IMPROVED FIRE RISK ANALYSIS METHODOLOGY FOR DETERMINATION OF THE FREQUENCY OF CHALLENGING FIRES

Phase 2 Final Report

DRAFT Rev. 2

Contract NRC-04-00-049

Dennis C. Bley

Robert J. Budnitz

Stan Kaplan

Richard S. Magee

Submitted by Buttonwood Consulting, Inc.

Draft September, 2002

Improved Fire Risk Analysis Methodology for Determination of the Frequency of Challenging Fires

Table of Contents

Improved Fire Risk Analysis Methodology for Determination of the Frequency of Challenging Fires

1 Introduction

An "Improved Fire Risk Analysis (FRA) Methodology for Determination of the Frequency of Challenging Fires" focuses on fires that are challenging from a risk point of view, i.e., fires that can challenge risk-important targets within the plant. The goal is to provide a more mechanistic methodology for developing the frequency of potentially challenging fires and a mechanistic link between fire initiation and subsequent fire modeling. This report demonstrates the feasibility of developing a practical, mechanistic, improved methodology for defining, characterizing, and quantifying the frequency of nuclear power plant fire scenarios. It presents a new mechanistic model for the initial stages of fire development and demonstrated that the initial stages of a variety of challenging, real-world fires fit the proposed model. The model was developed from a theoretical basis and was refined based on the study of data from many fires.

This report develops the beginnings of a catalog of *fire initial phase scenarios* (FIPS) that can be used by FRA analysts to model potentially challenging fires in their plants. Although a number of test cases have been performed, the methodology has yet to be applied to a full FRA. It is envisioned that, when the proposed methodology is first applied, revisions will be required and new FIPS will be generated for inclusion in the generic catalog.

The FIPS approach provides current benefits that should improve the clarity of FRA, encourage more attention to important uncertainties that affect the risk, and enable more informed use of available data. The new approach:

- improves realism: analysts can model how ignition occurs and how it progresses toward burning a large source of fuel, as well as specifying a probability distribution on heat release rate that will support subsequent fire modeling
- eliminates some known conservatisms and possible non-conservatisms in the current severity-factor approach, allowing a better focus on the subset of subcategories that represent the larger part of the overall risk
- treats uncertainties inherently
- permits inclusion of all available evidence; provides a structure for improved use of available data and expert judgment
- improves discrimination among different initiating-event subcategories

Furthermore, several future benefits are anticipated:

- the methodology can grow with experience - analysts can add to a growing catalog of FIPS
- there will be less uncertainty in quantification, after data are collected and made available in a form that directly supports the new methodology

A broad range of data and information sources was consulted during the project. The project used U.S. nuclear power plant fire data and event reports from Sandia National Laboratories, EPRI, USNRC LERs, NPRDS, EPIX, and NEIL. Data and fire event reports from other industries were consulted, including those from NFPA, NTSB, the U.S. Coast Guard, and the review of major fire experience performed as part of the USNRC's FRA Research Plan. In addition, discussions were held with representatives from the following organizations: NFPA, NTSB, the U.S. Coast Guard, NIST, FAA, Doble Engineering, and the U.S. Navy to provide guidance in the methodology development and to identify additional relevant data.

The data and information sources were used to refine the catalog of fire initial phase scenarios (FIPS) and the methodology, to identify and frame difficult issues, to provide insights into the nature of challenging fires, and to serve as a foundation for quantification of the frequency of challenging fires. The FIPS models, the methodology, the identified issues, and quantification are the topics of the remainder of this report.

In addition to the methodology and the FIPS themselves, the study of the available fire information has led to a number of specific lessons learned:

- Electrically induced multiple (often simultaneous) fires are observed; although they represent a small fraction of fires in the general fire database, they are involved in a substantial fraction of the identified challenging fires
- Self-ignited cable fires all involved power cables, with the fires due to low cable rating, mechanical damage, or excessive current caused by electrical faults
- Few transient fuel challenging fires are represented in the data (but staging for outages may be increasing exposure)
- Room-to-room fire propagation has been observed

  - Plants in the former Soviet Union – doors left open or cable penetrations not sealed

  - Plants in U.S.– fire barriers failed in vertical cable trays
- Most large nuclear power plant fires occurred in the turbine building
- Three fires were identified where a suppression system was defeated by sheer magnitude of fire (turbine building, large oil-filled transformer, and an area where large quantities of flammable liquid was stored)
- A number of fires affected multiple safety trains
- The effects of fire and smoke on plant operators are not well documented or analyzed

- Fires in other industries have shown characteristics that could be applicable in nuclear power plants
  - Fire can spread very rapidly through dust in ventilation ductwork
  - Invisible spread of fire can occur along temporary cables run through ductwork
  - Direct heating of digital control systems from fire in ventilation ducts can cause permanent control system failure
  - Spray of oil onto hot equipment can cause rapid fire growth and extensive damage
  - Major fires can occur from simple errors during routine operations and maintenance, when steps in procedures or standards are skipped
  - Presence of oxidizers can greatly enhance the rate of fire growth and compromise fire containment designs that rely on oxygen starvation

The remaining sections of the report include:

2. A Formal Model for Fire Risk Assessment. A formal model for FRA is developed from first principles of risk assessment. In its detail, it addresses the initial phase of the fire evolution; i.e., it defines a set of FIPS and requirements for determining their frequencies.

3. A Methodology for Characterizing and Quantifying the Frequency of Challenging Fires. The FIPS model is imbedded in a methodology for characterizing and quantifying the frequency of challenging fires on a plant-specific basis. The methodology begins in the manner of the traditional approach, first screening unimportant rooms and then developing scenarios room by room. The scenario development process is new. Next, unimportant scenarios are screened (bounded), and finally, potentially important scenarios are quantified. Combined data analysis/expert elicitation approaches are introduced for quantifying FIPS at the present time, until data can be collected in a form that can support the FIPS methodology directly. The overall focus is to improve the quantification of important contributors, replacing conservatism and optimism with more realistic analysis. A structure for treating uncertainty is integral to the quantification.

4. Findings and Recommendations.

5. References

[This page intentionally blank]

2 A Formal Model for Fire Risk Assessment

This project addresses the problem of developing an improved fire risk analysis (FRA) methodology for determination of the frequency of challenging fires. The research team asked the question: How would I address this issue, if I were starting from scratch? The team found that they could only begin by considering the entire FRA problem, defining it anew, developing a modeling framework for the full FRA, and allowing the modeling strategy for the frequency of challenging fires to emerge from that process. Part of the difficulty is that the traditional point of separation for this part of the analysis may not be conceptually optimal. In fact, the methodology proposed later in this section includes some aspects and considerations of issues that have been traditionally separated from the initiating event analysis. This section develops a formal model for FRA and especially for the initial phase of the fire evolution; i.e., for defining a set of fire initial phase scenarios (FIPS) and determining their frequencies. A methodology for using these FIPS or initiation models to determine the frequency of challenging fires in real power plants is presented in Section 3.

2.1 DEFINITION OF TERMS

Risk is defined, for nuclear power plants, as the set of answers to three questions (Garrick 1981):

(1) What can go wrong, in this plant?

(2) How likely is that to happen?

(3) If it does happen, what are the consequences?

The answers to question (1) are called "*scenarios*," the i^{th} one of which would be denoted by S_i. The set of possible scenarios is typically laid out in the form of a set of *scenario "trees,"* each path through the tree representing a single scenario. Each scenario starts with an "*Initiating Event* (IE)" and ends with an "*End State* (ES)." The branchings in the tree represent different events that can happen during the course of a risk scenario.

Risk Assessment is the process of answering the above three questions.

A *Quantitative Risk Assessment* is one in which questions (2) and (3) are answered quantitatively, usually in the form of "state of knowledge" probability curves expressing what the available evidence tells us about the answers to (2) and (3).

Risk Management is the taking of actions to reduce the likelihood and/or consequences of the risk scenarios.

A *Fire Risk Scenario* is a risk scenario involving a fire.

The *Fire Risk* of a plant is the set of fire risk scenarios, for that plant, each accompanied by a quantification of its likelihood and its consequences.

Challenging Fires are those fire scenarios whose consequences are "severe," "serious," or "significant."

The purpose of quantifying the answers to (2) and (3), of course, is to guide our risk management decision making, so that we may be efficient in the allocation of our resources to the goal of risk reduction.

When the answers to (3) are large, the answers to (2) become less important in the decision making process. In the case of challenging fires, for example, the most important thing is to become aware of the scenarios (1). That awareness may already bring to mind creative management actions that can reduce or effectively eliminate the scenarios at moderate cost. In such cases the risk management decisions may be readily made without a need for high precision in the quantification of likelihood (2).

2.2 THE PROCESS OF IDENTIFYING CHALLENGING FIRE RISK SCENARIOS IN NUCLEAR POWER PLANTS

For the purpose of discovering and identifying fire risk scenarios in nuclear power plants we outline in Figure 1 the general structure of such scenarios.

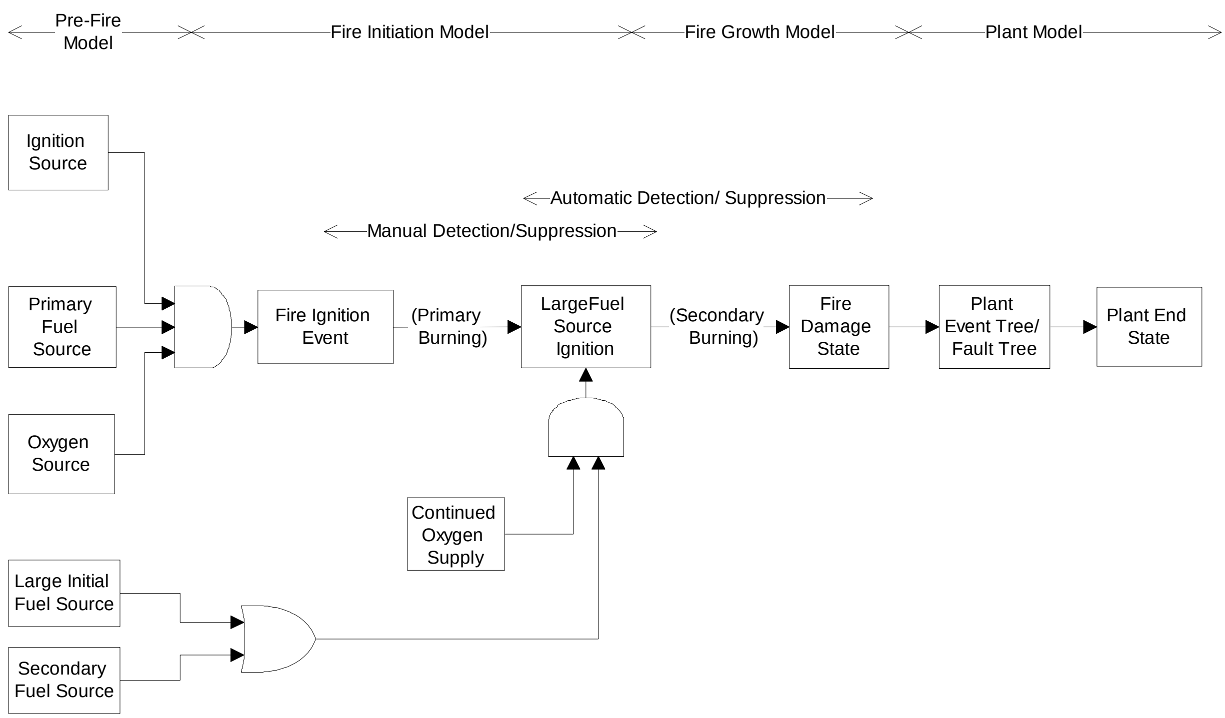


Figure 1. General Structure of a Fire Scenario

2.2.1 The General Structure of a Fire Risk Scenario

At the left in Figure 1 we identify the pre-fire situation, in which, if a fire is to occur, there must exist an initial fuel source, an ignition source and an oxygen source. The coming together of these three results in a fire ignition event. When the physical configuration is such that the generated heat is effectively applied to a reactive mix of oxygen and fuel, a "primary burning" stage occurs, in which the fire, still small, establishes itself upon the initial fuel source. Next, if the initial fuel is large or if a large secondary source of fuel is present in close proximity and the fuel ignites, then “secondary burning” begins. The events up to this point are included in the “Fire Initial Phase Model,” the focus of the current study. With secondary burning, the fire enters a stage of growth and spreading. This phase is usually modeled by a "Fire Growth Model," which describes the life history of the fire as it spreads and ultimately either burns itself out or is extinguished by safety systems and/or human action. In parallel with the Fire Initial Phase Model and the Fire Growth Model, fire detection and suppression activities may begin. Of major interest during the fire growth phase is whether the fire damages or causes improper operation of important plant equipment, such as control circuits, pumps, valves, cables, etc., or of plant personnel.

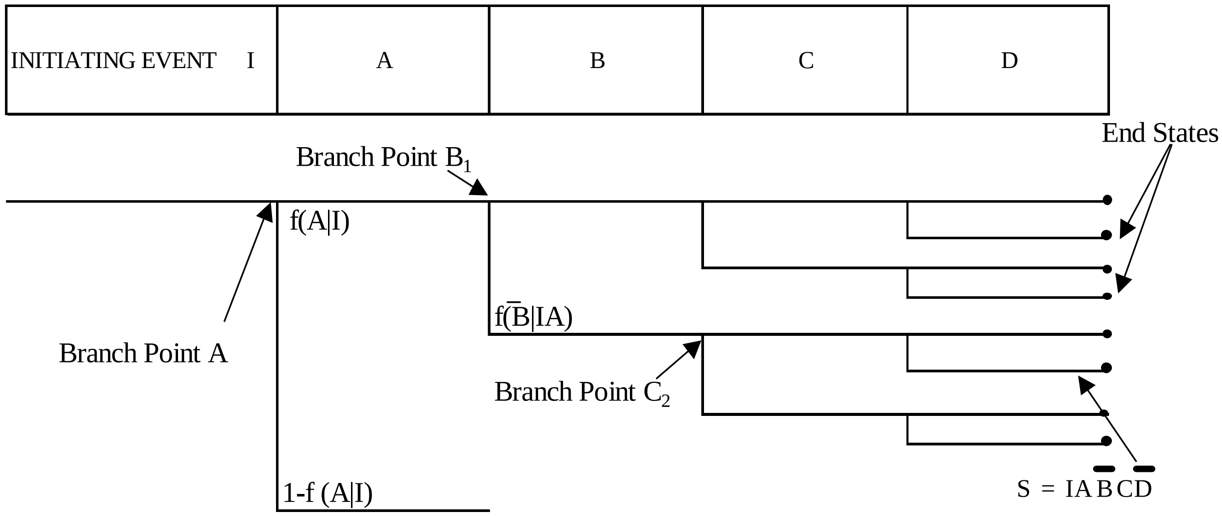
If such damage or improper operation occurs, the consequences to the plant as a whole are usually analyzed with the aid of a "Plant Model."

