
- an initial chemical screening for common hazardous materials (CHMs) and basis for screening criteria

Fire Hazard Analysis

The Facility Fire Hazard Analysis (FHA) is prepared to the *Guideline for the Preparation of Fire Hazards Analyses for the Savannah River Site* (Ref. 10). SRS is presently replacing this guide with a Source and Compliance Document (SCD-10). The FHA is not typically considered part of a facility's authorization basis (AB), however it does provide input to the AB. When a SAR is prepared there is a mandatory requirement in DOE Order 420.1(Ref. 11) to present information from the FHA in the SAR.

An important output of the FHA is the definition of fire areas. Fire Areas are facility segments that are separated by fire rated construction exceeding a rating of 2 hours or by physical separation. Their primary function is to divide the facility into acceptable loss increments. These segments are not segments in the sense of Facility Segments as used in the Hazard Assessment Document (HAD). Propagation between fire areas is a common fire scenario that must be evaluated in a SAR. Typically, such scenarios are unlikely (1.0E-02 ≥ frequency > 1.0E-04/year) or extremely unlikely (1.0E-04 ≥ frequency > 1.0E-06/year).

Hazard Analysis

Preparation of the Hazard Analysis is described in the *Hazard Analysis Methodology Manual (U)* WSRC-IM-97-9, Revision 1 (Ref. 12). The primary purpose of the HA is to identify hazards and categorize the facility safety risks using a structured, comprehensive hazards identification and classification process.

Hazard Analysis Methodology

A significant strength of the Hazard Analysis is the systematic process that has been implemented. The steps in this process:

1. Hazard Identification. Characterize the form, quantity, and location of hazardous material or energy sources. WSMS uses a checklist as a guide to aid in this process.
2. Scenario Development. Propose detailed, reasonable-worst-case, credible scenarios describing process upsets, human errors, system failures, etc.

3. Risk Assessment. Estimate the likelihood and severity of occurrence for each scenario or scenario set proposed in Step 2.

4. Risk Binning. Assess the risk of each scenario based risk-binning matrix shown in Figure 3.

The *HA Methodology Manual* (Ref. 12) recommends that a facility be divided into sections to facilitate hazard identification and evaluation. This method greatly facilitates the evaluation of process equipment hazards. The manual does recommend that a single general hazard facility-section that could involve more than one facility-section (e.g., facility fire and earthquake) be prepared. This paper recommends how to prepare this "general hazard facility-section" for fire events.

Frequency → / Consequence	Beyond extremely unlikely	Extremely unlikely	Unlikely	Anticipated
High		7	4	1
Moderate	10	8	5	2
Low		9	6	3
Negligible	11	12		

High risk

Low risk

Moderate risk

Negligible risk

Figure 3--Risk binning matrix (risk titles align with final risk acceptance criteria, other steps in the HA and AA process use slightly different matrix criteria)

Typically, events are grouped into 7 categories. These are:

- E-1 Fire
- E-2 Explosion
- E-3 Loss of Containment/Confinement
- E-4 Direct Radiological/Chemical Exposure
- E-5 Nuclear Criticality
- E-6 External Hazards
- E-7 Natural Phenomena

The output of the HA task is a technical report that includes:

- Hazard Identification Tables, which provide a comprehensive lists of hazards
- Hazard Evaluation Tables, which summarize possible accident scenarios, their frequency, potential consequence and risk category.

Addressing Industrial Fire Events

It is expected that fire will be a hazard for any facility. To ensure that it is properly addressed, the general hazard facility-section shall present the following fires in the E-1 category. The frequencies presented are the default values when no other information is available.

- Glove box or major component fire – This event represents a small fire involving one piece of process equipment. The postulated scenario should involve the glove box or major component, which if involved in a fire, results in the largest consequences. Fire events involving damage to other equipment should not be evaluated for this "small fire" event. The default release duration for the hazard evaluation is 3 minutes. Since this is a representative accident for all glove box and equipment fires it is typically treated as anticipated.
- Room fire – This event represents a fire where full room involvement occurs. The fire severity is assumed to be severe with a typical duration exceeding 1 hour. The postulated scenario should involve the room, which if involved in a fire, results in the largest consequences. Fire events involving damage to other rooms, resulting in radiological releases, should not be evaluated for this "room fire" event. The default release duration for the hazard evaluation is 30 minutes, unless two or fewer containers must fail to produce the estimated consequence. When this is the case the 3 minute release model should be used since the release will occur by one or two failures. Because this is a representative accident for all room fires, it is typically treated as anticipated.
- Fire area fire – The FHA will normally divide the facility into one or more fire areas. This event represents a fire where full fire area involvement occurs. The fire severity is assumed to be severe with a typical duration exceeding 2 hours. (The default radiological release duration is typically 30 minutes). The Hazard Evaluation Table may present a

scenario for each fire area or may use the worst-case fire area fire as a representative fire area fire. Fire area fires are typically treated as anticipated.

- Multiple fire area fire – This event represents a fire where propagation between fire areas has occurred. This is sometimes referred to as the full-facility fire, however this term should be avoided since there is a connotation that everything must burn to produce the estimated consequence. The fire severity is assumed to be severe with a typical duration exceeding 2 hours. (The default radiological release duration is typically 30 minutes).

There may be instances where unique fire hazards are present. The most common example is vehicle loading and unloading operations. (Note: The default frequency for vehicle fires is unlikely.) During such situations, this fire can sometimes be much more severe than the fire scenario presented above. Unique fire events may be tabulated in the general hazard table or any of the segment hazard tables. Except for those situations discussed below, all of these events should be placed in the E-1 group.

Wildland Fires

Wildland fires (i.e., forest fires) have the potential to propagate to any operating area at SRS. The unmitigated frequency for these events is anticipated. The mitigated frequency is unlikely based on US Forest Service intervention. The consequence should consider involvement of the entire facility inventory. Wildland fires are considered an external event (E-6).

Post-Seismic Fires

Post-seismic fires have the potential to cause significant damage, event in PC-3 structures. The default frequency for these events is unlikely. The consequence should consider involvement of the entire facility inventory. Post-seismic fires are considered a natural phenomena event (E-7).

Lightning

Lightning has been know to initiate both industrial and wildland fires. The generic incipient fire frequencies used in the FRA reflect the fraction of fires caused by lightning. Thus, no specific lightning event followed by fire should be presented in the HA, unless a unique situation exists. Such a unique lightning induced fire would be considered a natural phenomena event (E-7).

Fire Risk Analysis

The primary purpose of the Fire Risk Analysis is to quantitatively evaluate the fire risk as an input to the Chapter 3 Accident Analysis. Preparation of the FRA is a multi-disciplined effort involving the development of fire, frequency, radiological, chemical and dispersion evaluations. Input from the various disciplines can be by direct reference to an appropriate source document or by development of supporting calc-notes developed as inputs to the FRA. The FRA evaluates the risk from all E-1 events, wildfire events and post-seismic fire events.

The fire risk analysis is a step by step process that is iterated to achieve an acceptable result within acceptable risk limits. These "acceptable risk limits" are usually not the evaluation guidelines, but some fraction (e.g., 10 percent) of the evaluation guidelines. This iterative process is graphically depicted in the Consequence and Risk Analysis Process Flow Chart. (See Figure 4.) The iterative process starts by taking no credit for mitigating features and

*Facility description is part of Section 2.0.

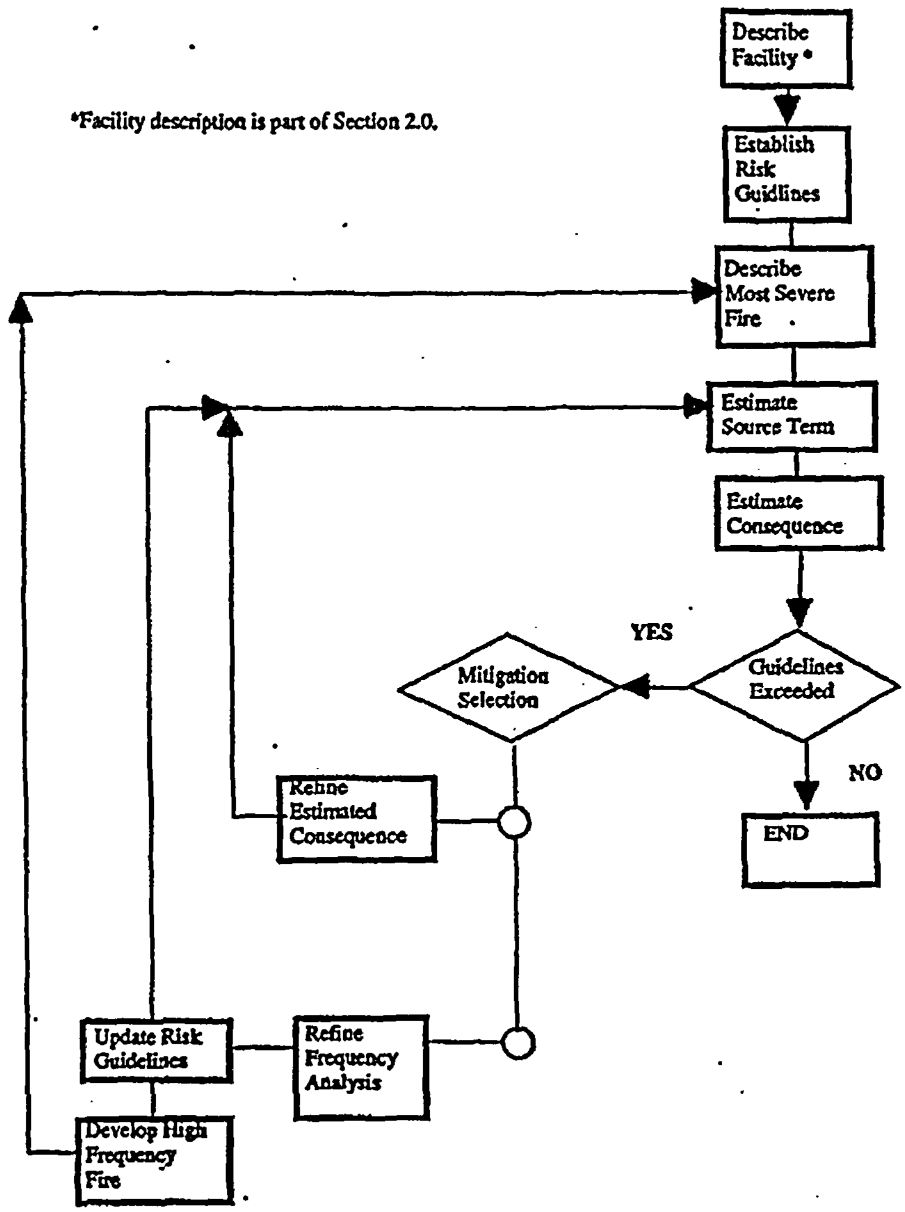

Figure 4--Fire Risk Analysis Flow Chart

comparing results to the release guidelines. The process then takes continuing credit for additional mitigating features incrementally and comparing the results to the release guidelines, until a result is achieved that is below the guidelines. Fire areas and facilities should be analyzed as they.exist and credit should be given to the physical features of the facility that will mitigate the accident. The following are the steps generally followed when preparing a fire risk analysis:

1. Establish the allowable risk guidelines and goals – These goals are provided by the regulatory program lead for the SAR. The goals are typically much less than the guidelines, which are documented in WSRC 11Q (Ref. 13).

2. Describe the extent of the most severe fire - Summarize the most severe fire expected for the facility if no mitigation occurs (e.g., sprinklers fail, no manual intervention). This should include the largest expected extent of fire spread with the material in the worst credible form. (If necessary a separate analysis can be produced to demonstrate that existence of some material forms would be considered beyond extremely unlikely.)

3. Estimate source term for most severe fire - Analyze "the material at risk, the release fraction or rate that determines the initial source term, and the overall facility leak path factors that determine the final source term released external to the facility." (Ref. 1). Bounding assumptions should be used as much as practical to reduce the expense of the calculation. For the first iteration, it is acceptable to assume a damage ratio, release fraction, respirable fraction, and leak path factor of 1.0. If the consequence goals are exceeded, a more detailed release fraction can be developed.

4. Estimate consequence for most severe fire – Using the most current ground-release Dose Conversion Factors (DCFs), estimate the consequences.

5. Are allowable risk guidelines exceeded? - Compare the estimated consequences with the allowable risk guidelines. If the facility has been shown to meet the risk goals the analysis is complete. If the guidelines are not met, then analysis iteration must be completed.

6. Iteration of analysis - Identify most economic method to reduce estimated consequence (e.g. more accurate analysis, return to step 4) or increase the risk guidelines (e.g. frequency analysis, step 8).

7. Produce frequency analysis - Estimate the frequency of the expected most severe fire. Bounding assumptions should be used as much as practical to reduce the expense of the calculation. The frequency of selected fire scenarios need only be estimated if the consequence criteria has been exceeded for the facility. The frequency estimate should not be estimated if the consequence is demonstrated to be less than the most demanding risk criterion. If a detailed frequency estimate must be prepared (i.e., formalized event trees) the frequency results should be prepared using best-estimate information.

8. Update allowable risk guidelines - Select a revised allowable risk goal based on frequency estimate.

9. Develop the high frequency fire - If frequency analysis is used to increase the allowable risk guideline then determine a less severe, but more frequent fire for analysis. This results in a second bin for the fire accidents. Analysis at this second bin starts at step 3.

10. Return to step 4 or 6 as appropriate.

11. Completion - When compliance with risk goals has been achieved or the calculated risk is deemed accurate and representative of the actual risk, the analysis is complete. If, after a complete analysis, the risk is unacceptable the regulatory SAR manager should be consulted for direction.

Accident Analysis Development

The accident analysis quantitatively evaluates the non-fire HA scenarios that are in the high and moderate risk bins of Figure 4 (Ref. 10) crediting preventive and mitigative features as necessary to meet the consequence goals.

Accident Analysis Master Calc-Note

The results of the FRA and Accident Analysis are compiled into a single document. This document is commonly referred to as the Master Calc-Note. The intent is to summarize all analyzed accidents with their respective frequency and consequence. This information is presented in tabular form with supporting text. The Master Calc-Note may also contain recommended text for inclusion in Chapter 3 of the SAR.

FIRE CONSEQUENCE ANALYSIS

Fire severity is evaluated at two different levels. For smaller fires the energy evolved from the fire is relatively unaffected by the surroundings. For larger fires the walls and other surroundings can have a significant effect on the fire output. This section discusses each of this situations separately. The first section, Fuel Package Behavior, focuses on smaller fires were the interaction of the fire with is surroundings is relatively minor. The second section, Compartment Fires, discusses how the surroundings can significantly affect the fire energy output.

Fuel Package Behavior

Individual items in a room or groups of items which are in close physical proximity to each other that readily[1] allow fire propagation are considered a fuel package. These fuel packages, if ignited, are expected to burn independently prior to the heat flux induced ignition of any neighboring item. Further discussion of fuel packages is presented in Chapter 4 of NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover* (Ref. 14).

By defining fuel packages it is possible to use empirical data that has been generated for individual burning items. This allows for analytic evaluation for item to item fire propagation, and the prediction of room temperatures.

There are three important parameters to consider in describing a fuel package. These are: total energy content [kJ], Heat Release Rate (HRR) [kW], and ignition heat flux [kW/m2]. The total energy content can be explicitly specified or provided as a combination of the mass and the specific combustion energy [kJ/kg]. The HRR might be specified as the average HRR, peak HRR (PHRR), or mass loss rate. In addition, the HRR might be specified using a time dependant function (either empirical data or correlation).

Heat Release Rate

The HRR of many items has been empirically measured. These tests are conducted in a free-burn (i.e., non-oxygen limited) arrangement. Tests are typically conducted in a calorimeter. For this test, the item in question is burned in a controlled situation where the plume flow rate and oxygen concentration can be accurately measured. This data is then used to calculate the HRR.

[1] NFPA 555 uses the phrase "ignition delays associated with object-to-object spread do not dominate the heat release rate history" in discussing fuel packages formed by groups of items.

Empirical Heat Release Rates

HRR data for many upholstered furniture items are readily available. This is the result of efforts to reduce the fire risk in residential fires. Most of this data is obtained from a calorimeter test apparatus as described in NFPA 266, *Standard Method of Test for Fire Characteristics of Upholstered Furniture Exposed to Flaming Ignition Source* (Ref. 15).

Other well-studied items include; wood cribs and wood pallets, and mattresses. These objects and others are described Section 3, Chapter 1 of *The SFPE Handbook*, (Ref. 9) and on the BFRL Internet site *Fire On The Web* at http://www.bfrl.nist.gov/info/fire.html (Ref. 16).

Liquid Pool Fires

Liquid pool fires have been studied in great detail. The Heat Release Rate (HRR) from liquid fuel fires is an important element in many fire protection studies. It may be used to aid in determination of barrier adequacy, propagation probability, and operational parameters. Pool fires include spills and open top liquid container fires. Pools are assumed to be circular, but square and similar shapes can be estimated using an equivalent area circle. Highly elongated shapes are not applicable to the methods described. Available energy, heat release rate, and duration of liquid pool fires may be calculated as follows.

The mass loss rate from the pool is:

(1) $\dot{m}'' = \dot{m}''_{\infty}\left(1 - e^{-k\beta D}\right)$.

where	$\dot{m}''$	=	mass loss rate per unit area [kg/s·m2]
	D	=	pool diameter [m]
	k	=	extinction-absorption coefficient of the flame
	β	=	mean-beam-length correction

The HRR rate would be:

(2) $\dot{Q} = \Delta H_c \cdot \dot{m}'' \cdot A$

where	$\dot{Q}$	=	heat release rate [kW]
	ΔH_c	=	heat of combustion [kJ/kg]
	$\dot{m}''$	=	mass loss rate per unit area [kg/s·m^2]
	A	=	area of pool [m^2]

For fire diameters that are greater than 1 meter the mass loss rate is usually independent of area. Thus, the duration of the flammable liquid fire would be:

(3) $t = \frac{h\rho}{\dot{m}''}$

where r is the liquid density [kg/m3]

h is the pool depth

The equation holds for diameters that are less than 1 meter when the pool edges are perpendicular to the ground.

The data recommended for use in the above correlations is presented in Table 3-1.2 of the *SFPE Handbook, 2nd Edition* (Ref. 9, page 3-2).

Example

For illustration, the following scenario will be used. A 100-gallon (0.38 m^3) diesel fuel spill, which is contained by a 15 m^2 diked area, is ignited. The objective is to estimate the HRR from the burning pool. The liquid combustion rate is limited by the spill area, which has an effective pool diameter of 4.4 m. The method presented below come from Reference 9.

$$(4)\quad \dot{m}'' = \left(0.035\frac{kg}{m^2 \cdot s}\right)\left(1 - e^{-(1.7\,m^{-1})(4.4\,m)}\right) = 0.035\frac{kg}{m^2 \cdot s}$$

$$(5)\quad \dot{Q} = \left(39{,}700\frac{kJ}{kg}\right)\left(0.035\frac{kg}{m^2 \cdot s}\right)\left(15\,m^2\right) = 21{,}000\,kW$$

The duration of this fire would be:

$$(6)\quad t = \frac{h\rho}{\dot{m}''} = \left(\frac{0.38\,m^3}{15\,m^2}\right)\left(\frac{970\frac{kg}{m^3}}{0.035\frac{kg}{m^2 \cdot s}}\right) = 700\,s = 12\,minutes$$

Pallet Heat Release Rate

The energy release rate from a stack of wood pallets is (Ref. 9):

$$(7)\quad \dot{q}'' = 0.97(1 + 2.14h_c)(1 - 0.027M)$$

where: $\dot{q}''$ is the HRR per unit area [MW/m²]

h_c is the stack height [m]

M is the wood moisture content [percent]

This equation is valid for stacks which are higher than 0.5 m. Below this height the equation overpredicts the burning rate.

Analytical Heat Release Rates

The HRR for burning solids should be predicted using the methods described in Chapter 6 of NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover* (Ref. 14). Since the amount of data available is very limited, empirical data must be extrapolated for the fuel packages of interest. Where other data are not available, the technique described below may be used to estimate the equivalent pallet HRR for untested solid fuel packages. The technique is based on the pallet correlation above (Equation 8 below) and the gross energy density of a pallet.

The gross energy density is based on a heat of combustion of 19 MJ/kg, and a pallet weight of 27 kg (60 pounds) with the dimensions of 1.22 (48") by 1.22 (48") by 0.14 m (5.5").

$$(8) \quad L''' = \frac{513\,\text{MJ}}{0.21\,\text{m}^3} = 2400\frac{\text{MJ}}{\text{m}^3}$$

By combining the gross energy density of a wooden pallet, the available energy of the fuel package, and the fuel package footprint area, the equivalent wooden pallet height can be estimated.

$$(9) \quad h_e = \frac{L}{L'''_{pallet}A}$$

From Equation (7) the PHRR would be:

$$(10) \quad \dot{Q} = \dot{q}'' \cdot A = 0.97(1 + 2.14h_e)(1 - 0.027M)A$$

where A is the footprint area of the fuel package [m2]

L is the energy content [MJ]

When using the above equation, a moisture content of 12 percent is recommended.

The heat release curve for the fuel package can be developed if a growth rate is estimated, and the fuel is then assumed to burn as defined by this curve and the PHRR established by Equation 8 until the fuel is exhausted.

Example

This example describes a simplified fire situation in a standard office cubicle, using the analytical methods described above. Though simplified, this example problem gives a clear picture of how these calculations can be put into practice.

The cubicle contains a desk and computer, assorted paper products, and fabric walls. The first step is to determine the types and quantities of the materials in question. This is determined by the engineer. For this problem, assume the following:

Computer / monitor / printer arrangement	20 Lbs. PVC
Desk, typical plastic on metal frame	55 Lbs. Polyurethane
Miscellaneous paper products (papers, books, picture frames)	40 Lbs. Cellulose

Cube wall – fabric only (cube wall foam included with desk) 10 Lbs. Wool

To determine the theoretical Heat Release Rate from an average cubicle arrangement, calculate the raw energy equivalent:

Computer:

Mass = (20) lbs (plastic) = (9.1) kg

HRR = (9.1) kg * (18.0) MJ/kg (PVC) = (162.8) MJ

Paper Products:

Mass = (40) lbs (cellulose) = (18.1) kg

HRR = (18.1) kg * (17.47) MJ/kg (cellulose) = (317.0) MJ

Desk:

Mass = (55) lbs (plastic) = (24.9) kg

HRR = (24.9) kg * (23.9) MJ/kg (Polyurethane) = (596.2) MJ

Cube Wall:

Mass = (10) lbs (fabric) = (4.5) kg

HRR = (4.5) kg * (23.65) MJ/kg (wool) = (107.3) MJ

Total energy = (1183.3) MJ

The energy density of the office is then expressed in terms of a stack of average pallets. The gross energy density for an average pallet is expressed as above by the equation:

$L''' = 513\ MJ/0.21 m^3 = 2400\ MJ/m^3$

Therefore, by combining the gross energy density of a wooden pallet, the available energy of the office fuel package, and the fuel package footprint area, the equivalent wooden pallet height for the office can be estimated using the following equation:

$$(11)\quad h_e = \frac{1183 MJ}{(2400) MJ/m^3 (0.74) m^2} = 0.66\ m$$

Thus, the HRR from Equation 11 is:

$$(12)\quad q'' = 0.97\ (1 + 2.14\ (0.66) m)\ (1 - 0.027\ (12)) = 1.59\ MW/m^2$$

So, for the 8 ft^2 (0.74322 m^2) office the HRR is 1.2 MW.

Vehicle Fires

Based on the analytical heat release rate method described above the PHRR values for various vehicles has been estimated:

Table 1--Vehicle PHRR values

Vehicle description	Median PHRR (MW)	Bounding PHRR (MW)
Automobile	5.5	11
Forklift	2.2	5.6 *
Utility vehicle	4.6	9.2
Tractor trailer	50	100 **

* Based on a medium size forklift, 7200 – 10,000 lbs.
** Peak PHRR was 160 MW depending on fuel tank size.

Example

This example describes a simplified fire situation in a midsize automobile using the analytical methods described above. Like the previous example, the energy content of the automobile is converted to an equivalent pallet stack. Though simplified, this example problem shows how these calculations can be expanded to be used with more diverse situations.

An average midsize automobile contains rubber, plastics, metals, and flammable liquids. The first step is to determine the types and quantities of the materials in question. This is determined by the engineer. For this problem, assume the following:

Hoses and tires	100 Lbs. Rubber
Assorted interior and electrical components	55 Lbs. PVC
Insulation and fabrics	30 Lbs. Cellulose
Flammable liquid	12 Lbs. Gasoline

Note: This vehicle does not contain combustible metals.

To determine the theoretical Heat Release Rate from an average midsize automobile, calculate the raw energy equivalent:

Tires:

Mass = (100) lbs = (45.4) kg

HRR = (45.4) kg * (32.6) MJ/kg (rubber) = (1478.7) MJ

Paper Products:

Mass = (30) lbs = (13.6) kg

HRR = (13.6) kg * (17.47) MJ/kg (cellulose) = (237.7) MJ

Plastics:

Mass = (500) lbs = (226.8) kg

HRR = (226.8) kg * (18.0) MJ/kg (PVC) = (4071.0) MJ

Liquid Fuels:

Mass = (12) gal. = (30.9) kg

HRR = (30.9) kg * (46.8) MJ/kg (gasoline) = (1446.2) MJ

Total energy = (7233.7) MJ

The energy density of the automobile is then expressed in terms of a stack of average pallets. The gross energy density for an average pallet is expressed as above by the equation:

(13) $L''' = 513 MJ/0.21 m^3 = 2400\ MJ/m^3$

The equivalent wooden pallet height for the automobile is:

$$(14)\quad h_c = \frac{(7200)MJ}{(2400)MJ/m^3(8.4)m^2} = 0.36m = 1.18ft$$

Thus, the HRR is:

(15) $q'' = 0.97\ (1 + 2.14\ (0.36)m)\ (1 - 0.027\ (12)) = 1.16\ MW/m^2$

So, for the 90 ft^2 (8.36127 m^2) automobile the HRR is 9.71 MW.

Fuel Package Classifications

To simplify the analysis process it is useful to group fuel packages based on their PHRR. The recommended ranges were proposed by Bukowski, et.al. (Ref. 2) and are shown in Table 2. The PHRR groupings allows the fuel package HRR estimates to be selected based on generic fuel packages. This reduces the analysis cost, improves analysis repeatability and simplifies protective control implementation. The most recent set of generic PHRR values is shown in Table 3. The material codes used in Table 3 are based on a modification of NFPA 901 (i.e., National Fire Incident Reporting System, Ref. 8) because of its wide acceptance and the availability of historical data.

Table 2--Peak heat release rate ranges suggested by Bukowski, et. al. (Ref. 2)

	Energy emission range MW	Benchmark value MW
low	$P < 0.35$	0.25
medium	$0.35 \leq P < 0.71$	0.5
high	$0.71 \leq P$	1.0

Table 3--Generic PHRR, ease-of-ignition and growth rate design data

Material code	Description	Classifications: peak heat release	ease-of-ignition	growth rate
14.7300	floor covering, carpet	low	hard	...
15.0001	wall panel, wood	low	normal	...
15.0002	wall panel, gypsum board	low	hard	...
15.0003	wall panel, FR wood	low	hard	...
15.0004	wall panel, PMMA	medium	normal	...
15.0005	wall panel, polycarbonate	medium	hard	...
15.0006	wall panel, fabric	medium	easy	...
16.6900	ceiling covering	low	hard	...
21.0001	upholstered furnishings, small, < 10 kg	low	easy	...
21.0002	upholstered furnishings, intermediate	medium	easy	medium
21.0003	upholstered furnishings, large, ≥ 20 kg	high	easy	fast
21.0004	upholstered furnishings, highly fire retarded	low	easy	...
22.4101	nonupholstered seating, plastic	low	easy	fast
22.4102	nonupholstered seating, wood	low	normal	...
23.0001	cabinetry, wood	high	normal	ultra-fast
23.0002	cabinetry, steel, combustible contents	high	normal	ultra-fast
25.4101	appliance housing, plastic	medium	normal	...
25.4102	appliance housing, FR plastic	low	normal	...
25.6300	appliance housing, wood	low	normal	...
31.0001	mattress	high	easy	medium
33.7000	linen	medium	easy	...
34.7000	wearing apparel	medium	easy	ultra-fast
36.7200	curtain	low	easy	...
41.5901	Christmas tree, fresh	low	normal	...
41.5902	Christmas tree, dry	medium	easy	...
51.6800	box, carton, bag - wood	high	normal	...
51.7000	box, carton, bag - fabric	low	easy	medium
52.2400	basket, barrel	low	normal	ultra-fast
53.4100	pallet, plastic (not in use)	high	easy	fast
53.6300	pallet, wood (not in use)	high	normal	fast
61.0001	electrical wire, plastic	low	normal	...
61.0002	electrical wire, silicon glass braid	low	...	...
67.4200	pipe, duct insulation, rigid	medium	easy	...
67.4400	pipe, duct insulation, flexible	medium	easy	...
75.9301	trash, ≤ 2 bags	low	easy	...
75.9302	trash, > 2 bags	medium	easy	...
87.4300	rolled material	high	easy	ultra-fast
87.6700	rolled material	high	easy	ultra-fast

Other Fire Types

Organic solids, combustible liquids and flammable liquids are the most common fuels involved in fires, but other fire types such as gases and metals, may pose greater hazards due to their properties and burning characteristics.

A flammable gas is any gas that will burn in the normal concentrations of oxygen in the air. Other types of gases that present hazards include reactive gases, toxic gases, and nonflammable gases. Gases expand when heated, producing an increase in pressure on a container, which can result in gas release and/or cause container failure. Evaluation of the storage environment and expected operational and emergency conditions is warranted. When gases are released from their containers, the hazards vary according to the chemical and physical properties of the gas and the nature of the environment in which the release occur (Ref. 17).

Metals pose special fire protection problems which must be evaluated on a case by case basis taking into account the properties, storage, handling, and use of the materials. The following are some examples of characteristics of metals. Nearly all metals will burn in air under certain conditions. The metals of greatest concern are referred to as combustible metals because of their ease of ignition as thin sections, fine particles, or molten metal. Alloys, consisting of different metals combined in varying proportion, may differ widely in combustibility from their constituent elements. Metals tend to be most reactive when finely divided, and dust clouds of most metals in air are explosive. Temperatures produced by burning metals are generally much higher than temperatures generated by burning flammable liquids (Ref. 18).