2.2.2 The Plant Model

Typically, a reactor plant model is expressed in the form of a set of "event trees," a very simplified example of which is shown in Figure 2. Usually this plant model is constructed before the FRA, during the internal events PRA. It models how the plant responds functionally to process upsets and includes automatic and manual responses and the possibility of functional failure due to equipment failure and human actions. For fires to challenge the plant, they must interrupt steady-state operation through one of the functional upsets (plant initiating events) described in the plant model and additional functional failures must occur as defined in the plant model. Therefore, the plant model provides the structure to evaluate the frequency and consequences of fires. In addition, it defines the equipment (targets) that must be examined in the FRA.

The tree starts, on the left, with a "plant initiating event," for example a turbine trip. The tree then branches at various points according to whether subsequent plant safety systems respond to the plant initiating event successfully or not. Each path through the tree thus represents a "plant scenario" leading from the plant initiating event to a plant end state which could be a safe shutdown, or a "plant damage state" which might include release of some quantity of radioactive material.

We might also refer to such a tree diagram as an "outgoing scenario tree" since it portrays the possible scenarios emerging from the plant initiating event. This outgoing tree is usually supplemented by incoming "subtrees," at each branch point (as represented in Figure 3), to delineate ways that the safety systems can fail to respond properly. There would also be such a subtree leading to the plant initiating event itself.



$$S = IA\bar{B}C\bar{D}$$

$$\phi(S) = \phi(I)\ f(A|I)\ f(\bar{B}|IA)\ f(C|I\bar{A}B)\ f(\bar{D}|IA\bar{B}C)$$

Figure 2. A Simple Event Tree Showing a Direct Process for Quantifying Scenarios

These supplemental subtrees provide the "connection points" by which the fire scenarios hook into the plant model. Given the effect of the fire on these subtrees the plant model then tells us what kind of plant end state results.

2.2.3 The Fire Growth Model

The fire growth model is usually a computer simulation [e.g. (Siu 1983), (Ho 1988), (Peacock 1993)] of the life history of the fire from “secondary” fuel ignition to extinguishment. Thus, if secondary burning initiates in a certain location, in a certain room of the plant, current fire growth models typically simulate this as an "equivalent pool fire" and then predict how it will grow, and spread, and what damage it will render to plant equipment and personnel before it either burns itself out or is extinguished. This "fire damage state" hooks into the plant model, either through an incoming subtree to a plant initiating event, thus creating a plant initiating event, or through one or more of the incoming trees to the branch points, thus compromising the ability of the corresponding safety systems to function if called upon, or both.

We note that the concept of fire damage state includes not just equipment damage, but also damage to the humans in control of the plant. This includes both physical damage and also damage to the state of mind, in that a fire can result in panic, confusion, wrong diagnoses, and wrong actions on the part of the humans.

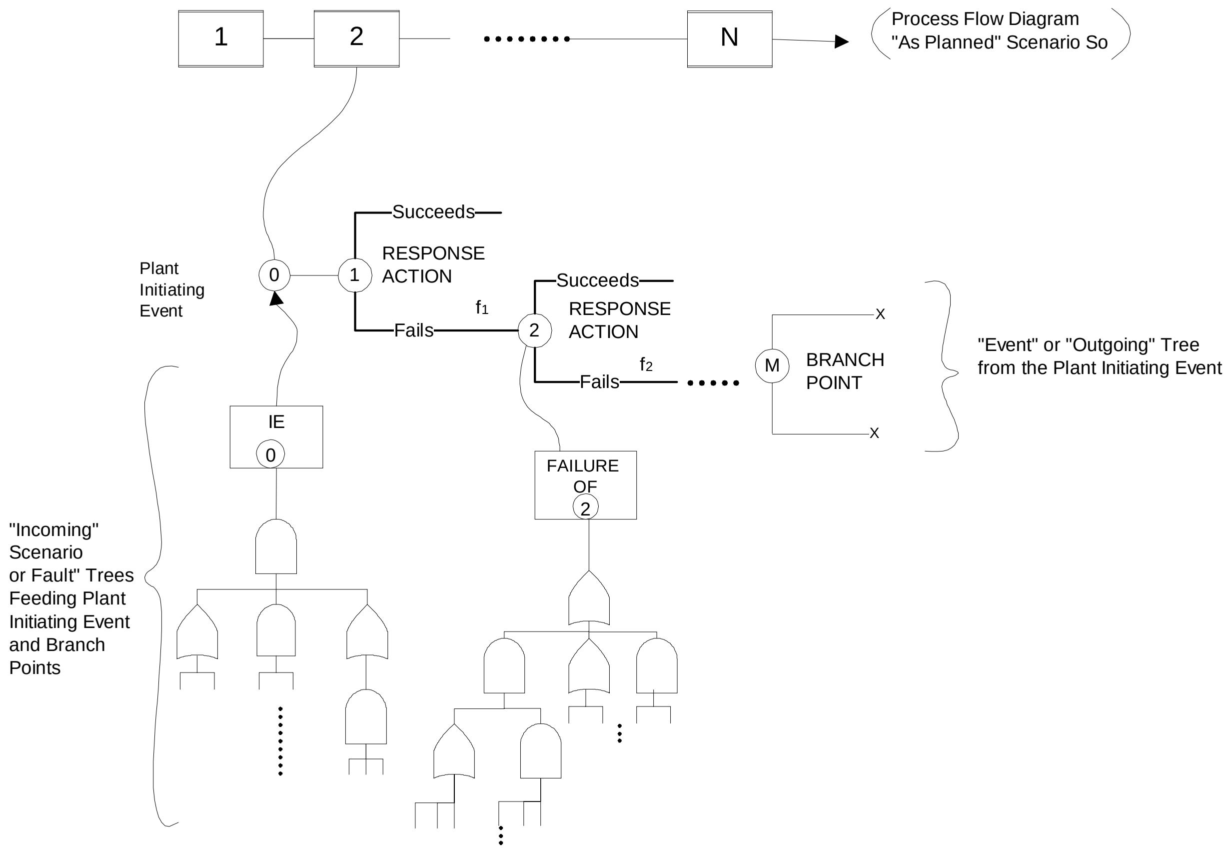


Figure 3. Use of Outgoing Tree and Incoming Subtrees In Relation to the "Success" or "As Planned" Scenario, S_0

2.2.4 The Fire Initiation Model

The fire initiation model begins with our understanding of the ways a fire could get started. Typically, such a model would be developed for various specific locations or rooms within the plant. The ignition source, initial fuel source, and oxygen source are "resources" for the occurrence of a fire ignition event. Note that these resources are both necessary and sufficient. If all three are present, in the proper physical configuration, there will be a fire initiation. If any one is absent there will be no initiation.

Given that a fire has initiated, it will not grow into a challenging fire unless a large source of fuel is involved, i.e., the primary or a secondary fuel. Large fuel sources (e.g., a pool of liquid) are generally difficult to ignite and burn. Usually, the initial fire must provide a sustained heat source. Then that heat source, the secondary fuel, and available oxygen must be configured in a way that supports ignition and growth, e.g., a vertical rather than horizontal cable tray, oil in a pool on the floor rather than contained within a piece of equipment. Generation of a sufficient heat source and ignition of a significant quantity of fuel is considered part of the fire initiation model.

2.2.4.1 The Pre-Fire Model

The pre-fire model identifies the presence or absence of the three resources necessary for a challenging fire and the configuration of those resources. Note that if an area of the plant is inerted to eliminate the presence of oxygen, this would be an important condition.

2.2.4.2 The Fire Initial Phase Model

The fire initial phase model is the name we give to the combination of the pre-fire model and the fire initiation model. When the model is specialized to a specific case, that case is called a "fire initial phase scenario" (FIPS). The methodology for characterizing and quantifying the frequency of challenging fires is based on the FIPS: how to define them and how to quantify them.

2.3 DISCUSSION OF THE GENERAL STRUCTURE

2.3.1 Pre-Fire Model

In general, important events in the fire scenario occur long before the ignition source sets the fire in motion. Information regarding fixed (in-situ) and transient combustibles and fixed and transient ignition sources should be gathered. For example, for fixed combustibles are they: anticipated (e.g., insulation, lube oil, fuel oil) or unanticipated (e.g., wrong material, unprotected material). In the case of transient combustibles, are they: used in a room (e.g., maintenance, construction) or stored in a room (e.g., planned storage, administrative violation). Likewise, for fixed ignition sources are they: normally present (e.g., hot surfaces, electrical) or a result of component failure (e.g., electrical, mechanical). For transient ignition sources are they: used in maintenance/construction activities (e.g., welding) or an administrative violation (e.g., smoking). Attention should also be given to maintenance/construction activities which may damage systems or require deactivation of plant systems, or to plant operational anomalies. Whether or not the fire location is attended or unattended is also important. The pre-fire situation determines the potential for a challenging fire.

2.3.2 Fire Initiation Model (Fire Source)

The fire initiates when an ignition source of sufficient strength (e.g., temperature, energy release rate) contacts a combustible (e.g., insulation, oil) in the presence of oxygen for a sufficient time to cause flaming or smoldering combustion. A fire source includes the ignition source and the initial fuel source, also called the "primary fuel." This initiating event may occur in a component or piece of equipment (e.g., motor, switchgear cable) or may be a consequence of a transient ignition source contacting a transient or fixed combustible. In many instances, ignition of the target combustible is marginal, i.e., an electrical short in motor windings results in smoke, but no flame, or a welding torch impinges on a plywood panel, but only chars it. Unless the initiating event releases sufficient energy to enable the fire to grow and involve additional (secondary) combustibles (e.g., an electric motor fire igniting pump lubrication oil, a dry (no oil) transformer fire that spreads to cable), the initiating event may not grow to become a challenging fire. Furthermore, the growth of the fire depends not only on the presence and combustibility of these fuels, but also upon their configuration or orientation, e.g. vertical rather than horizontal for solids, confined or unconfined for liquids.

Thus the identification of FIPS requires a knowledge of components/equipment in the area, their associated combustibles (e.g., insulation, oil), their configurations, ignition potentials, energy release rates, and the total heat content for each fixed ignition source. In general, there are large uncertainties in information to characterize their heat release rates.

2.3.3 Fire Growth Model

If the total energy released by the primary fuel source is insufficient to result in a challenging fire, another combustible, such as cable or oil, must become involved. The rate of fire spread is important, because it determines the time after ignition when the fire reaches a dangerous size, i.e., one that is difficult to extinguish. Fire may spread either between contiguous fuel elements (e.g., switchgear transformer/cabling) or by impinging on or jumping across the gap from the initially ignited material to a nearby combustible item (e.g., pump fire/transient flammable liquid). If the contiguous material is arranged to permit upward flame propagation, fire growth will occur very rapidly and at a progressively accelerating rate. If the secondary combustible is a liquid, flame spread over the surface is relatively slow when the liquid is well below its flash point, but possibly a hundred times as rapid if the liquid is above its flash point. If the liquid has atomized, fire spread will be very rapid.

When the original burning material is separated by a gap from the nearest secondary combustible, and the flame does not impinge directly on this secondary material, the fire will die out after the original material is consumed, unless by some mode the fire can spread across the gap. This can occur in numerous ways. A fire may heat the secondary combustible by direct radiation, or indirectly by radiation from walls, the ceiling, or the hot gas layer resulting from the initial fire. In any event, radiation may preheat the secondary material until it pyrolyzes, emitting flammable vapors, which then ignite. The fire may spread by melting or dripping (e.g., thermoplastic polymers) or by mechanical collapse of the original burning material. In the generation of FIPS, the analyst must explore all potential routes for fire spread to secondary materials. Challenging fires often involve significant quantities of secondary combustibles.

2.3.4 Detection and Suppression

When and how a fire is detected have major impacts on the FIPS. The earlier the fire is detected, generally, the smaller it is and the easier it is to control and extinguish. Detection may be done manually, almost simultaneously with the initiating event, e.g., detected by the fire watch during welding, during routine plant activities, or in response to investigating the smell of smoke. If the detected fire is small, extinguishment with portable fire extinguishers or other means may be possible. However if the fire has progressed to the point that the plant fire brigade or outside fire fighters must be called, the fire has the potential to result in a challenging fire. The effectiveness of automatic detection systems depends on the specific situation, such as the nature of the fire, the type and location of the detector, and the compartment ventilation. In developing the FIPS the analyst must include the time and means of detection[1], since these parameters will greatly influence the subsequent growth of the fire.

2.4 IDENTIFYING THE FIRE INITIAL PHASE SCENARIOS (FIPS)

The quantitative assessment of the risk from fire in a nuclear plant, like any other risk assessment, begins with the definition of risk as a "set of triplets" (Garrick 1981)

$$R = \{<S_i , L_i , X_i >\}_C$$

where S_i denotes the "i^{th} fire risk scenario, L_i denotes the likelihood of that scenario, and X_i denotes its consequences. Clearly then, the first and most important part of a fire risk analysis is to identify the possible scenarios S_i . If our goal is to assess the fire risk, we do not necessarily have to explicitly identify the individual incoming scenarios to the fire ignition event. It would be sufficient to estimate the frequencies of these ignition events, primary and secondary fuel ignition, and fire damage states from the operating experience of nuclear plants, if data were available at that level.

On the other hand, if our goal is risk management and risk reduction, then it is useful to identify the individual incoming scenarios explicitly, as many as we can think of. It is best that this be done in a systematic way, with the scenarios organized in categories and subcategories, etc. For this purpose we shall apply the ideas of the Theory of Scenario Structuring (Kaplan 1998).

The first principle of this theory is that, before identifying the risk scenarios S_i, we should very clearly define the "success scenario," which we denote by S_0. In its application to nuclear power plant fire risk this principle means that for each "room" or "fire area" in the plant we should identify the contents of that room, the equipment and materials that are present, the functions and operations that go on there, the personnel present during various stages of plant operation, the fire protection/suppression equipment present, etc.

The second principle of this theory is that any risk scenario S_i , being a departure from S_0 , must have a point of departure. Applied to fire scenarios this means that there must be a fuel present, there must be a source of ignition, and there must be a supply of oxygen. These are the "resources" necessary for a significant fire to occur.