Heat Flux Predictions

When evaluating the heat flux on an object during a fire, the location of the object with respect to the flame is very important. If the flames are impinging on an object, the surface where impingement is occurring will approach the flame temperature. For situations without flame impingement, the heat flux can be estimated using common radiation heat transfer techniques.

Radiation Heat Transfer

The radiation heat transfer relationship between two objects is:

$$q_r'' = \sigma F_v F_e \left(T_r^4 - T_o^4\right) \tag{16}$$

where:

- q_r'' is the radiation heat flux [kW/m²]
- σ is the Stefan-Boltzmann constant [5.669E-11 kW/m²·K⁴]
- F_v is the view factor [unitless]
- F_e is the emmissivity function [unitless]
- T_r is the transmitter temperature [K]
- T_o is the object (i.e., target) temperature [K]

Equation (16) assumes that the bodies are diffuse-gray and the media (i.e., air) is non-participating (between the fire and the object).

When an object is placed near an uncontrolled flame, it will resemble a blackbody. This will occur for even very shiny materials, since most uncontrolled flames produce significant quantities of soot. Thus, the value of F_v and F_e will approach unity as the two objects are brought together.

The net radiation heat flux would be:

(17) $$q_r'' = \sigma\left(T_f^4 - T_s^4\right)$$

where: T_f is the fire temperature [K]

T_s is the surface temperature of the object in the flame [K]

Flame temperatures reported in the literature vary from 900°C to 1500°C (Ref. 19). The higher values occur for solid materials. For a flame temperature of 1130°C and an object at 20°C, the radiation heat flux would be:

(18) $$Q_r'' = \left(5.669\text{E-}11 \frac{\text{kW}}{\text{m}^2 \cdot \text{K}}\right)\left[(1400\ \text{K})^4 - (293\ \text{K})^4\right] = 217 \frac{\text{kW}}{\text{m}^2}$$

Emissive Power

Often it is convenient to neglect the temperature of the exposed fuel package, and concentrate on the radiation energy emitted by the fire. This emitted energy is refereed to as the emissive power, E_b. The emissive power can be predicted based on the flame temperature of the fire.

(19) $$E_b = \sigma\left(T_f^4\right)$$

Thus, for an effective flame temperature of 1400 K, the theoretical emissive power in the fire would be:

(20) $$E_b = \left(5.669\text{E-}5 \frac{\text{kW}}{\text{m}^2 \cdot \text{K}}\right)(1400\ \text{K})^4 = 218 \frac{\text{kW}}{\text{m}^2}$$

For an effective flame temperature of 1240 K the theoretical emissive power would be 134 kW/m^2.

In hydrocarbon fires thick black smoke along the periphery of the fire will absorb a significant part of the radiation and reduce the effective emissive power from the fire. Thus, the periphery of the fire is a composite of highly emissive luminous zones and colder zones with lower emissive power. The average emissive power for large, sooty hydrocarbon fires can be estimated from (Ref. 20):

(21) $$E_{ave} = E_m e^{-SD} + E_s\left(1 - e^{-SD}\right)$$

where: E_m the maximum emissive power of the luminous spots [140 kW/m^2]

E_s the emissive power of smoke [20 kW/m^2]
S an empirical constant [0.12 m^{-1}]
D is the pool diameter [m]

Based on Equation (21) the effective emissive power for a 1 meter diameter pool fire is 126 kW/m^2.

Some analyses have assumed that the fire is a point source and have assumed the emissive power is inversely-proportional to the distance to the forthpower between the exposed object and the fire ($E \propto D^4$). This approach, while appropriate when the fire and object are far apart, is nonconservative for spacings that are similar in magnitude to the fire's dimensions (height and diameter).

Flame Impingement Heat Transfer

Where direct flame impingement occurs on a metallic object, the object's temperature is usually expected to approach the flame temperature. The flame temperature can be estimated from empirical data. If the object's temperature is assumed equal to the flame temperature, the result will be slightly conservative. The level of over-prediction is considered to be less than the uncertainty of the flame temperature.

An exception to this is where the object is a container that holds a liquid. The liquid will tend to absorb heat thus lowering the temperature of the container wall. The heat transfer to the liquid can be approximated from Equation (16) where the object temperature is assumed to be the saturation temperature of the liquid. This has the effect of under-predicting the object temperature and hence over-predicting the heat flux, which is a conservative approach.

The flame impingement heat transfer will be estimated based on the flame temperature and the saturation temperature of the liquid (which is assumed to be the object temperature). Both the view factor and emmissivity function will be taken as unity.

Heat Flux Design Values for Vessels and Tanks

In estimating the sufficiently bounding heat flux that might occur during a severe fire it is possible to use data developed for the chemical and petroleum industries. Many tests have been conducted to determine the design criteria for the sizing of relief protection for containers that are exposed to fire. This section will derive a sufficiently bounding heat flux from these design criteria based on the information used to develop the venting requirements for NFPA 30, *Flammable and Combustible Liquids Code* (Ref. 21).

The fire design bases for NFPA 30 consists of four equations:

$$(22)\quad q'' = \begin{cases} 20{,}000A & A \le 200\ \text{ft}^2 \\ 199{,}300A^{0.566} & 200 < A \le 1{,}000\ \text{ft}^2 \\ 963{,}400A^{0.338} & 1{,}000 < A \le 2{,}800\ \text{ft}^2 \\ 21{,}000A^{0.82} & 2{,}800 < A \end{cases}$$

where the heat flux, q", is in terms of Btu/hr, and the tank surface area, A, is in terms of ft^2. The top and bottom equations were developed empirically. The equations between 200 and 2,800 ft^2 are interpolations from the empirical results (Ref. 22).

The most severe flux is thus:

$$(23)\quad q'' = 20{,}000\frac{Btu}{hr \cdot ft^2} = 63\frac{kW}{m^2}$$

This value has been used as the heat flux during a severe fire in a process room. It is considered to be a reasonably bounding value.

View Factors

When an object is not in the flame some portion of the radiation energy will not strike the object. This reduced emissive power effect is accounted for using a view factor. The view factor, F_v, for typical fires is developed by assuming the fire to be a right cylinder. Thus, the view factor would be (Ref. 23):

$$(24)\quad F = \frac{1}{\pi H}\tan^{-1}\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{L}{\pi}\left(\frac{(X-2H)}{H\sqrt{XY}}\right)\tan^{-1}\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right) - \frac{1}{H}\tan^{-1}\left(\sqrt{\frac{(H-1)}{(H+1)}}\right)$$

where:
- h — is distance from the object to the centerline of the cylinder
- l — is the height of the cylinder
- r — is the radius of the cylinder
- H — is the distance from the object to cylinder diameter ratio (h/r)
- L — is the cylinder height to diameter ratio (l/r)
- X — $(1+H)^2+L^2$
- Y — $(1-H)^2+L^2$

Since the above solution is for a right cylinder with the differential area at the base of the cylinder (i.e., fire), to obtain the peak heat flux, which occurs at the mid-height of the cylinder, the actual view factor is twice the value calculated using Equation (24), if the cylinder height is taken as half the fire height.

The flame height can be estimated using (Ref. 24):

$$(25)\quad H = 0.235Q^{2/5} - 1.02D$$

where:
- D — is the fire diameter [m]
- Q — is the heat release rate [kW]
- H — is the flame height [m]

View factor formulations have been prepared for other geometries. For a cylindrical fire that is leaning due to wind, a view factor formation is provided in the *SFPE Handbook of Fire Protection Engineering*, page 3-210 (Ref. 9). For fires that are rectangular, a view factor formulation is provided in NPFA 80A (Ref. 25).

Example

The heat release rate for a fire is taken as 2 MW based on a diameter of 1.2 meters: From Equation (25) the flame height would be:

$$(26)\ H = 0.235(2{,}000\text{kW})^{2/5} - 1.02(1.2\text{m}) = 3.69\text{m}$$

The emissivity of painted, corroded or fire exposed structural steel will be taken as 0.9. This is a typical value observed in the literature. The maximum theoretical value would be 1.0. Since the fire emissivity approaches unity, the emissivity function, F_e, is approximately equal to the emissivity of the steel. It is expected to be somewhere between this value and 1.0. A value of 0.9 will be used for the calculation.

The view factor for typical fires is developed by assuming the fire to be a right cylinder. The sample calculation, which is based on Equation (24), for a fire to object separation of 0.5 meters is presented below:

$l = 3.69/2 = 1.845$ m
$r = 1.2/2 = 0.6$ m
$h = 0.5 + 0.6 = 1.1$ m
$H = h/r = 1.1/0.6 = 1.833$
$L = l/r = 1.845/0.6 = 3.075$
$X = (1+H)^2 + L^2 = (1+1.833)^2 + (3.075)^2 = 17.48$
$Y = (1-H)^2 + L^2 = (1-1.833)^2 + (3.075)^2 = 10.15$

$$F = \frac{\tan^{-1}\left(\frac{3.075}{\sqrt{(1.833)^2 - 1}}\right)}{\pi(1.833)} + \frac{3.075}{\pi}\left(\frac{((17.48) - 2(1.833))}{(1.833)\sqrt{17.48(10.15)}}\right)\tan^{-1}\left(\sqrt{\frac{(17.48)((1.833)-1)}{(10.15)((1.833)+1)}}\right) - \frac{\tan^{-1}\left(\sqrt{\frac{((1.833)-1)}{((1.833)+1)}}\right)}{1.833}$$

$$= 0.26$$

As discussed previously this view factor is for a half-cylinder. The effective view factor is thus twice this value, 0.52.

For a flame temperature of 1000°C (1270 K) and an object temperature of 100°C (373 K), the radiation heat transfer between the fire and the object is:

$$q''_r = \left(5.669\text{E}-11\frac{\text{kW}}{\text{m}^2\text{K}^4}\right)(0.52)(0.9)\left[(1270\text{K})^4 - (373)^4\right] = 68\frac{\text{kW}}{\text{m}^2}$$

Fire Propagation Between Fuel Packages

For a given fire intensity (kW) it is possible to determine if a second object will be ignited. The maximum ignition distance, L_i, between the fire and the second object can be determined if the peak heat release rate (PHRR) of the fire (based on first item) and the ignition heat flux of the second item (kW/m^2) are known [22] (Ref. 9). As with the PHRR information, the ignition heat flux is grouped into three classes, which represent the ease-of-ignition for the second fuel package. These classes are presented in Table 4. Generic design data is presented in Table 3. Table 5 provides the minimum distance for ignition of the second item, L_i, for each possible fire intensity (emitter energy) and ease-of-ignition combination (Ref. 2). Thus, if the objects are closer than the value established in Table 5, the second item is considered to ignite. If the objects are further apart than the distance indicated in Table 5 ignition of the second item by thermal radiation is considered incredible.

Table 4--Fuel package ignition heat flux (flaming heat source flux required for ignition)

Ease-of-ignition class	Range kW/m^2	Benchmark value kW/m^2
Easy	$0.0 \leq P < 14.1$	10
Normal	$14.1 \leq P < 28.3$	20
Hard	$28.3 \leq P$	40

Table 5--Maximum separation for ignition, L_i (inches)

Ease-of-ignition range (nominal value), kW/m^2	Emitter energy range (nominal value), kW		
	low (250)	medium (500)	high (1,000)
Easy (10)	31	47	55
Normal (20)	12	24	35
Hard (40)	4	8	16

Flammable Liquid Ignition

Liquids that form an open pool at atmospheric pressure evolve vapors at their surface. The vapor generation rate varies with the liquid and its temperature. When flames are observed above a liquid pool the physical process that is occurring is evaporation at the liquid-vapor interface and combustion above this interface in a vapor-air region. Ignition of this vapor region occurs when sufficient energy is available to support sustained combustion. There are two common criteria used to judge when a liquid will ignite: flashpoint and autoignition temperature.

The flashpoint is the lowest liquid temperature that produces adequate vapors to allow ignition in the presence of an ignition source. There are many techniques to evaluate the flashpoint, such as ASTM D56, ASTM D93, ASTM D3278, and others (Refs 26, 27 and 28). It is widely understood that the measured flashpoint will vary slightly with the test method (e.g., ignition

source energy, air movement, atmospheric pressure). For most design purposes these variations will have little effect.

The autoigntion temperature is the lowest liquid temperature that produces adequate vapors to allow self-sustained ignition without an ignition source being present. It is always higher than the flashpoint temperature often by several hundred degrees. As an example the flashpoint of gasoline ranges from –43 to –38°C (-45 to –36°F), while the autoigntion temperature is ~280 to ~456°C (-536 to –853°F) (Ref. 29). Thus, a pool spill of gasoline would not be expected to ignite unless an ignition source was present. Possible ignition sources might be sparks, electrical equipment, or hot metals (e.g., exhaust pipe, bearings, brakes).

Liquids are grouped by their tendency to evolve flammable vapors at atmospheric pressure. The most common measure or metric for this is the flashpoint. There are two common classification approaches. In the first, which is described in NFPA 30 (Ref. 21), a flammable liquid has a flashpoint of 100°F or less. Those liquids with a flashpoint greater than 100°F are considered combustible liquids. The other approach, which is used by ANSI/CMA Z129.1 and DOT, the transition temperature between a flammable and a combustible liquid is 60°C (140°F).

Common sources for flashpoint and autoigntion criteria are:

- NFPA Haz-Mat Quick Guide (Ref. 29)
- NFPA 497, (Ref. 30) Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas

Fire Compartment Behavior

A typical zone model is simply a representation of two layers of gas in a compartment (not to be confused with fire zones as separate compartments, or rooms). The upper, or hot, gas layer and the lower, cool gas layer occur when a fire burns because of the stratification created by the buoyancy of the hot gas layer. Conservation of mass, species and energy equations have been applied to this phenomena for analytical purposes. A key feature of a zone model is that as a fire burns, air is entrained into the plume. The entrained air comprises most of the volume of the plume, with the consumed fuel making up the rest. Again, conservation of mass and energy equations are applied to this phenomena for idealized conditions. Essentially, the mass of plume gas is equal to the mass of the fuel burned plus the mass of the air entrained. The reader is referred to the *SFPE Handbook of Fire Protection Engineering* for a complete explanation of this.

If a compartment were completely enclosed (i.e., airtight), a fire would quickly use the oxygen in the compartment. Is it useful to model a compartment with an opening that lets hot gases out as well as letting air (oxygen) in. When the mass burning rate of the fuel is small compared to the mass flow rate of air into the compartment, the mass flow out an opening (a window or door) is approximately equal to the mass flow of air into the opening. Simplified equations can be used to approximate the mass flow of air into a compartment through an opening, the mass burning rate of the fuel, and the resulting mass flow of hot gas out the opening.

During a severe fire, it is common for two distinct layers to form in the fire compartment. The upper layer is comprised of the combustion products and will be relatively hot. The lower layer

will be a mix of room air and ambient air entering the room. Thus, the lower layer is relatively cool.

The upper-layer temperature predictions do not represent the peak temperatures in a fire compartment. Temperatures in the flame and the plume above the flame are expected to be higher. Thus, objects in the room may be at higher temperatures than the upper-layer temperature.

ASTM E-119 curve (Ref. 7) defines the required furnace temperature for building component fire tests. The curve is considered to provide a reasonable qualification test for firewalls and doors. It is important to note that the furnace tests using this curve only measure structural and conduction properties. Fire spread by convection, the most common mode is not measured in standard furnace tests.

There is no exact temperature at which flashover occurs. This phenomenon is typically captured in a room with an upper layer temperature of 600°C. By selecting a temperature and certain room conditions, equations have been developed to determine the energy release rate required to attain that temperature. When a particular energy release rate is used, other equations can be used to determine temperatures over time leading up to and beyond flashover. For this reason, flashover is discussed first, followed by pre-flashover and post-flashover.

Table 6.--Fire intensity and duration

Wood equivalent combustible loading			Fire severity [Ingberg]	E-119 temperature at the specified time [Standard Test Methods for Fire Tests of Building Construction Materials]
psf	Btu/ft^2	kg/m^2	hours	°C
5	40,000	24	0.5	843
10	80,000	49	1	927
15	120,000	73	1.5	985
20	160,000	98	2	1010
30	240,000	146	3	1052
40	320,000	195	4.5	1121
50	380,000	244	7	1218
60	432,000	293	8	1260
70	500,000	342	9	1260

Flashover

Temperature predictions in a fire compartment must account for a potential instability phenomenon that is commonly referred to as flashover. After ignition, the growth stage of the fire is primarily a function of the fuel. Flashover is the transition from a growing fire to a fully developed fire where all combustible items in the compartment ignite simultaneously. There is no single threshold or criteria that has successfully characterized this phenomenon, however an upper layer room temperature of 600°C is a commonly used threshold (Ref. 14). A reasonable uncertainty band on this value would be 450°C to 700°C.

In preparing a fire temperature profile, if the 600°C threshold is not achieved, temperatures are expected to be relatively low. If the threshold is reached, additional heat generation in the fire compartment is expected and temperatures will be higher. In general, if the upper-layer room temperature remains below 450°C then room temperature predictions are assumed to be reasonably accurate. If the prediction is that the 600°C flashover threshold will be exceeded, then temperatures are again usually considered reasonable predictions. When predicted peak temperatures are in the range of 450 to 600°C, then the analysis must account for the flashover criterion uncertainty.

Example

The following example problem will be used for determining the heat required for flashover of a particular size room. This flashover heat will then be used to estimate pre-flashover and post-flashover temperatures. The calculation is performed in metric units, and the results converted to inch-pound units. Some slight discrepancies may be noticed when the calculation is performed using inch-pound units.

A 5 m (16.4 ft) x 5 m (16.4 ft) x 3 m (9.8 ft) high room has a 2 m^2 (1 m x 2 m) [21.5 ft^2 (3.28 ft x 6.56 ft)] opening 2 m (6.56 ft) above the floor. Thomas' equation (deemed the best by NFPA 555) assumes a delta flashover temperature of 600°C (1112°F). When ambient temperature is 20°C (68°F), the gas temperature is 580°C (1076°F). Using Thomas' equation:

$$Q = 7.8\,A_T + 378\,A_v\sqrt{H_v}$$

Where: Q = heat required for flashover

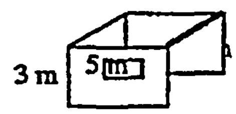

Fig. 1

A_T = total area of walls, floor and ceiling minus A_V
= 108 m^2 (1162.5 ft^2)

A_v = area of vent
= 2 m^2 (21.5 ft^2)

H_v = height of vent
= 2 m (6.56 ft)

$Q = 7.8 * 108 + 378 * 2 * \sqrt{2}$
= 1911.5 kW (1813.4 BTU/sec)
= 1.9 MW

Pre-flashover Correlations

Prior to flashover the room temperature can be estimated from the following correlation suggested by McCaffrey, Quintiere and Harkleroad where the numerical constant of 6.85 is predicated on the physical properties of air at 22°C. The method uses a simple conservation of energy expression correlated with data to develop an approximation of the upper layer temperature in the compartment. The conservation of energy principle is as follows: the energy added to the hot upper layer by the fire equals the energy lost from the hot upper layer plus the time rate of change of energy within the hot upper layer. The correlation is based on limited experimental data and does not contain extensive data on ventilation-controlled fires nor combustible walls or ceilings.

(27) $$\Delta T_g = 6.85\left(\frac{\dot{Q}^2}{A_o\sqrt{H_o}\,h_k A_T}\right)^{1/3}$$

where:
- $\dot{Q}$ is the heat release rate from the fire (kW)
- A_o Area of opening (m^2)
- H_o Opening height (m)
- h_k Effective wall heat transfer coefficient (kW/m·°C)
- ΔT_g Upper gas temperature rise above ambient, $T_g - T_\infty$ (C)
- T_g Temperature of the upper gas layer (C)
- T_∞ Ambient temperature (C)
- A_T Total surface area of the fire compartment (m^2)

The effective wall heat transfer coefficient, h_k, is estimated based on the thermal penetration time and the wall (ceiling or floor) properties and thickness. (In a standard heat transfer text, this coefficient might be referred to as the wall conductance coefficient. The above nomenclature was maintained to be consistent with the reference material.)

(28) $$t_p = \frac{\rho c}{k}\left(\frac{\delta}{2}\right)^2$$

(29) $$h_k = \begin{cases} \dfrac{k}{\delta} & t_p < t \\ \left(\dfrac{k\rho c}{t}\right)^{1/2} & t \leq t_p \end{cases}$$

where:
- t_p is the thermal penetration time (s)
- ρ is the wall (ceiling, or floor) density (kg/m3)
- c is the wall (ceiling, or floor) specific heat (kJ/kg·K)
- k is the wall (ceiling, or floor) thermal conductivity (kW/m·K)
- δ is the wall (ceiling, or floor) thickness (m)
- t is the exposure time (s)

When flashover was not expected the method of McCaffrey, Quintiere and Harkleroad 31 was used. The analysis procedure was:

- Establish the most likely ventilation conditions and geometry
- Establish a range of heat release rates (kW)
- Establish the room temperature for the range of HRR's.

Example

Pre-flashover temperatures can be determined using the heat release rate calculated for flashover in the McCaffrey, Quintierre, Harkleford method (Ref. 31). This equation is expressed as follows:

$$(30)\quad \frac{\Delta T}{T_\infty} = 1.63\left[\frac{Q}{C_p T_\infty \rho_\infty A_v \sqrt{gH_v}}\right]^{2/3}\left[\frac{h_K A_T}{C_p \rho_\infty A_v \sqrt{gH_v}}\right]^{-1/3}$$

For ambient conditions and conditions from the previous flashover example:

Q	= heat required for flashover = 1911.5 kW
C_p	= 1.05 kJ/(kg K) (0.25 BTU/(lb °F))
ρ_∞	= 1.2 kg/m^3 (0.075 lb/ft^3)
T_∞	= 295 K (71.3°F)
g	= 9.8 m/s^2 (32.2 ft/s^2)
A_v	= 2 m^2 (21.5 ft^2)
H_v	= 2 m (6.56 ft)
A_T	= 108 m^2 (1162.5 ft^2)

When $t \le t_p$, $h_k = \sqrt{k_{wall}\rho_{wall}C_{wall} / t}$

When $t > t_p$, $h_k = k_{wall} / \delta$

k_{wall}	= 0.48 W/m k = 4.8 x 10^{-3} kW/m K (0.28 BTU / (hr ft °F))
ρ_{wall}	= 1440 kg/m^3 (89.9 lb/ft^3)
C_{wall}	= 0.84 kJ/(kg K) (0.20 BTU/(lb °F))
δ	= 0.016 m (0.63 in)

Wall penetration temperature is calculated to be:

$$t_p = (\rho_{wall}\, c_{wall} / k_{wall})\,(\delta / 2)^2$$
$$= 161.3 \text{ sec}$$

At 10 sec after ignition:

$$h_{k@10sec} = \sqrt{\frac{k_{wall}\,\rho_{wall}C_{wall}}{t}} = \sqrt{\frac{0.581}{10}} = 0.24\frac{kW}{m\cdot K} = 1.4E-04\frac{BTU}{hr\cdot ft\cdot °F}$$

$$\Delta T_{@10sec} = 1.63(295)\left[\frac{1911.5}{1.05(1.2)295(2)\sqrt{9.8(2)}}\right]^{2/3}\left[\frac{0.24(108)}{1.05(1.2)2\sqrt{9.8(2)}}\right]^{-1/3} = 253K$$

$$T_{gas} = T_\infty + \Delta T = 295\,K + 253\,K = 545\,K = 527°F$$

At 150 sec after ignition:

$$h_{k@150sec} = \sqrt{\frac{0.581}{150}} = 0.06\frac{kW}{m\cdot K} = 3.5E-05\frac{BTU}{hr\cdot ft\cdot °F}$$

$$\Delta T_{@150sec} = 1.63(295)\left[\frac{1911.5}{1.05(1.2)295(2)\sqrt{9.8(2)}}\right]^{2/3}\left[\frac{0.06(108)}{1.05(1.2)2\sqrt{9.8(2)}}\right]^{-1/3} = 401\,K$$

$$T_{gas} = T_\infty + \Delta T = 295\,K + 401\,K = 696\,K = 793°F$$

At 600 sec ignition:

$$h_{k@600\,sec} = \frac{k_{wall}}{\delta} = \frac{0.0048}{0.016} = 0.03\frac{kW}{m \cdot K} = 1.7\,E\text{-}05\frac{BTU}{hr \cdot ft \cdot {}^\circ F}$$

$$\Delta T_{@300\,sec} = 1.63(295)\left[\frac{1911.5}{1.05(1.2)295(2)\sqrt{9.8(2)}}\right]^{2/3}\left[\frac{0.03(108)}{1.05(1.2)2\sqrt{9.8(2)}}\right]^{-1/3} = 506\,K$$

$$T_{gas} = T_{\infty} + \Delta T = 295\,K + 506\,K = 802\,K = 982^\circ F$$

Post-flashover Correlations

Lie (Ref. 32) developed a simplified method to predict the temperature in a fire compartment during a ventilation-controlled fire.

$$(31) \quad T = 250(10F)\left(\frac{0.1}{F^{0.3}}\right)e^{-F^2 t}\left\{3\left(1-e^{-0.6t}\right)-\left(1-e^{-3t}\right)+4\left(1-e^{-12t}\right)\right\}+C\left(\frac{600}{F}\right)^{0.5}$$

where T is the fire temperature, t is time, C is a constant to account for the properties of the boundary material, and

$$(32) \quad F = \frac{A_v\sqrt{H_v}}{A_T}$$

For heavy materials ($\rho \geq 1600$ kg/m^3) C is zero. For light materials ($\rho < 1600$ kg/m^3) C is unity.

The expression is considered valid for:

$$(33) \quad t \leq \frac{0.08}{F} + 1 \qquad \text{and} \qquad 0.01 \leq F < 0.15$$

- When the time, t, is greater than 0.08/F+1, a value of 0.08/F+1 is recommended.
- If ventilation parameter, F, is greater than 0.015, then a value of 0.15 is recommended.
- The expression only applies for fully involved rooms. If flashover does not occur because of limited combustibles or limited ventilation then the expression overpredicts the temperature.

The duration of the fire, τ, is a function of the fire load, Q, and the ventilation parameter, F:

$$(34) \quad \tau = \frac{Q}{330F}$$

Note that this fire load is normalized by the surface area of the room, rather than the more common floor area.

At the end of the fire duration, all of the building's contents will be at an elevated temperature. It will take time for the contents to cool to ambient conditions. Unless the fire department intervenes, most of this cooling will occur by natural convection. Lie recommends a decay period that is based on:

$$(35)\quad T=-600\left(\frac{t}{\tau}-1\right)+T_\tau$$

where t is the time of interest and with the condition

$$(36)\quad T=20 \text{ if } T<20°C$$

The analysis procedure should be:

- Establish a median fire loading (psf, kg/m²)
- Establish the most likely ventilation conditions and geometry
- Establish the room temperature profile for the above conditions.
- Iterate the ventilation conditions and fire loading to demonstrate the sensitivity of the solution to these parameters.

Fire Duration

Harmathy (Ref. 33) derived an alternate form of the fire duration equation:

$$(37)\quad \begin{aligned} \tau &= 0.011\frac{A_F L}{\Phi} && \text{if } \frac{\Phi}{A_f}<0.263 \\ \tau &= \frac{0.0419}{\varphi} && \text{if } \frac{\Phi}{A_f}\geq 0.263 \end{aligned}$$

where:

$\Phi=\rho A_v\sqrt{gH_v}$, the ventilation parameter

$A_f=LA_F\varphi$, aggregate surface area of the fuel (burnable objects) [m^2]

Harmothy notes that the specific surface area, φ, of most conventional furniture is 0.13 m^2/kg. Thus from this equation for a well-ventilated fire, the minimum fire duration is 0.32 hours (19 minutes). Thus, for a single compartment fire, where there is no limitation on ventilation rate and conventional furniture is present, the minimum duration is 19 minutes.

Lie's and Harmathy's correlation are both representations that account for ventilation effects. Except for the accounting for density and Harmonthy's accounting for fuel surface controlled fires, they are basically the same equation. Equation can be rewritten as (Ref. 34):

$$(38)\quad \tau = \frac{\frac{LA_F}{A_T}}{330\frac{A_v\sqrt{H_v}}{A_T}} = \left(\frac{1}{300}\right)\frac{LA_F}{A_v\sqrt{H_v}} = 0.0033\frac{LA_F}{A_v\sqrt{H_v}}$$

The equation for an unventilated fire can be rewritten as:

$$(39)\quad \tau = \left(\frac{0.011}{\rho\sqrt{g}}\right)\frac{LA_F}{A_v\sqrt{H_v}} = \left(\frac{0.011}{\left(1.184\frac{kg}{m^3}\right)\sqrt{9.81\frac{m}{s}}}\right)\frac{LA_F}{A_v\sqrt{H_v}} = 0.0030\frac{LA_F}{A_v\sqrt{H_v}}$$

Thus the two equations, within the accuracy of the correlation, are the same.

The type of materials present has a strong secondary effect on the fire severity and duration. This effect is normally accounted for by adjusting the loading to a wood equivalent value. Most cellulosic materials burn with the same intensity and have similar heats of combustion; thus there is no significant adjustment required. Flammable and combustible liquids have higher heats of combustion. The wood equivalent for most flammable or combustible liquids is 2.4. (Based on 19,000 Btu/lb lowers heating value for flammable liquids and 8,000 Btu/lb for wood.)

For modern materials (i.e., plastics) the heat of combustion can be 1.5 to 2 times the value for wood (12,000 to 16,000 Btu/lb). In addition, since some plastics melt and form pools during fires, they tend to burn like a liquid rather than a solid. (i.e., No energy is required to pyrolize the solid and there is no char layer to inhibit pyrolization.) For further discussion of this subject the reader is referred to Harmathy (Ref. 33).

Computer-Based Approach – FAST Method

The phenomenon of flashover can be readily accounted for by separating the analysis procedure into logical steps. These are:

- Establish a sufficiently bounding HRR curve
- Establish the most likely ventilation conditions and geometry
- Establish the room temperature profile for the above conditions.
- Iterate the ventilation conditions and geometry to maximize the upper level temperature.
    - If flashover is not expected (i.e., $T_{max} < 450°C$), maximize the upper-layer room temperature. If this value exceeds 450°C, follow the method in the next bullet.
    - If flashover is uncertain ($450°C \leq T_{max} < 600°C$), increase the HRR curve (higher PHRR, longer duration, or both) to account for the flashover threshold uncertainty. Also, iterate when vents are opened, closed, or created to allow the buildup of uncombusted hydrocarbons. If flashover is predicted, follow the method in the next bullet

- If flashover is predicted ($T_{max} \geq 600°C$), maximize the sustained upper-layer room temperature. High short-term peaks should not be maximized. The intent is to generate curves that have extended high temperatures.

- Report the time-temperature profiles developed above as sufficiently bounding temperature profiles.

Fire Effects

The physical effect of fire on objects and materials is very important to estimate the potential damage state. Different mechanisms (e.g., smoke, and heat) can damage different items. A specialized instrument may function well at high temperatures, but when exposed to smoke or combustion products it fails catastrophically. Storage containers, while unaffected by smoke, might rupture at relatively low temperatures. In discussing fire severity, it is very important to define the damage mechanism and unacceptable damage state. If this information is unavailable, the fire severity description must be overly complex, capturing all potential building uses, equipment functions and failure mechanisms. For nuclear material storage and shipping containers failure is defined as the release of material (in any quantity) from the container.

Uncontrolled fire can produce a significant quantity of heat. Even small fires involving one item can routinely produce 1 MW. For a room with a single door at 100 percent efficiency the output can approach 5 MW. For a large building this energy release rate can be orders of magnitude greater. Such large amounts of heat generation produce significant thermal gradients. These gradients result in strong convective movement of air and combustion products, and high thermal stresses in exposed structure and containers. In addition, these behaviors can produce secondary effects such as buffeting from convective motion and impact from falling objects.

During a fire storage containers can either slowly vent their contents, leak, or catastrophically burst immediately releasing their entire contents. The first failure mode (venting) is more likely in open or light duty containers, the latter mode (bursting) is more likely in sealed containers with moderate to significant strength.

Venting can be modeled as vaporization for liquids or as pyrolysis for solids. When the offgassing vapors are combustible, there is the potential for ignition. This can result in a vapor jet at the vent point (open vent or leak) or a backflash into the storage container.

Leaking containers will spill their contents onto the ground or floor. The leaks might occur because of thermal stresses or mechanical damage. If flammable or combustible the fluid can ignite, thus increasing the heat input to the storage container. A variation on leaking is spillover. This occurs when the specific volume of the stored liquid volume increases such that the container volume is no longer adequate.

Bursting will be the most violent response to fire. This occurs when the pressure/temperature rating for the container is exceeded. For non-flammable and non-combustible materials the bursting will result in dispersion of the contents to its surroundings. For flammable and combustible materials (gases, liquids and solid) bursting can result in good mixing, allowing a significant increase in energy release if ignited. This energy release would be characterized as an explosion. (Both detonations and deflagrations are possible.)

Fire Severity

Fire severity has historically been defined as the room average temperature as a function of time. This approach was developed in the early 1920s based on testing by Ingberg (Ref. 35). The fire protection community still routinely uses the results of the Ingberg tests to estimate fire duration. Table 6 shows the equivalent fire severity for given wood equivalent fire loading. Based on this table, a building with a 10-psf loading would be expected to have an equivalent fire severity of 1 hour as defined in ASTM E-119.

This room average value is commonly used as the nominal fire temperature and can be very misleading. The conditions in an actual fire compartment are often not well mixed. Stratification is very common. In typical compartments there are usually two layers, a hot layer in contact with the ceiling and a cooler layer on the floor. The height of the interface between these two layers is strongly dependent on the combustion rate (energy release from the fire), room ventilation (energy removal by convection) and the room geometry (energy loss to the walls). The temperature difference between the layers can be substantial. Upper layer temperatures exceeding 800°C are common. Since the lower layer will be about ambient, the average temperature will vary with the interface height.

The tests are still considered accurate for well-ventilated fires involving cellulose materials. As is discussed below, the test conclusions may not apply to under-ventilated or non-cellulose fires.

Care must be taken when using the units of "hours" to report fire severity. This reported severity is sometimes confused with fire duration. The situation is analogous to pounds-force and pounds-mass in the U.S. customary units. In some applications the adoption of d and s subscripts might be appropriate (duration and severity). Such a convention for this paper is not necessary since the remainder of the document will use time as a duration and not a severity.

The Ingberg tests were conducted early in this century when wood and paper were the dominant combustible materials. Since plastics burn quite differently than wood, there is a concern that the wood equivalent method is no longer appropriate. Unfortunately, no simple replacement to this method has been universally accepted.

In a closed container a predictable equilibrium vapor concentration will form above the liquid. This equilibrium concentration is referred to as the liquid vapor pressure. The higher the liquid temperature, the higher the vapor pressure. In most situations if a liquid in a closed container is sufficiently heated it is possible to generate enough pressure to rupture the container. Thus, it is common to provide relief protection (e.g., safety relief valve, rupture disk, melt-out plug) on large containers and vessels. In smaller containers, reliance is often placed on container failure prior to a significant pressure hazard occurring.

Evaluation of container failure is usually a mechanical process that must consider container design specifics. Thus, in most instances container response is part of the design process. Once the container is postulated to fail, ignition of the liquid can be predicted based on the flashpoint and the autoigntion temperature. When evaluating such container failures the reader is cautioned to consider the possibility of a Boiling Liquid Expanding Vapor Explosion (BLEVE). The reader should consult the NFPA Fire Protection Handbook (Ref. 17) on this subject.

FIRE FREQUENCY ANALYSIS

The FRA presents the frequency that specified radiological and chemical consequences will be exceeded. The consequence values are based on mechanistic models that assume specific fire protection preventative features fail to function as designed and is discussed in Fire Consequence Analysis.

Several methods may be used to predict the frequency that these fire protection preventative features will fail as postulated. Preventive features are typically credited in the frequency estimates as most fire protection preventative features are not redundant. Thus, when identified as safety class, they will have a defined probability for successfully preventing an unacceptable consequence. The individual probability credits may be combined using one of several techniques.

Frequency Estimation Methods

The most common frequency estimation methods are event trees, fault trees and the L-Curve. The methods and some advantages and potential shortcomings are discussed below.

Event Trees

Event trees are a classic method used to develop frequency estimates for safety analysis work. Because they readily produce multiple outcome results, they are especially suited for fire analysis. Some other benefits include:

- Because a fire progress logic model is used, the potential for omitting key aspects of an analysis are greatly reduced.
- A logical thought process is used that can be defended at each stage of the progression analysis.
- It is a convenient tool that can be used to make decisions on facility upgrades, fire pre-plans and emergency preparedness planning.

The SRS generic event tree is shown in Figure 5.

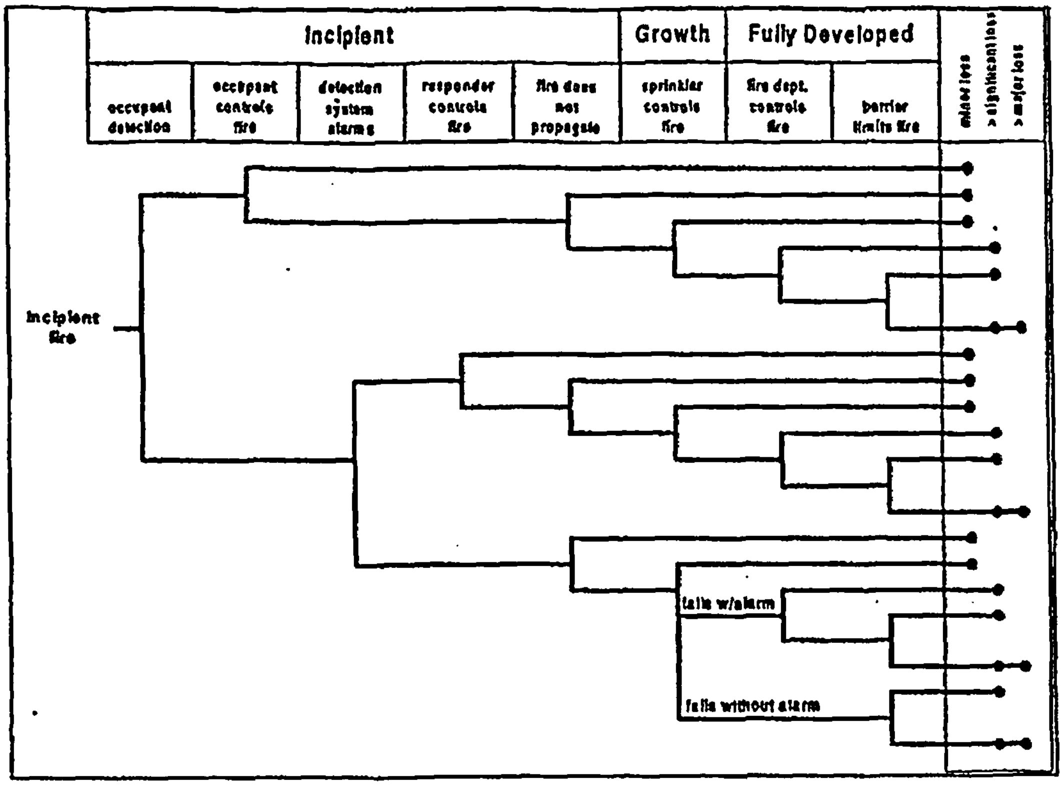

Figure 5--Generic Event Tree

Fault Trees

Fault trees are very good at developing frequency estimates for safety analysis work where there is a single, well-defined, unacceptable outcome. Typically they are best used where there is extensive understanding of the system components and their interactions. The fault tree nodes can be developed to represent the individual components. These nodes are normally populated with component specific data. There are few examples of fault trees that have effectively modeled the fire problem. The principal shortcomings are:

- The failure data for individual component nodes is usually not available
- The interactions between components are not well understood
- The trees tend to be overly complex given the significant assumptions that are required in developing fire scenarios
- The trees don't readily accommodate multiple outcomes

L-Curves

L-curves were developed for the fire service over the past 20 years. The best available description is in Harvey (Ref. 36). The intent was to provide a tool that allowed evaluation of different protective options. The input data is similar to that used for event trees, although it is very common to rely on expert judgement. The weakness of the L-curve method is that it does not account for the initiation frequency of the fire. Thus, the results are the probability of a particular loss, given a fire occurs.

Event Tree Methodology

Event trees are the method of choice for estimating fire frequencies. Severe fire frequencies are estimated using a modification of the event tree technique described in WSRC-TR-94-0188, *Fire Risk Assessment Methodology Generic Event Tree Description (U)* (Ref. 5). This technique separates the fire event tree into several stages: incipient, growth, level 1, level 2 and level 3. A variety of sources (building specific data, site generic data and national data) have been used to estimate the event tree inputs. Notation is presented below followed by a description of the methodology.

There are multiple operational techniques and equipment that can prevent propagation of fires to the more severe stages. Rapid fire propagation, which overwhelms the defense-in-depth, is accounted for as individual failures of each protection level. The effects of these multiple preventative mechanisms are presented below.

Subscript Notation

To assist the reader in following the event tree logic, a three digit subscript notation has been adopted. The first two digits reflect the particular event, where the first digit, i, indicates the fire stage and the second, j, is sequentially assigned in the order of appearance on the tree.

Double Subscripts - ij notation

00	incipient fire initiator event frequency
11	incipient fire occupant detects fire and provides notification
12	incipient fire occupant controls fire
13	incipient fire alarm system detects fire
14	incipient fire responder controls fire
15	incipient fire does not propagate
16	incipient fire halon system controls fire
21	growth stage sprinkler system controls fire
22	growth stage alarms system notifies fire department
31	zone fire barrier limits fire
32	fire department controls fire at zone level
41	area fire barrier limits fire
42	fire department notification by local personnel
43	fire department controls fire at area level

The third digit, k, reflects whether the stated value is a success or failure.

Single Subscripts - k notation

1	success probability
2	failure probability

Incipient Fire Frequencies ($P_{00,1}$)

At SRS, the frequency of an incipient fire is typically assumed to be uniformly distributed by floor area throughout the facility. Major exceptions to this are large buildings that appear to be multiple occupancy types that are separated by substantial fire walls (greater than 3 hour rating). In this situation, the incipient fire frequency is computed separately for each fire area.

Prior to FY2000 the correlation applied to all occupancies was estimated from:

(40) $P_{00,1} = F_{fire} A$

where F_{fire} is 33 fires/km²·yr (0.031 fires/10,000 ft²/yr)(Ref. 5). This constant is based on the average of the area-specific frequencies estimated from the SRS Industrial Fire Records (Ref. 37). Based on the original data presentation no significant variation was observed between process and administrative areas.

The *Australian Performance Based Design Guide* (Ref 38) and *British Fire Protection Design Guide* (Ref. 39) published incipient fire frequency correlations of the form $P = K_1 A^D$. The SRS Fire Department loss data was re-evaluated using this correlation. The new analysis, which accounted for building size, demonstrated that the original uniform frequency method was over-conservative for large production and industrial buildings, but under-estimated the frequency for smaller production and industrial buildings. For administrative occupancies, no size effect was observed.

Based on the most recent study, the recommended incipient fire frequency predictors for use at SRS are (Ref. 40):

(41)	Office occupancies	$P_{00,1} = 1.0E\text{-}5\,A$
(42)	General storage occupancies	$P_{00,1} = 3.3E\text{-}5\,A$
(43)	Production and industrial facilities	$P_{00,1} = 0.0017\,K\,A^{0.53}$
(44)	Other locations	$P_{00,1} = 0.0027\,A^{0.52}$

Where $P_{00,1}$ is the incipient fire frequency (fires/year), A is the building area (m²) and K is an occupancy-based multiplier, determined as follows:

Low potential (vault storage, reactor operations)	0.8
Nominal potential (general industry, simple operations)	1.5
High potential (laboratories, material processing facilities)	3.0

Figure 6 presents a comparison of the more important recommended design and analysis frequency predictors listed above with the previous uniform frequency method.

Other normalization schemes have been proposed (e.g., distribution of fire frequency based on the number of facility personnel present); however, these methods have not proven satisfactory.

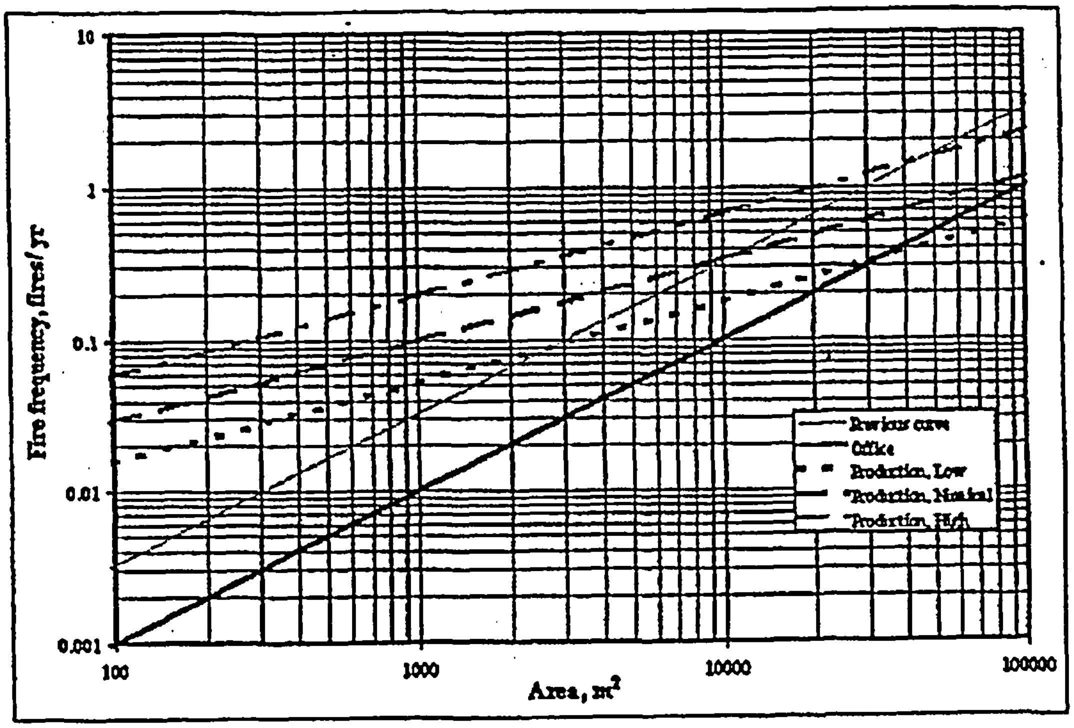

Figure 6—Recommended design and analysis incipient fire frequency correlations

Occupant Detection ($P_{11,1}$)

Personnel located in the area where a fire starts can often detect the fire. Typically, their success rate, when present, is fairly high. A typical value for successfully reporting a detected fire is 0.95 (Ref. 41). When an area is unoccupied, the probability of success is assumed to be zero. Since severe fires can develop quickly (in less than 5 minutes) the actual occupied time is a reasonable estimate for the occupant detection capability. In areas that are routinely patrolled, the occupancy is taken to be 5 minutes per tour unless other data is available.

In nuclear facilities, the radioactive contamination containment ventilation system is expected to limit smoke migration. Thus, fire detection will be by an occupant in the room of origin or with line-of-sight to the room of origin. For this reason, in nuclear facilities, occupancy is considered on the room level.

In other environments, where smoke migration can occur, the occupancy definition should be modified slightly; however, this modification should be very limited. In no circumstances should

a single occupant be considered to successfully detect incipient fires throughout a multi-room facility. Without other supporting information, smoke migration should be limited to:

- travel through two open doors
- the floor of fire origin
- corridor travel of 50 feet

Where necessary, weighted occupancy values should be used.

The above evaluation is dependent on assumptions (prerequisites) as stated in Appendix 2.

Examples

The following sample calculations are based on a 12 hour shift:

For locations that are continuously occupied the probability of successful occupant fire detection and proper response is:

$$(45)\quad P_{11,1}=\left(\frac{12\text{ hours}}{12\text{ hours}}\right)(0.95)=0.95$$

For locations that are inspected one time per shift, the probability of successful occupant fire detection and proper response is:

$$(46)\quad P_{11,1}=\left(\frac{5\text{ minutes}}{12\text{ hours}}\right)\left(\frac{1\text{ hour}}{60\text{ minutes}}\right)(0.95)=0.007$$

For locations that are patrolled one time per hour and inspected one time per shift, the probability of successful occupant fire detection and proper response is:

$$(47)\quad P_{11,1}=\left(\frac{5\text{ minutes}}{1\text{ hour}}+\frac{5\text{ minutes}}{12\text{ hours}}\right)\left(\frac{1\text{ hour}}{60\text{ minutes}}\right)(0.95)=0.09$$

For offices and support areas operating on a ten hour weekday shift that are partially occupied on off-shifts, the probability of successful occupant fire detection and proper response is:

$$(48)\quad P_{11,1}=\frac{\left[(5\text{ days})\left(\frac{10\text{ hours}}{24\text{ hours}}\right)+(2\text{ days})\left(\frac{3\text{ hours}}{24\text{ hours}}\right)\right]}{7\text{ days}}(0.95)=0.32$$

Facility Occupant Controls Fire ($P_{12,1}$)

In most facilities, occupants are provided with basic fire extinguisher training and are instructed that they may attempt to extinguish a fire after they have notified emergency services personnel (GET training). Thus operator action may be credited to control fires. The effectiveness of an occupant controlling a fire is dependent on fire extinguisher availability, level of training and the fire size at discovery. In evaluating the capabilities of occupant suppression, there are three basic assumptions: (1) the fire must involve only a single fuel package (2) fire output cannot exceed 300 kW peak heat release rate (approximately two bags of paper trash) and (3) fire extinguishers must be available (Ref. 5).

The acceptability of extinguisher coverage within any building should be based on NFPA 10 (Ref. 42). If the building under analysis does not comply with NFPA 10, an adjustment to the probability presented below is appropriate.

Table 7 suggests several success probabilities that have been proposed. Benhardt, et al. (Ref. 41) estimated the probability for successful control of a fire by manual intervention from SRS specific data. Berry and Minor (Ref. 43) estimated their values based on the judgement and experience of fire protection engineers. Bryan (Ref. 44) reports on a University of Maryland study that demonstrated that 57% of the subjects who had fire extinguisher training were able to extinguish a fire when tested two weeks after the training had occurred.

Table 7--Probability that a fire is controlled by facility occupant

	Success frequency	Reference
High degree of fire extinguisher training	0.9	Benhardt (41)
Basic fire extinguisher training	0.7	Benhardt (41)
Fire extinguisher training	0.6	Bryan (44)
No fire extinguisher training	0.5	Berry & Minor (43)
No fire extinguishers present	0.0	Berry & Minor (43)

Prior to FY2000 the value used in most FRAs was 0.7 based on the Benhardt result. However, for new analyses, based on the presently available results, the recommended success probability for facility occupant controls fire, $P_{12,1}$, is 0.6.

The above evaluation is dependent on assumptions (prerequisites) as stated in Appendix B.

Alarm System Detects Fire ($P_{13,1}$)

Fire detection and alarm systems are a key element among the fire protection features of any building. When properly designed, installed, operated, tested and maintained, a fire alarm system can help limit property fire losses in buildings, regardless of occupancy. The basic features of each system include system control; main power supply; secondary or standby power supply; a "trouble" power supply; initiating devices (heat detectors, manual pull stations, etc.) and one or more alarm indicating appliances. Usually fire alarm systems are installed and operated to the requirements of NFPA 72 (Ref. 45). Where this in not true, adjustments must be made in evaluating the system's capabilities.

Automatic fire alarm systems can successfully notify facility occupants and emergency response forces to respond to a fire. At SRS, such systems, when in service, are maintained to the requirements of NFPA 72 (Ref. 45) and connected to the Site Fire Alarm Reporting System. Recent information published by Hall (Ref. 46) indicates that the success experience for alarm systems detecting a fire and initiating a response in general industrial and manufacturing facilities is 0.80. This value is based on reliability data from National Fire Incident Reporting System (NFIRS) and thus includes both reliability and availability. A site specific study (Ref. 47) using data from Buildings 221-F and 221-H demonstrated the availability of detection systems is 0.9. Thus the 0.8 success probability (reliability and availability) is considered reasonable.

For partial systems, the probability of detection can be estimated by multiplying the generic success probability by the percentage of floor covered.

$$(49)\quad P_{13,1} = \frac{\text{area equipped with alarm system}}{\text{total area}}(0.80)$$

The effect of overlap or minor gaps in multiple fire protection systems can usually be neglected. If the overlaps or gaps are significant, the unprotected and protected areas can be treated as separate fire zones.

The above evaluation is dependent on assumptions (prerequisites) as stated in Appendix B.

Facility Responder Controls Fire ($P_{14,1}$)

A facility responder is an individual who responds to a fire alarm in a role to extinguish the fire. As previously discussed in "Facility Occupant Controls Fire ($P_{12,1}$)" the responding occupant's success is dependent on his training, fire extinguisher availability and the size of the fire. Typically, the 0.6 value in Table 7 is recommended for use, however the 0.7 value was used for earlier work.

In some locations, early response (less then 10 minutes) by the fire department operators with special training (e.g., brigade) is expected. In such instances a higher success probability may be appropriate and a value of 0.7 or 0.9 is recommended depending on the level of training. To implement these values, an adjustment in the upper portion of the generic event tree is required. This adjustment reflects the common cause failure modes between *Facility Occupant ($P_{12,1}$)* and *Facility Responder ($P_{14,1}$)*. The adjusted value, $P^*_{14,1}$, is computed as follows:

$$(50)\quad P^*_{14,1} = \begin{cases} 1-\left(\dfrac{1-P_{14,1}}{1-P_{12,1}}\right) & \text{if } P_{12,1} \le P_{14,1} \\ 0 & \text{if } P_{12,1} > P_{14,1} \end{cases}$$

The above evaluation is dependent on assumptions (prerequisites) as stated in Appendix B.

Fire Does Not Propagate ($P_{15,1}$)

For most fires to grow beyond the incipient stage, more than one object must burn. This is related to the heat release rate (HRR) necessary to cause high room temperatures. (Usually the HRR

required for flashover is greater than 1,000 kW, while most fuel packages have peak heat release rate [PHRR] values below 1,000 kW.) Thus, the likelihood that multiple items do not burn should be accounted for in any fire risk analysis. This likelihood is affected by energy emittance from the first burning object, the ignition heat flux of the second item and the spacing between the two objects. The first two values establish the critical spacing for ignition. (See Table 5.) If the spacing is below this critical value, ignition of the second item can be assumed. If it is above this value, ignition will not occur. (See Table 2 for the definition of PHRR categories and Table 4 for ignition heat flux categories.)

Typically if the second item is considered to ignite, the fire is assumed to propagate within the room of origin. While it is possible that two burning items may not create the conditions necessary for flashover, high temperatures or excessive smoke, developing the likelihood of propagation to a third or fourth item is usually not warranted.

In rooms where a single burning object can cause flashover (or some other failure criterion) to occur, the probability estimate for propagation should reflect the likelihood of this behavior. The example demonstrated later in this section provides one technique to address this situation.

The evaluation presented in this section is dependent on assumptions (prerequisites) as stated in Appendix B.

Probabilistic Estimate

The actual location of any combustible object within a room is often unknown, but it is possible to establish a range of potential locations within a room. This limitation can be accommodated because, for most fire risk work, determination of the specific item to be the second to ignite is not important. What must be determined is the likelihood that there is a second item close enough to the incipient fire for fire propagation to occur.

If the maximum distance for successful radiative ignition, L_i, is known, then the probability of igniting a second item can be estimated from the probability that the second object will be within the distance, L_i. Bukowski, et. al. (Ref. 2) established the location of combustible products using a gaussian probability distribution. This distribution, when coupled with the maximum ignition distances in Table 5 allows the probability of ignition to be estimated.

Other distributions are also possible. If the minimum, mode (most likely) and maximum locations of potential second-items-to-ignite are known, a histogram can be drawn as shown in Figure 7.

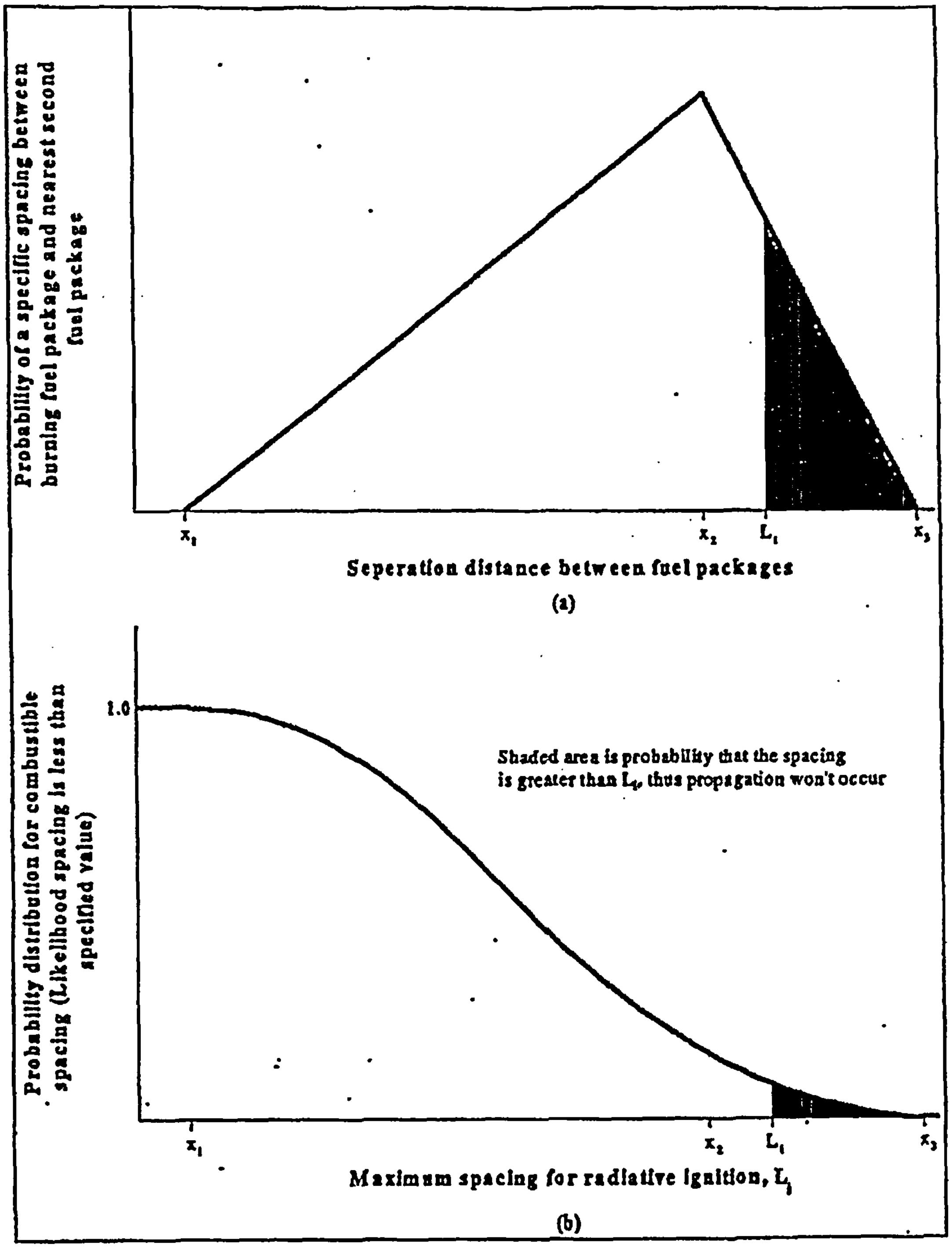

Figure 7--Probability of fire non-propagation to second item (a) distribution histogram (b) distribution probability

This triangular distribution has been found to provide reasonable estimates and to be easier to develop than other histogram shapes. The probability that a fire will not propagate due to an unfavorable distribution of combustibles within the room is (Ref. 5):

$$(51)\quad P_{15,1} = \begin{cases} 1.0 & L_i < x_1 \\ 1 - \dfrac{h(L_i - x_1)^2}{2(x_2 - x_1)} & x_1 \le L_i < x_2 \\ 1 - \dfrac{h}{2}\left[L_i - x_1 + \dfrac{(L_i - x_2)(x_3 - L_i)}{x_3 - x_2}\right] & x_2 \le L_i < x_3 \\ 0.0 & x_3 \le L_i \end{cases}$$

where:

$$(52)\quad h = \frac{2}{x_3 - x_1}$$

and the values of x_1, x_2 and x_3, are the minimum, mode and maximum separation distances between the first item to ignite and the second item to ignite.