Actually, we find it useful to distinguish what we call primary and secondary fuels. The primary fuel is the fuel that ignites initially. It catches fire easily and then provides enough heat to ignite the secondary fuel, which then leads to a significant fire. (In some cases the primary and secondary fuel are the same.) In developing scenarios, it often helps to stimulate our creative juices, by asking ourselves the provocative question: "If I wanted to create a fire ignition event in this location, how could I do it?"

---

[1] Early manual detection/suppression is part of the FIPS. While detection/suppression characteristics could often be associated with the FIPS, we choose to rely on the detection/suppression data (Kolazkowski 2000), except in cases not covered in the data or cases where unique characteristics argue against using average results.

2.4.1 The Concept of "Resources"

In furtherance of this last question we could now ask ourselves: "What resources would I need to create a fire ignition event in this room?" and "What resources are present?"

Thus, as we have seen, in order to create an ignition event we need three things, an initial fuel, oxygen, and an ignition source.[2]

We then look at the situation in the location and ask "Are these three resources present?" If they are, and they are together, then ignition will occur, guaranteed!

If one of the resources is not present, we ask ourselves: "Is there a way this resource could be created from other resources that are present? In this way we arrive at the concept of a "resource tree" as suggested in Figure 4.

Recalling, now, that our goal is risk management, we recognize that if one of the necessary resources is not present, and cannot be created from other resources that are present, then that fire ignition event cannot occur.[3]

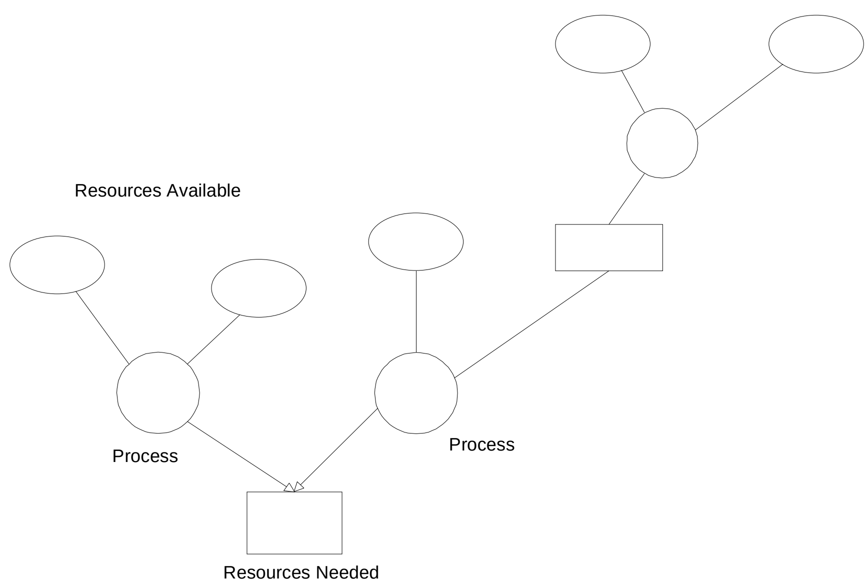


Figure 4. Resource Tree

[2] We need also to bring these three resources together. This could be thought of as a fourth necessary resource.

[3] This line of thinking may suggest some risk management actions to us. For example, suppose we could eliminate, or limit the amount of oxygen available in the room in question.

2.4.2 Resources and FIPS

A major part of FRA is to identify all potential challenging fires in a select group of areas (“critical areas”). Table 1 provides an example starting point for this task. In matrix form, it lists the critical areas where a challenging fire could be risk significant and the class of combustible that could, as a primary or secondary fuel source, generate such a fire. As described above the energy released by the ignition source and the primary fuel alone may be insufficient to result in a challenging fire. Consequently the fire would have to spread to additional (secondary) combustibles to grow to a point that would be risk significant.

The combustible listed in Table 1 should be considered as the major energy release component, either a large initial source or a large secondary source. It must be recognized in the table that challenging fires may involve several secondary combustibles and that secondary fuels may be "created" by the primary source (e.g., primary burning leading to volatilization of combustible gases or a spray of oil that ignites, burning partially as a spray and also creating a larger pool for continued burning).

Also, while Table 1 simply lists “fixed oil”, it must be recognized that in nuclear power plants there are numerous sources of fixed oil, e.g., pump and turbine lubrication oil, transformer oil. Similarly, there are numerous electrical components and transient fuels that must be considered. It may be possible to identify combustibles that are not present in sufficient quantity, e.g., oil in small pumps, to pose a significant risk alone.

Combustible / Area	Fixed Oil	Electrical Component	Cable Insulation	Hydrogen	Transient	...			
Turbine Building									
Switchgear Room									
Control Room									
Battery Room									
...									

Table 1. Critical Areas and Major Combustibles in Nuclear Power Plants

The idea of Table 1 has been used to assist the team to envision, identify and invent possible FIPS that could lead to challenging fires in various areas of the plant. For this purpose it is useful to divide the plant into a finite set of "rooms," or "locations." For each such location or room we then ask ourselves "How could a fire ignition event happen?" The first approach was to move room by room through a plant looking for ways challenging fires could begin. This was done through a combination of brainstorming and elicitation sessions (Budnitz 1997). The FIPS thus identified (1) were of potentially high consequence and not insignificant likelihood, and (2) were confirmed to include important issues identified in previous work (Siu 1997). The second approach was to examine a broad variety of nuclear power plant fires and fit them to the general structure of the FIPS. The FIPS identified in this manner (1) were generally of lower potential consequence and (2) were found to fit the FIPS structure very well.

Brainstorming for Challenging Fire FIPS

The process for searching for challenging fire FIPS began with a survey of rooms in the plant. In each room, fire sources (ignition sources and fuel) are identified. Typically these include switchgear, rotating equipment (pumps, valve motors, turbine generators), oil sources (storage sumps and pressurized lines), cables (instrument, control and power), and instruments. Potential for transient fuels and ignition sources should also be considered. Each piece of equipment is investigated and each investigation is organized as a brainstorming session, rather than a deductive analysis. The idea is to consider as many fire initiation scenarios as possible, even farfetched ones. The approach is inclusive, rather than ordered, and many possibilities are identified from multiple directions. Then the local configuration is addressed and the potential for fire development to the point that a large source of fuel can be involved is evaluated.

The project team has developed an initial set of FIPS using this approach. Analysts can use these directly, if they fit plant-specific conditions, adapt them to local conditions, or develop further FIPS as needed. The initial set began with a wide variety of equipment sources including motor stator winding fires, bearing overheating, oil spray from pressurized lube oil systems, switchgear arcs, fault currents, opening disconnects under power, transformers, diesel generators, turbogenerators, motor generators and batteries.

The brainstorming approach began in these equipment and developed scenarios that went beyond the initial considerations. For example, the session that began with motor stator winding fires also identified oil spray fires and fires due to overheating when bearings seize. It identified key issues such as the possibility of open flames or contained smoldering or cooking, the spatial “danger zone” from various fires, and the factors affecting heat release rate. A sample of the generated FIPS is shown in Table 2. Additional FIPS are recorded in project working notes and are available for future applications.

Key FIPS developed using this approach included four key areas identified as having substantial uncertainty including cable tray fires, pressurized pump oil fires, turbine generator fires and cabinet fires in the main control room.

Table 2. Example of FIPS Developed from Brainstorming Session for Challenging Fires

FIPS ID	Room/location	Equipment/ component	Initial fuel	Ignition source	Secondary fuel	Configuration	Heat release rate
M1	any	motor stator	insulation	high temperature: short	none required	open flame, well ventillated stator area	
M2	any	motor stator	insulation	high temperature: short	none required	tight packed, restricted air flow (smoldering)	
M3	any	motor stator	oil	spark	insulation	open flame, well ventillated stator area	
M4	any	motor stator	insulation	high temperature: release of kinetic energy	oil	open flame, well ventillated stator area	

Fitting Real Fires to the FIPS Structure

In light of the above observations we can set forth the general structure of nuclear power plant fire risk scenarios as shown in the top line of Figure 5. The first box in this scenario tree describes the room or area where the fire starts. The second box describes the specific location within the room and the equipment in which the fire starts. The third box specifies the primary fuel(s) present in that location. The fourth box describes how the ignition came about and the fifth describes the secondary fuel and how it is ignited.

These five boxes describe the "Fire Initial Phase Scenario (FIPS)." From here on a continuation of the scenario would describe the growth of the fire, its effect on plant operation, the effectiveness of the automatic fire suppression equipment, the actions of plant personnel, etc.

We note that the structure laid out in Figure 5 allows for cases in which the primary and secondary fuels could be the same substance, as for example, a gasoline air mixture. which would lead then to an explosion or deflagration,

The structure in Figure 5 also encompasses the possibility of simultaneous, or near simultaneous, ignition at different spatial locations, even different rooms, from a common initial cause, which could result, for example, from overload current in a power cable.

The remaining lines in Figure 5 show how selected actual historical nuclear plant fires lay out against our proposed standardized general scenario.

This approach of laying the general FIPS structure against real fire events was carried out for the 25 significant fires examined in (Nowlen 2001a) and a larger database (Houghton 1997) that includes a broad range of fires. Both are examined in Appendix B. Additional examples are listed in Table 3 and a more complete list of FIPS is recorded in Appendix C to be available for future applications.

Categories of FIPS

The broad-based review of fire events in Appendix B pointed out that our initial FIPS map

ignition source ⇒ primary fuel ⇒ secondary fuel ⇒ large fire

was overly restrictive. Significant numbers of challenging fires fit different pictures as indicated in the four classes of FIPS summarized in Figure 6.

Class 1 (solids, liquids and sprays) is our initial point of view. It covers the obvious cases of a small pilot fire in an easily combustible fuel that, over time, ignites a much larger source of fuel, much as we have all seen in a fireplace or campfire. Note that it is also descriptive of an oil spray that ignites and simultaneously creates a large pool that becomes the secondary fuel.

Class 2 (solids and liquids) recognizes that a large, generally difficult to ignite, fuel source can be directly ignited, if the ignition energy is high enough. A number of self-ignited cable fires have occurred in this manner, when subjected to very high fault current, either too severe for the trip circuits to operate in time or as a result of protective system failure.

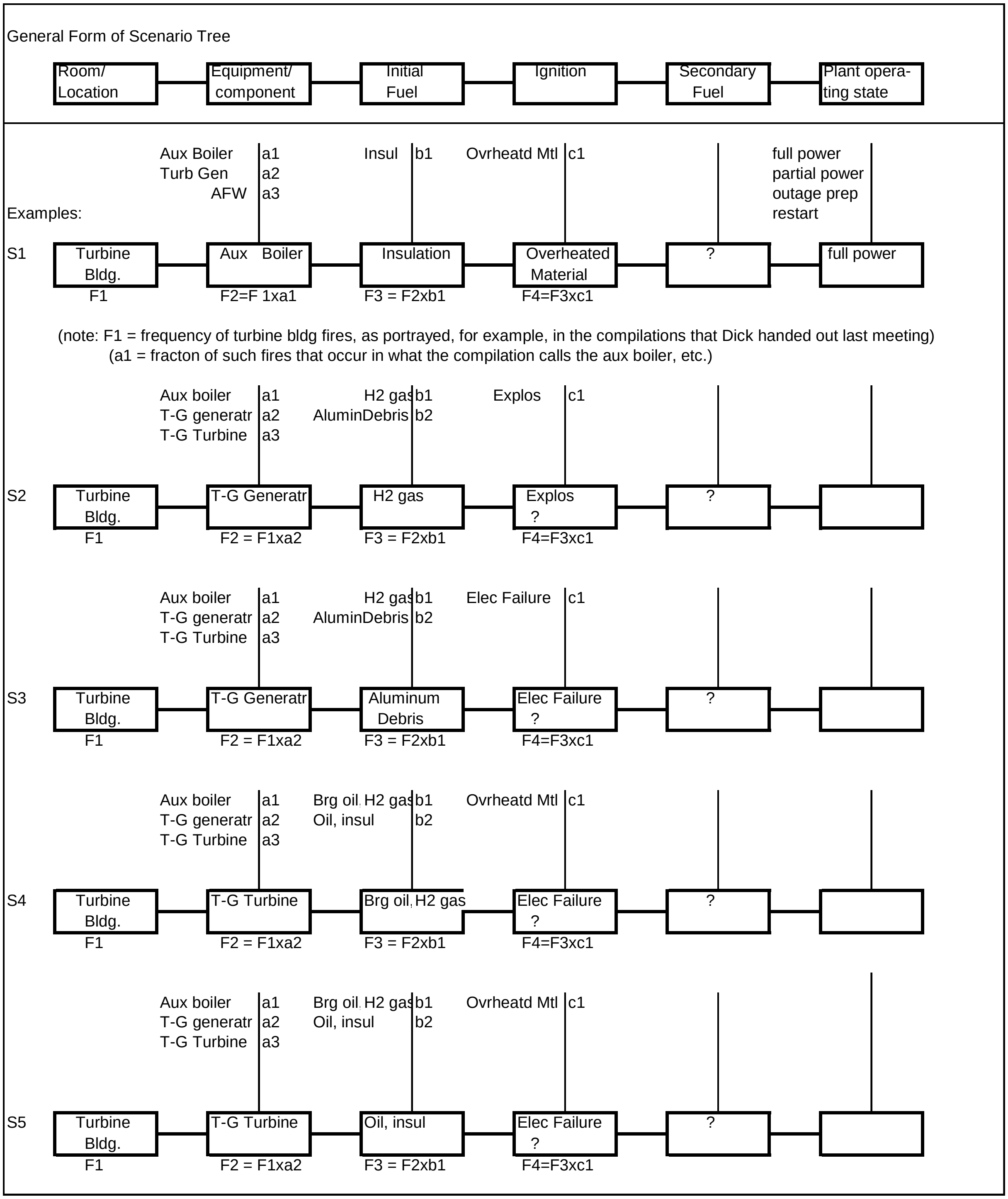


Figure 5. FIPS from Event Data

Table 3. Examples of FIPS Developed from Event Data

FIPS ID	Room/Location	Equipment/ Component	Initial Fuel	Ignition Source	Secondary Fuel	Configuration
Armenia NPP	SW building, 2 separate cable galleries	SW pump	6 kV power cables	high current due to short circuit	none required	open flame in 2 cable galleries
Ignalina-2	cable spreading room	220 VAC cables	cables	short circuit led to high temperatures	none required	open flame in large-volume room
Chernobyl-2	cables in underground duct	control cable for 330 kV air breaker	cables	short circuit led to high temperatures	none required	open flame in poorly ventilated duct
Kalinen-1	turbine building	SW pump	cable connection to motor	arc in pump motor	adjacent cables	fire in closed breaker cubicle
Zaporizhzhya-1	control building	terminal box: loose item fell, caused short	cabling inside terminal box	short circuit in terminal box	cables adjacent to terminal box	closed volume inside terminal box
Beloyarsk-2	turbine building	lubicating oil piping system break	lubricating oil	oil fell on hot surfaces at or adjacent to turbine	none required	open flame in large-volume room
Vandellos-1	turbine building	turbine shaft	hydrogen from turbine after turbine-blade and turbine-casing	hydrogen ignited on hot turbine-shaft metal	oil	open flame in large-volume room; hydrogen deflagration
Greifswald-1	switchgear area	switchgear	cables	short circuit caused by electrician's switching error	adjacent cables	open area

Class 1	**ignition source (typically low to moderate energy) ➜ primary fuel ➜ secondary fuel**	**large fire:** **• flames** **• heat** **• smoke** **• toxic gasses**
Class 2	**high energy ignition source ➜ larger (difficult to ignite) fuel source**	
Class 3	**dispersed air/fuel mixture ➜ ignition source ➜ deflagration (➜ secondary fuel)**	**large fire + deflagration overpressure**
Class 4	**dispersed air/fuel mixture ➜ ignition source ➜ detonation (➜ secondary fuel)**	**large fire + detonation shock wave**

Figure 6. Four Classes of FIPS

A potentially significant database of electrical fault events (at Doble Engineering) has recently been identified in discussions with NRC fire protection engineers. Substantial questions about the nature of cable fires might be answered, if this database is directly relevant.