Generic Data

Table 3provides the design data for developing facility specific fire non-propagation probabilities.

Default Values

Default fire propagation values for use in FRA work are given in Table 8.

Table 8--Default values for fire non-propagation probability by room type

Room Type	$P_{15,1}$
Office/Supply*	0.10
Open Process:	
Very limited combustibles (LC)	0.95
Minimal combustibles (MC)	0.90
Corridors, Fan Rooms	0.90
Stairwells	0.95
Other	0.50

* Reference WSRC-TR-95-0221

Example

A facility consists of six separate rooms. Three of the rooms are offices that comprise about 20 percent of the floor area. The remaining rooms are a process room (40 % of the building), a corridor (10 %) and a storage area (30 %). The combustible distribution information is presented in Table 9. In the process area, two distributions are used since there is a mix of materials. In the storage area, there are some fuel packages that have very high heat release rates, thus fire propagation is expected if these items become involved. Non-propagation probabilities for the individual locations) are estimated using Equations (51) and (52) and are presented in Table 9.

For the process area, it is necessary to estimate the likelihood that a fire starts in the medium and high PHRR fuel packages. If the respective values are 0.6 and 0.4, then the value of $P_{15,1}$ for the process area is:

$$(53)\quad P_{15,1} = 0.6(0.86) + 0.4(0.94) = 0.89$$

For the storage area, a similar estimate is required due to the very high heat release rate fuel packages. If the fraction of fires starting among the high heat release rate items is 0.3, then the value of $P_{15,1}$ for the storage area is:

$$(54)\quad P_{15,1} = 0.3(0) + (1-0.3)(0.28) = 0.20$$

The composite non-propagation probability for the facility is then estimated by combining the values for the individual rooms in Table 10. For this example facility the probability of non-propagation for a fire is 0.5. Although the composite non-propagation value has been calculated for this example, for most FRAs the individual zone level probabilities (i.e., the four locations as presented in the example) are usually used directly in the event tree.

Table 9--Non-propagation probability for individual locations of example facility

Location	Ease of ignition	PHRR	L_1	X_1	X_2	X_3	$P_{15,1}$
offices	easy	medium	1.19	0.0	0.6	1.5	0.07
process	normal	medium	0.61	0.0	0.5	5.0	0.86
	normal	high	0.89	0.0	2.5	5.0	0.94
corridor	easy	medium	1.19	0.0	0.6	5.0	0.66
storage	normal	medium	0.61	0.5	0.6	0.7	0.28

Table 10--Composite non-propagation probability for example facility

Location	Location specific $P_{15,1}$	Location fraction	Weighted $P_{15,1}$
offices	0.07	0.2	0.01
process	0.89	0.4	0.36
corridor	0.66	0.1	0.07
storage	0.20	0.3	0.06
		1.0	0.50

Early Suppression System Success Probability ($P_{16,1}$)

Early suppression systems include those automatic suppression systems that rely on the fire detection system to activate (i.e., halon, water spray, open head deluge, etc.). The generic event tree keeps the detection system function separate from the suppression system activation to account for fire department notification.

The original generic event tree identified the early suppression system as the halon system because, at the time the generic event tree was developed, only halon was used at SRS for early suppression systems.

The evaluation presented in this section is dependent on assumptions (prerequisites) as stated in Appendix B.

Halon Systems

Automatic 1301 halon fire protection systems constructed to NFPA 12A (Ref. 48) combine several electrical, mechanical, and architectural elements to create an effective fire suppression system. These elements include: automatic fire detection, halon storage, releasing circuitry, fire zone perimeter integrity and ventilation components. These elements must operate in harmony for a fire to be successfully controlled until fire department arrival. The halon system only limits the damage until arrival of the fire department; the fire department is expected to extinguish the fire. The probability that a NFPA 12A (Ref. 48) compliant halon system successfully controls a fire, given successful fire detection, was estimated for HB-Line (Ref. 49). The success value, $P_{16,1}$, for halon systems was determined to be 0.85. Input for determination of this value considered:

- Halon system does not correctly activate
- Alarm system fails to notify the fire department
- Fire department fails to extinguish and control fire
- Ventilation system does not respond to halon alarm
- Design or initial testing error limits system effectiveness
- Testing or maintenance error prevents system activation
- Unanticipated enclosure modification limits system effectiveness
- Room doors do not close

Water Spray Systems

For water spray systems that are compliant with NFPA 15 (Ref. 50) and maintained to NFPA 25 (Ref. 51), the recommended probability of successful fire control is 0.94 unless other information is available. This value is based on the standard wet-pipe sprinkler success value (0.96) combined with an SRS specific study on halon system activations. In this study Cramer (Ref. 52) identified 221 halon system activations in the Separation Facilities Fault Tree Data Bank. Five of

these activations did not result in a full release of halon. The conditional probability for successful release of halon given a fire detection signal is then 0.98.

The combined value for water spray systems is computed as follows:

$$(55) \quad P_{16,1} = 1 - [(1-0.96)+(1-0.98)] = 0.94$$

Open Sprinkler Deluge Systems

For open sprinkler deluge systems that are compliant with NFPA 13 (Ref. 53) and maintained to NFPA 25 (Ref. 51) the recommended probability of successful fire control, $P_{16,1}$, is 0.94 based on the logic presented for water spray systems.

Other Early Intervention Suppression Systems

For other types of early intervention suppression, success probabilities will need to be developed. In developing such values the following information may be useful:

- Cramer (Ref. 52) identified 221 halon system activations in the Separation Facilities Fault Tree Data Bank. Five of these activations did not result in a full release of halon. The conditional probability for successful release of halon given a fire detection signal is then 0.98.
- The probability of successful transmission of a fire alarm to the SRS fire service is expected to be very high. A nominal value of 0.995 will be assumed since the system is continuously monitored. This equates to an unavailability of slightly less than 2 days per year.

(Automatic) Sprinkler System Controls Fire ($P_{21,1}$)

Automatic sprinkler systems are a key component in a comprehensive fire protection program. These systems have been demonstrated to be highly effective in reducing fire deaths, injuries and property losses.

The evaluation presented in this section is dependent on assumptions (prerequisites) as stated in Appendix B.

Historical Performance

The National Fire Protection Association (NFPA) tracked the performance of automatic sprinkler systems from 1897 to 1970 (Ref. 46). This data demonstrates that the fire risk in buildings equipped with automatic suppression systems is significantly lower than that in a comparable unprotected building. In addition to the data published by the NFPA, extensive evaluation of Australia and New Zealand (Ref. 54) and Department of Energy (DOE) (Ref. 55) fire loss records have been published. (See Table 11.) The success probabilities from these reviews range from 0.96 to 0.99. Table 11 includes selected data from industrial and educational occupancies as published by the NFPA.

Table 11–Sprinkler system performance

Description	Years	Reference	Success probability
United States			
all fires	1897-1924	1	0.958
all fires	1925-1969	1	0.962
all fires	1965-1969	1	0.957
residential	1925-1969	1	0.955
assembly	1925-1969	1	0.955
educational	1925-1969	1	0.917
institutional	1925-1969	1	0.961
office	1925-1969	1	0.974
mercantile	1925-1969	1	0.972
industrial - textiles	1925-1969	1	0.982
industrial - total	1925-1969	1	0.965
storage occupancies	1925-1969	1	0.910
other occupancies	1925-1969	1	0.792
U.S. DOE	1952-1980	4	0.983
Australia and New Zealand			
	1886-1968	3	0.991
	1886-1986	3	

The highest observed success probability in the NFPA study was for the textile industry. This was attributed to the experience of the textile industry with sprinklers, strong management support and complete coverage. With the exception of other occupancies (a category that includes abandoned buildings), the poorest sprinkler performance was observed in educational occupancies, 0.917, which was attributed primarily to incomplete sprinkler system coverage and storage occupancies, 0.910, in which methods of piling account for protection problems.

In addition to the data in Table 11, Melinek (Ref. 56) published 1987 United Kingdom data for industrial and commercial buildings. (See Table 12.) The success probability of a sprinkler system to control or extinguish a fire based on this data is:

$$(56)\quad P = \frac{169 \text{ extinguished} + 347 \text{ controlled}}{1{,}354 \text{ total} - 658 \text{ too small}} = 0.74$$

A review of 1966 through 1972 data indicated that perhaps 45 percent of fires in sprinkled buildings are not reported because they are controlled or extinguished by the suppression system (Ref. 56). Using this information it is possible to adjust the data in Table 12 to account for unreported fires.

$$(57)\quad N_{unreported} = \left(\frac{0.45}{1-0.45}\right)(1{,}354 \text{ fires}) = 1{,}110 \text{ fires}$$

This correction is distributed equally between the extinguished fire and controlled fire results. The success probability for suppression systems, based on the corrected data, is thus:

(58) $$P = \frac{724\,\text{extinguished} + 902\,\text{controlled}}{2{,}464\,\text{total} - 658\,\text{too small}} = 0.90$$

Harvey (Ref. 36) recommends a range of values for sprinkler system success from 0.85 to 0.98 with a extreme upper bound of 0.985. This range is consistent with the NFPA, DOE and UK data and is slightly lower than the Australian and New Zealand experience.

Table 12--Sprinkler system performance in United Kingdom industrial and commercial buildings during 1987

Sprinkler behavior	Number of fires	
	original	corrected
Failed to operate because fire too small	658	658
Extinguished fire	169	724
Controlled fire	347	902
Operated but failed to control fire	61	61
Failed to operate other than because fire too small	109	109
Behavior not specified	10	10
Total	1,354	2,464

Defining Successful Operation

A sprinkler system is considered to function as designed if it is able to flow water of sufficient quantity to control or extinguish a fire without excessive fire spread. The recommended success probabilities do not imply the extent of fire damage or the number of sprinkler heads that will open. For most facilities, the recommended approach to account for this fact is to assume that direct fire damage occurs to all equipment in the room of fire origin when the sprinkler system is considered to control the fire. Outside the room of origin, damage should be limited to that caused by smoke migration and radiant heat transfer.

If necessary, to reduce the consequences associated with successful sprinkler system operation, facility specific evaluations should be performed. In discussing the results of such an evaluation the material-at-risk is the inventory in the room. The damage ratio is estimated to account for the mitigated consequences associated with sprinkler system operation.

Alarm Function

There are three significant responses for an automatic sprinkler system. (1) It can operate successfully and control the fire. (2) It can fail to control the fire but successfully notify the fire department about the fire. (3) It can fail to control the fire and fail to initiate a fire department response. To account for these outcomes, the generic event tree contains a three-response event in the lower branch. This three-response approach is not necessary for the other branches where fire is detected by building occupants or automatic detection systems.

In developing the values for the three response-event, the recommended conditional probability for failure without notification is 0.534. This is based on an evaluation of sprinkler failure modes by Hall (Ref. 46). Failure to maintain operation system status resulted in 53.4 percent of sprinkler system failures, which is a failure mode that would preclude fire department notification.

Wet-Pipe and Dry-Pipe Sprinkler Systems

All sprinkler systems consist of a network of piping that allows water to flow from a supply source to the sprinklers. Sprinklers are the nozzles that regulate the flow of water on a fire. In most instances, the sprinklers (e.g., heads) are closed and intended to open when a specific air temperature is exceeded.

Wet sprinkler systems are constantly filled with water and provide a distinct advantage. Water flows immediately on the fire area after actuation of a sprinkler head. Dry-pipe systems are pressurized with air until the heat from a fire activates a sprinkler. The air escaping from the system allows water to enter the piping network, flow to the fused (i.e., opened) sprinklers and discharge on the fire.

The following recommended success probabilities, $P_{21,1}$, are based on the preceding discussion:

- Wet-pipe sprinkler systems — 0.96
- Wet-pipe sprinkler systems if two independent inspections are conducted after the system is returned to service (Ref. 57) — 0.97
- Dry-pipe sprinkler systems — 0.96

Pre-action Sprinkler Systems

Pre-action systems are similar to dry-pipe systems but must also have a supplementary heat-detecting device activated to allow flow to the system. The recommended success probability for such systems is based on the discussion presented in the section on *Early Suppression System Success Probability ($P_{16,1}$)*. Because detection system activation is required to allow pre-action systems to automatically flow water, they should usually be treated as early suppression systems in the generic event trees. This is not to imply that pre-action systems are early suppression systems, but rather is a construct to fully utilize the generic event trees.

The recommended success probability for pre-action systems is 0.94 and should be incorporated in the event tree as *Early Suppression System Success Probability ($P_{16,1}$)*.

Deluge Sprinkler Systems

Deluge systems typically are equipped with open sprinklers. Thus, in their normal mode they are not filled with water. Water flow is initiated by the activation of heat-detecting devices. As with pre-action sprinkler systems, deluge sprinkler systems should be treated as early suppression systems in the generic event trees.

The recommended success probability for deluge systems is 0.94 and should be incorporated in the event tree as *Early Suppression System Success Probability ($P_{16,1}$)*.

Fire Loading Effect

Sprinkler systems are not designed as one-size-fits-all. NFPA 13 (Ref. 53) defines five performance levels. (See Table 13.) The appropriate level is selected based on the quantity and combustibility of the materials present and the expected fire development. Thus, some

adjustment may be necessary if the combustible loading exceeds the rated capability of the sprinkler system.

Cohn (Ref. 58) equated the probability of success of full automatic suppression with the fire loading. Four curves were generated depending on the type of hazard (e.g., ordinary class A combustibles, low flashpoint class B flammable liquids) and the type of system (e.g., wet-pipe, dry-pipe). (See also Reference 43.) Selected points from the wet-pipe curves are presented in Table 14. Because the highest success value is 0.999, it is assumed that the probabilities are contingent on the sprinkler system being available.

Cohn's predictions do not account for the different performance levels listed in Table 13. The transition between Ordinary Hazard Group 1 and Ordinary Hazard Group 2 occurs at combustible loadings of 15 to 20 psf. Using Table 14, this equates to a reliability of 0.95 for a wet-pipe sprinkler system protecting Class A combustibles. For an availability of 0.98, the overall effectiveness is:

$$(59)\quad P_F = P_A P_R = (0.98)(0.95) = 0.93$$

Table 13--Sprinkler system performance levels defined in NFPA 13

Hazard	Combustible Quantity	Combustibility	Fire development
Light	low	low	low heat release rate (HRR)
Ordinary, Group 1	moderate	low	moderate HRR
Ordinary, Group 2	high*	high*	high* HRR
Extra Hazard, Group 1	high	high	rapid with high HRR†
Extra Hazard, Group 2	high	high	rapid with high HRR‡

*NFPA 13 specifies this as moderate to high.
†limited quantities of flammable and combustible liquids
‡moderate to substantial quantities of flammable and combustible liquids

For Ordinary Hazard Group 1, an adjustment is suggested when the fire load exceeds 20 psf. The reliability should be taken directly from Table 14. The overall effectiveness is then the product of this value and the standard sprinkler system availability (0.98).

For light hazard occupancies, the adjustment should be made when the loading exceeds 15 psf. The fire load is normalized to the values in Table 14. The adjustment would be:

$$(60)\quad L^{*}_{LH} = K_{LH}L = \frac{20\,\text{psf}}{15\,\text{psf}}L = 1.33L$$

Table 14--Wet-pipe automatic suppression probabilities based on combustible loading

Probability		Combustible loading (psf)	
failure	Success	ordinary hazard	fast developing fire
0.001	0.999	7	3
0.005	0.995	10	5
0.01	0.99	12	6
0.05	0.95	18	12
0.1	0.9	22	14
0.5	0.5	48	29
0.9	0.1	80	45
0.95	0.05	90	49
0.99	0.01	...	59
0.999	0.001	...	70

where: L^{*}_{LH} = adjusted success probability for light hazard occupancies that exceed 15 psf

K_{LH} = combustible loading multiplier

L = success probability based on combustible loading (Table 14)

For other standard occupancies (High Hazard and Ordinary Hazard Group 2), the adjustment should be made when the loading exceeds 30 psf. This adjustment should be:

$$(61)\quad L^{*}_{HH} = K_{HH}L = \frac{20\,\text{psf}}{30\,\text{psf}}L = 0.67L$$

where: L^{*}_{HH} = adjusted success probability for other standard occupancies that exceed 30 psf

K_{HH} = combustible loading multiplier

L = success probability based on combustible loading (Table 14)

NFPA 231, *Standard for General Storage*, (Ref. 59) specifies the use of automatic sprinkler systems in warehouses. Combustible loadings in such buildings can readily exceed 100 psf. Since warehouse sprinkler systems are considered reliable, strict adherence to Table 14 adjustment is not recommended. The table does, however, provide a potential adjustment when the actual combustible loading exceeds the design capability of the sprinkler system. This approach does not account for sprinkler systems that have been designed to accommodate high combustible loadings.

Effectiveness

An important concept in evaluating the performance of most automatic sprinkler systems is that they are not designed to extinguish fires. (There are exceptions to this for special systems that are designed for specific storage configurations.) Although they sometimes do extinguish fires, their purpose is to control the fire until the fire department can intervene and extinguish it. Thus, if fire department response is not expected, the recommended success probabilities listed below should be adjusted. Additional adjustments should be made to account for fire loading effects when the combustible loading exceeds the rated capability of the sprinkler system.

The following success probabilities for automatic sprinklers, which are constructed per NFPA 13 (Ref. 53) and maintained to NFPA 25 (Ref. 51), should be used.

- Wet-pipe sprinkler systems 0.96
- Wet-pipe sprinkler systems if two independent inspections are conducted after the system is returned to service (Ref. 57) 0.97
- Dry-pipe sprinkler systems 0.96
- Pre-action systems (treat as early suppression systems) 0.94
- Deluge systems (treat as early suppression systems) 0.94

Alarm System Notifies Fire Department ($P_{22,1}$)

The probability of successful alarm receipt using the Site Fire Alarm Reporting System (people and equipment) and the subsequent dispatch of the SRS fire service is expected to be very high. A nominal value of 0.995 is recommended since the system is continuously monitored (Ref. 5). This equates to an unavailability of slightly less than 2 days per year. This value represents any failure that might occur between alarm transmission from a fire detector or sprinkler system alarm panel to receipt by the alarm dispatcher. It also includes errors made by the dispatcher in providing dispatch information to the fire department. Errors by the fire department in receiving dispatch information are considered in the fire department success probabilities.

The evaluation presented above is dependent on assumptions (prerequisites) as stated in Appendix B.

Fire Barriers ($P_{31,1}$ and $P_{41,1}$)

Fire barriers are often required by code to limit the spread of fire. They can be walls, ceilings/floors, doors and dampers within a ventilation system. Depending on thickness, type and quality of material, a typical fire barrier rating ranges from 0.5 to 4 hours although some barriers can have ratings exceeding 8 hours. The fire barrier rating does not imply that the barrier will successfully contain a fire for the defined rating but rather that the barrier can withstand a particular defined test curve for the specified duration. For example, a two-hour wall might only last 45 minutes during one scenario, while lasting multiple hours for a slower burning scenario.

The evaluation presented in this section is dependent on assumptions (prerequisites) as stated in Appendix B.

Fire Barrier Rating

The fire barrier rating should be as stated in the Fire Hazard Analysis (if the information is correct) or derived from an appropriate source document (e.g. Refs. 60, 61, 62 and 63). A barrier does not need to be designated as a fire barrier in order to take credit for it in fire risk analyses.

For most lightweight non-rated construction, the equivalent fire rating should be taken as 40 minutes. This is the fire resistance of 2 layers of 1/2" gypsum wallboard on wood (Ref. Table 7-4N)

For load-bearing reinforced concrete walls with an unknown aggregate, where the wall thickness is greater than 7.5 inches, the equivalent fire resistance should be taken as 4 hours (Ref. 62, Table 2). This rating does not account for doors or penetrations.

Barriers that are rated for 2 hours, which have doors that are rated for 1.5 hours, should be treated as 2 hour barriers. (The installation of 1.5 hour doors where 2 hour barriers are required is standard construction practice.)

Fire Loadings

Historically, fire loadings are reported in units of pounds per square foot (psf) of wood equivalent energy. Thus, the fire loading value is a unit of energy content per unit of floor space. At SRS, fire loadings are rounded to the following values: 2.5, 5, 10, 15, 20, 30, 40 psf. Loadings greater than 20 psf are reported to one significant digit. This approach is used because it is considered to reflect the accuracy of the loading surveys and simplifies the analysis.

Table 15 (Ref. 64, Table 7-5B) provides survey results for the combustible loading in private office buildings. The 95 percent coverage values are calculated based on twice the sample standard deviation. From these results, it is recommended that offices be taken as having an average fire load of 10 psf and a sufficiently bounding fire load of 15 psf. A library would have an average load of 25 psf and a sufficiently bounding load of 45 psf.

The recommended default fire loadings for safety analysis work at SRS are:

Room use	Mean, (psf)	sufficiently bounding, (psf)
SNM vaults	...	2.5
Process rooms	5	10
Offices	10	15
Storage	15	40

In process rooms where rigorous combustible control is practiced, it is appropriate to reduce the sufficiently bounding loading to 5 psf.

Table 15--Fire loading for office buildings

Room use	Mean		Standard deviation		95% coverage	
	kg/m²	psf	kg/m²	psf	kg/m²	psf
General	38	7.7	21	4.3	80	16.3
Clerical	33	6.8	20	4.0	73	14.8
Lobby	24	5.0	20	4.2	64	13.4
Conference	29	5.9	22	4.6	73	15.1
File	79	16.2	63	12.9	205	42.0
Storage	64	13.2	57	11.7	178	36.6
Library	115	23.6	53	10.8	221	45.2

Wearout Probability

The wearout probability is the likelihood that a barrier will fail by collapse or excessive conductive heat transfer during the fire exposure. Berry and Minor (Ref. 43) provide fire barrier

wearout probabilities based on uniform fire loading (kg/m^2) and the barrier fire rating. These wearout probabilities vary from 0.001 to 0.998. The standard deviation can be estimated using Equation (62) (Ref. 65.) The fire load that results in a particular failure rate, $P_{x\%}$, can be read directly from Figure 9 of Reference 43.

$$(62)\quad \sigma = \frac{2}{5}\left(P_{90\%} - P_{10\%}\right)$$

The fire load that results in a given failure rate and the resultant standard deviation is tabulated below in Table 16 for various barrier ratings.

For safety analysis work, the combustible loading should represent the 95 percent coverage value. Where the combustible loading in the fire area or zone is not uniform, a localized average should be used. This compensates for the increased fire severity created by concentrations of combustibles such as diesel fuel and laundry.

Table 16--Fire barrier "wearout" failure rates

Barrier rating	Fire load for $P_{50\%}$		Fire load for $P_{10\%}$		Fire load for $P_{90\%}$		Standard deviation, σ	
hour	kg/m^2	psf	kg/m^2	psf	kg/m^2	psf	kg/m^2	psf
0.5	39	8	24	5	54	11	12	2.4
1	73	15	49	10	103	21	21	4.4
2	151	31	98	20	205	42	43	8.8
3	225	46	146	30	308	63	64	13.2
4	303	62	195	40	415	85	88	18

Analyses using the uniform fire loading techniques are discouraged in the DOE complex (Ref. 66) based on the widespread misapplication of the uniform loading method to establish fire severities during the 1980s. However, until a new method is developed this is the only available technique to evaluate success probabilities.

Since localized averages, rather than global averages, and 95 percent coverage values are used in estimating fire barrier success probabilities, the uniform loading technique is considered acceptable.

Multiple Barriers

For some fire analysis work, it is necessary to postulate that fires initiating in particular zones must cross multiple barriers in order to reach a zone that would cause a severe consequence. As the generic event tree only accounts for 2 barriers ($P_{31,t}$ and $P_{41,t}$), $P_{41,t}$ must be adjusted to represent the combination of the success rates for the second barrier and any additional barriers as follows:

$$(63)\quad P_{41,t} = 1 - \left[\left(1 - P_N\right)\left(1 - P_{N-1}\right)\ldots\right]$$

where:

N	is the number of additional barriers beyond the first ($P_{31,t}$)
P_N, P_{N-1} ...	are the additional fire barrier success probabilities

Physical Separation

Physical separation between buildings can provide a considerable barrier to fire propagation. NFPA 80A (Ref. 25) presents a mechanistic analysis that determines the minimum separation distance, x_r, below which neighboring buildings are evaluated as an exposing hazard. This distance must be increased by a factor of 3 to eliminate the fire department credit incorporated in the NFPA 80A (Ref. 25) analysis. Thus, any outlying buildings (i.e., exposing buildings) that are within a distance ≤3 x_r from the building concern are evaluated to determine the frequency at which they expose the building of concern.

When estimating the minimum separation distance, x_r, no credit should be taken for the exterior wall of the exposed building or the sprinkler system in the exposing building. The methodology described below inherently credits the following preventive mechanisms:

- Distance (separation between the exposed and exposing building)
- Exterior walls
- Fire Department response
- Sprinklers (in the exposed building)

For the non-propagation calculation below, credit for sprinklers in the exposing building and for fire department response are incorporated elsewhere in the event tree.

The success probability for non-propagation across open space should be computed from (Ref. 67):

$$(64)\quad P_{t,1} = P_{s,1} + (1 - P_{s,1})\left(P_{w,1} + \frac{(1 - P_{w,1})x}{3x_r}\right)$$

where:

$P_{s,1}$	is the effect of a sprinkler system in the exposed structure
$P_{w,1}$	is the barrier success probability of the exterior wall of the exposed building
x	is the distance between the exposure and the exposed building
x_r	is the minimum separation distance required between the exposure and the exposed building per NFPA 80A (Ref. 25)

If sprinklers are maintained in the exposed building but not in the exposing building, $P_{s,1}$ is 0.96. If both structures have sprinklers, use 0.9 for $P_{s,1}$ to account for common cause failures. Otherwise, $P_{s,1}$ is zero. The value for $P_{w,1}$ is determined based on evaluation using the wearout methodology as indicated previously. $P_{w,1}$ can include credit for the walls in both the exposed and the exposing buildings. Calculation of this value is accomplished by applying the methodology described for multiple barriers.

Fire department response is not expected for exposure fires; thus, credit for fire department response is eliminated by increasing the minimum separation distance by a factor of 3, which has been incorporated in Equation (64).

Effectiveness

Fire barrier success probability may be determined based on the fire barrier rating, the fire load and the quality of the barrier. A modified version of the wearout values suggested by Berry and Minor (Ref. 43) is recommended:

$$(65) \quad P_{1,1} = D(1 - P_{wearout})$$

where: $P_{1,1}$ is the success probability of the barrier

$P_{wearout}$ is the failure probability of a fully compliant fire barrier based on the fire rating (hours) and the fire load (kg/m^2)

D is the barrier quality factor

The barrier quality factor, D, accounts for unsealed penetrations and fire propagation by modes other than barrier destruction. Barrier quality factors are typically based on engineering judgment. The following default values are recommended:

- multiple small unprotected openings 0.9
- unrated doors, windows and other closed, unprotected openings 0.8
- single unprotected openings with no doors, windows, etc. 0.7
- multiple unprotected openings with no doors, windows, etc. 0.5

Fire Department Controls Fire ($P_{32,1}$ and $P_{43,1}$)

For a fire department to successfully extinguish a fire, they must arrive in a timely manner with an adequate number of personnel to control the fire. In general, the longer a fire burns before fire department suppression efforts, the more manpower is required to successfully control the fire. The success probability (i.e., effectiveness) for the fire department can be estimated from the product of three terms: timing, availability, and reliability.

$$(66) \quad P_{FD,1} = P_T \cdot P_A \cdot P_R$$

Timing, P_T, is the probability that the fire severity is such that the planned response is sufficient to control the fire at the specified intervention time. Availability, P_A, is the probability that the required fire fighting personnel and equipment are on site, in their response zone and not engaged in a previous emergency response. Reliability, P_R, is the probability that the fire department can limit fire damage to a defined area given that sufficient personnel and equipment are available and the intervention effort is timely.

The form of the generic event tree is based on the premise that the frequency of severe slowly developing fires is small when compared with the frequency of fast developing fires and it is the rapidly developing fire which dominates the risk. This is the result of the fact that the effectiveness of the fire department approaches unity for most slow developing fires since in such instances, the fire department has time to evaluate the situation and respond with the most effective tactics. Thus, slow developing fires are neglected in the generic event trees and the discussion below focuses on fast developing fires (i.e., fires that achieve full room involvement

prior to fire department intervention). The method is, however, fully compatible with evaluation of slower developing fires.

The evaluation presented above is dependent on assumptions (prerequisites) as stated in Appendix B.

Timing, P_T

The arrival of the fire department in a timely manner is critical for their success. Timing is the probability that the fire severity is such that the planned response is sufficient to control the fire at a specified intervention time (Ref. 68). Determination of the timing is based on three components (Ref. 69). The first is notification time. Second is the fire department response time, the time required for the fire department to reach the fire scene once an alarm has been received, referred to as the intervention time. The longer the notification and intervention times, the larger the fire will be at the start of fire suppression and the more difficult it will be to control. The final component is the rate at which the fire grows.

Commencement of fire suppression efforts requires a series of steps that are herein referred to as the response timeline:

1. The fire is detected.
2. The fire department dispatcher is notified.
3. The dispatcher notifies the appropriate Fire Company.
4. The Fire Company prepares to leave the fire station.
5. The fire response vehicle (company) leaves the fire station and travels to the operating area.
6. The fire response vehicle enters the operating area and travels to the fire location.
7. The Fire Company prepares to fight the fire.
8. The Fire Company establishes fire-fighting efforts.

In evaluating the above steps, there are many that the fire department can manage. Those that cannot be managed by the fire department are detection and reporting (Steps 1 and 2, respectively). This time delay between fire ignition and the transmittal of an alarm to the fire department dispatcher is the notification time (Ref. 70). The delays that can be managed by the fire department (Steps 3 through 8) are defined as the intervention time. (Managed implies that fire department staffing or equipment changes can modify the effectiveness of this activity.)

There are two other milestone times that must be considered when crediting fire department response. These are the suppression time and the extinguishment time. The suppression time is the time delay from fire ignition to the start of fire suppression efforts by the fire department. Extinguishment time is the time from fire ignition to when the fire is extinguished (i.e., no flame). See Figure 8 for a graphical representation of the response timeline.

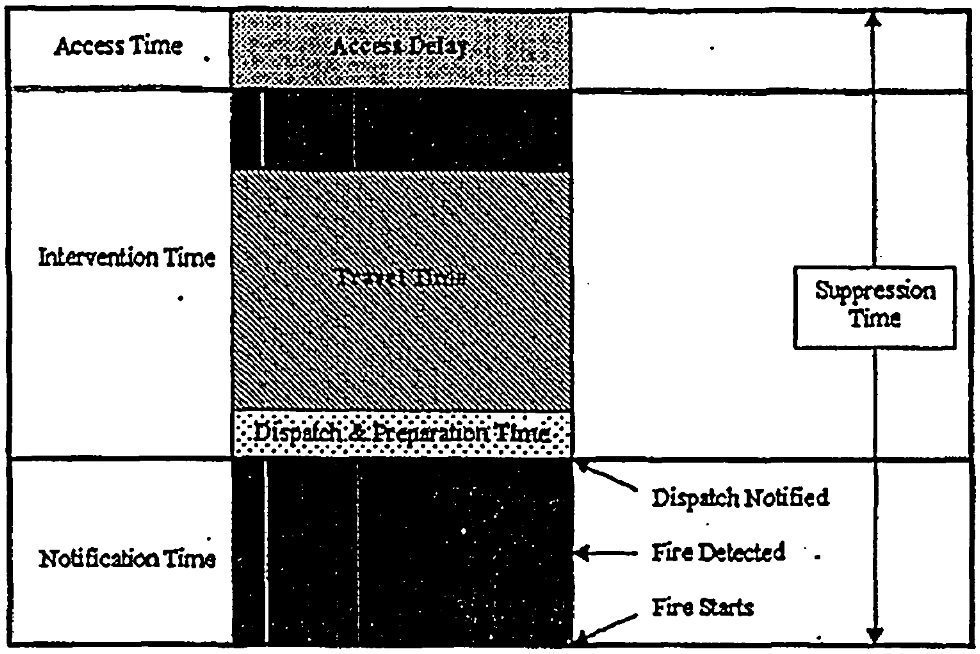

Figure 8--Response timeline

Notification Time

Delays associated with fire detection and alarm reporting can markedly increase the potential for a severe fire loss. A common rule-of-thumb is that the growth rate of an uncombated fire will double every 7 seconds during its early stages (Ref. 71). When fire detection is delayed, the fire is more intense at fire department arrival and may require additional manpower before effective fire fighting efforts can be initiated. Delays associated with the arrival of this additional manpower may further exasperate the fire loss.

The <u>notification time</u> is the delay between the start of flaming combustion to the notification of the SRSOC (i.e., Fire Department dispatcher). The notification time will vary considerably depending on the detection method. In general, the smallest notification times will be for alarms initiated by automatic fire detection, while longer times are expected where detection is accomplished by building occupants who must then notify the fire dispatcher. The longest times are attributed to fires that are detected by personnel who are outside the burning building.

The standard fire sprinkler will activate approximately 5 minutes after the initiation of the fire. Other detection methods are faster and slower than this, so 5 minutes is used as a best estimate for the notification time.

Intervention Time

The intervention time is the response time plus any facility specific activities that must be accomplished prior to initiating substantive fire fighting efforts. Activities that would be considered facility specific include the determination of the fire involvement and the

establishment of hose lays. An estimate of the intervention time must consider the expected strategy and tactics to be used.

The intervention time can best be estimated by considering the incremental steps that must be accomplished prior to initiating substantive fire fighting efforts. These incremental steps (Steps 3 through 8) are discussed below.

The dispatch time is the time necessary for the dispatcher to receive and process an alarm. The National Research Council of Canada (NRCC) has estimated that this time varies between 30 and 60 seconds (Ref. 70). This generic time is considered applicable for both automatic and manual alarms.

The preparation time is the time necessary for firefighters to receive notification from the dispatcher, don protective clothing and sit in the fire response vehicle (Ref. 70). Prior to the fire apparatus moving, all vehicle occupants must be seated and secured (Ref. 72). The NRCC suggests that this value can also vary from 30 to 60 seconds.

Travel time is the time delay between a fire response vehicle leaving the station and its arrival at the fire (Ref. 70). In evaluating the travel time the local operating restrictions and those established in NFPA 1500 (Ref. 72) must be considered (e.g., speed limits, full stops at stop signs, full stops at unguarded railroad grade crossings).

Set-up time is the time between fire department arrival and the fire department being ready to enter a building to begin fire suppression efforts. This time will vary depending on how the incident commander chooses to fight the fire. One method to obtain estimates of set-up time is to use the maximum acceptable evaluation times in NFPA 1410, *Standard on Training for Initial Fire Attack* (Ref. 34). For example if the fire department is assumed to establish a hose lay from the most appropriate fire hydrant to the pumper truck to reinforce the sprinkler system water supply, the NFPA recommended evaluation time is 3.5 minutes. If the nominal value were assumed to be 60 percent of the maximum, the estimated set-up time would be 2.1 minutes. NFPA 1410 provides a variety of potential attack arrangements.

Access Delays

There are many complications related to emergency entry into nuclear facilities. These include radiological hazards, chemical hazards and physical security equipment. These complications can delay the entry of the fire department into a building. Prior to entry into most nuclear facilities, a fire department must obtain permission from the Radiological Control Officer (RADCON). RADCON must determine if it is safe to enter the building based on the available contamination detection instrumentation. In many cases, fires are expected to create a false positive indication of a contamination release. Diagnosis of such a false positive indication will delay fire department entry.

Security forces must grant access where security doors must be opened to gain entry. This should impart a minimum delay unless the fire disables control systems or procedures are not adequately defined. If security related delays occur, entry times may be protracted.

Estimating P_T

Data for timing factors are assumed to be normally distributed (i.e., 95% of the data is within twice the standard deviation, σ, of the mean, μ, of the population). As such, the data can be represented by the probability density function for normal distribution:

$$(67)\quad P(t) = \frac{1}{\sqrt{2\pi\sigma}} e^{-(t-\mu)/2\sigma^2}$$

Figure 9 shows a typical fire department response probability density function.

The probability that a normally distributed random variable having a given mean and standard deviation lies in an interval can be calculated. It is the value of the cumulative normal distribution:

$$(68)\quad \frac{1}{\sqrt{2\pi\sigma}} \int_{-\infty}^{x} e^{-(t-\mu)^2/2\sigma^2} dt$$

Hence, the fire department response timeline and the fire timeline can be represented. Data for the mean and standard deviation for the timing factors is taken from Table 17.

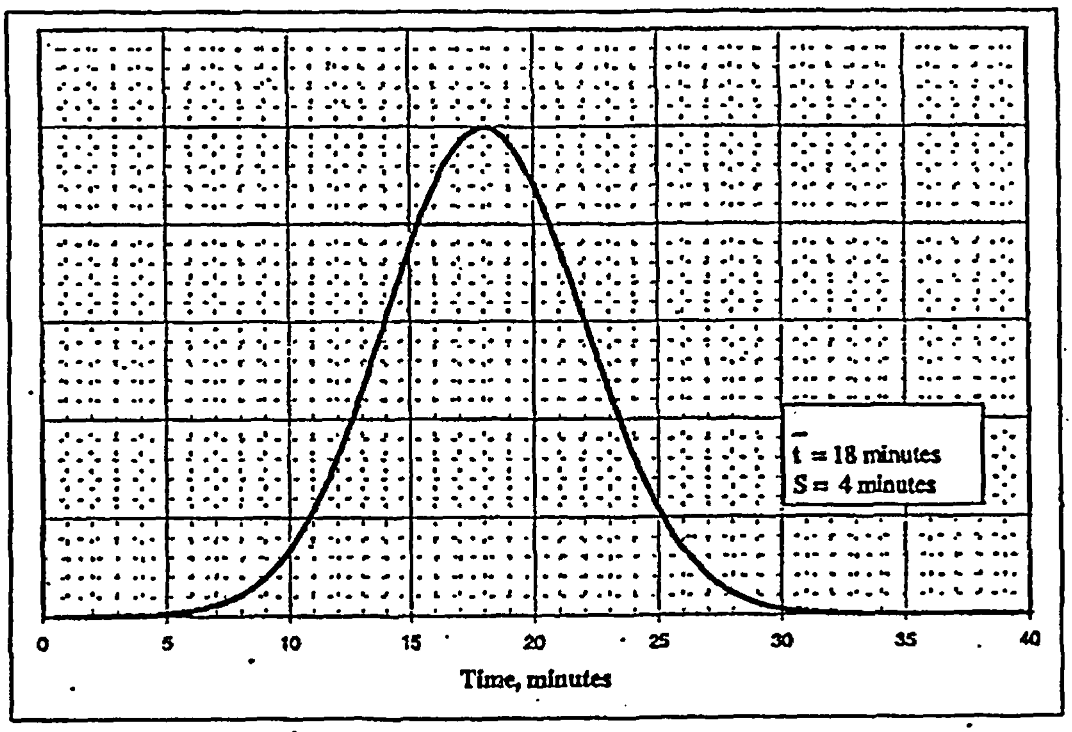

Figure 9–Fire department response probability diagram

Table 17--Fire department timing factor example values

	Activity	Time, minutes	
		Mean	Standard deviation
t_F	time to flashover or full-room involvement	5	2.4
t_P	time to propagation from a fully involved room to a second room	25	11
t_N	notification time	9	3.5
t_{FD}	fire department intervention time	9	2

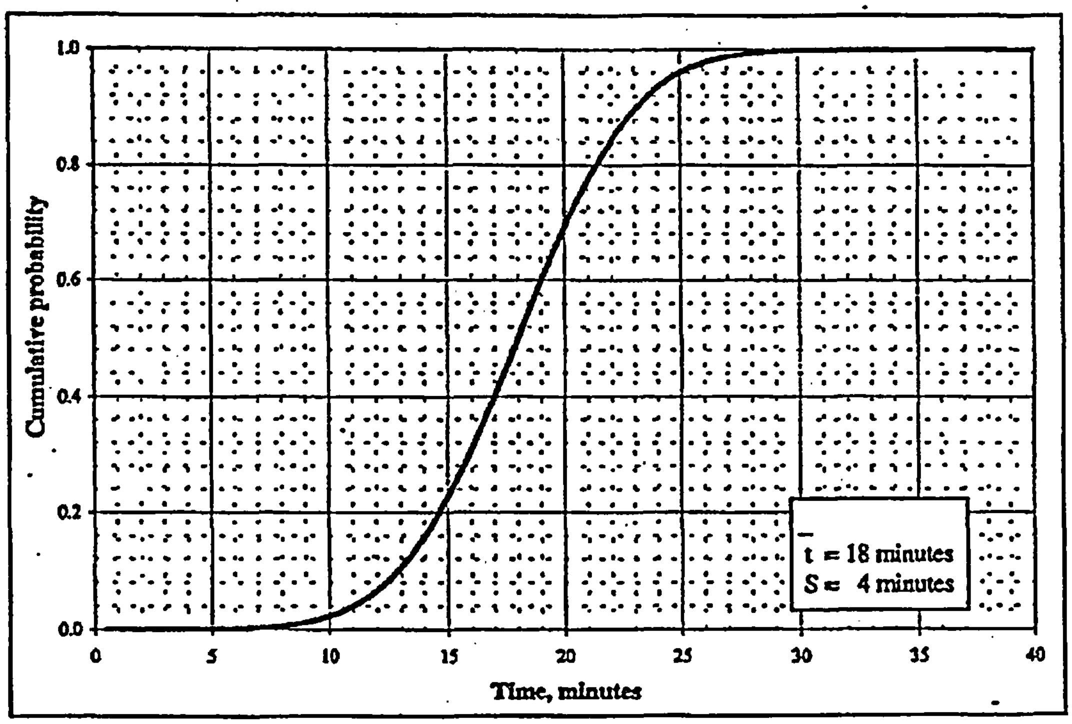

Figure 10--Cumulative probability fire department response timeline ($t_N + t_{FD}$)

The fire department response timeline, $t_{response\ timeline}$, can then be estimated using Equation (69) based on the mean and standard deviation of the expected response and considering the effects of notification time, t_N, and intervention time, t_{FD}, as previously discussed.

(69) $\bar{t}_{response\ timeline} = t_N + t_{FD}$

Figure 10 shows the cumulative probability diagram for the fire department response timeline.

The fire timeline, $t_{fire\ timeline}$, (critical threshold time) can also be estimated using Equation (70) based on the mean and standard deviation (Table 17) and considering the effects of time to flashover or full-room involvement, t_F, and time to propagation from a fully involved room to a second room, t_P.

(70) $t_{fire\ timeline} = t_F + t_P$

Figure 11 shows the cumulative probability diagram for two rooms being involved at a defined time.

When the fire department response timing, $t_{response\ timeline}$, is less than the critical threshold time, $t_{fire\ timeline}$, control of the fire is assumed to be feasible. Otherwise, fire department efforts are assumed to be ineffective.

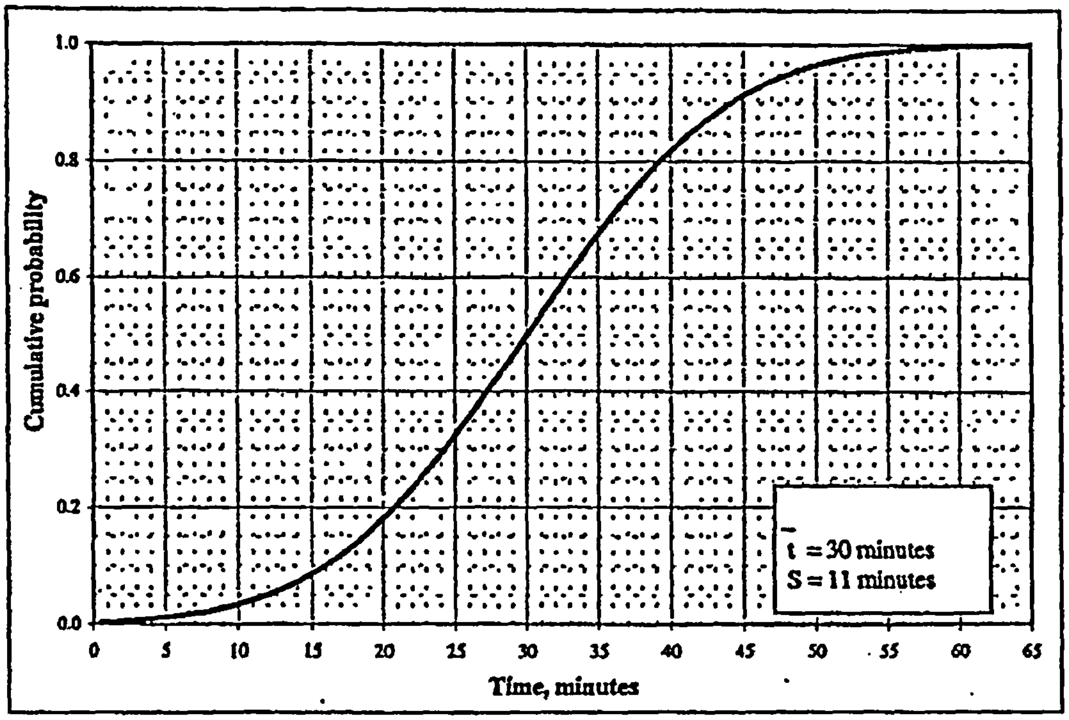

Figure 11--Cumulative probability fire timeline ($t_F + t_P$)

Combining the Results

To estimate the net timing factor, a comparison is made between the fire timeline and the fire department response timeline. The results of Figure 10and Figure 11 can be combined to form Figure 12 as follows. The net time to fire department intervention would be:

(71) $t_{net} = t_{fire\ timeline} - t_{response\ timeline}$

When t_{net} is positive, the fire department is able to control the fire. If t_{net} is negative, the fire department is considered to arrive with insufficient resources to control the fire. If the standard deviation for each time interval in Equations (69) and (70) were considered independent, then the standard deviation for the net time to fire department intervention would be:

(72) $S_{net} = \sqrt{S_F^{\ 2} + S_P^{\ 2} + S_N^{\ 2} + S_{FD}^{\ 2}}$

Since there is wide variability in the fire threshold timing, a probabilistic evaluation will be used. The likelihood that a fire will be greater than the fire department's capability to control it can be evaluated with the statistic:

$$(73)\quad Z_{fire} = \frac{t_{net}}{S_{net}} .$$

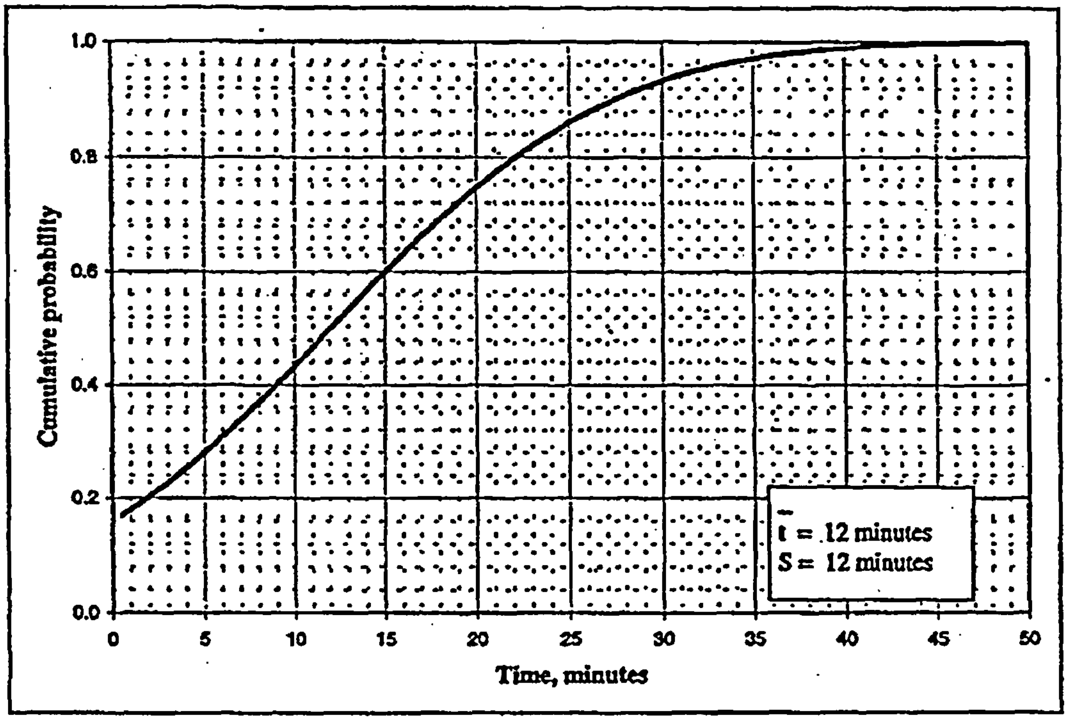

Figure 12--Cumulative probability fire timing factor

Example

Input for the sample problems is taken from Table 17.

$$\begin{aligned} t_{net} &= (t_F + t_P) - (t_N + t_{FD}) \\ &= (5\text{ minutes} + 25\text{ minutes}) - (9\text{ minutes} + 9\text{ minutes}) \\ &= 12\text{ minutes} \end{aligned}$$

$$\begin{aligned} S_{net} &= \sqrt{(S_F)^2 + (S_P)^2 + (S_N)^2 + (S_{FD})^2} \\ &= \sqrt{(24\text{minutes})^2 + (11\text{minutes})^2 + (3.5\text{minutes})^2 + (2\text{minutes})^2} \\ &= 12\text{minutes} \end{aligned}$$

From Equation (73), the z statistic is:

$$Z_{fire} = \frac{t_{net}}{S_{net}} = 1$$

This value corresponds to a likelihood of 0.84.

Figure 12 presents the solutions for the data in Table 17. The combination of this data results in a median net time of 12 minutes with a standard deviation of 12 minutes. From Figure 12 the probability that a fire will be more severe than the fire department can control is 0.16. Thus, the timing factor is 0.84.

Availability, P_A

Fire departments are not static support teams that await a single call. Typically, fire departments are very active and dynamic. Duties can include inspection, testing, maintenance and training in addition to emergency services. Thus, when crediting the fire department, the availability of response must be considered. Availability, as used in this manual, is the probability that the required fire fighting personnel and equipment are on site, in their response zone and not engaged in a previous emergency response. It should represent the fraction of time that a department can send an adequate response in a timely manner. The recommended availabilities for the SRS Fire Department are (Ref. 68):

- Two stations to a fire incident immediately after alarm receipt — 0.9
- Three stations to a fire incident (Note: This does not imply immediate dispatch of all three stations.) — 0.95

Reliability, P_R

Reliability represents the probability that a fire department can limit fire damage to a defined area given that sufficient personnel and equipment are available and the intervention effort is timely as defined above. Table 18 provides a range of success values from the indicated literature. There are significant variations in the literature, so the actual reliability value used should be location specific. In general it is doubtful that the reliability value should be greater than 0.9, except for the most simple of fires.

Table 18--Fire department reliability

Description	Benhardt, et.al.	Berry & Minor
Simple fire	0.97	---
Fixed manual extinguishing system installed in space under consideration but manual controlled from outside immediate fire area	---	0.7
Intervention in less than 3 minutes	---	0.5
Intervention in less than 10 minutes	0.9	0.4
Intervention in greater than 10 minutes	0.7	0.3

The recommend reliabilities for suppression by the SRS Fire Department that are presented in Table 19 were extrapolated from Table 18. The minimum fire department response requirements in Table 19 account for other demands and commitments (e.g., occupant rescue) that are encountered at a typical fire scene. They do not imply that suppression efforts will be delayed until the stated minimum response arrives.

Table 19--Recommended fire department reliabilities

Fire description	Complicating factors	Require response (# stations)	Probability of success
Incipient fire		1	0.97
Room fire	none	2	0.9
	difficult access	2	0.7
	special hazards	2	0.7
2 Room fire	none	3	0.7
(< 800 ft^2, < 74 m^2)	difficult access	3	0.7
	special hazards	3	0.5
Multi-room fire	none	3	0.7
	difficult access	All call	0.5
	special hazards	All call	0.5
Fire wall support	none	2	0.9
	difficult access	3	0.5
	special hazards	3	0.5
Exposure fires	light	1	0.999
	moderate	2	0.99
	severe	3	0.9

Effectiveness

There are recommended default values for *Fire Department Controls Fire ($P_{32,1}$ and $P_{43,1}$)* in common situations. These are:

- The generic values used in the event trees (with the exception of vaults) are summarized below in Table 20.
- If the fire department is not expected on-scene during the zone stage, then $P_{32,1}$ is set to zero.
- Fire severities requiring off-site or all-call responses are assumed to be fire department failures in safety analyses hence $P_{32,1}$ and $P_{43,1}$ are set to zero. This assumption simplifies the analysis and avoids the need for functional classification evaluation of non-SRS personnel.

Table 20--Fire department effectiveness

Fire description	Complicating factors	Reliability	Availability	Timing	Effectiveness
Incipient fire		0.97	0.96	0.02	0.02
Room fire	None	0.9	0.96	0.91	0.8
	difficult access	0.7	0.96	0.91	0.6
	special hazards	0.7	0.96	0.91	0.6
2 Room fire	None	0.7	0.96	0.91	0.6
	difficult access	0.7	0.96	0.91	0.6
	special hazards	0.5	0.96	0.91	0.4
Multi-room fire	none	0.7	0.96	0.97	0.7
	difficult access	0.5	0.96	0.97	0.5
	special hazards	0.5	0.96	0.97	0.5
Exposure fires	light	0.999	0.96	0.99	0.95
	moderate	0.99	0.96	0.99	0.9
	severe	0.9	0.96	0.99	0.9
	extreme	0.7	0.96	0.99	0.7

Notification of Fire Department by Area Personnel ($P_{42,1}$)

Occupant detection ($P_{11,1}$) is credited during the incipient stage of the fire. This detection mode is based on the percentage of time that a location where a fire could initiate is occupied. To account for detection during growth, zone and area fires, a second personnel detection event is included in the event tree. This event considers the combined detection success by facility occupants, security patrols, random visitors, and facility non-occupants near the involved building. Notification of the fire department by these people is assumed to occur after flashover (or other full room involvement mechanisms).

For most locations at SRS the recommended value is 0.9. This aligns with the nominal value for manual fire detection proposed by Benhardt, et. al. (Ref. 41) based on site specific data.

For a location that is highly visible and where the fire is expected to readily vent though a window or roof, a value of 0.95 is recommended.

For inactive buildings where there are few passersby the detection value will vary between 0 and 0.5. The higher value equates to the low success value for manual fire detection probability by Benhardt, et. al. (Ref. 41) based on site specific data.

The evaluation presented above is dependent on assumptions (prerequisites) as stated in Appendix B.

COMBINING THE RESULTS

As previously discussed the typical FRA considers both the consequence and the frequency of a fire-induced release. When the preliminary consequence estimates are available, it is possible to estimate the frequency that these consequences will be exceeded. The sequence of producing these estimates is presented in Figure 4, however this figure can not convey the analyst's insight necessary to coordinate the consequence and frequency estimates.

The first step in conducting the FRA is to section the facility into fire areas. Usually this is based on the Fire Hazards Analysis. These areas are defined by fire rated walls and barriers where the rating is 2 hours or greater. If the fire area is not uniform (e.g., partial sprinkler system, uneven combustible loading) then it may be prudent to subdivide the fire area into fire zones. Further subdivision to the room level may be appropriate in some situations. Experience has demonstrated that a very coarse subdivision (only fire areas) leads to estimates that are conservative but sometimes overly restrictive. Excessive subdivision results in additional work, with little change in the stated risk. Thus, there is an optimum selection of fire areas, zones and rooms to evaluate. Identifying the optimum level is a trial-and-error process in selecting which areas, zones and rooms must be individually evaluated.

Once the facility and its fire exposures are subdivided, it is possible to establish the consequences for each subdivision should that subdivision become involved in a severe fire. It is then possible to identify which combinations of zones might become involved in the same fire and subsequently exceed the risk goals. It is then necessary to estimate the frequency that these areas would become involved in the same fire using the techniques presented earlier. A frequency estimate must be prepared for each subdivision (fire area, fire zone or room). Where there are multiple combinations of subdivisions that would exceed the risk goal for a fire starting in a specific subdivision, the higher frequency event should be carried forward. This approach is warranted since usually one specific combination dominates the frequency. If there are two combinations that have similar frequency it may be prudent to modify the highest frequency combination estimate slightly. This can be accomplished by combining the two frequencies together. This can be accomplished arithmetically, although this approach is very conservative; or by a root-sum-square approach. The latter approach, which results in a slightly lower value, accounts for the intersection of the two frequency estimates, which are both initiated by the same event.

Table 21 presents a typical fire risk table where radiological material is located in zones 201 and 301. To determine the frequency that the consequences, as determined for zones 201 and 301, are exceeded, the frequency calculations for fires that initiate in all zones and propagate to zones 201 and 301 are summed. Hence, the frequency for fires that generate the specified consequence for zones 201 and 301 is 1.0E-03 fires/year.

Table 21--Typical fire risk table

Fire starts in zone:	Propagates to zone:	Fire Magnitude	Reference event tree	Frequency (fires/yr)	Ratio of total frequency
101	201 or 301	Level 3	B-1	5.0E-05	0.05
102	201 or 301	Level 3	B-2	3.0E-05	0.03
201	201	> growth	B-3	6.0E-04	0.56
301	301	> growth	B-4	4.0E-04	0.37
Total				1.0E-03	

CONCLUSIONS

The SRS Fire Risk Analysis Methodology has been consolidated into one document. This method includes a comprehensive method to evaluate the fire hazards present in a facility. This includes fires initiated by seismic events, lightning, wildland fires, as well as randomly occurring industrial fires. The report provides a comprehensive approach to estimate the consequences from any fire and the to estimate the frequency of industrial fires. The techniques presented conform with the best practices established in DOE-STD-3009-94 (Ref. 1).

A standardized treatment for evaluating the fire hazards has been proposed. This method provides a consistent approach that avoids the perception of inconsistencies between the facility SAR and Fire Hazard Analysis. By properly categorizing the fire events, rework that has been observed in previous SAR development efforts should be avoided.

The most current fire protection techniques and methods have been integrated into the fire consequence estimate techniques. These techniques build on the concept of fuel packages that burn with a known heat release rate. Engineering-based methods have been proposed to evaluate the temperature and fire severity of compartment fires. These build on proven correlations. Solutions techniques are proposed to address the variability that occurs in most fire protection problems (e.g. ventilation, combustible loading).

The fire frequency estimates are based on a generic event tree that accounts for building occupant intervention, automatic detection systems, combustible loading controls, automatic suppression systems, fire department response, and fire barriers. The initiating frequency is based on site specific fire data. The event probabilities are based on a mix of site specific, industry, and general fire loss data.

The industrial fire risk is quantified by estimating the frequency of exceeding specific radiological doses. The frequency of exceeding the specified dose is then evaluated based on the SRS Evaluation Guidelines, which are established in WSRC 11Q (Ref. 13).

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APPENDIX A, DEFINITIONS

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DEFINITIONS

General

Autoignition Temperature. - The autoignition temperature is the minimum temperature of a substance, which will initiate or cause self-sustained combustion independently of any sparks or other means of ignition. (Ref. 73).

Consequence- the resulting harm from a postulated event

Controls- Administrative programs, and structures, systems, & components designed to reduce the risk

Fire Area- Normally implies the existence of fire rated construction (commonly rated at better than 2 hours). The fire rated construction separates a building into Fire Areas that are anticipated to not become involved in the same fire event. When the fire rated construction and the responding fire department fail to respond as intended, propagation between fire areas has occurred.

Fire Compartment- A fire compartment is a single room that can confine the fire for a finite amount of time. The walls of the compartment may or may not be rated.