Classes 3 and 4 (vapor clouds) admit to the possibility of explosion: either deflagration with modest overpressure or detonation that introduces physically damaging shock waves. Both have high potential for secondary fires, if secondary fuels are available and directly affected.

Note that all four classes introduce the possibility of dense smoke and toxic gas generation.

2.4.3 The Properties of "Completeness" and "Finiteness" of a Set of Scenarios.

In nuclear plant fire risk analysis, as in any other kind of risk analysis, the key step is to identify the risk scenarios, S_i. In retrospective analysis of real fire events and in prospective development of mechanistic scenarios we structure the development around the four elements of the model presented earlier: pre-fire, fire source, fire growth, and detection/suppression.

At this point the development shifts to the questions of finiteness, completeness, and quantification, so the model may be slightly recast to support that effort. The set of such scenarios should be finite, and it should be "complete," in the sense that it contains all possible scenarios. The first of these properties is required for the practical purpose of computing the frequencies (quantification); the second is required for the philosophical and practical purpose of convincing ourselves and our audience that we have not omitted, in our risk assessment, any significant portion of the actual risk.

So our task now is to outline how we may identify and define a complete and finite set of FIPS. In approaching this task it is useful to remind ourselves that any scenario we can define is itself actually a set, i.e. a category, of scenarios, and as such has subsets of itself and supersets of which it is a member. So we need to exercise care in defining these scenario categories in such a way that they are non-overlapping, and so that in aggregate they are complete. Also, for computational purposes, as stated above, we also need the number of these categories to be finite.

2.5. Quantifying the Frequencies of the FIPS's

Since, by the way we have defined them, there is only a finite number of such FIPS vectors, we could now go to the history records and see how often each of these vectors has occurred, if data were rigorously collected at a level to support this effort. This would give us actual experience data from which to produce probability curves against the frequency of each such vector.

To produce these probability curves, we should process all the available evidence through Bayes theorem. In doing so we should recognize that the experience of our particular plant is most relevant, the experience of similar other plants is next most relevant, the experience of different types of industrial facilities, naval vessels, etc. is relevant, but less so, etc. Similarly, the experience of recent years is more relevant than the experience of early years. Also, we want to recognize the specific situation at the specific plant at issue, e.g. management controls, fire safety consciousness, special hardware/software measures that have been installed, fire drills, inspections, etc.[4]

For the Class 1 FIPS, a typical 5-vector represents a category of challenging fire initial phase scenarios. Only slight modifications are needed for the other classes. It characterizes this category of scenarios by identifying the key points of the scenarios, namely: the ignition source, the primary fuel, the secondary fuel, the source of oxygen, and the room or location of the fire. If all but one are present, say the ignition source, and in the required configuration, then when the final element is added, the fire will start. To help us quantify the frequency of this category of scenarios, it can be useful to employ the device of a scenario tree. For example, suppose an electrical fault causes a high current in a particular cable in the cable spreading room. This is the fire ignition event. This current causes ignition of the cable insulation (the primary fuel). The radiation and hot gas rising from this initial burning cause ignition of a vertical cable run (the secondary fuel) above the fire, thus resulting in the beginning of a challenging fire. We might draw a scenario tree for this sequence of events as in Figure 7.

This tree can be thought of as a "breakdown," or more detailed presentation of, the category of scenarios represented by the 5-vector (i.e. the FIPS). This presentation helps us in the quantification of the FIPS in the following way: When we ask for the frequency of the FIPS, we are led to look in the historical record for occurrences of the whole sequence. In terms of Figure 7 we would be looking for experience directly related to the frequency $Ø_8$. But the formula given in Figure 7 relates the frequency $Ø_8$ to a number of other parameters. This means that in

---

[4] It is useful here also to make explicit an interesting conceptual point. We have defined the scenarios by abstracting from actual fire incidents. We can now estimate the frequency of occurrence of this abstracted category from the history of nuclear plants and other industrial facilities, etc. This frequency will be a finite, nonzero, number. On the other hand the frequency of the specific scenario ever occurring again, exactly the way it did, is zero. The generalization/abstraction is essential for moving to the stage of quantification. It allows us to define a finite set of categories of scenarios instead of the infinite set we would get if we tried to define the scenarios precisely.

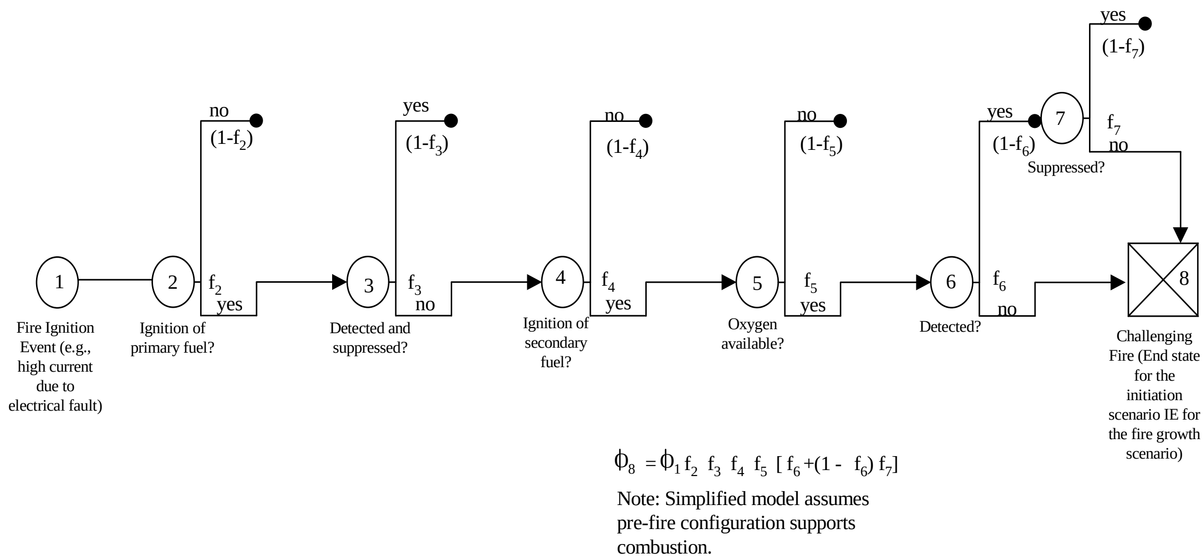


Figure 7. A Typical Scenario Tree for a Challenging Fire Initiation

trying to evaluate $Ø_8$ we can now make use of, "harvest" so to speak, all the historical experience and knowledge we have relating to the numerical values of the other parameters $Ø_1$, f_2 , f_3 , etc.

In the following sections, we discuss approaches for quantification, when the data have not been collected with the FIPS approach in mind.

2.5.1 How the FIPS Approach Aligns with traditional fire-PRA

In the traditional fire-PRA methodology, the frequency of a potentially challenging fire is the product of two factors, the ignition source frequency multiplied by the severity factor.

Ignition Source Frequency. At the outset, it is important to note that when we speak here of a database for "ignition source frequency" we are speaking of data on all fires that have been reported, whether large or small -- only a fraction of these have the potential to become what we call "challenging" fires.

The ignition source frequency is developed from one or another fire-ignition database, in which all reported fires, whether large or small, are collected and sorted by two parameters -- by Room Type (RT) and by Large Component Group (LCG). (For example, all fires in motor control centers in reactor turbine buildings would be compiled into a separate "bin" in the database.) The relevant databases used for this purpose in principle collect their data from all nuclear-power-reactor facilities.

Three important assumptions are implicit in this approach: (a) first, it is assumed that all members of the same LCG within a Room Type are equally likely to be an ignition source; (b) second, it is assumed that all Room Types in different reactor facilities are identical for the purposes of the frequency of fire initiation; and (c) third, it is assumed that there is no difference among sub-areas or sub-rooms within a Room Type.

These assumptions are equivalent to assuming that all members of a Large Component Group within a similar Room Type are identical, and that within a Room Type, fire ignition frequency is independent of location. While we know that these assumptions are reasonable at some high level, we also know that they cannot be true at a very detailed level. Of course, because of the way the fire-ignition data are now reported, it is often true that differentiating further (for example, subdividing the ignition frequency into sub-areas or sub-rooms within a Room Type, or differentiating a RT in one reactor facility from the seemingly same RT in another facility) cannot be supported by today's existing data. Indeed, we give credit to the efforts of the data-base compilers, who have worked diligently to sub-divide the existing fire-ignition data into RT-LCG "bins" as finely as they can given the current reporting methods.

Severity Factors. The severity factor (SF) is a number between 0 and 1 that represents the fraction of fires in each ignition-source-frequency database "bin" that have the potential to become a challenging fire. The use of the SF allows the analyst to eliminate those fires in the fire-ignition database that do not have such a potential.

There are two important assumptions in this approach: (a) First, a single Severity Factor is applied to each LCG-RT "bin" emerging from the fire-ignition database described above, which means that all of the assumptions above remain as embedded assumptions here. (b) Second, for any individual LCG-RT "bin", the analyst uses a single stylized fire type --- specifically, a fire with a selected fuel, an amount of fuel, and a selected Heat Release Rate --- as the stylized "challenging fire" that is contemplated when developing the SF. Said another way, after the SF is applied to a given LCG-RT "bin" in the fire-ignition database, the resulting frequency of a "challenging fire" is intended to characterize a single typical or stylized fire for that LCG-RT "bin". This stylized fire is taken as representative of all challenging fires within that "bin."

It is widely acknowledged that there is a certain amount of subjectivity or expert judgment involved in the numerical Severity Factor assignments for the LCG-RT "bins". This is inevitable, given that today's nuclear-plant fire databases do not have enough challenging fires to support the assignment of Severity Factors solely from the data -- fortunately, there have not been many large fires.

2.5.2 The FIPS Approach

In order to do better, one needs both a more mechanistic approach and different fire initiation data -- data collected specifically to support this mechanistic approach. The mechanistic approach can also capture the uncertainties in the fire-initiation frequencies in a more useful way and in a way supported by specific mechanistic understanding.

In our new approach here --- the Fire Initial Phase Scenario or FIPS approach -- the function of the fire-ignition data grouped into Large Component Groups is, in effect, replaced by a "scenario pre-tree" approach. Referring to Figure 3 and Figure 7, one sees that

(a) the frequency with which a fire ignites for a given Large Component Group is captured by the scenario pre-trees shown in Figure 3, along with the factors f1, f2, and f3 of Figure 7;

(b) the Severity Factors aspect is captured by the factors f4, f5, f6, and f7; and

(c) the overall frequency of a challenging fire is thus captured not by the product of the LCG term and the SF term, but by the expression in Figure 7 that encompasses f1 through f7.

In effect, binning the ignition frequency data by Large Component Groups is replaced by using the pre-trees, differentiated by Room Type as appropriate and supported where feasible by explicit data.

Furthermore, the traditional approach assigns a best-estimate HRR (heat release rate) to each LCG-RT "bin", whereas in the FIPS approach the same concept is targeted better, accounting intrinsically for the variabilities and uncertainties in the specific scenario.

At least in principle, actual fire data can be collected in a manner that supports this approach, thereby obviating the need for using much judgment in the groupings. Until such data exist --- until the data are gathered and compiled in a way that can support the new approach -- it will still be necessary to employ judgment in assigning the numerical values to some of the inputs.

2.6 The Mechanistic Link to the Fire Growth Model

The FIPS lays out a mechanistic pathway for fire initiation. It is also the link between fire initiation and subsequent fire modeling.

Addressing uncertainty directly in the consideration of the HRR process brings important issues to the front of the analysis, where they can be examined and clarified. The existing approach is an odd mix of the conservative and the optimistic; therefore the integrated position vis a vis uncertainty is unclear.

Fire growth rates depend on a number of variables, including fuel type, fuel configurations, and ignition energy. Current fire modeling, e.g., COMPBRN, employs a conservative approach to estimate peak heat release rates, but only for selected fires. That is, while the use of peak HRR would appear to be very conservative, it is usually a single peak HRR selected as being “typical” or “realistic.” It is often the result of a single “reasonable” experiment, when the range of observed HRRs over many experiments includes much higher cases.

Generally these estimates are made by multiplying a unit heat release rate for a given fuel associated with fully involved conditions times the total exposed surface area of the fuel. This methodology of estimating peak fire intensities is unrealistic. It assumes that the entire exposed surface area of the fuel will be actively burning; it neglects the period of fire development during which the actual fire intensity is diminished from the peak rate. During this time opportunities for detection and suppression exist. Further, many fuels are three-dimensional in configuration, making the estimate of the burning area as a function of time (a necessary parameter to appropriately estimate heat release rates) difficult. The FIPS Methodology with its attention to fire spread and growth, should focus attention on the specifics of real challenging fire scenarios that determine the heat release rate history. It is anticipated that the current approach may need to be modified to ensure realistic target-in-plume, target-in-ceiling jet and radiant exposure scenarios.

The approach recommended here is to offer several stepwise improvements and the analyst can use the one that best fits the FIPS in question.

For FIPS involving pool fires, the simplified calculations based on the SFPE Handbook (SFPE 1995), as developed by NRC's fire protection engineers (Iqbal 2000) offers the ability to calculate flame height for a wide range of potential conditions. Thus uncertainty in the fire characteristics can be calculated directly, if approximately.

For FIPS involving estimates of HRR over time, uncertainty can be addressed in two steps, (1) simplify the problem by using an average HRR for a fixed time and (2) refine the problem by using the correct density of HRR over time. The average HRR can be estimated from the HRR curves for a number of cases in the Sandia and other data. The SFPE Handbook gives a number of these as well. For example, Figure 8 for wood pallets is taken from Section 3, Chapter 1. The important requirement is to look at the full range of uncertainty, not just a single "reasonable" case, when the results vary by large amounts.

2.7 Treatment of Uncertainty

A formal approach for the treatment of uncertainty has been developed and is consistent with recent U.S. Nuclear Regulatory Commission efforts to establish a standard systematic approach for treating uncertainty. In particular, all factors that can affect quantification-including-uncertainty should be included (at least conceptually). Of these many factors, those that have the potential to affect quantification-including-uncertainty must be examined in detail (as noted in the description of the process above). This involves a determination of which of the three cases vis-à-vis uncertainty apply:

- Deterministic. When there is no variability or imperfect state-of-knowledge that leads to variability in the results.
- Aleatory uncertainty. When there is random variability in any of the factors that lead to variability in the results.
- Epistemic uncertainty. When the state of knowledge is less than perfect, given the budget and the model.

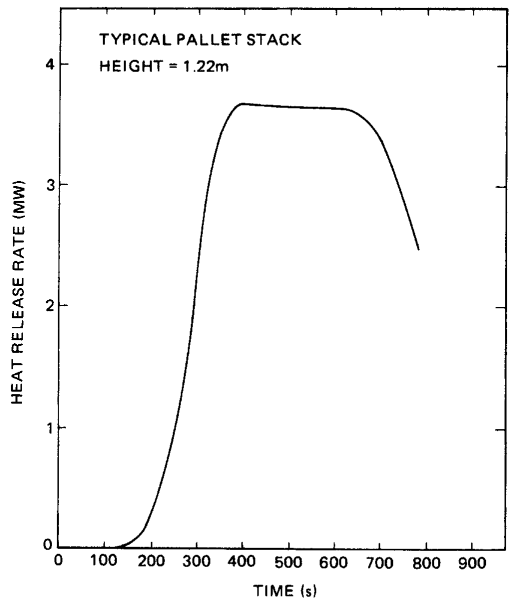


Fig. 3-1.4. Typical heat release rate for a wood pallet stack.

Figure 8 Example HRR Curve Taken from (SFPE 1995)

A more operational point of view is that uncertainty is aleatory if:

- It is (or is modeled as) irreducible or
- The uncertainty is observable; i.e., repeated trials yield different results or
- Repeated trials of an idealized thought experiment will lead to a distribution of outcomes for the variable and then this distribution is a measure of the aleatory uncertainties in the variable.

Aleatory uncertainties are quantified using variability distributions from observations or aleatory probability models, such as the Poisson process.

The uncertainty is epistemic if:

- We are dealing with uncertainties in a deterministic variable whose true value is unknown or
- Repeated trials of a thought experiment involving the variable will result in a single outcome, the true value of the variable or
- It is reducible (at least in principle).

Epistemic uncertainties are quantified using probability distributions.

Looking specifically at the factors affecting uncertainty in the FIPS quantification, we offer the following catalog.

Pre-existing Conditions. All appear to be aleatory.

- Doors open/closed:
  - Between compartments
  - Electrical cabinets
  - Safety (storage) cabinets
- Inoperative instrumentation/electrical components
  - Sensors (e.g., flammability limits, heat and smoke detectors)
  - Electrical protective devices (e.g., breakers)
- Improperly positioned (open/closed) valves (e.g., suppression system)
- Open flammable liquid containers
- Transient Fuels.
  - Location (e.g., near motor windings, piled in a corner)
  - Improperly abandoned (e.g., in cable trays or electrical cabinets)
- Combustibles (e.g., dust in HVAC ducts and return plenums)
- Out of specification lube oil (e.g., low flash point)
- Code violations
  - Non-fire treated wood
  - Non-IEEE-383 cable
  - Improperly sized electrical protection equipment

Conditions During Fire

Solids

- Initial temperature (e.g., aleatory if wire insulation has been preheated prior to flaming combustion).
- Availability of oxygen. Burning rate decreases as oxygen is depleted since combustibility of pyrolysis products decreases. Epistemic for the specific configuration; aleatory as affected by HVAC functionality.
- Heat losses/heat feedback. The rate of burning of an object is dependent on the heat flux to the surface. This is influenced by the position of the solid in the room and the subsequent heat feedback from the flames, hot gases, walls and ceiling, other objects. For example, the burning rate of a chair in an open field will be slower than in the middle of a small room; the burning rate of the chair would be even higher in a corner of the room. For a fixed configuration, this is epistemic; nevertheless, there is some indication (non-repeatability of some experiments) that random factors, beyond our ability to discriminate among seemingly identical conditions sometimes obtain.

- Geometry (including thickness). For example, a telephone book is difficult to burn, but a loose pile of pages ripped out are not. A single log in a fire place cannot burn alone; wood shavings can. Epistemic.
- Combustibility of fuel. Some solids are easy to burn, others are not. It depends on chemical composition and presence or absence of flame retardants. Epistemic.
- Presence of a second fuel. Another fuel, once ignited, will increase the heat flux to the solid increasing its burning rate. Epistemic for fixed fuels.
- Presence and effectiveness of a suppression system. Gaseous suppression system (e.g., N_2, CO_2, halon) reduce (or remove) the oxygen availability. Liquid suppression systems (e.g., water) cool the burning surface and the surrounding gases, reducing the burning rate. Presence is fixed; effectiveness is epistemic in principle for a fixed configuration; nevertheless, there is some indication (non-repeatability of some experiments) that random factors, beyond our ability to discriminate among seemingly identical conditions sometimes obtain.

Liquids

- Type of liquid. Some liquids burn readily (low flash point) other are more difficult to burn. Epistemic.
- Rate of fuel supplied to the fire [i.e., size (diameter) of the leak, pressure of the fuel (oil), whether or not contained]. This is primarily aleatory, because of randomness in break size and location, and pump operability.
- Geometry (form) of the fuel (e.g., pool, diameter, depth of the pool, spray). Epistemic to the extent that situations are repeatable.
- Initial fuel temperature. Aleatory.
- Availability of oxygen. Epistemic for the specific configuration; aleatory as affected by HVAC functionality.
- Heat losses, heat feedback. Epistemic to the extent that situations are repeatable.
- Presence (or absence) of a second fuel. Epistemic.
- Presence of a suppression system. Fixed.

Other (than HRR) Important Factors for FIPS

- Magnitude (i.e., intensity - temperature, energy) and duration (time in contact with a fuel) of the ignition source. Aleatory.
- Physical dimensions of initial fuel, i.e., thermally thin or thermally thick. Epistemic
- Availability and proximity of a secondary fuel, if initial fuel source is limited or has a low HRR. Epistemic.
- Detection means and delay. Aleatory for manual detection.
- Initial Suppression Activity. Alkeatory for manual.
    - Method (manual or automatic)
    - How quickly initiated
    - For how long suppressant applied (affects possibility of flare-up)

2.8 Conclusion

What have we done in this section? In traditional fire risk assessment for nuclear power plants, the fire scenarios typically begin with a "pool fire" representing the burning of fuel. The frequencies of such events are estimated directly. The analysis then traces the growth of these fires using a fire growth model. This model calculates the possible fire damage states (FDSs), showing the impacts of the fire on plant equipment and personnel, including alarms, automatic shutdowns, activation of sprinkler systems, etc. The effect of these impacts is evaluated by entering them into the plant model (PM) which then calculates the plant damage states (PDSs), showing what damages, if any, result to the plant and/or its surrounding environment. The traditional method assesses the frequencies of these scenarios from reactor plant operating experience.

What we are proposing here, is the addition of a fire initial phase scenario (FIPS) that leads from the pre-fire situation through the ignition of the primary/secondary fuel. This model will allow us to more explicitly identify, understand, standardize, and quantify the FIPS that lead up to challenging fires.

[This page intentionally blank]

3 A Methodology for Characterizing and Quantifying the Frequency of Challenging Fires

The FIPS method involves:

(a) Screening out unimportant rooms, then proceeding room-by-room (as in current methods)

(b) Developing FIPS scenarios

(c) Screening out the unimportant fire initiation scenarios

(d) Quantifying the potentially important initiation scenarios

3.1 Screening Unimportant Rooms

The first step in the analysis involves evaluating each "room" in the nuclear power plant. Here we use the term "room" to describe loosely any defined fire area, zone, or other circumscribed part of the plant that is surrounded by fire barriers or spaces sufficient so that a fire starting in that "room" has only a very small chance of spreading beyond the boundaries. The objective of this first -stage evaluation is to screen out those "rooms" that cannot possibly contribute significantly to overall risk.

The standard approach (FIVE 1992) to this screening is to assume that a fire in the room entirely destroys everything in the room. Using a PRA model, or sometimes even without such a sophisticated model, it is often possible to conclude for a given "room" that there cannot be an important compromise to plant safety. For example, if there is no safety equipment whatsoever in the room the screening is easy. If there is such equipment, then the PRA model can be used to work out the conditional core-damage probability (CCDP) assuming its total destruction. Using a conservative frequency F for fires within the room, based on data or judgment, a conservative estimate of core-damage frequency CDF is:

$$CDF = F \times CCDP.$$

If this value is below some screening level, then the entire "room" can be screened out.

The approach to this preliminary screening is well described in the FIVE methodology, which contains detailed guidance on issues to be considered. Other equivalent guidance on screening methods can also be used. For some rooms, this screening might not even require a visit to the room, but such a visit will be necessary for others.

The next series of steps is undertaken room-by-room for those rooms that cannot be screened out using the conservative approach just discussed.

3.2 Identifying Resources, Fuel, Oxygen, Ignition Sources, and Configuration in the Room

This step involves identifying and recording the specific contents/attributes of the "room" that could contribute to the initiation of a challenging fire. This work almost invariably involves a physical visit ("walkdown") of the room to ascertain the actual physical configuration.

The purpose of this step is to identify and record all relevant equipment and configuration information in the room, as well as to identify the frequency of any activities that could involve transient fuels --- this would include activities such as cleaning, welding, and various repairs. Experience with evaluating how challenging fires might start is a prerequisite for accomplishing this step effectively.

The identification work involves the following, all of which must be documented:

(a) Identifying the boundaries of the "room".

(b) Identifying the air-intake and air-exhaust aspects, including both active and passive air-exchange mechanisms and paths. This includes identifying features (seals, dampers, doors, etc.) connecting through barriers to outside the room that might be initially open or closed, and also the circumstances under which these features might be opened or closed, actively or passively, after a fire were to begin. This work supports the evaluation of whether oxygen availability would be limited or unlimited during a fire.

(c) Identifying the presence, amount, and character of all combustibles in the room, whether fixed (cables, oil reservoirs, free chemicals, etc.) or transient. This includes identifying the presence of natural-gas or other combustible gases such as hydrogen in the room, whether piped in or in containers.

(d) Identifying all activities in the room (welding, repair, etc.) that could lead to a fire, i.e., contribute an ignition source for primary fuel, even under abnormal conditions. The approximate frequencies and durations of each such activity should also be identified.

(e) Identifying the electrical-power situation in the room – the presence of power cables or high-electrical-density equipment such as transformers, switchgear, etc.

(f) Identifying all fire-ignition energy or fuel sources in the room. This includes electrical, mechanical, and chemical energy sources. To assist in this evaluation, use of standard combustion-source lists is encouraged, supplemented by experience.

(g) Identifying the configuration of all equipment in the room relevant to initial fire spread beyond ignition. This involves recording the proximity of items one-to-another, in terms both of physical distance and of layout (relative elevation, intervening items that could shield from radiative or convective heat transfer, etc.)

(h) Identifying fire-detection capabilities in the room, whether active or passive, and including the frequency of occupancy by personnel. This includes an evaluation of the reliability of human detection of a small early fire in various locations.

(i) Identifying fire-suppression capabilities in the room, including installed automatic suppression, installed suppression actuated manually, manual fire-fighting equipment, and the capability to signal or observe the presence of a small early fire to personnel outside the room.

3.3 Inductive Analysis: Identify FIPS in the Room

This step builds on the information gathered and recorded in the previous step. It is to be performed for each room that is not screened out above. The objective is to identify the most appropriate FIPS for the room.

The analyst has several possible approaches to accomplish this task. They include:

(1) Consult the list of generic FIPS scenarios; if there is a close enough match between one of these and the room/configuration under review, the generic FIPS can be used directly.

2) If the match is close but not close enough, then an adaptation of the generic FIPS can be used. The nature of the adaptation will depend of course on the type and extent of the deviation between the actual room/configuration and the generic FIPS.

(3) A new FIPS scenario can be generated as discussed in Section 2. One or a combination of approaches can be used:

- Records can be used of actual fire events at the plant;
- Records can be used of actual fire events elsewhere in the nuclear-power industry, or more broadly if available and applicable, such as the data in Appendix B;
- Deductive analysis can be used.

Whichever approach is used, the analyst needs to realize that every analysis of this kind is only an abstraction of reality accomplished specifically for the analytical purpose at hand. The FIPS need only be applicable enough to provide the basis for quantifying a fire-initiation frequency -- features directly relevant to that quantification must be captured well enough to support it, but features that do not affect the quantification need less attention. This aspect requires considerable analyst judgment, and this will be especially true during the early trial periods using the FIPS approach -- after considerable experience has been accrued, the need for analyst judgment will diminish as more and more successful applications provide models (templates) for succeeding work.

3.4 Review and Quantify the Scenario List

Because scenario generation is an inductive process, it is prudent to perform consistency, bias, and completeness checks to gain confidence in the analysis. Review of the data-based insights in Appendix B can help the analyst ensure important scenarios have been considered. In addition, ensure that all rooms have been treated similarly.

Assign HRR (including flame height for liquid pools) distributions as described in Section 2.6, accounting for the uncertainties discussed in Section 2.7.

Quantify frequency of FIPS applying judgment to best data available using the approach set out in Section 2.5.2.

Because this is an expert redistribution of fire frequency based on the mechanistic FIPS information, use care to protect against bias as described below in Section 3.5.

3.5 Controls for Expert Elicitation

Any approach for quantification based on the elicitation of consensus expert judgment needs to protect against bias and to provide controls to enhance the information gathering process, improve intra and inter-rater reliability, ensure traceability, and provide consistency over time. In addition, when expert elicitation is needed, the group consensus approach offers significant advantages for situations where the primary need is to account for a broad range of expert information in cases lacking solid mathematical models.