Fire Levels- In presenting the frequency results, it is necessary to combine different fire magnitudes of similar radiological consequences. (e.g., A room fire, where a substantial amount of radiological inventory is located, has a similar consequence to a multi-room fire that must propagate to the same high-inventory room.) To facilitate the analysis, Fire Levels have been defined. These levels are related to the number of fire resistive barriers that are breached. *Note: The terms Level 1, Level 2 and Level 3 fires are specific to each FRA.* As a fire expands it will encounter several barriers (walls, floors, doors, etc.) that impede propagation. The first set of barriers is the light walls that surround the compartment (room of fire origin). When the fire has propagated out of the compartment, a Level 1 fire has occurred. When two fire barriers (or equivalent) have been breached, a Level 2 fire is considered to exist. The limitations on the expansion of a fire during this stage are the defined fire barriers (as established in the facility FHA) and fire department intervention. If a fire extends beyond the Level 2 stage (i.e., three or more barriers fail) a Level 3 fire is considered to occur.

Fire Zones- Fire zones are subsets of Fire Areas. Fire Zones imply non-fire rated construction, or fire rated construction of less than 2 hours. Typically within a FRA, a group of rooms might be defined as a Fire Zone.

Frequency- likelihood of an event occurring (yr^{-1})

Harm. physical injury or damage

Hazard. A potential source of harm or a source of danger with the potential to cause [harm].

Mitigative features- controls that reduce the harm

Preventative features. controls that are designed to prevent the release of material during an accident

Probability. likelihood of an outcome (between 0 and 1)

Pyrophoric. A chemical with an autoignition temperature in air at or below 130°F (54.4°C). (Ref. 74)

Residual risk- risk remaining after protective measures have been taken (see Figure 1) (Ref. 75).

Risk- a combination of probability of occurrence to harm and the severity of that harm

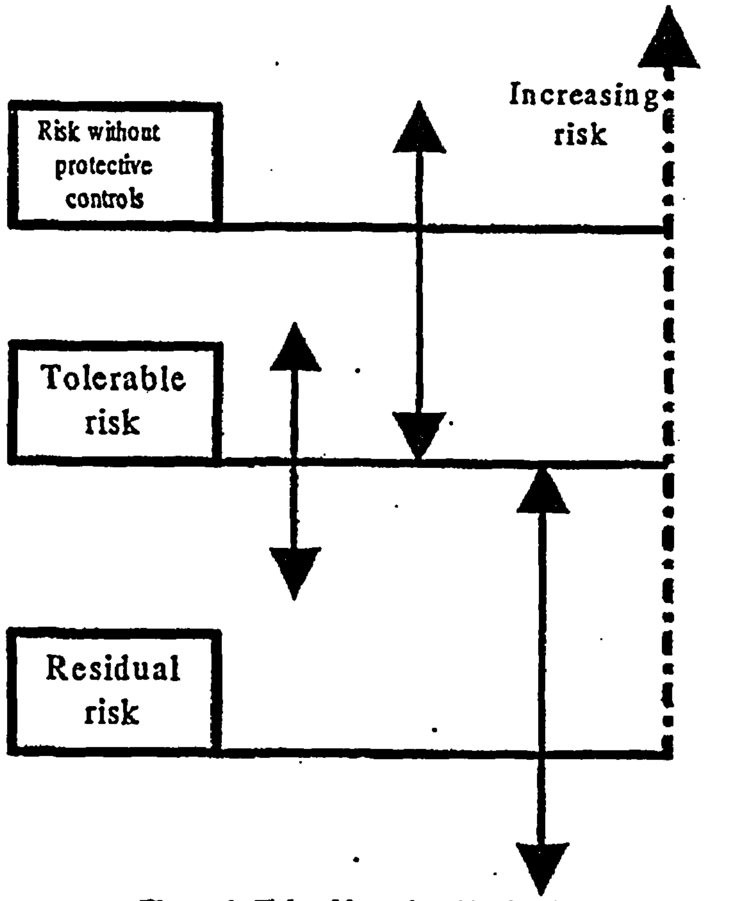

Figure 1–Tolerable and residual risk

Risk- The ... expression of possible loss that considers both the probability that an event will occur and the consequence of that event. (Ref. 1).

Risk- the combination of the consequence and frequency of an event

Severe Fires- Severe fires are assumed to always begin as a small fire. The small fire will grow through several stages, thus propagating into a severe fire. Historic instances where the event appears to start as a "large fire" can usually be traced to the ignition of one item followed by very rapid fire propagation.

Tolerable risk- risk which is accepted in a given context based on the current values of society (see Figure 1)

Construction Materials

Non-combustible – "A material that, in the form in which it is used and under the conditions anticipated, will not ignite, burn, support combustion, or release flammable vapors when subjected to fire or heat. Materials that are reported as passing ASTM E 136, Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C, shall be considered noncombustible materials."(Ref. 76).

Limited-combustible – "A building construction material not complying with the definition of noncombustible material that, in the form in which it is used, has a potential heat value not exceeding 3500 Btu/lb (8141 kJ/kg), where tested in accordance with NFPA 259 (Ref. 77), Standard Test Method for Potential Heat of Building Materials, and complies with (a) or (b): (a) Materials having a structural base of noncombustible material, with a surfacing not exceeding a thickness of 1/8 in. (3.2 mm) that has a flame spread index not greater than 50; and (b) Materials, in the form and thickness used, other than as described in (a), having neither a flame spread index greater than 25 nor evidence of continued progressive combustion and of such composition that surfaces that would be exposed by cutting through the material on any plane would have neither a flame spread index greater than 25 nor evidence of continued progressive combustion. (Materials subject to increase in combustibility or flame spread index beyond the limits herein established through the effects of age, moisture, or other atmospheric condition shall be considered combustible.)"(Ref. 76).

Combustible – A material that is neither noncombustible nor limited-combustible.

Liquids and Gases

Combustible Liquid – "A combustible liquid shall be defined as any liquid that has a closed-cup flash point at or above 100°F (37.8°C)" (Ref. 22). They are further subdivided into Class II, IIIA, and IIIB by flash point.

Flammable Compressed Gas. Any flammable gas that has been compressed, liquefied, or compressed and liquefied for the purpose of transportation and has a Reid vapor pressure exceeding 40 psia (2.76E05 Pa) (Ref. 78)

Flammable Gas. A gas that is flammable at atmospheric temperature and pressure in a mixture of 13 percent or less (by volume) with air, or that has a flammable range with air wider than 12 percent, regardless of the lower limit.(Ref. 79)

A gas that will burn in air (Ref. 80)

Any substance that exists in the gaseous state at normal atmospheric temperature and pressure and is capable of being ignited and burned when mixed with proper proportion of air, oxygen, or other oxidizers. (From NFPA 326, Standard Procedures for the Safe Entry of Underground Storage Tanks.)(Ref. 81).

Flammable Liquid. "Any liquid that has a closed-cup flash point below 100°F (37.8°C)" (Ref. 22). Such liquids are considered as Class I liquids.. They are further subdivided by the flash point.

Flammable Vapor. Any substance that exists in the gaseous state at normal atmospheric temperature and pressure and that is capable of being ignited and burned when mixed with the proper proportions of air, oxygen, or other oxidizer (Ref. 82).

Flashpoint- the lowest liquid temperature that produces adequate vapors to allow ignition in the presence of an ignition source

Nonflammable Gas. A gas that does not meet the definition of a flammable gas (Ref. 79).

Oxidizing Gas. A gas that can support and accelerate combustion of other materials (Ref. 79).

Pyrophoric Gas. A gas that will spontaneously ignite in air at or below a temperature of 130°F (54.4°C) (Ref. 79).

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APPENDIX B, ASSUMPTIONS

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ASSUMPTIONS

This section provides a summary of the assumptions and features that must be protected to ensure the adequacy of the analysis. In some cases an assumption or feature is credited for more than one protective feature (e.g., combustible control program, fire department, etc.). In addition, some of the assumption must be customized to the facility. Where this is necessary a blank is left for the user to complete.

Severity and Consequence Analysis

Combustible Control Program

Overall amount of combustibles (pounds of wood equivalent) does not exceed ___________ psf.

The localized combustible loading (pounds of wood equivalent) does not exceed ___________ psf.

The heat release rate from any individual fuel package does not exceed ___________ kW.

The total ventilation opening area does not exceed _________ ft^2.

The room construction is ____.

Hazards

The radiological inventory is ____.

Frequency

Incipient Fire Frequencies ($P_{00,1}$)

A housekeeping program exists that prevents the accumulation of excessive clutter, damaged electrical equipment, and similar hazards. (i.e., The condition of the facility must be managed and controlled.)

Hot work activities (cutting, welding, grinding, etc.) are controlled by a written procedure.

The electrical systems in the building are maintained to NFPA 70 (Ref. 83).

The piping that contains flammable liquids, combustible liquids and flammable gases is maintained to the applicable NFPA codes and standards.

Occupant Detection ($P_{11,1}$)

The effective occupied time for areas that are only subject to routine inspection/patrols is 5 minutes per inspection/patrol. This is the fire development time for a medium growth fire, which produces 1055 kW in 5 minutes.

Facility Occupant Controls Fire ($P_{12,1}$)

Facility occupants are provided with basic fire extinguisher training (GET training).

Facility occupants are instructed that they may attempt to extinguish a fire after they have notified emergency services personnel (GET training).

Alarm System Detects Fire ($P_{13,1}$)

Fire alarm systems are maintained to the requirements of NFPA 72 (Ref. 45).

Fire alarm systems are connected to the Site Fire Alarm Reporting System.

The probability of successful alarm receipt using the Site Fire Alarm Reporting System (people and equipment) is 0.995 (Ref. 5).

Facility Responder Controls Fire ($P_{14,1}$)

Facility occupants are provided with basic fire extinguisher training (GET training).

Facility occupants are instructed that they may attempt to extinguish a fire after they have notified emergency services personnel (GET training).

Fire Does Not Propagate ($P_{15,1}$)

General

The effective incipient fire duration is 180 seconds. This is the duration of peak energy release for many fuel packages in SRS facilities (Ref. 5). A longer time will increase the probability that the fire propagates, however this would be offset by an increased potential for occupant fire detection. Fires that do not readily propagate are extinguished by facility personnel or the fire department, or self extinguish prior to significant damage occurring.

The majority of combustible materials in SRS facilities are characterized as having either a low or medium PHRR. (This requirement must be customized to the facility being analyzed.)

The overall amount of combustibles and the localized combustible loading does not exceed predetermined loading requirements. Transient materials introduced by routine maintenance and operational activities have been considered in the localized loading and subsequently in the frequency and consequence calculations. The effects of transient material from special maintenance and operational activities (remodeling, major spill cleanup, etc.) have not been considered.

Easy-to-ignite items (i.e., trash) are not usually found in the vicinity of medium or high PHRR items. (This requirement must be customized to the facility being analyzed.)

The ease-of-ignition and PHRR material classifications do not change significantly with the age of the material.

In some cases, the existing housekeeping standards limit the combustibles such that they are within the assumed values of the calculation. However, it may be necessary to evaluate if the housekeeping standards need to be protected as an administrative program.

Occupant Suppression

Facility occupants are provided with basic fire extinguisher training (GET training).

Facility occupants are instructed that they may attempt to extinguish a fire after they have notified emergency services personnel (GET training).

Fire Department Response

SRS maintains a fire department that allows a multi-company fire response with approximately 16 responders.

SRS maintains a fire dispatch service that notifies the fire department of alarms occurring at SRS (e.g., transmitted by automatic signal, telephone, radio, etc).

For nuclear facilities, both facility and site procedures ensure that RADCON personnel are at the facility prior to the arrival of the fire department. (Permission from RADCON is considered a requirement prior to an interior structural fire attack.)

Early Suppression System Success Probability ($P_{16,1}$)

All fire alarm systems are maintained to the requirements of NFPA 72.

Combustible Control Procedure

The amount and types of combustibles in the protected rooms do not exceed the suppression system's ability to control a fire.

Fire Department Response

All fire alarm systems are connected to the Site Fire Alarm Reporting System.

The probability of successful alarm receipt using the Site Fire Alarm Reporting System (people and equipment) is 0.995(Ref. 5).

An alarm indicating system activation or fire detection must be transmitted to a continuously monitored location, such that a fire fighting response can be initiated. This should include both the facility central control room and the central fire alarm headquarters.

Facility procedures will permit fire fighters to enter the building after a suppression system is activated (facility and RADCON personnel will provide permission for the fire department to enter the facility, security door locking does not prevent facility re-entry, etc).

For nuclear facilities, both facility and site procedures ensure that RADCON personnel are at the facility prior to the arrival of the fire department. (Permission from RADCON is considered a requirement prior to an interior structural fire attack.)

Halon Systems

All halon suppression systems are maintained to the requirements of NFPA 12A (Ref. 48).

Facility personnel that evaluate the effects of potential facility modifications are acquainted with the theory of halon systems and the potential negative effects of enclosure modifications.

Facility personnel are aware that open doors can prevent halon systems from successfully controlling a fire.

Water Spray Systems

All water spray suppression systems are compliant with NFPA 15 (Ref. 50) and maintained to the requirements of NFPA 25 (Ref. 51).

Open Sprinkler Deluge Systems

All open sprinkler deluge systems are compliant with NFPA 13 (Ref. 53) and maintained to the requirements of NFPA 25 (Ref. 51).

Sprinkler System Controls Fire ($P_{21,1}$)

Sprinkler suppression systems are maintained to the requirements of NFPA 25.

All fire alarm systems that are associated with the sprinkler systems are maintained to the requirements of NFPA 72 (Ref. 45).

The amount and type of combustibles in the protected rooms do not exceed the sprinkler system's ability to control a fire.

Fire Department Response

SRS maintains a fire department that allows a multi-company fire response with approximately 16 responders.

SRS maintains a fire dispatch service that notifies the fire department of alarms occurring on the Site Fire Alarm System.

For nuclear facilities, both facility and site procedures ensure that RADCON personnel are at the facility prior to the arrival of the fire department. (Permission from RADCON is considered a requirement prior to an interior structural fire attack.)

Facility procedures will permit fire fighters to enter the building after a sprinkler system is activated (facility and RADCON personnel will provide permission for the fire department to enter the facility, security door locking will not prevent facility reentry, etc.).

Alarm System Notifies Fire Department ($P_{22,1}$)

The probability of successful alarm receipt using the Site Fire Alarm Reporting System (people and equipment) is 0.995 (Ref. 5).

Fire Barriers ($P_{31,1}$ and $P_{41,1}$)

The wearout probability is a function of both fire barrier rating and combustible loading. Note that the term fire barrier rating does not necessarily imply that the barrier be qualified as a fully compliant barrier (see discussion on barrier quality factor as discussed under effectiveness of fire barriers). Fire barrier ratings are protected by configuration management and combustible loading is protected by combustible control procedures. The rigor associated with protection of fire barriers is directly proportional to the protective credit provided by the barrier.

- Configuration management ensures that modifications are properly evaluated prior to incorporation of any modifications.

- Combustible control procedure ensures that the overall amount of combustibles and the localized combustible loading does not exceed predetermined loading requirements.

Fire Department Response

SRS maintains a fire department that allows a multi-company fire response with approximately 16 responders.

SRS maintains a fire dispatch service that notifies the fire department of alarms occurring on the Site Fire Alarm System.

For nuclear facilities, both facility and site procedures ensure that RADCON personnel are at the facility prior to the arrival of the fire department. (Permission from RADCON is considered a requirement prior to an interior structural fire attack.)

Fire Department Controls Fire ($P_{32,1}$ and $P_{43,1}$)

Preplanning and Procedural Controls

The SRS Fire Department (SRSFD) Baseline Needs Assessment (BNA) (Ref. 84) analyzes a representative set of significant fire scenarios that reasonably could occur at SRS. This assessment establishes the appropriate number and qualifications of on duty response personnel and apparatus, predicted and maximum acceptable response times and use of the SRSFD All-Call system and mutual aid for additional resources. SRSFD operational commitments related to the BNA are established in WSRC Manuals 2Q (Ref. 85) and 2Q2 (Ref. 86).

The Fire Control Preplan documents address facility layout, process and material hazards, installed fire protection equipment, some tactical considerations, and facility points of contact.

The specific dispatch protocol is established in accordance with Savannah River Site Operations Center (SRSOC) procedures, which ensure that an appropriate minimum response is dispatched on all alarms. SRSOC procedures also establish the protocols for follow-up responses and activation of the SRSFD All-Call system and mutual aid.

SRS maintains a fire dispatch service that notifies the fire department of alarms occurring on the Site Fire Alarm Reporting System.

The probability of successful alarm receipt using the Site Fire Alarm Reporting System (people and equipment) is 0.995 (Ref. 5).

A housekeeping program is maintained such that the fire department can enter the building.

Security procedures are maintained such that the fire department is allowed to enter the building.

For nuclear facilities, both facility and site procedures ensure that RADCON personnel are at the fire scene to assist the Fire Department during a severe fire. The timing of RADCON arrival must be prior to the end of the intervention time. (Permission from RADCON is considered a requirement prior to an interior structural fire attack.)

Fire Department Tactical Capability

SRS maintains a fire department that allows a multi-company fire response with approximately 16 responders (Ref. 84).

Fire Timing

Fire detection is assumed to occur 5 minutes after ignition. (An early warning fire detection system would reduce this time.) Very late detection times are considered failures to detect the fire and are handled in other events.

The [variability] of fire development times are represented using a normal (gaussian) distribution (Ref. 87). While the variability can be represented by many different distributions, the overall fire risk results are not considered to be significantly affected by this assumption.

The variability of the response timing is much less than that of the fire development timing, thus it can be neglected with minimum effect on the overall results.

The combustible loading, fuel form and building arrangement are assumed to allow the fire to burn indefinitely (e.g., the fire does not burn itself out) (Ref. 87). Fire burnout is addressed in the probability terms for Fire Does Not Propagate ($P_{15,1}$) and Fire Barriers ($P_{31,1}$ and $P_{41,1}$).

Notification of Fire Department by Area Personnel ($P_{42,1}$)

SRS maintains a fire dispatch service that notifies the fire department of alarms occurring on the Site Fire Alarm Reporting System.

The probability of successful alarm receipt using the Site Fire Alarm Reporting System (people and equipment) is 0.995 (Ref. 5).

Programs with Multiple Impacts

In some cases, an assumption or feature is credited for more than one protective feature (e.g., combustible control program, fire department, etc.). These programs are summarized below and the credits affected by the existence of the program are identified.

Combustible Control Program

Combustible control programs directly impact the severity analysis of the fire. In addition, credits within the frequency analysis that are affected by existence of this program are:

Fire Does Not Propagate ($P_{15,1}$)

Early Suppression System Success Probability ($P_{16,1}$)

Sprinkler System Controls Fire ($P_{21,1}$)

Fire Barriers($P_{31,1}$ and $P_{41,1}$)

Housekeeping Program

Credits within the frequency analysis that are affected by existence of this program are:

Incipient Fire Frequencies ($P_{00,1}$)

Fire Does Not Propagate ($P_{15,1}$)

Fire Department Controls Fire ($P_{32,1}$ and $P_{43,1}$)

GET Training

Credits within the frequency analysis that are affected by existence of this program are:

Fire Does Not Propagate ($P_{12,1}$)

Facility Responder Controls Fire ($P_{14,1}$)

Fire Does Not Propagate ($P_{15,1}$)

Fire Department Response

Credits within the frequency analysis that are affected by existence of this program are:

Fire Does Not Propagate ($P_{15,1}$)

Early Suppression System Success Probability ($P_{16,1}$)

Fire Barriers($P_{31,1}$ and $P_{41,1}$)

Fire Department Controls Fire ($P_{32,1}$ and $P_{43,1}$)

Site Fire Alarm Reporting Systems

Credits within the frequency analysis that are affected by existence of this program are:

Alarm System Detects Fire ($P_{13,1}$)

Early Suppression System Success Probability ($P_{16,1}$)

Alarm System Notifies Fire Department ($P_{22,1}$)

Fire Department Controls Fire ($P_{32,1}$ and $P_{43,1}$)

Notification of Fire Department by Area Personnel ($P_{42,1}$)

RADCON Procedures

Credits within the frequency analysis that are affected by existence of this program are:

Fire Does Not Propagate ($P_{15,1}$)

Early Suppression System Success Probability ($P_{16,1}$)

Sprinkler System Controls Fire ($P_{21,1}$)

Fire Barriers($P_{31,1}$ and $P_{41,1}$)

Fire Department Controls Fire ($P_{32,1}$ and $P_{43,1}$)

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APPENDIX C, AUTOMATIC SPRINKLER SYSTEM RELIABILITY

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Automatic Sprinkler System Reliability
Special Study to Support Building 773-A FRA

D. Allan Coutts

Abstract

Automatic sprinkler systems are a key component in a comprehensive fire protection program. These systems have been demonstrated to be highly effective in reducing fire deaths, injuries and property losses. When they don't perform as designed, the results can be catastrophic. Increasingly building codes are reducing prescriptive design requirements where automatic sprinklers are installed. As more reliance is placed on sprinkler systems, risk associated with sprinkler system failure increases.

This paper quantitatively estimates the reliability of automatic sprinkler systems. In addition to quantifying the probability of sprinkler system success, the paper evaluates potential techniques that can be used to increase sprinkler system reliability.

Introduction

The National Fire Protection Association (NFPA) tracked the performance of automatic sprinkler systems from 1897 to 1970[1,2]. This data demonstrates that the fire risk in buildings equipped with automatic suppression systems is significantly lower than that in a comparable unprotected building. Because of this high effectiveness building codes often relax prescriptive requirements (i.e., maximum travel distances) in fully sprinklered buildings. As the reliance on automatic suppression systems increases, the risk associated with system failure must be recognized. To allow this risk to be quantified, sprinkler system reliability must be estimated.

Reliability, as used in this paper, is the measure that a sprinkler system is available to operate and functions as designed. A sprinkler system is considered to function as designed if it is able to flow water of sufficient quantity to control or extinguish a fire without excessive fire spread. The reliability estimates in this paper do not imply the extent of fire damage or the number of sprinkler heads that will open. A system is considered available whenever there is an expectation by the building manager that the system will function on demand. Thus, the system is unavailable only during testing, unplanned maintenance, preventive maintenance and planned modifications. In addition, this paper does not deal with the complexities of preaction systems (e.g., detection system failure, preaction valve, etc.)

Operating Data

Sprinkler system operating data is available from many sources. In addition to the data published by NFPA, extensive evaluation of Australia and New Zealand[3] and Department of Energy (DOE)[4] fire loss records have been published. (See Table 22.) The success probabilities from these reviews range from 0.96 to 0.99. Table 22 includes selected data from industrial and educational occupancies as published by the NFPA.

Table 22--Sprinkler system performance

Description	Years	Reference	Success probability
United States			
all fires	1897-1924	1	0.958
all fires	1925-1969	1	0.962
all fires	1965-1969	1	0.957
industrial - textiles	1925-1969	1	0.982
industrial - total	1925-1969	1	0.965
educational	1925-1969	1	0.917
U.S. DOE	1952-1980	4	0.983
Australia and New Zealand			
	1886-1968	3	0.991
	1886-1986	3	

The highest observed success probability in the NFPA study was for the textile industry. This was attributed to experience of the textile industry with sprinklers, strong management support and complete coverage. With the exception of other occupancies (A category that includes abandoned buildings.) the poorest sprinkler performance was observed in educational occupancies. This value, 0.917, was attributed primarily to incomplete sprinkler system coverage.

Other Data

In addition to the data in Table 22, Melinck[5] published 1987 United Kingdom data for industrial and commercial buildings. (See Table 23.) The success probability of a sprinkler system to control or extinguish a fire based on this data is:

$$(1) \quad P = \frac{169 \text{ extinguished} + 347 \text{ controlled}}{1{,}354 \text{ total} - 658 \text{ too small}} = 0.74$$

A review of 1966 though 1972 indicated that perhaps 82 percent of fires in sprinklered buildings are not reported because they are controlled or extinguished by the suppression system[5]. Using this information it is possible to adjust the data in Table 23 to account for unreported fires. This correction is distributed equally between the extinguished fire controlled fire results.

$$(2) \quad N_{unreported} = (0.82)(1{,}354 \text{ fires}) = 1110 \text{ fires}$$

The success probability for suppression systems based on the corrected data is thus:

$$(3) \quad P = \frac{724 \text{ extinguished} + 902 \text{ controlled}}{2464 \text{ total} - 658 \text{ too small}} = 0.90$$

Harvey[6] recommends a range of values for sprinkler system success from 0.85 to 0.98 with a extreme upper bound of 0.985. This is consistent with the NFPA and DOE data presented

in Table 22 and the UK data. It is slightly lower than the Australian and New Zealand experience.

Table 23--Sprinkler system performance in United Kingdom industrial and commercial buildings during 1987

Sprinkler behavior	Number of fires original	Number of fires corrected
Failed to operate because fire too small	658	658
Extinguished fire	169	724
Controlled fire	347	902
Operated but failed to control fire	61	61
Failed to operate other than because fire too small	109	109
Behavior not specified	10	10
Total	1354	2464

Fire Loading Effect

Cohn[7] equated the probability of success full automatic suppression with the fire loading. Four curves were generated depending on the type of hazard (e.g., ordinary class A combustibles, low flashpoint class B flammable liquids) and the type of system (e.g., wet-pipe, dry-pipe). (See also Reference 8.) Selected points from the wet-pipe curves are presented in Table 24. Because the highest success value is 0.999 it is assumed that the probabilities are contingent on the sprinkler system being available.

Sprinkler systems are not designed as one-size-fits-all. NFPA 13 defines five different performance levels[9]. (See Table 25.) The appropriate level is selected based on the quantity and combustibility of the materials present, and the expected fire development. Cohn's predictions do not account for the different performance levels. The transition between Ordinary Hazard Group 1 and Ordinary Hazard Group 2 occurs at combustible loadings of 15 to 20 psf. Using Table 24, this equates to a success rate of 0.95 for a wet-pipe sprinkler system protecting Class A combustibles.

NFPA 231, *Standard for General Storage*[10], specifies the use of automatic sprinkler systems in warehouses. Combustible loadings in such buildings can readily exceed 100 psf. Since warehouse sprinkler systems are considered reliable, strict adherence to Table 24 is not recommended. The table does however provide an potential adjustment when the actual combustible loading exceeds the design capability of the sprinkler system. This approach does not account for sprinkler systems that have been designed to accommodate high combustible loadings.

Table 24--Wet-pipe automatic suppression probabilities based on combustible loading[7]

Probability		Combustible loading (psf)	
failure.	success	ordinary hazard	fast developing fire
0.001	0.999	7	3
0.005	0.995	10	5
0.01	0.99	12	6
0.05	0.95	18	12
0.1	0.9	22	14
0.5	0.5	48	29
0.9	0.1	80	45
0.95	0.05	90	49
0.99	0.01	...	59
0.999	0.001	...	70

Table 25--Sprinkler system performance levels defined in NFPA 13

Hazard	Quantity	Combustibility	Fire development
Light	low	low	low heat release rate (HRR)
Ordinary, Group 1	moderate	low	moderate HRR
Ordinary, Group 2	high*	high*	high* HRR
Extra Hazard, Group 1	high	high	rapid with high HRR†
Extra Hazard, Group 2	high	high	rapid with high HRR‡

*NFPA 13 specifies this as moderate to high.
†limited quantities of flammable and combustible liquids
‡moderage to substantial quantities of flammable and combustible liquids

System Performance

Hall[2] reviewed the leading reasons for unsatisfactory sprinkler system performance. These are presented inTable 26. If 0.96 is used as the success value for a sprinkler system, the corresponding failure rate (0.04) can be distributed across each failure mode as shown in Table 26.

NFPA 25 specifies the minimu periodic inspection, testing and maintence required on sprinkler system[11]. The dominate failure mode is the water supply being shut-off. The inspection, testing and maintenance activities listed in Table 27 that most affect the probability that the water is shut off are 1, 11, 13, 19 and 20. Inspection of the control valve (item 1) and the main drain test (item 13) are techniques to identify if the system shutoff. The internal valve inspection (item 11) and maintenance activities (items 19 and 20) are potential initiators for the system being shut off.

Table 26--Leading reasons sprinkler system performance is unsatisfactory [Hall]

Problem	Fraction	Probability of failure all	Probability of failure wet-pipe
Water shut off	0.354	0.0142	0.0040
System not adequate for level of hazard in occupancy	0.135	0.0054	0.0054
Inadequate water supplies	0.099	0.0040	0.0040
Inadequate maintenance	0.084	0.0034	0.0034
Obstruction to water distribution	0.082	0.0033	0.0033
System design for partial protection only	0.081	0.0032	0.0032
Faulty building construction	0.060	0.0024	0.0024
Antiquated system	0.021	0.0008	0.0008
Slow operation	0.018	0.0007	0.0007
Defective dry-pipe valve	0.017	0.0007	0.0000
Exposure fire	0.017	0.0007	0.0000*
System frozen	0.014	0.0006	0.0006
Other or unknown	0.019	0.0008	0.0008
Total	1.000	0.0402	0.0402

*For risk evaluation, this failure mode is normally handled separately.