The issue of the group consensus expert elicitation process has been clearly addressed by the Senior Seismic Hazard Analysis Committee, authors of the “SSHAC” report (Budnitz 1997). In Appendix J of that report, the authors provide a very helpful comparison of mathematical and behavioral schemes for aggregation of information from multiple experts. Both approaches have been used in HRA. SSHAC cites the following advantages for mathematical aggregation:

- logic is clear and can be reviewed
- mathematical formulae can separate “assessments of dependence, expertise, and overlap, so that sensitivity studies are straightforward”

Despite the appearance of objectivity, consideration of subjective factors is important.

- there are no credible data for all the important factors
- no single “objective” model can fit all cases
- none of the existing methods provides a mechanism to account for uncertainty in a convincing way

The alternative, behavioral approaches seek some type of consensus. Although there are a number of behavioral approaches such as Delphi methods (Linstone 1975), we prefer the expert “information” focused group interaction (Bley 1992). SSHAC points out that the primary advantage of the group consensus approach is that, “if the information exchange is full and unbiased, and if the result truly reflects each expert’s state of information, then the consensus result is credible and non-controversial.” The primary concerns include:

- the result may not be a true consensus reflecting the combined expertise and experience of the group, but some negotiated position
- strong personalities may influence the result
- the group discussion may have been inadequate, so that uncertainty is understated

The formalism of structured expert elicitation [e.g., see the SSHAC report (Budnitz 1997)] can permit us to address the concerns raised above and can address the complex, highly interdependent conditions involved in fire initiation. Of course it can also provide good results for cases with less severe, but well-defined context. The SSHAC report offers an effective structure to make the elicitation process consistent. Our experience indicates that when all parties fully share the available information (share their evidence), rather than claiming superior opinion, consensus can be reached, but only when uncertainty is explicitly addressed. When the judges are forced to explain the basis for their judgments, these bases can be debated and a consensus distribution can be developed to represent the state-of-knowledge of the technical and scientific community.

To gain the advantages of the expert evidence/consensus approach, a strong facilitator is required or strong judges who understand the process and enforce a formal, structured interaction. We require each judge to develop their distribution independently and further require them to defend their position with all the evidence of which they are aware. No one is allowed “off-the-hook,” i.e, to capitulate to another judge’s unsupported opinion. In our experience, the process levels the playing field as everyone shares evidence and the basis for their opinions, often simplifies the issues, sometimes splits the current question into two or more related conditions, and makes it easier to reach consensus.

Beyond the controls discussed above, there is an important issue of unintentional bias. When a subjective process is adopted for estimating key parameters, such as probability distributions, strong controls are needed to prevent bias from distorting the results. The experts themselves are the first defense against intentional bias. Unintentional bias is more troublesome and must also be addressed. Perhaps the best approach is to thoroughly understand how unintended bias can occur. With that knowledge, the team can guard against its influence in their deliberations.

A number of studies present substantial evidence that people [both naïve judges and subject matter (domain) experts] are not naturally good at estimating probability (including uncertainty in the form of probability distributions or variance). [(Hogarth 1975), (Tversky 1974)] For example, Hogarth notes that psychologists conclude that man has only limited information processing capacity. This in turn infers that his perception of information is selective, that he must apply heuristics and cognitive simplification mechanisms, and that he processes information in sequential fashion. These characteristics in turn lead to a number of problems in assessing subjective probability – evaluators often:

- Ignore uncertainty (a simplification mechanism; uncertainty is uncomfortable and complicating, and beyond most people's training)
- Lack an understanding of the impact of sample size on uncertainty (domain experts often give more credit to their experience than it deserves; e.g., if they have not seen it happen in 20 years, they may assume it cannot happen or that it is much more unlikely than once in 20 years)
- Lack of understanding of independence and dependence

- Have a need to structure the situation, which leads to imagining patterns, even when there are none
- Are fairly accurate at judging central tendency, especially the mode
- Significantly underestimate the range of uncertainty; e.g., in half the cases people's estimates of the 98% intervals fail to include the true values

Lest we agree prematurely that people are irretrievably poor at this evaluation task, it is significant to realize that there are many successful applications. Hogarth himself points out that studies of experienced meteorologists have shown excellent agreement with actual facts. So we need to understand what techniques can help make good assessments.

(Winkler 1968) makes a useful distinction between two kinds of expertise or "goodness." "Substantive" expertise refers to knowledge about the subject matter of concern. "Normative" expertise is the ability to express opinions in probabilistic form. Hogarth points out that the subjects in most of the studies were neither substantive nor normative experts. A number of studies have shown that normative experts can generate appropriate probability distributions, but that substantive experts require significant training and experience to do well.

Our purpose here is to understand how these biases occur and to use that information to combat their influence.

Biases and heuristics. Another view of these problems can be seen in the following discussion of psychological difficulties in elicitation (Tversky 1974):

- Inadequacies of individuals. Influenced by beliefs of colleagues, limited experience assessing probabilities, sequential information processing, anticipations and emotions
- Representiveness. Insensitive to prior information and sample size, misconceptions of chance, insensitive to predictability, illusions of validity, misconceptions of regression
- Availability. Retrievability, effectiveness of a search set, bias of imaginability
- Anchoring and Adjustment. Hard to change existing (first) estimates, biases (conjunctive and disjunctive)

While some of these are self-evident, others require a bit of explanation. We deal with the inadequacies of individuals by selecting judges with a variety of expertise and by facilitating the process, challenging participants to explain the basis for their judgments. As to the next three issues, people tend to rely on a number of heuristics to simplify the process of assessing probability distributions. Some of these introduce bias into the assessment process. In particular, the three heuristics of representativeness, availability, and anchoring and adjustment will be examined.

In using the representativeness heuristic, people assess probabilities by the degree to which A is representative of B. A simple example presented by Tversky and Kahneman (1974) can illustrate how this approach can cause serious errors. If we describe traits of an individual as a "meek and tidy" man and then ask if we think he is a "farmer, salesman, airline pilot, librarian, or physician" naïve assessors often give the highest probability to librarian, because he fits the stereotype.

Representativeness also ignores the prior probability. Clearly the prior should have an impact on the posterior probability, but basing our judgment on similarity alone ignores that point. Representativeness is also insensitive to sample size and many of the experimental subjects give the same answer, regardless of sample size. All the failings of representativeness involve ignoring available information and replacing a careful evaluation of that information with jumping to conclusions based on over-focus on part of the information or allowing irrelevant information to affect conclusions. Here the current process challenges judges, asking them to explain their opinions. The facilitator must use his own judgment to sense when an individual is not using the full information.

Sometimes people assess the probability of an event by the ease with which instances can be recalled. This availability of the information is confused with its occurrence rate. Availability is a useful cue, but is affected by factors other than probability. Several associated biases have been observed:

- biases due to the retrievability of instances - recency, familiarity and salience
- biases due to the effectiveness of a search set - the mode of search may affect the ability to recall.
- biases of imaginability - the ease of constructing inferences is not always connected with the probability (of course, helping judges build models to help with such searches can help)

One of the most common problems is anchoring and adjustment. People start with an initial value and adjust it to account for other factors affecting the analysis. The problem is that it appears to be difficult to make appropriate adjustment. It is easy to imagine being locked to one’s initial estimate, but anchoring is much more sinister than that alone. A number of experiments have shown that even when the initial estimates are totally arbitrary, and represented as such to the participants the effect is strong. Two groups are each told we pick a starting point randomly just to have a place to work from. The one given the higher arbitrary starting point generates higher probability. One technique we have found helpful is to develop estimates for the upper and lower bounds before addressing most likely values.

Given all these problems, is there a way to develop "good" estimates? The following paragraphs give some evidence and additional guidance. Who is successful at this process? Many of the above studies ask judges to sketch their probability distributions for general questions such as: How long is the Mississippi River? What is the ratio between the suicide rates in the U.S. and in Japan? When first attempting tests of this kind, (1) we all do very poorly - most of the correct answers fall well outside our 10th and 90th percentiles (of course, only 20% should fall outside those limits) and (2) we usually believe that the reason we do so poorly is that the questions were not limited to our area of expertise. After sufficiently additional experience, it becomes clear that the main problem is not the domain of the questions, but our lack of normative experience. This is supported by studies of substantive experts and normative experts, where only the normative experts - statisticians, domain experts with experience at normative tasks, and domain experts supported by normative expert facilitators - were successful in developing distributions such that they covered the span of the real world answers and covered that span consistent with their proffered distributions.

How can we be successful? If we can understand the heuristics people use to develop subjective probability distributions and the biases that attend those techniques, that awareness can help us avoid the same traps. If we can learn which framings for eliciting distributions cause problems, we can use those that work better. In his comments published with the Hogarth paper, Ward Edwards objects to his fellow psychologists' focus on unaided, untrained judges. He observes that humans use tools in all tasks and there are tools that can help us do a very good job in the elicitation process. (Hogarth 1975).

So we need to develop a tool kit to help in the elicitation process. The following tools are currently in use either explicitly or implicitly through the questioning of the Facilitator as described in the SSHAC report (Budnitz, et al. 1997). The first tool is simply an awareness of the problems discussed above. (Tversky 1974) gives many detailed examples useful for developing such familiarity.

Some specific approaches have proved helpful. They offer a structured, facilitated process. Because the facilitator is familiar with the potential biases, she can test the group's ideas and push them in the right direction. Some of the simplest and best aids that we have used include:

- Modeling. Cconstruct simple models of the maximum and minimum points of the distribution, avoiding focus on the central tendency until the end points are studied to avoid anchoring; test these models to examine the evidence supporting them rather than relying on opinion alone.
- Seek consensus on the evidence considered by the technical community (Bley.1992).
- Test distributions by asking, if the assessor agrees it is equally likely for the real answer to lie between the 25-75%-tiles or outside them; or between the 40-60%-tiles and outside the 10% and 90%-tiles. Sometimes these questions must be phrased in ways to avoid suggesting the answer.
- Establish a strong facilitator who ensures each participant must individually put his evidence on the table and justify it (Budnitz 1997). The facilitator must use his judgment on when to push the participants, rather than going through a long and tedious checklist.
- Ensure that the evidence used to generate the distribution is relevant to the estimation problem. Obvious as this may sound, there are practical situations where this can be a

concern. The assessment team should be alert to the validity of their sources of evidence. If there is a concern with the applicability of a particular body of evidence, the evaluators should consider generating a distribution that excludes this evidence and then updating the distribution. (Siu 1998) Ensuring all participants speak their mind and challenge each other is effective.

- Be careful when assessing parameters that are not directly observable. The distribution is supposed to reflect the analyst's evidence concerning a particular parameter. If the analyst has little direct experience with the parameter, it can be difficult to justify an informative prior distribution. (Siu 1998)
- Challenge apparent conservatism. The natural tendency of engineers, when faced with uncertainty, is to employ conservative assumptions. The problem is that the degree of conservatism can vary from evaluator to evaluator, thereby upsetting the ranking of alternatives. More generally, a conservative evaluator injects his/her own values into the analysis, and to some extent usurps the decision-maker's role. (Siu 1998) Require defense of judgments.

Our experience indicates that once the full story is developed and shared, experienced evaluators provide reasonably consistent judgments. They almost always see the merit of arguments offered by their colleagues and can reach agreement on a consensus distribution that gives weight to each argument; this means that they also can reach agreement on the relative strength of those arguments and the supporting evidence.

4 Findings and Potential Improvements

Our primary motivation for the new FIPS approach is to improve the way that the major contributors to fire PRA are modeled and quantified, by improving how the fire-initiating-event aspect is analyzed. We believe that with the FIPS approach it is feasible to identify and remove excessive conservatisms, to identify any non-conservatisms, and thereby to make the analysis more realistic.

Several weaknesses in the existing approach are well-known. Perhaps the most important is that in the current approach there is a lumping together of fire data into Major Component Groups and Room Types --- important information is lost in this lumping. Although the true frequency of potentially challenging fires is obviously different depending on the detailed circumstances in which a major component finds itself, the current approach "smooths out" these differences, in part for lack of supporting data. It is our expectation that, if the data can be gathered in a way that supports our new FIPS approach, the ability to discriminate at a finer level-of-detail will pay large dividends to the analyst.

Indeed, we believe that the new FIPS approach can produce some of those dividends even before any new data, developed to support it, are generated. The new insights will arise because the FIPS methodology forces the analyst to think about the fire-frequency problem in a different way.

One might be troubled by the prospect that, until new data to support the FIPS methodology come into existence, the application of the new approach will lead to a degraded understanding, because it appears that there would be a move away from an "objective" approach based on real fire-ignition data (albeit one which lumps the data together too coarsely) to a more "subjective" approach. In fact, however, applying the FIPS methodology even in the absence of new data to support it does not omit any of the existing underlying data -- it is all used. We believe that even rough judgments, when folded into the richer FIPS model, will be an improvement over the existing less refined approach.

The proposed FIPS method appears to provide the benefit of clarity with no loss of rigor. It can permit the use of existing data, providing the analyst with a basis to adjust that existing data judgmentally until new data are generated by the industry. It provides a structured approach to combine data and judgment. The clear framework for classes of FIPS shows the place of smoke and explosion, for example, in fire analysis.

The FIPS methodology will yield scenarios with more realistic characteristics. Since they will evolve from a more mechanistic approach, they will involve fire dynamic principles, i.e., flame spread and fire growth. This will generate a more realistic heat release rate history of the fire, the most important parameter affecting the hazard development potential of an enclosure fire.

Addressing uncertainty directly in the quantification process brings important issues to the front of the analysis, where they can be examined and clarified. The existing approach is an uneven mix of the conservative and the optimistic; therefore the integrated position vis a vis uncertainty is unclear. In the new approach, care is given to considering the epistemic/aleatory distinction in uncertainty. This exercise forces deeper thinking and generally yields improved clarity.

Fire growth rates depend on a number of variables, including fuel type, fuel configurations, and ignition energy. Current use of fire modeling, e.g., COMPBRN, involves a conservative approach to estimate peak heat release rates, but only for selected fires. That is, while the use of peak HRR would appear to be very conservative, it is usually a single peak HRR selected as being "typical" or "realistic." It is often the result of a single "reasonable" experiment, when the range of observed HRRs over many experiments includes much higher cases.

Improvement of the mechanistic link to fire growth model is possible through three approaches:

- there is good HRR information in original Sandia studies (Nowlen 1989) and more recent experiments; these can be used to characterize the uncertainty in the HRR over time
- it may be possible to develop a catalog of peak to average HRR correlations to provide a simple, reasonable approach to the use of existing data to model the uncertainty in HRR
- simplified calculations based on methods in (SFPE 1995) can permit use of many calculations to address issues of uncertainty (Iqbal 2000)

Improvements in the frequency of FIPS may follow from

- pursuing (or using data from) the SAIC/Army approach (Amico 2002) of using equipment based initiating event frequencies from larger data set; note too that propagation data from chemical plants indicates a higher probability of growth to very large fire than models predict
- investigating data on challenging electrical fires from Doble Engineering
- pursuing additional expert elicitation panels on difficult/uncertain issues
- revising the way data are collected for fire events

5 References

(Amico 2002) Amico, P., and C. Ching, "Using Historical Data to Assess the Frequency of Fire Initiating Events at Industrial Facilities," to be published in *Proceedings of PSAM 6*, San Juan, Puerto Rico, June 23-28, 2002.

(Bley 1992) Bley, D. C., S. Kaplan, and D. H. Johnson, "The Strengths and Limitations of PSA: Where We Stand," Reliability Engineering and Systems Safety, vol. 38, 1992.

(Budnitz, 1997). Budnitz, R.J., G. Apostolakis, D.M. Boore, L.S. Cluff, K.J. Coppersmith, C.A. Cornell, and P.A. Morris, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," NUREG/CR-6372, U.S. Nuclear Regulatory Commission, Washington, D.C., 1997.

(FIVE 1992) "Fire-Induced Vulnerability Evaluation (FIVE)," TR-100370, Research Project 3000-41, Professional Loss Control, Inc., for Electric Power Research Institute, April 1992.

(Garrick 1981) Garrick, B.J., and S. Kaplan, "On the Quantitative Definition of Risk," *Risk Analysis*, vol.1, no. 1, pp 11-27, 1981.

(Houghton 1997) Houghton, J.R., "Special Study: Fire Events - Feedback of U.S. Operating Experience," AEOD/S97-03, U.S. Nuclear Regulatory Commission, June 1997.

(Ho 1988) Ho, V., N. Siu, and G. Apostolakis, "COMPBRN III – A Fire Hazard Model for Risk Analysis", Fire Safety Journal, Vol. 13, p. 137-154, 1988.

(Hogarth 1975) Hogarth, R.M, "Cognitive Process and the Assessment of Subjective Probability Distributions," Journal of the American Statistical Association, Vol. 70, No. 350, pp 271-294, June 1975.

(Iqbal 2000) Iqbal, N., and M.H. Salley, "Development of a Quantitative Fire Scenario Estimating Tool for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program,"Structural Mechanics in Reactor Technology (SMiRT) Post-Conference Fire Protection Seminar No. 1, August 20-23, 2001, at the Millstone Nuclear Power Station Conference Facility in Waterford, Connecticut, USA.

(Kaplan 1998) Kaplan, S., "Finding Failures before They Find Us: An Introduction to the Theory of Scenario Structuring and the Method of Anticipatory Failure Determination," *Proceedings of the Ninth Symposium on Quality Function Deployment*, June, 1998.

(Lambright 1997) Lambright, J., and M. Kazarians, "Review of the EPRI Fire PRA Implementation Guide," ERI/NRC 97-501, Energy Research, Inc. for U.S. Nuclear Regulatory Commission, August 1997.

(Linstone 1975). Linstone, H.A., and M. Turoff, The Delphi Method: Techniques and Applications, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1975.

(NEI 1999) Letter from D. Modeen, Nuclear Energy Institute, to T.L. King, U.S. Nuclear Regulatory Commission, “Response to Request for Additional Information on the EPRI Fire PRA Implementation Guide,” May 24, 1999.

(NFPA 1999) “NFPA 805 Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants,” Draft 7.0, National Fire Prevention Association, 1999.

(Nowlen 1989) Nowlen, S.P., “A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975-1987,” NUREG/CR-5384, SAND89-1359, Sandia National Laboratories for U.S. Nuclear Regulatory Commission, December 1989.

(Nowlen 2001a) Nowlen, S.P., M. Kazarians, and F. Wyant, "Risk Method Insights Gained from Fire Incidents,” NUREG/CR-6738, Sandia National Laboratories, prepared for U.S. Nuclear Regulatory Commission, Washington, DC, September 2001.

{Nowlen 2001b) Steven P. Nowlen, S.P., A. Kolaczkowski, and D. Kelly, “Fire Detection and Suppression Analysis: Development of Modeling Tools and Data,” Final Letter Report, Sandia National Laboratories, prepared for U.S. Nuclear Regulatory Commission, 2001.

(NRC 1997) Letter from M.W. Hodges, U.S. Nuclear Regulatory Commission, to D. Modeen, Nuclear Energy Institute, “Request for Additional Information on the EPRI Fire PRA Implementation Guide,” December 3, 1997.

(Parkinson 1995) Parkinson, W.J., K.M. Bateman, W.S. Gough, J.A. Lee, B. Najafi, J. Schloss, and G. Simon, “Fire PRA Implementation Guide,” TR-105928, Science Applications International Corporation for Electric Power Research Institute, December 1995.

(Peacock 1993) Peacock, R.D., G.P. Forney, P. Reneke, R. Portier, and W.W. Jones, “CFAST, the consolidated Model of Fire Growth and Smoke Transport”, US Dept. of Commerce, National Institute for Science and Technology, NIST Technical Note 1299, 1993.

(Rohr 1999) Rohr, K.D., National Fire Protection Association International, letter to D.C. Bley, Buttonwood Consulting, Inc., November 1, 1999.

(SFPE 1995) *SFPE Handbook of Fire Protection Engineering*, Second Edition, National Fire Protection Association, Quincy, Massachusetts 1995.

(Siu 1983) Siu, N, “COMPBRN, A Computer Code for Modeling Compartment Fires”, Report NUREG.CR-3239, 1983.

(Siu 1997) Siu, N., J.T. Chen, and E. Chelliah, “Research Needs in Fire Risk Assessment,” U.S. Nuclear Regulatory Commission 25th Water Reactor Safety Information Meeting, Bethesda, Maryland, October 20-22, 1997.

(Siu 1998). Siu, N.O., and D.L. Kelly, "Bayesian Parameter Estimation in Probabilistic Risk Assessment," Reliability Engineering and System Safety, vol. 62, pp 89-116, 1998.

(Tversky 1974) Tversky, A., and D. Kahneman, "Judgment under Uncertainty: Heuristics and Biases: Biases in judgments reveal some heuristics of thinking under uncertainty." Science, Vol. 185, pp 1124-1131, 27 September 1974.

(Winkler 1968) Winkler, R.L., and A.H. Murphy, "'Good' Probability Assessors," Journal of Applied Meteorology, 7 pp 751-758, October 1968.

Appendix A

The Model Compared with Historical Approaches

This appendix compares the FRA model developed in Section 2 of the main report with previous models and analyses. The traditional FRA model is revisited along with a discussion of how it has been applied in practice. With this background, the model, along with expectations of how they are applied are compared, and advantages and disadvantages envisioned using the new approach are examined.

A.1 The Historical Fire Risk Assessment Model

Historical scenario trees for FRA (Siu 1997) have generally been simple three step trees such as the model:

$$CDF = \sum_i \lambda_i \left(\sum_j p_{ed,\, j|i} \left(\sum_k p_{CD,k|i,j} \right) \right)$$

where

λ_i is the frequency of fire scenario i,

$p_{ed,\, j|i}$ is the conditional probability of damage to critical equipment set j, given fire scenario i,

$p_{CD,\, k|i,\, j}$ is the conditional probability of core damage due to plant response scenario k, given i, j

Note that

- the first term includes the notion of severity factor
- the second term addresses fire growth, detection/suppression, and component damageability
- the third term addresses the unavailability of equipment and human actions; i.e., failures not directly attributed to the fire

At this level, the historical model and the model of Section 2 of the main report are conceptually compatible. Differences emerge only when we consider how the models are applied in practice. We believe that the new model, with its emphasis on the mechanisms leading to challenging fires, can focus the analysts' attention on those aspects of the analysis that are in need of improvement. But the evidence lies in the details and the next section looks closely at many of the details of current practice.

A.2 Current Practice in the Use of the Traditional Model

In current FRA practice, there is no one "standard method" for working out fire initiating-event frequencies, but there is a standardized set of steps that is generally used. These will be outlined here to provide background for our discussion of where improvements might be realized.

1) Analysis is done compartment by compartment: The entire plant is always differentiated into different areas (the definitions vary: the areas are sometimes called zones or compartments, and these words sometimes have specific meanings), and the FRA methodology always deals with a fire that starts in one specific compartment. The compartment is generally defined for the purposes of the PRA analysis so that the postulated fire is, by plant design, supposed to be confined to that compartment by effective fire barriers or stand-off distances.

Within each compartment, the analyst will sometimes differentiate among sub-areas -- sub-compartments, effectively -- if it is judged appropriate to do so.

The spread of a postulated fire between compartments is considered in FRAs, but it is beyond our scope here, because we will concentrate on initiating-event scenarios.

2) Equipment locations: Because many fires start in specific pieces of equipment, and because it is equipment damage that is the issue, it is necessary to ascertain the locations of various items of equipment that reside within the compartment being examined. Standard and uncontroversial counting methods are used, which can involve specific counting of items, or an allocation of the total known number of plant equipment items to various compartments based on certain rules-of-thumb. While the allocation methods are only approximately correct, the uncertainty introduced by these methods is generally not large.

Knowing the locations of each type of equipment in a compartment is necessary because the equipment is the issue – specifically, some items of equipment can be the source of a fire, other items can be the target of a fire that starts elsewhere, and sometimes a given item can be both. Also, an item of equipment could provide an additional source of fuel to accelerate the growth of the fire.

3) Fire initiating event frequency database: The analyst will almost always use one or another generic fire-initiating-event-frequency database as the starting point. Examples of such databases are ones compiled by EPRI and by Sandia for NRC. A recent combined database is examined in Appendix B. For fires that start in fixed sources, these databases consist of generic fire frequencies sorted by location and fire ignition source -- for example, one entry would be the number of fires per reactor year observed in electrical cabinets in switchgear rooms (the database might contain, say, 20 such electrical-cabinet fires in switchgear rooms, which might cover 1000 reactor-years, yielding an observed frequency of 0.02 per reactor year.) The database would also contain other locations for electrical cabinets, as well as other equipment types located in switchgear rooms.

In principle, the generic database should be modified to account for plant-specific differences–for example, by using the generic database as the prior distribution for a Bayesian plant-specific update. However, this is not generally done, because the number of fires at a given plant is generally too small to provide a lot of useful plant-specific data, and reviews of the data do not reveal much in the way of plant-specific anomalies.

One plant-specific adjustment that is generally made is to account for the fact that a given nuclear plant may have more of one type of equipment than the "average" plant from which the data are drawn. So-called location weighting factors are used to account for this, and standard methods for working out these factors are in wide use.

Another adjustment is used to account for the number of a given type of equipment in the compartment being evaluated, as a fraction of the number located in some larger area. For example, the database may present only the total number of fires starting in large pumps in the entire Auxiliary Building; it is necessary to allocate that frequency among the various compartments in the specific Auxiliary Building being evaluated, by noting how many large pumps are in each compartment.

4) Transient fires: The analyst must also use a database to work out the annual frequency of transient fuel and transient ignition source fires by activity (say, welding or pump maintenance) which must then be allocated by location, based on annual activity records at the given plant. There are various methods in use that account for the frequencies and types of specific activities undertaken in the compartment being examined, by allocating from the broader database. These methods are approximations, but are usually relatively straightforward and uncontroversial.

5) Multiple ignition sources in a given compartment: If, for example, a compartment contains both switchgear and junction boxes, each of which might be a fire ignition source, it is necessary to develop the frequency per-year for each, and to add them in order to obtain the total frequency for the compartment. If transient fires are also an issue for that compartment, then the frequency for these must also be added in. Of course, the different sources can produce fires with different characteristics, which must be accounted for in the subsequent parts of the analysis.

6) Uncertainties due to database incompleteness: One key part of the uncertainty in the overall analysis of fire initiation event frequencies is that the database itself is incomplete–not so much incomplete in the sense that some fires are missing (although this is likely also), but incomplete insofar as the descriptions of the fires in the database are often poor. The missing fires issue is probably not crucial: it is very unlikely, for example, that only half of all the fires that ought to be in the database are recorded, but even if this were true there would only be a factor of two overall change in frequency, and the problems with the database can be much more severe than factor-of-two types of effects.

A major problem is the fact that many of the reported fires are poorly described. Poor descriptions mean that, for many of the fires recorded, both the database compiler and the analyst-user are not certain of such key features as

- the duration of the fire from ignition to detection and suppression
- whether detection and/or suppression were automatic or manual
- which combustibles were actually burned and which were not

- the sequence of combustibles ignited and the subsequent fire spread and growth rates, etc.

Thus the actual and potential severity of many of the fires in the database itself is not understood well, leaving the FRA analyst with irreducible uncertainties in how to deal with these fires as the database is applied.

7) Fire severity factors: Generally, the fire-growth/spread-modeling step of the analysis presumes that the fire has become fully developed, and the analysis attempts to describe the phenomena from there. However, not all incipient fires reach such a fully-developed stage, and the so-called "severity factor" is used to account for this: it is defined as the fraction of fires in the database that reach whatever fully-developed stage is assumed in the subsequent fire-growth/spread modeling aspect.

Over the years estimates of the frequency of fires in particular rooms has not changed appreciably, as evidenced by a recent NRC study (Houghton 1997). However, the approaches for generating severity factors has changed. In early studies, these factors were often location fractions, attempting to account judgmentally for geometrical factors within the room. More recent approaches are described below.

Usually, the analyst will use severity factors taken from a generic tabulation, such as EPRI's "Fire PRA Implementation Guide" (Parkinson 1995) that has been developed for different categories of ignition sources (pump fires, transformer fires, etc.). The tabulation itself relies on a combination of data for real fires, and modeling that attempts to ascertain what fraction of fires of a certain type would produce the conditions that can cause damage to the target (a cable tray, a pump, etc.) Neither experience from real fires nor the modeling work that supports these severity factors is very refined, so these factors often have a weak technical basis, and therefore are only approximate -- and they represent an important source of uncertainty in the whole FRA exercise.

To determine a severity factor, the analyst should attempt to understand the variety of reasons why a fire event may not develop into a damaging fire. Such reasons might include insufficient energy in the ignition source (for example, if that source is an electrical discharge); insufficient total available fuel; a geometrical configuration that might preclude fire growth (for example, a single item alone at the center of the room); insufficient ventilation leading to oxygen starvation; long heat-up periods allowing detection and suppression to be effective; early detection leading to early suppression, including both human detection if the area is manned (either continuously or with a known probability), and effective automatic detection and/or suppression; and several other factors.