The Savannah River Site has collected a large amount of operating data that has been used to develop human error probabilities. This data can be used to evaluate the probability that a sprinkler system is shut off. Data used in this calculation are:

System out-of-service	
Obstruction investigation (8 hours every 5 years)	
Miscellaneous outages (24 hours per year)	
Failure to restore following maintenance (single person, no checks)	0.05
Failure to restore following maintenance (single-person, operator check)	0.005
Failure of visual inspection (nominal)	0.1
Failure of visual inspection (low)	0.01

The total out-of-service probability from Table 26 is 0.014. For the outages defined above the out-of-service probability is:

$$(4) \qquad P_{\text{shut off}} = \frac{\left(\frac{8\text{ hours}}{5\text{ years}}\right) + \left(\frac{24\text{ hours}}{\text{year}}\right)}{\frac{8760\text{ hours}}{\text{year}}} = 0.003$$

This probability does not include out-of-service because the system is not restored after maintenance. Figure 13 provides an event tree for a sprinkler system not being returned to service after maintenance. It assumes there are two valves one on the riser and a second on yard main. Thus the probability that the system is not restored to service is:

Table 27--NFPA 25 inspection, testing and maintenance requirements for wet-pipe sprinkler systems

Item	Activity	Frequency
1. Control valves	inspection	weekly if sealed monthly if locked monthly if equipped with tamper switch
2. Alarm devices	inspection	quarterly
3. Gauges	inspection	monthly
4. Hydraulic nameplate	inspection	quarterly
5. Buildings	inspection	annually (prior to freezing weather)
6. Hanger/seismic bracing	inspection	annually
7. Pipe and fittings	inspection	annually
8. Sprinklers	inspection	annually
9. Spare sprinklers	inspection	annually
10. Fire department connection	inspection	quarterly
11. Valves (all types)		
alarm (exterior)	inspection	monthly
alarm (interior)	inspection	5 years
check (interior)	inspection	5 years
12. Alarm devices	test	quarterly
13. Main drain	test	quarterly
14. Antifreeze solution	test	annually
15. Gauges	test	5 years
16. Sprinklers - extra-high temperature	test	5 years
17. Sprinklers - fast response	test	20 years and every 10 years thereafter
18. Sprinklers	test	50 years and every 10 years thereafter
19. Valves (all types)	maintenance	annually or as needed
20. Obstruction investigation	maintenance	5 years or as needed

Figure 13--System left out of service following maintenance - base case

valve closed	restored after maintenance	monthly inspection	main drain test	Pclosed	Event duration	Months out-of-service per closure
1	0.95			0.95		
	0.05	0.9		0.045	0.5	0.0225
		0.1	0.99	0.00495	6	0.0297
			0.01	0.00005	12	0.0006
				1.0		0.0528

Figure 14--System left out of service following maintenance - improved program

valve closed	restored after maintenance	monthly inspection	main drain test	Pclosed	Event duration	Months out-of-service per closure
1	0.995			0.995		
	0.005	0.9		0.0045	0.5	0.00225
		0.1	0.99	0.000495	6	0.00297
			0.01	0.000005	12	0.00006
				1.0		0.00528

(5) $$P_{shut\ off} = (2\ \text{valves})\left(\frac{12\ \text{closures}}{12\ \text{months}}\right)\left(0.0528\frac{\text{months out of service}}{\text{closure}}\right) = 0.011$$

The total failure probability for the water supply being off is 0.014.

If the an operator inspection was required to be conducted after maintenance is complete, the probability that the system would not be restored would be reduced. The reduced probability would be:

(6) $$P_{shut\ off} = (2\ \text{valves})\left(\frac{12\ \text{closures}}{12\ \text{months}}\right)\left(0.00528\frac{\text{months out of service}}{\text{closure}}\right) = 0.0011$$

When combined with the system out-of-service time, the water supply failure probability is dominated to water unavailability. Thus the overall system probability will become 0.97.

Results

1. Based on the above results it is recommended that if the sprinkler system is maintained using the criteria established in NFPA 25 the success probability range be considered as 0.9 to 0.99.

2. The average success probability for a sprinkler system is 0.96. (This value should not be used for preaction systems.)

3. If two independent inspections are conducted after a sprinkler system is returned to services the average success probability for a sprinkler system is 0.97.

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APPENDIX D, SPRINKLER SYSTEM RELIABILITY AND PERFORMANCE

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Sprinkler System Reliability and Performance

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Abstract

Automatic sprinklers are a very effective method of reducing fire risk.[1] When such systems are successful in controlling a fire, losses can be minimal. Historically, SRS has used a 96 percent success probability for a standard sprinkler system to control an unwanted fire.[2] In 1999 a paper was presented at the Third International Conference on Fire Research and Engineering (ICFRE3) that suggested a 95 percent reliability value for automatic wet-pipe sprinkler systems.[3] This whitepaper reviews the 1999 ICFRE3 paper and reconciles the two values.

Introduction

In 1999 Bukowski, Budnick and Schemel presented at the ICFRE3 a summary of published reliability data for automatic sprinkler systems.[3] These data are presented in Table 1. These values were averaged to produce the results presented in Table 2. A conclusion of their paper was that while the mean sprinkler success performance was 95 percent and "the use of a single value for estimating operational reliability of a fire protection strategy is not appropriate." The paper suggests that the entire confidence interval and not just a single value be used in the evaluation of fire protection strategies.

This whitepaper presents a review of the ICFRE3 paper that consists of replicating the numerical results of the ICFRE3 paper, evaluating the methodology used in the ICFRE3 paper, suggesting alternate analytical techniques and recommending an SRS position that addresses the differences between generic and ICFRE3 success probability values.

Replication of ICFRE3 Paper Results

It was possible to replicate the results presented at the ICFRE3. This is shown in Table 3. The differences for commercial occupancies (93.1 to 93.2) and general occupancies (96.1 to 96.0) are attributed to round-off. The uncertainty bands in Table 2 do coordinate with the Table 3 standard deviations of the mean when the sample size is accounted for.

Table 28--Sprinkler success data from Bukowski, Budnick, and Schemel

Occupancy	Description	Reliability value*
Commercial	Milne [1959]	97.6
	Automatic Sprinkler [1970]	94.5
	Miller [1974]	86.0
	DOE [1982]	98.9
	Maybee [1988]	99.5
	Kook [1990]	87.6
	Taylor [1990]	81.3
	Sprinkler Focus [1993]	97.1
	Linder [1993]	96.0
General	Building Research Est. [1973]	92.1
	Miller [1974]	95.8
	miller [1974]	94.8
	Powers [1979]	96.2
	Richardson [1985]	96.0
	Finucane et. al. [1987]	97.4
	Marryat [1988]	99.5
Residential	Milne [1959]	96.6
Institutional	Milne [1959]	96.6

*Where a range of values was presented in Bukowski, Budnick, and Schemel, the midpoint of the range is provided.

Table 29--Automatic sprinkler system results published in Bukowski, Budnick and Schemel

Occupancy	Number data sets	Mean	Uncertainty
Commercial	9	93.1	5.0
General	7	96.1	2.1
Institutional	1	96.6	---
Residential	1	96.6	---
Overall	18	94.6	2.5

While the data presented in Table 1 was not verified, many of the data sets have been cited in SRS fire risk evaluations.[4] The ICFRE3 paper does not evaluate the size of the data sets however, it is recognized that several are very large. Marryat[5] included 100 years of data from Australia and Automatic Sprinkler [1970][6] covered 73 years of data from the United States. Typically, when analyzing data sets of widely varying sample size it is appropriate to weight the sets based on sample size. This avoids the problem of a small sample size disproportionately affecting the resultant.

As an alternative to weighting, a more robust statistic than the mean (i.e., arithmetic average) can be computed. Such a statistic is the median, which represents the middle of the sample set. Thus, half the samples are larger than the median and half the samples would be smaller. This method avoids any particular data set from dominating the resultant. The median values are presented in Table 3. In addition, a probability diagram is also attached as Figure 1. If the data was normally distributed it would lie on a straight line. Since it does not, it can be concluded that the ICFRE3

data are not normally distributed. This reinforces the use of a median value rather than a mean value.

Table 30--Replication of results presented in the ICFRE3 paper

Occupancy	Number data sets	Mean	Median	Standard Deviation	Standard Deviation of the Mean	t-statistic	Uncertainty
Commercial	9	93.2	96.0	6.5	2.2	2.306	5.1
General	7	96.0	96.0	2.3	0.9	2.447	2.2
Institutional	1	96.6	96.6	---	---	---	---
Residential	1	96.6	96.6	---	---	---	---
Overall	18	94.6	96.1	4.9	1.2	2.110	2.5

Discussion of ICFRE3 Results

The ICFRE3 paper reinforces the use of the 96 percent sprinkler success probability at SRS. The 95 percent value as presented in the ICFRE3 paper was published with an uncertainty band (95 percent coverage) of 92.2 to 97.1. This brackets the 96 percent value. In addition, when the data published in the ICFRE3 paper is evaluated using robust statistics, the result is 96 percent.

The numeric difference between the two results are small. If the SRS generic value (0.96) is replace with the ICFRE3 value (0.95) the severe fire frequency in a fully sprinklered building would increase by 25 percent. This difference is considered to be well within the uncertainty of any fire frequency estimate.

The ICFRE3 paper recommends that fire frequency analysis be conducted using the entire confidence interval rather than a single value. This approach requires individual histograms be prepared for each event. These histograms would then be combined using event tree or fault trees. This approach, while statistically elegant, is labor intensive and is similar to the Accident Progression Event Tree (APET) that were generated to support reactor safety analyses. Typically at SRS event trees and fault trees have been developed using single value inputs for each event.

The uncertainty of statistics used in event tree and fault tree analyses are typically presented as error factors (EF) based on the failure probabilities, where:[7]

$$EF = \frac{95\text{th percentile}}{50\text{th percentile}}$$

For the combined results in Table 2, the EF would be 1.5.[1] Since EF's of 10 are commonly accepted in SRS safety analyses[8] (both fire and non-fire), there is little benefit to handling sprinklers using the histogram-based approach as recommended by the ICFRE3 paper.

[1] EF=[1-(0.946-0.025)]/(1-0.946)=1.5

Alternate Data Analysis

It can be advantageous to evaluate system response in terms of failure rather than success. For many engineering problems the failure data can be represented with a lognormal probability distribution. This is accomplished by transforming the data in Table 1:

$$P^{*}_{fail} = ln(1 - P_{success})$$

Table 4 presents the transformed results. The data are also plotted in Figure 1. Based on this plot it is appropriate to treat the failure data as lognormal. From Table 4 the mean failure probability based on a lognormal distribution is 0.036. The corresponding success probability would be 0.964. The 95 percent failure values would be:

$$P_{fail,high} = exp[-3.322 + (2.11)(0.233)] = 0.059$$
$$P_{fail,low} = exp[-3.322 - (2.11)(0.233)] = 0.022$$

Thus, the 95 percent coverage range for the success values would be 0.94 to 0.98. Before these values are used for safety related work, it is recommended that the lognormal analysis be redone with weights that reflect the sample sizes. Because of the effort involved and the small uncertainties calculated above, this work is not presently warranted.

Conclusions

The sprinkler system success probabilities recommended by Bukowski, Budnick and Schemel and presented in the ICFRE3 paper have been evaluated and compared to the generic sprinkler system success probability used at SRS. The difference between the ICFRE3 recommended value (95%) and the SRS recommended value (96%) is within the expected uncertainties. It is recommended that SRS continue to use the 96 percent value.

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3. Bukowski, R. W.; Budnick, E.K.; and Schemel, C.F. 1999. Estimates of the Operational Reliability of Fire Protection Systems. *Third International Conference on Fire Research and Engineering (ICFRE3) 4-8 October 1999, Chicago, IL,* pp 87-98.

4. Coutts, D.A. 1997. *Fire Risk Analysis for Building 773-A (U).* Aiken, SC: Westinghouse Savannah River Company. (September) F-CLC-A-00008. (Committed).

5. Marryatt, H.W. 1988. *Fire, A Century of Automatic Sprinkler Protection in Australia and New Zealand, 1886-1986.* North Melbourne, Victoria, Australia: Australian Fire Protection Association.

6. "Automatic Sprinkler Performance Tables, 1970 Edition." 1970. *Fire Journal.* (July)Volume 64, Number 4. 35-9.

Table 31--Sprinkler success data from Bukowski, Budnick, and Schemel

	$P_{success}$	P_{fail}	P_{fail}*
	0.976	0.024	-3.730
	0.945	0.055	-2.900
	0.860	0.140	-1.966
	0.989	0.011	-4.510
	0.995	0.005	-5.298
	0.876	0.124	-2.087
	0.813	0.187	-1.677
	0.971	0.029	-3.540
	0.960	0.040	-3.219
	0.921	0.079	-2.538
	0.958	0.042	-3.170
	0.948	0.052	-2.957
	0.962	0.038	-3.270
	0.960	0.040	-3.219
	0.974	0.026	-3.650
	0.995	0.005	-5.298
	0.966	0.034	-3.381
	0.966	0.034	-3.381
Median	0.961	0.039	-3.245
Mean	0.946	0.054	-3.322
Standard deviation of mean	0.012	0.012	0.233

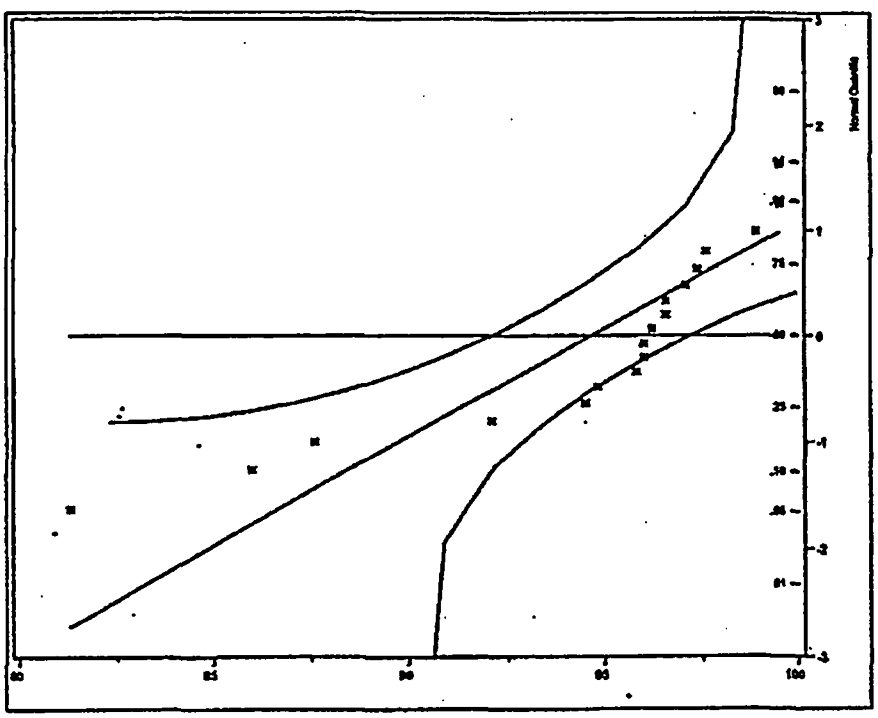

Figure 15--Probability Diagram – Success Data

7. Benhardt, H.C., Eide; S.A., Held; J.E., Olsen, L.M.; and Vail, R.E. 1994. *Savannah River Site Human Error Data Base Development For Nonreactor Nuclear Facilities (U).* Aiken, SC: Westinghouse Savannah River Company. (February) WSRC-TR-93-581.

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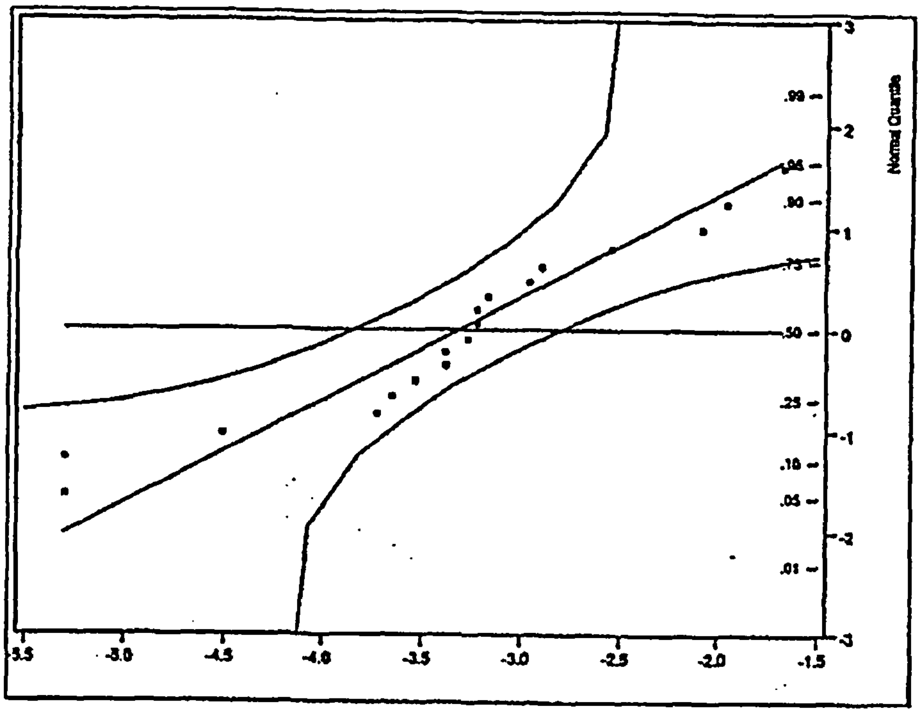

Figure 16-- Probability Diagram – Lognormal Failure Data

APPENDIX E, FUEL PACKAGE MODELING

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Pool Fires

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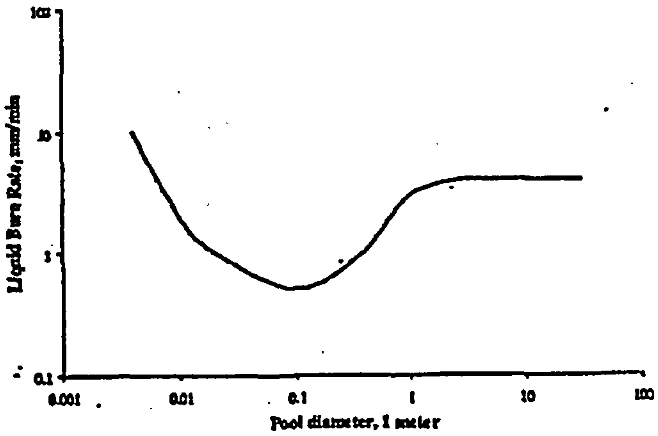
Pool Fire Behavior



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Pool Fires

$$\dot{m}'' = \dot{m}''_{\infty}\left(1 - e^{-k\beta D}\right)$$

$\dot{m}''$ = the is the mass loss rate per unit area [kg/s·m²]

D = the pool diameter [m]

k = is the extinction-absorption coefficient of the flame [m^{-1}]

β =the mean-beam-length correction

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Typical Pool Fire Data

	Heat of combustion MJ/kg	Base mass loss rate kg/m²·s	kβ m^{-1}
Methanol	20.0	0.017	---
Gasoline	43.7	0.055	2.1
Kerosene	43.2	0.039	3.5
Oil	39.7	0.035	1.7

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Heat Release Rate

- Heat Release Rate (HRR) is the energy released by the fire.
- It is the basic measure of fire behavior.
- It is typically an empirical value

Pool Fires

$$\dot{Q} = \dot{m}'' A_{pool} \Delta H_c$$

$\dot{Q}$ = the heat release rate [kW]
$\dot{m}''$ = the mass loss rate per unit area [kg/s·m²]
A = the pool area [m²]
ΔH_c = heat of combustion [MJ/kg]

Pool Fires - Diesel Fuel Example

Spill size: 100 gallons (0.38 m^3)

Diked area: 15 m^2

Effective spill diameter: 4.4 m

$$\dot{m}'' = \left(0.035\frac{kg}{m^2 \cdot s}\right)\left(1 - e^{-(1.7\,m^{-1})(4.4\,m)}\right) = 0.035\frac{kg}{m^2 \cdot s}$$

$$\dot{Q} = \left(39.7\frac{MJ}{kg}\right)\left(0.035\frac{kg}{m^2 \cdot s}\right)\left(15\,m^2\right) = 21\,MW$$

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Pool Fire Duration

$$t = \frac{V}{A}\frac{\rho}{\dot{m}''} = \left(\frac{0.38\,m^3}{15\,m^2}\right)\left(\frac{970\frac{kg}{m^3}}{0.035\frac{kg}{m^2 \cdot s}}\right) \doteq 700\,s = 12\text{ minutes}$$

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Pool Fire Duration

$$t = \frac{V}{A}\frac{\rho}{\dot{m}''} = \left(\frac{0.38\,m^3}{15\,m^2}\right)\left(\frac{970\frac{kg}{m^3}}{0.035\frac{kg}{m^2\cdot s}}\right) = 700\,s = 12\text{ minutes}$$

$$t = \frac{V}{A}\frac{\rho}{\dot{m}''} = h\frac{\rho}{\dot{m}''} = \frac{h}{\dot{y}}$$

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Solid Heat Release Rates

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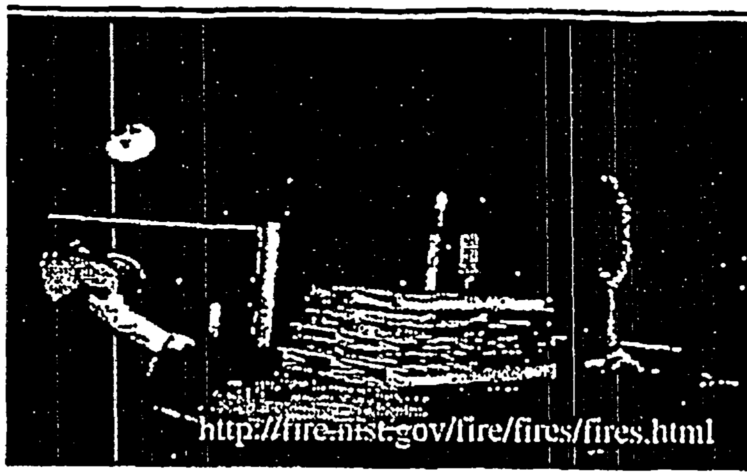
NIST Pallet Test



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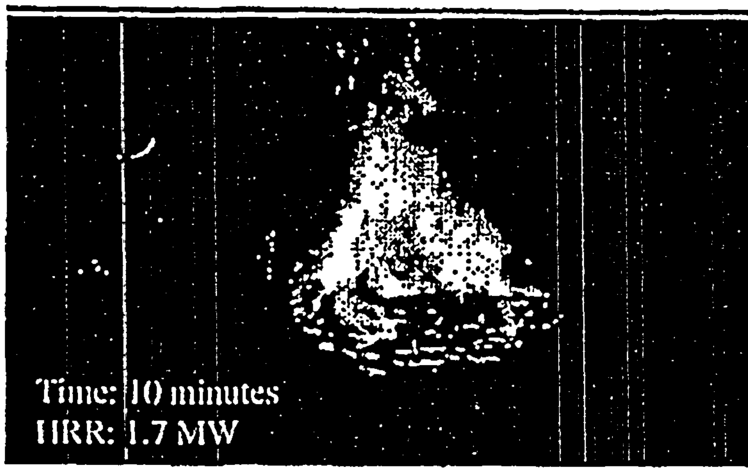
NIST Pallet Test



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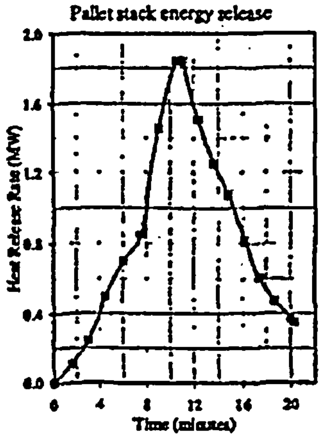
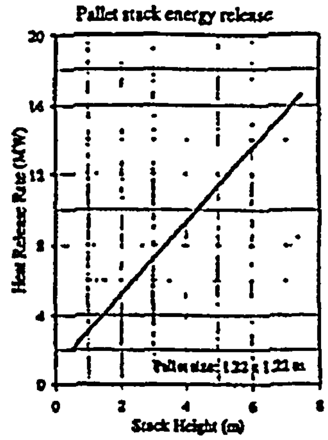
Pallet Stacks





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Pallet Stacks

$$\dot{q}'' = 0.97(1 + 2.14h_c)(1 - 0.027M)$$

$\dot{q}''$ = HRR per unit area [MW/m²]

h_c = the stack height [m]

M = wood moisture content [percent]

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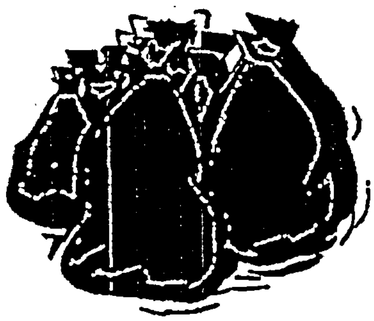
Typical Heat Release Rates (kW)



Trash

1 or 2 bags	250
> 3 bags	500

Upholstered furnishings

small (< 10 kg)	250
large (> 20 kg)	1000

Appliance housing

plastic	250

Christmas tree

fresh	250
dry	500

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t^2-Curves

- Standard FP practice is to approximate the growth period as:

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

- Constant is defined based on the time to reach 1,055 kW (1,000 Btu/s)

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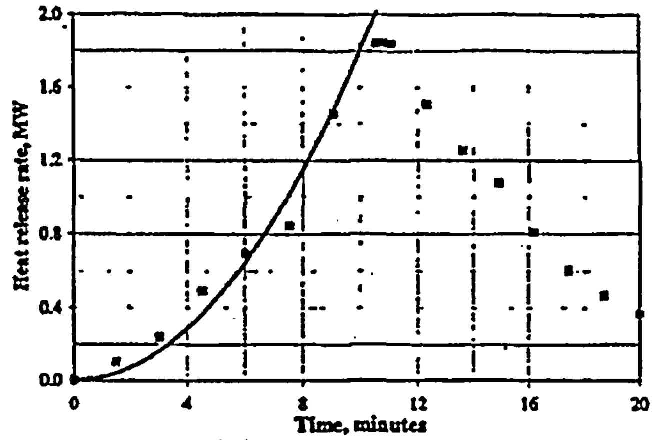
t²-Curves



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Typical t²-Curve Constants

- Constant is defined based on the time to reach 1,055 kW (1,000 Btu/s)

	Time to reach 1,055 kW	Constant K, kW/s²
slow	600	0.00293
medium	300	0.0117
high	150	0.0469
ultra-fast	75	0.188

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

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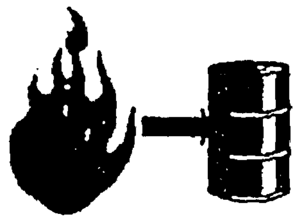
Fire Heat Flux



Emissive Power

$$q'' = \sigma T_f^{\,4}$$

q'' = emissive power [W/m2]

σ =Stefan-Boltzmann constant [5.669E-11 kW/m²·K⁴]

T_f= flame temperature [K]

Emissive Power

$$q'' = \sigma T_f^{\,4}$$

	Flame temperature		Power,
	C	K	kW/m²
gasoline	967	1240	134
methane	1016	1289	157
polystyrene	1213	1486	276
plexiglas	1265	1538	317
kerosene	1327	1600	372
wood	1459	1732	510

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Pool Fire Emissive Power

$$E_{ave} = E_m e^{-SD} + E_s\left(1 - e^{-SD}\right)$$

E_m = maximum emissive power of the luminous spots [140 kW/m²]

E_s = emissive power of smoke [20 kW/m²]

S = empirical constant [0.12 m⁻¹]

D = pool diameter [m]

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Heat Transfer

Heat Transfer

$$q_r'' = \sigma F_v F_e \left(T_f^{\,4} - T_o^{\,4}\right)$$

q_r'' = heat flux [kW/m²]

σ =Stefan-Boltzmann constant

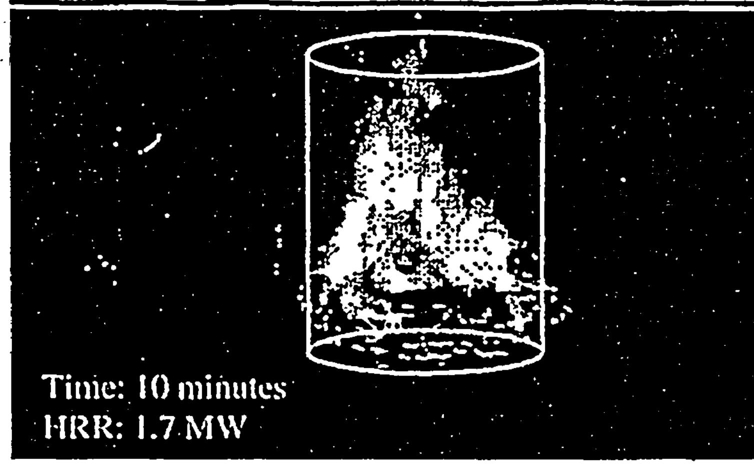
T_f= flame temperature [K]

F_v= view factor [unitless]

F_e= emissivity function [unitless]

T_o= object temperature [K]

Modeling Flame Geometry



Flame geometry (NFPA 555)

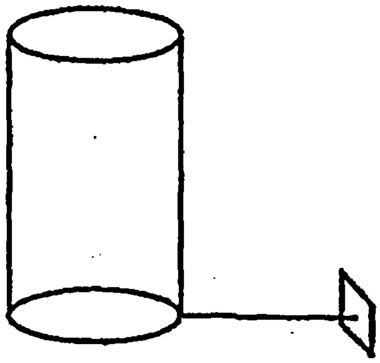
For small fires, the flame can be modeled as cylinder

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

H = Flame height (m)
Q = Heat release rate (kW)
D = Fire diameter (m)
E = Emissive power (kW/m^2)

View Factor

$$F_v = \frac{1}{\pi H}\tan^{-1}\left(\frac{L}{\sqrt{H^2-1}}\right)+\frac{L}{\pi}\left(\frac{(X-2H)}{H\sqrt{XY}}\right)\tan^{-1}\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right)-\frac{1}{H}\tan^{-1}\left(\sqrt{\frac{(H-1)}{(H+1)}}\right)$$



h = distance from the object to cylinder centerline
l = cylinder height
r = cylinder radius
H = h/r
L = l/r
X = (1+H)2+L2
Y = (1-H)2+L2

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Heat Flux Sample Problem

- Given: Stack of pallets
- Foot print: 1.49 m²
- Peak HRR: 1,850 kW
- What is the heat flux at 0.5 meters?

$$D_{eff} = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(1.49\ m^2)}{\pi}} = 1.38\ m$$

$$H = 0.235(1{,}850\ MW)^{2/5} - 1.02(1.38\ m) = 3.4\ m$$

$$F_v = 0.266$$

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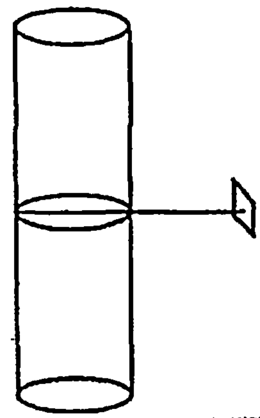
View Factor

$$q_r'' = \left(5.669\ \mathrm{E}-11\,\frac{\mathrm{kW}}{\mathrm{m^2 \cdot K}}\right)[2(0.266)](1.0)\left[(1{,}732)^4-(373)^4\right]$$

$$= 270\ \frac{\mathrm{kW}}{\mathrm{m^2}}$$

For T_{flame} = 1260 K the heat flux is 76 kW/m^2



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APPENDIX F, FIRE SEVERITY ESTIMATES

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Fire Compartment Temperature Predictions

Energy Balance Correlation

(McCaffrey, Quintiere and Harkleroad)

$$\Delta T_g = 6.85 \left(\frac{\dot{Q}^2}{A_o \sqrt{H_o}\, h_k A_T} \right)^{1/3}$$

$$h_k = \begin{cases} \frac{k}{\delta} & t_p < t \\ \left(\frac{k\rho c}{t}\right)^{1/2} & t \leq t_p \end{cases} \qquad t_p = \frac{\rho c}{k}\left(\frac{\delta}{2}\right)^2$$

Energy Balance Correlation

$\dot{Q}$ = fire heat release rate (kW)
A_o = area of opening (m^2)
H_o = opening height (m)
A_T = Total surface area of the fire compartment (m^2)
ρ = wall (ceiling/floor) density (kg/m^3)
c = wall (ceiling/floor) specific heat (kJ/kg·K)
k = wall (ceiling/floor) thermal conductivity (kW/m·K)
δ = wall (ceiling/floor) thickness (m)
t = exposure time (s)

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Energy Balance Correlation

$\dot{Q}$ = 2,000 kW from pallet test
A_o = 1.9 m^2
H_o = 2.1 m
A_T = 110 m^2 (5 m x 5 m x 3 m high)
ρ = 700/2,100 kg/m^3 (gypsum/concrete)
c = 1.0/0.88 kJ/kg·K (gypsum/concrete)
k = 0.2/1.37 W/m·K (gypsum/concrete)
δ = 0.016/0.15 m (gypsum/concrete)

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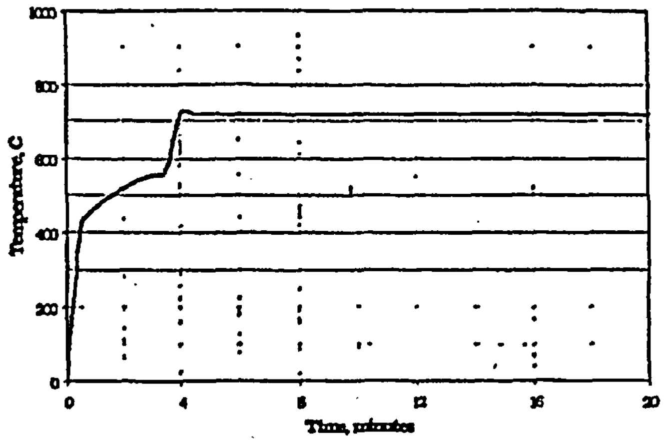
Temperature Prediction - Gypsum



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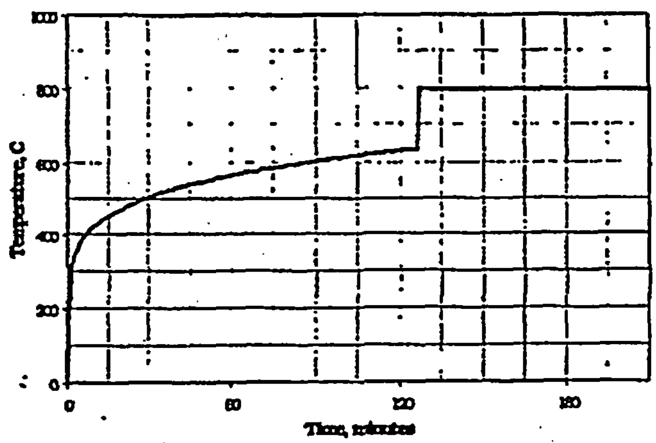
Temperature Prediction - Concrete



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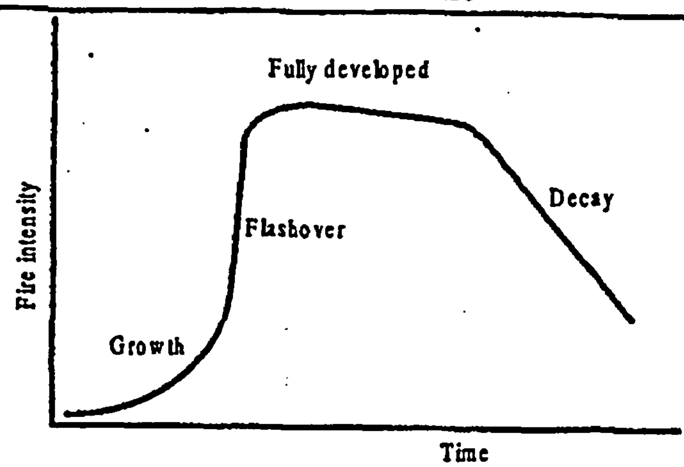
Flashover

Flashover

- SFPE Handbook
  - A transitional state between a growing fire and fully developed burning.
- NFPA 555
  - A stage in the development of a contained fire in which all exposed surfaces reach ignition temperatures more or less simultaneously and fire spreads rapidly throughout the space.

Fire Timeline



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Flashover

- Consider as an instability, which occurs during a compartment fire, between the expanding phase and the fully developed phase.
- Accept that if flashover occurs, conditions are extreme.

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Flashover Predictions

- Heat flux at the floor
  - Nominal value: 20 kW/m^2
- Heat release rate
  - Smaller rooms: 1,000 kW (1,000 Btu/s)
- Temperature near the ceiling
  - Nominal value: 600°C
  - Typical values: 500 to 600°C
  - Extreme values: 300 to 650°C

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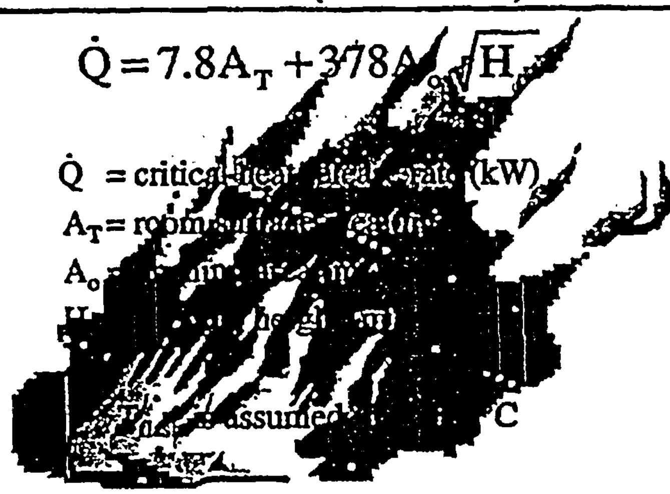
Flashover (NFPA 555)

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



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

A_T = room [illegible]

A_o [illegible]

H [illegible]

[illegible] assumed [illegible] C

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Sample Based on Preflashover Problem

$\dot{Q}$ = 2,000 kW from pallet test

A_o = 1.9 m^2

H_o = 2.1 m

A_T = 110 m^2 (5 m x 5 m x 3 m high)

$$\dot{Q}_c = 7.8(110\,m^2) + 378(1.9\,m^2)\sqrt{2.1\,m}$$
$$= 1{,}900\,kW$$

Since the pallet fire (2,000 kW) is larger than the HRR required for flashover, flashover should be assumed to occur.

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Post-flashover Correlations

Lie (1974)

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Lie's Correlation

Growth and fully developed burning phases:

$$T = 250(10F)^{\left(\frac{0.1}{F^3}\right)} \exp\left\{-F^2 t\left[3\left(1-e^{-0.6t}\right)-\left(1-e^{-3t}\right)+4\left(1-e^{-12t}\right)\right]\right\}+C\left(\frac{600}{F}\right)^{0.5}$$

Decay phase:

$$T = -600\left(\frac{t}{\tau}-1\right)+T_\tau \quad \text{where: } \tau = \frac{Q}{330F} \quad \text{and} \quad F = \frac{A_v\sqrt{H_v}}{A_T}$$

Notes:

$T = 20$ if $T < 20°C$ $\quad t = \frac{0.08}{F}$ if $t \le \frac{0.08}{F}+1$

Valid for: $0.01 \le F < 0.15$

Lie's Correlation

A_T = surface area of compartment [m²]

A_v = area of ventilation opening(s) [m²]

C = constant for wall (1 if ρ <1600 kg/m³ or 0 otherwise)

H_v = height of ventilation opening(s) [m]

Q = fuel load based on room surface area [kg/m²]

t = time [hours]

T = temperature [°C]

τ = duration of fully developed burning [hours]

Energy Balance Correlation

- Combustible loading
  - L $= 49\ kg/m^2$ (10 psf)
  - Q $= 11\ kg/m^2$
- Other data
  - $A_o = 1.9\ m^2$
  - $H_o = 2.1\ m$
  - $A_T = 110\ m^2$ (5 m x 5 m x 3 m high)
  - $\rho = 700/2{,}100\ kg/m^3$ (gypsum/concrete)

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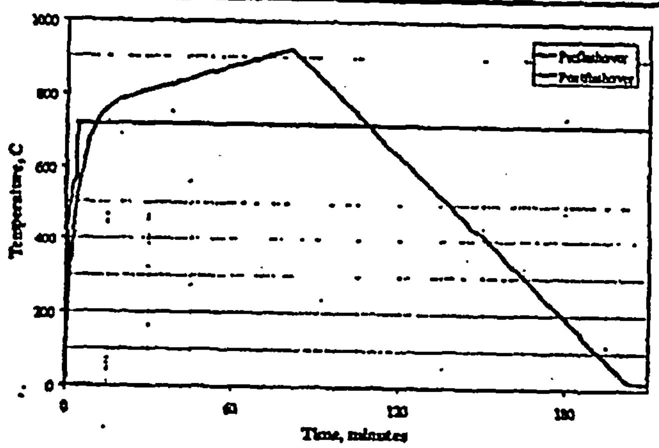
Postflashover Temperature - Gypsum



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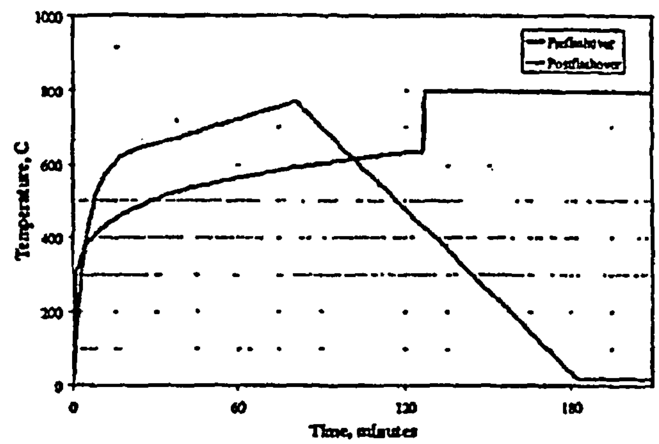
Postflashover Temperature - Concrete



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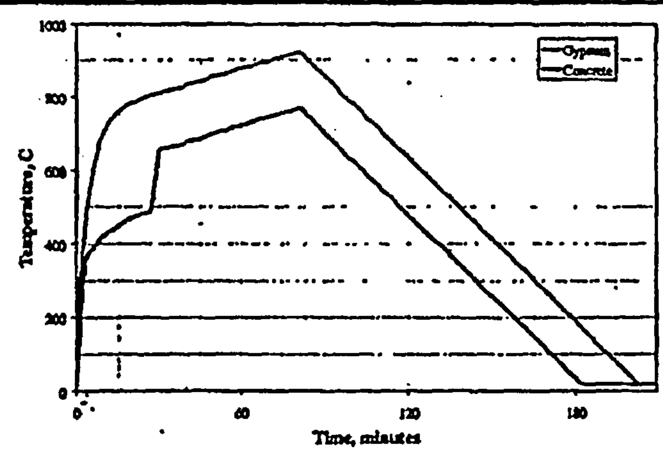
Composite Temperature Prediction



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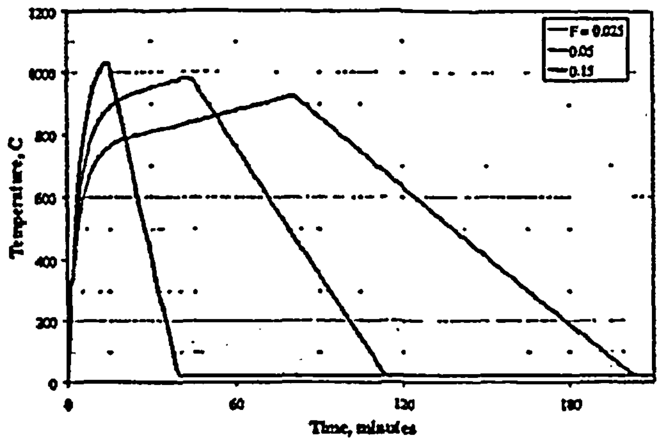
Ventilation Effect



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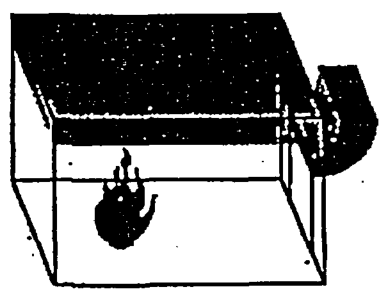
Generalized Fire Behavior

NFPA 555 - Guide on Methods for Evaluating Potential for Room Flashover

- Sprinkler systems
- Ventilation
- Fuel packages
- Flashover
- Heat release rates



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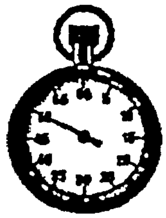
Fire Duration



Harmathy's Correlation

Growth and fully developed burning phases:

$$\tau = 0.011\frac{A_F L}{\Phi} \quad \text{if} \quad \frac{\Phi}{A_f} < 0.263$$

$$\tau = \frac{0.0419}{\varphi} \quad \text{if} \quad \frac{\Phi}{A_f} \geq 0.263$$

Ventilation parameter: $\Phi = \rho A_v \sqrt{g H_v}$

Aggregate surface area: $A_f = L A_F \varphi$

Harmathy's Correlation

A_f = aggregate surface area of the fuel (burnable objects) [m^2]

A_F = floor area of compartment [m^2]

A_v = area of ventilation opening(s) [m^2]

g = acceleration due to gravity [9.81 m/s^2]

H_v = height of ventilation opening(s) [m]

L = fuel load based on room floor area [kg/m^2]

φ = specific surface area [typical value 0.13 m^2/kg]

Φ = the ventilation parameter

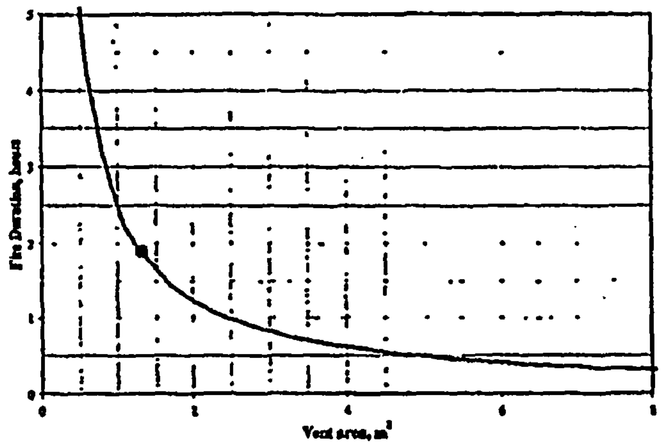
τ = duration of fully developed burning [hours]

Minimum Fire Duration

$$\text{if} \quad \frac{\Phi}{A_f} \geq 0.263 \quad \text{then} \quad \tau = \frac{0.0419}{\varphi}$$

- For most conventional furniture φ is 0.13 m2/kg
- Thus for a well-ventilated fire, the minimum fire duration is 0.32 hours (19 minutes)

Fire Duration



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The Effect of Decreasing Ventilation

- If fire is not extinguished
  - Reduces combustion rate
  - Increases damage
  - Extends fire duration
  - Results in additional smoke generation
  - Increases potential for backdraft
- Discussion Point
  - As ventilation is reduced, the fire behavior becomes less stable and less predictable

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APPENDIX G, DOSE CONSEQUENCE ESTIMATES

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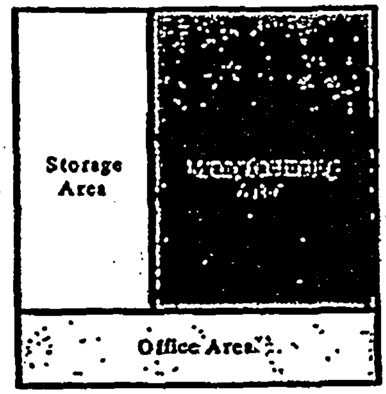
Problem Description

- Multi-use building
  - Office
  - Manufacturing
  - Storage
- NS Goal: 5 rem
- Inventory
  - Manufacturing
    - 10 kg Pu_{239}
    - 1 kg Pu_{238}
  - Storage
    - 30 kg Pu_{239}



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Storage Area Analysis

- Container size
  - height 0.3 m
  - diameter 0.2 m
- Container properties
  - failure criteria limit 10. MJ

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Storage Area Analysis

- Assumed fire conditions
  - Direct flame impingement
  - Incident heat flux: 63 kW/m²
  - Duration: 20 minutes
- Container surface area:

$$A = 2\left[\frac{\pi d^2}{4}\right] + [\pi d]h = 2\left[\frac{\pi(0.2\,m)^2}{4}\right] + [\pi(0.2\,m)](0.3\,m) = 0.25\,m^2$$

- Energy absorbed:

$$E = A\dot{q}''t = (0.25\,m^2)\left(63\frac{kW}{m^2}\right)(1{,}200\,s) = 19{,}000\,kW = 19\,MW$$

Storage Area Analysis

- Assumed fire conditions
  - Standoff is 0.5 meters
  - HRR: 500 kW
  - Diameter: 1 meter
  - Duration: 20 minutes
- Fire Height: $H = 0.235(500\,kW)^{2/5} - 1.02(1\,m) = 1.8\,m$
- View Factor: 0.46
- View Area: $A = (0.2\,m)(0.3\,m) = 0.06\,m^2$

Storage Area Analysis

- Energy absorbed
  - 0.5 meter standoff

$$E = A\dot{q}''t = (0.06\,m^2)\left[(0.46)\left(510\frac{kW}{m^2}\right)\right](1{,}200\,s) = 17{,}000\,kW = 17\,MW$$

  - 1.0 meter standoff

$$E = A\dot{q}''t = (0.06\,m^2)\left[(0.25)\left(510\frac{kW}{m^2}\right)\right](1{,}200\,s) = 9{,}000\,kW = 9\,MW$$

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Storage Area Analysis Assumptions

- Container size
  - height 0.3 m
  - diameter 0.2 m
- Container integrity
  - Minimum absorbed energy is 10 MW
- Combustible loading limit
  - Fuel packages limited to 500 kW
  - Standoff from fuel packages is 1 meter

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Multiple Fire Area Fire

- Inventory with damaged containers
  - Manufacturing - all containers
    - 10 kg Pu_{239} and 1 kg Pu_{238}
  - Storage - one container
    - 1 kg Pu_{239}
- Release duration: 20 minutes
- Release mode
  - Manufacturing - loose power, ARF 10^{-3}
  - Storage - burst container, ARF 10^{-2}

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Multiple Fire Area Fire

	MAR, kg	ARF	RF	Ci/kg	rem/Ci	rem
Pu_{238}, power	1	6E-3	1E-2	17100	0.261	0.27
Pu_{239}, power	10	6E-3	1E-2	62.1	0.263	0.0098
Pu_{239}, leak	1	0.1	0.7	62.1	0.263	1.1
						1.4

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APPENDIX H, FIRE DEPARTMENT RESPONSE

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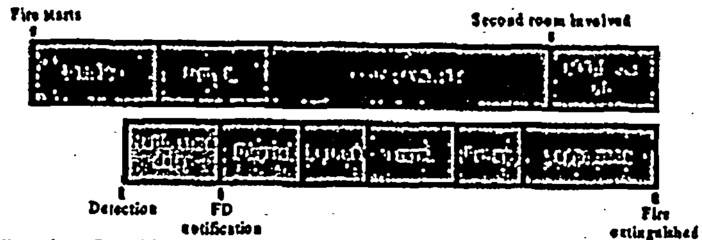
Fire Department Response - Timelines

Compare timing of key events

- Occupant notification
- Room flashover
- Second room involvement
- Fire Department arrival

Basic timelines

- Fire timeline (fire progress)
- Occupant response timeline (evacuation, etc.)
- Fire Department response timeline



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Timeline Evaluation

Objective : Fire Department intervention before 2nd room involved

- Notification time
  - mean 9.0 minutes
  - σ 3.5
- FD intervention time
  - mean 9.0
  - σ 2.0
- Flashover occurs
  - mean 5.0 minutes
  - σ 2.4 minutes
- 2nd Room propagation
  - mean 25.0 minutes
  - σ 11.0 minutes

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Simple Math Method

$$t_{notification} + t_{FD\ response} < t_{flashover} + t_{propagate}$$

$$9\ \text{minutes} + 9\ \text{minutes} < 5\ \text{minutes} + 25\ \text{minutes}$$

$$18\ \text{minutes} < 30\ \text{minutes}$$

Since FD arrived before 2nd room involved, conclude that the facility is safe.

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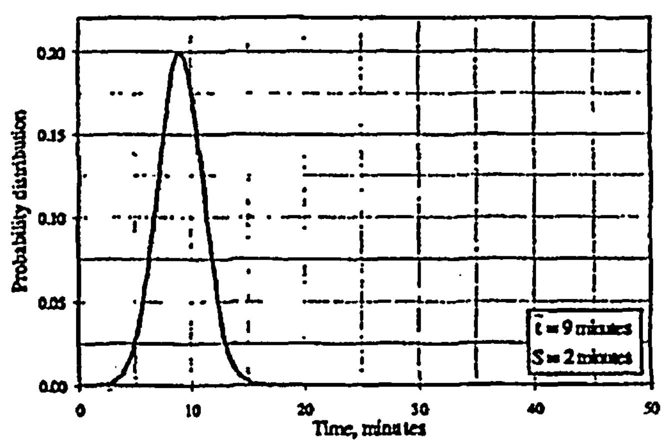
Simple Timing Evaluation



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Bounding Timing Evaluation

Notification time: $9.0 + 2(3.5) = 16$ minutes

FD intervention time: $9.0 + 2(2.0) = 13$

Flashover occurs: $5.0 - 2(2.4) = 0.2$

2nd Room propagation: $25.0 - 2(11.0) = 3$

$$t_{notification} + t_{FD\ response} < t_{flashover} + t_{propagate}$$

$$16\text{ minutes} + 13\text{ minutes} ?<? 0.2\text{ minutes} + 3\text{ minutes}$$

$$28\text{ minutes} > 3.2\text{ minutes}$$

Since FD arrived after 2nd room involved, don't credit Fire Department.

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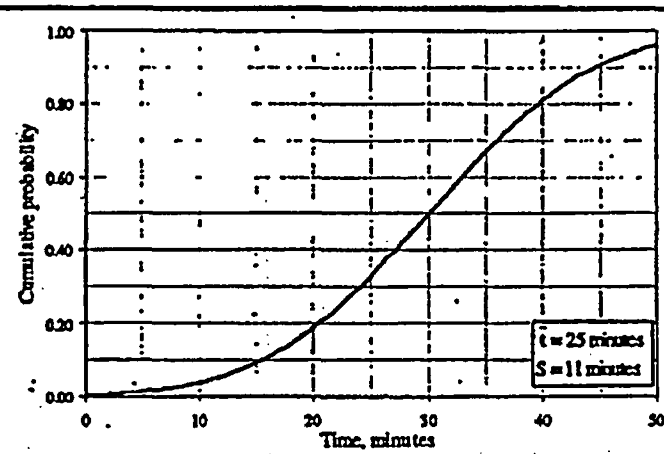
Time to 2nd Room Involvement



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Timing Evaluation - Uncertainty Based

$$t_{net} = (t_{flashover} + t_{propagate}) - (t_{notification} + t_{FD\ response})$$
$$= (5\ \text{minutes} + 25\ \text{minutes}) - (9\ \text{minutes} + 9\ \text{minutes})$$
$$= 12\ \text{minutes}$$
$$S_{net} = \sqrt{(S_{flashover})^2 + (S_{propagate})^2 + (S_{notification})^2 + (S_{FD\ response})^2}$$
$$= \sqrt{(2.4\ \text{min})^2 + (11\ \text{min})^2 + (3.5\ \text{min})^2 + (2\ \text{min})^2}$$
$$= 12\ \text{minutes}$$

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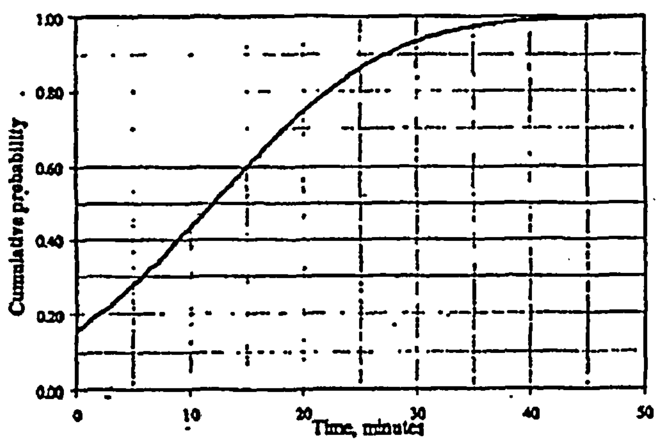
Net Time to 2nd Room Involvement



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Which is the Correct Answer?

- Simple math
  - FD responds before 2nd room involved
- Bounding math
  - FD arrives after 2nd room involved
- Uncertainty-based
  - FD arrives before 2nd room involved 82% of the time

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APPENDIX I, FIRE FREQUENCY ESTIMATES

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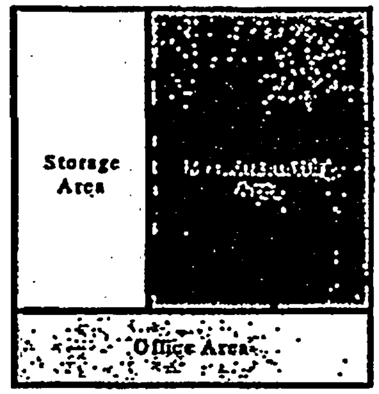
Resumption of Yesterday's Problem

- Multi-use building
- Estimated MOIs
  - Manufacturing 0.3 rem
  - Storage 1.1 rem
- What is exceedence frequency for an MOI of:
  - 0.3 rem
  - 1.1 rem
  - 1.4 rem



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Frequency Results by Zone

Fire Path: starts in	Fire Path: goes to	Incipient fire frequency yr^{-1}	Frequency growth fire exceeded yr^{-1}	Frequency two areas involved yr^{-1}
storage	manufacturing	0.3	2.2E-3	1.3E-5
manufacturing	storage	0.5	7.6E-4	3.8E-5
office	manufacturing	0.2	1.6E-3	1.6E-5
		1.0	4.6E-3	6.7E-5

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Events To Exceed 0.3 rem

- Manufacturing Area
  - A fire that is not controlled by the sprinkler system (i.e. exceeds growth stage)
- Storage Area
  - Incipient fire in storage area could cause a container to fail
- Office Area
  - Fire propagating to either Manufacturing or Storage Area

Exceedence Frequency for 0.3 rem

Fire Path.		Exceedence frequency yr^{-1}
starts in	goes to	
storage		0.3
manufacturing		7.6E-4
office	manufacturing	1.6E-5
		0.3

Events To Reach 1.1 rem

- Manufacturing Area
  - Fire propagating to the Storage Area
- Storage Area
  - Incipient fire in storage area could cause a container to fail
- Office Area
  - Fire propagating to either Manufacturing or Storage Area

Exceedence Frequency for 1.1 rem

Fire Path		Exceedence frequency
starts in	goes to	yr^{-1}
storage		0.3
manufacturing	storage	7.6E-4
office	manufacturing	1.6E-5
		0.3

Events To Reach 1.4 rem

- Manufacturing Area
  - Fire propagating to the Storage Area
- Storage Area
  - Fire propagating to the Manufacturing Area
- Office Area
  - Fire propagating to both the Manufacturing and Storage Area

Exceedence Frequency for 1.4 rem

Fire Path		Exceedence frequency yr^{-1}
starts in	goes to	
storage	manufacturing	1.3E-5
manufacturing	storage	3.8E-5
office	both	1.6E-5
		6.7E-5

Risk Binning Matrix

Frequency

Anticipated
f >10-2/yr.

Unlikely
10-4<f ≤ 10-2/yr.

Extremely Unlikely
10-6<f ≤ 10-4/yr.

Beyond Extremely Unlikely
f ≤ 10-6/yr.

Frequency → / Consequence	Beyond extremely unlikely	Extremely unlikely	Unlikely	Anticipated
High	10	7	4	1
Moderate		8	5	2
Low		9	6	3
Negligible	11	12		

High risk — Low risk
Moderate risk — Negligible risk

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Enclosure 2 to AET 05-0070

Submittal of Changed Pages for the License Application and Supporting Documents
(Non-Proprietary Information)

Remove and Insert Instructions
Enclosure 2 of AET 05-0070

Remove and Properly Destroy	Insert
LA-3605-0001, License Application for the American Centrifuge Plant	
Cover Page – Revision 8	Cover Page – Revision 9
Inside Cover Page – Revision 8	Inside Cover Page – Revision 9
ULOEP-1 through ULOEP-4	ULOEP-1 through ULOEP-4
Table of Contents – i/ii	Table of Contents – i/ii
Chapter 1.0 – pages 1-15 through 1-20; 1-47/1-48; 1-55 through 1-60; 1-101/1-102; and 1-105 through 1-124	Chapter 1.0 – pages 1-15 through 1-20; 1-47/1-48; 1-55 through 1-60; 1-101/1-102; and 1-105 through 1-126
Chapter 3.0 – pages 3-15 through 3-20 and 3-23/3-24	Chapter 3.0 – pages 3-15 through 3-20 and 3-23/3-24
NR-3605-0008, Emergency Plan for the American Centrifuge Plant	
Cover Page – Revision 4	Cover Page – Revision 5
Inside Cover Page – Revision 4	Inside Cover Page – Revision 5
ULOEP-1/ULOEP-2	ULOEP-1/ULOEP-2
Appendix A – pages A-7 through A-12	Appendix A – pages A-7 through A-12