Typically, the FRA analyst will develop a severity factor for a given fire in a given compartment based on evaluations of these many factors, with a heavy dose of judgment to sort them out, involving for example how to account for differences between events in the database and the specific condition being analyzed, that can affect the fire's severity. Guidance to assist in these judgments is available, for example in the EPRI guidance, and can be of great benefit as a guide to the issues, but expert judgment still remains a central aspect of severity-factor development.

8) Stylized Pilot Fires for Subsequent Fire Modeling: Given a fire that has initiated, and given its "severity" (however defined), the next crucial aspect of the fire-FRA methodology is estimating damage to safety equipment. Making this transition in the analysis comes down to specifying the initial conditions for the subsequent analysis.

Fire simulation modeling is used for this aspect, to work out the growth rate of the given fire, and its key characteristics. Specifically, there exist a number of analytical tools that have been developed for this purpose (for example, COMPBRN), which evaluate a set of stylized types of fires. One always must try to account for the actual configuration, including geometrical arrangements, ventilation conditions, and so on. There is always considerable analyst judgment involved in this step: uncertainties exist even when the real conditions are reasonably close to those modeled.

There is a lot of literature on this subject, which will not be reviewed here. Suffice it to say that neither the modeling approximations made nor the experimental databases used are really adequate to support the analysis, except in an approximate way. Thus important uncertainties inevitably arise in the numerical "results" of the fire simulation modeling, namely in the time-temperature profile as a function of location that is the key figure-of-merit for determining subsequent equipment damage.

9) Modeling of Detection And Suppression: One key issue in FRA analysis is working out at what time, and how, the fire is detected, and then at what time, and how, suppression is brought to bear to put the fire out. Of course, in general, detection can be either automatic or human; and suppression can also be either automatic or manual.

Working out whether a given piece of equipment is damaged comes down to working out the thermal environment reached --- usually just the temperature is used as the figure-of-merit --- and comparing that temperature against the temperature at which the equipment item is known (or thought) to be damaged. And whether the fire produces the requisite damage temperature comes down to whether detection/suppression occurs early in the fire’s growth (before the damage temperature is reached at the equipment of concern).

Simplifying assumptions are often made, such as assuming that if an automatic suppression system actuates, it will be immediately effective, even though this is clearly non-conservative. Sometimes, lookup tables are used to determine the automatic system's actuation time. For the likelihood that an automatic suppression system will fail to operate when it receives the actuation signal, generic values are typically used, based on data. However, the generic database fails to account for what is likely to be very wide variability, from plant to plant, in the actual value of this key parameter, due to geometrical factors, maintenance practices, and the like. More importantly, if the fire grows rapidly, it can overwhelm the suppression system.

For manual suppression, which is needed either if the automatic system fails or if it is absent, the analyst must work out the arrival time of the fire brigade based on drill data, distance-to-the-fire data, access information, and so on. Then, the time required to extinguish the fire must be worked out, including accounting for the presence or absence of smoke, lights-out darkness, and so on. The effectiveness of a fire-watch, if any, must also be considered.

All in all, the determination that a specific fire will be suppressed (or not) before the equipment-damage temperature threshold occurs involves important uncertainties of various kinds just in the detection/suppression arena, over-and-above the uncertainties in the fire-growth-and-spread-modeling arena.

A.3 Comparison of the New and Traditional Models

What is apparent in the examination of the application of the traditional model is that there is substantial analyst discretion in how the model is applied. Furthermore, such discretion has led to wide differences in modeling and results among studies. To a large extent the approach to applying FRA has never been reduced to a narrowly defined process; i.e., to strong methodological guidance. Previous procedures guides [(Bohn 1990), (IAEA 1995), (USNRC 1983)] leave broad areas of application only loosely defined. The EPRI FIVE methodology (FIVE 1992) does provide strong structured guidance for screening and the EPRI Fire PRA Implementation Guide (Parkinson 1995) provides extensive information that can be used to give the analyst a sound basis for judgments, but again, there is wide discretion in how this information is used. A few special topics are discussed in more detail below.

1) Conservatism and potential optimism. There are many similarities between the new model and traditional approaches. The differences are primarily matters of application, analyst discretion, detail, and some conceptual advantages in the new approach that focuses the analyst on key issues.

Much of the pressure to develop improved FRA methods comes from a general belief that the current approach to FRA is fraught with conservatism. Several of the most significant beliefs include:

- Initiating event frequencies for fires in rooms and fires associated with components are too high, because the database includes many minor fires that are not relevant. Note that severity factors were originally conjured up to deal with this problem.
- Severity factors are too conservative. The original judgmental severity factors had no theoretical or experiential basis. More recent severity factors, such as those described in EPRI guidance (Parkinson 1995) are still based on fires that caused no core damage and are therefore conservative.
- Input assumptions for COMPBRN and other fire growth models are extremely conservative. There is no formal, standard approach for selecting the stylized pool fires for COMPBRN, after application of the severity factor. These pool fires generally overstate the severity of the fires and lead to overly pessimistic results.

Because of these conservative assumptions or model selections, many people believe that the results of FRA are greatly overstated. Unfortunately that is not the whole story. There are a number of factors that are or may be overly optimistic in the analyses. The following list includes some of the most troublesome:

- Few, if any, FRAs carefully account for the potential effects of fires on the human operators. It is not only the hot smoky environment of the fire that can affect human performance. It is also the unanticipated nature of the effect of the fire on equipment over time. Overheating instrument and control (I&C) circuits can create unstable conditions and unexpected deviations in I&C response. Even more dramatic effects can be caused by hot shorts, shorts to ground, and open circuits that occur randomly over time.

- The uncertainty in the time until isolating dedicated or alternate equipment (and therefore until damage to that equipment) caused by ambiguous fire procedures and uncertainty in the time until irreparable damage to dedicated/alternate equipment is generally not modeled.
- Few, if any, FRAs carefully account for the potential effects of fires on the human fire brigade. Assumptions such as fire fighters no longer hesitating to put water on electrical fires, as at Browns Ferry, are not supported by actual fire events. Long delays in setting the fire brigade still occur. The impact of losing operating staff to the fire brigade is seldom modeled.
- The fact that particular configurations of primary and secondary fuels, ignition sources and oxygen availability in particular rooms could be more severe than current models suggest (albeit less likely) is not considered.
- Lessons learned and new research from other industries with similar equipment that have a more pressing fire risk problem, may not have been fully considered in nuclear power plant fire protection; i.e., fires aboard ship (particularly engine and equipment room fires), fires in communications facilities, some fires in chemical plants, and some aircraft fires are cases in point.
- A number of significant fires in nuclear power plants have demonstrated that multiple simultaneous fires and secondary fires occur. These are not considered in current fire models.

2) Mechanistic Analysis and How it Fits with Respect to Severity Factors. The current state-of-the-art in FRA allows significant variability in qualitative and quantitative results, relying heavily on the analyst's judgment on the frequency with which fires occur and the damage that they cause. Since the FRA is designed to analyze the impact of challenging fires, i.e., rare events that have not occurred in nuclear power plant experience, it should be both inclusive and realistic. Traditionally, methodologies have estimated ignition event frequency from event experience and damage from fire models, while attempting to overcome the weaknesses of fire models and ignition frequency by the use of severity factors. A severity factor is simply a conditional probability that the ignition source is sufficiently severe to cause the conditions, e.g., one-foot diameter oil pool fire, represented by the model. These severity factors were historically based on analyst judgment, but because this was often poorly justified by analysts with little direct experience in power plant fires, more data driven approaches were developed (Parkinson 1995). However, even in these cases judgment enters the approach in at least two ways: in the screening of insignificant fires and in the assignment of a pilot fire (pool fire, point fire, etc.) as input to the fire growth model (e.g., COMPBRN or CFAST). The combination of those two judgments allows significant discretion to the analyst that is often weakly tied to plant-specific and location-specific attributes. Consequently, the current state-of-the-art has important weaknesses that need to be addressed to allow expanded, more confident use of the analysis results in regulatory applications.

The Fire Initial Phase Scenario (FIPS) methodology involves the generation of specific fire scenarios involving plant components in various locations. These FIPSs are not factual accounts of specific fire incidents; they are however, inclusive and realistic of all potentially challenging fires in NPPs. Developed from a mechanistic approach, they contain essential fire dynamic elements. As such the methodology is an evolutionary improvement on existing approaches. By asking the question, "How can I make this challenging fire occur?", numerous FIPSs previously not considered emerge. For example, the importance of the fire initiating in the corner of a room (the corner effect) can be considered; as can a consideration of multiple fires or multiple initiating events. These new FIPSs may reveal a new set of challenging fire scenarios that have been previously overlooked.

The FIPS methodology can:

- Identify a generic listing of challenging fire scenarios.
- Expand our understanding of the implications of actual fire events, most of which do not become challenging fires.
- Improve our estimate of the frequencies of challenging fires.
- Improve our qualitative and quantitative understanding of the risk contribution due to fires in NPPs.
- Focus attention on key issues, narrowing the range of each problem where judgment must be applied and suggesting areas for best payoff for research to reduce dependence on judgment.

A.4 References

(Bohn) Bohn, M.P., and J.A. Lambright, "Procedures for the External Event Core Damage Frequency Analysis for NUREG-1150," NUREG/CR-4840, SAND88-3102, Sandia National Laboratories, November 1990.

(FIVE 1992) "Fire-Induced Vulnerability Evaluation (FIVE)," TR-100370, Research Project 3000-41, Professional Loss Control, Inc., for Electric Power Research Institute, April 1992.

(Gallucci 1999) Gallucci, R., M.D. Flaherty, D.F. Wilson, and E.J. Jorgenson, "Applying a Fire IPEEE: Hot Shorts and Appendix R Verification," American Nuclear Society, Proceedings of the International Topical Meeting on Probabilistic Safety Assessment (PSA '99), p. 161, Washington, August 1999.

(Houghton 1997) Houghton, J.R., "Special Study: Fire Events - Feedback of U.S. Operating Experience," AEOD/S97-03, U.S. Nuclear Regulatory Commission, June 1997.

(IAEA 1995) "Treatment of External Hazards in Probabilistic Safety Assessment for Nuclear Power Plants: A Safety Practice," Safety Series No. 50-P-7, International Atomic Energy Agency, Vienna, 1995.

(Parkinson 1995) Parkinson, W.J., K.M. Bateman, W.S. Gough, J.A. Lee, B. Najafi, J. Schloss, and G. Simon, "Fire PRA Implementation Guide," TR-105928, Science Applications International Corporation for Electric Power Research Institute, December 1995.

(Siu 1997) Siu, N., J.T. Chen, and E. Chelliah, "Research Needs in Fire Risk Assessment," U.S. Nuclear Regulatory Commission 25th Water Reactor Safety Information Meeting, Bethesda, Maryland, October 20-22, 1997.

(USNRC 1983) "PRA Procedures Guide: A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants," NUREG/CR-2300, prepared under the auspices of The American Nuclear Society and the Institute of Electrical and Electronic Engineers, under a grant from The U.S. Nuclear Regulatory Commission, January 1983.

[This page intentionally blank]

APPENDIX B

LESSONS LEARNED FROM FIRE EXPERIENCE DATA

Fire experience data from various nuclear and non-nuclear power sources was assembled, analyzed and compared to identify critical elements in challenging fire scenarios. Of particular interest were those elements that could support the mechanistic development of fire initial phase scenarios (FIPS) and those elements that are not currently addressed in NPP fire probabilistic risk assessments (FRA). This appendix first addresses what we have learned from nuclear power plant fires. Next we highlight major findings from analysis of the non-nuclear power fire data. Finally, we provide a concise summary of the main insights that we gleaned from examining the entire fire experience database.

B.1 Nuclear Power Sources

Two major studies “Risk Methods Insights Gained from Fire Incidents” (Nowlen 2001), and “Special Study, Fire Events – Feedback of U.S. Operating Experience” (Houghton 1997) were deemed extremely valuable to our task. These were examined in-depth and key elements in challenging fire scenarios identified. These two studies are discussed below. In addition, meetings were held with NRC fire protection engineers to solicit their concerns regarding potential areas of risk not adequately addressed in current FRAs. The major findings from these discussions are highlighted below as well.

B.1.1 Lessons Learned about the Initial Phase of Challenging Fires from the Study, “Risk Methods Insights Gained from Fire Incidents”

This report presents the analysis and results of 25 select fire incidents from an FRA perspective. The authors defined three categories of incidents:

- *Large or severe fires*, which led to severe or widespread damage; these are severe in the traditional sense of fire protection
- *Challenging fires*, which led to a significant actual challenge to nuclear safety
- *Interesting fires*, which were minor fires that provide insight into FRA methods and assumptions

The authors note that “a large number of fire events were considered” and caution that “no attempt was made to ensure an exhaustive search of all fire incidents...” They are confident that they have identified all challenging fires; they acknowledge that they may have missed some severe fires in plants outside the U.S.; and they state that it is impossible to have identified all interesting fires.

Therefore, the information provided cannot be directly used for a statistical analysis of various parameters of FRA methodology. Note that the current study is interested in fires that are potentially challenging to nuclear safety. This potential depends on plant-specific features of the design. Thus all severe and challenging fires, as defined in (Nowlen 2001), have potential to challenge safety at some plants. Even some of the interesting fires have that potential, particularly if some change in initial conditions or specific design could lead to situations not currently modeled well in FRA. Thus all the fire incidents in this report were examined in detail to identify key elements that impact FIPS and to gain insight into areas for FRA improvements.

Table B.1 summarizes our findings on the relevant information gleaned from these fires. The column headings in the table were selected to focus on the key elements in the initial stages of the fire and to parallel the data reported below in Section B.1.2. Of particular interest is the last column, which highlights FRA issues implied or addressed. Table 4-1 of (Nowlen 2001), "Summary of Incident Review Results," provides a similar summary analysis of these fires under three major headings: Fire Initiation, Fire Protection, Nuclear Safety. These two tables analyzed together indicated to the authors of this report the following Lessons Learned:

1. Eight of the 25 fires were identified by Nowlen (2001) as challenging (i.e., created a demand for safe shutdown systems and rendered such systems unavailable); in the judgment of the authors of that report, two others would have resulted in a severe nuclear power plant safety challenge had the plant been in operation at the time of the fire, and another became challenging because of an operator error set up by fire damage and conditions, for a total of 11 challenging fires.
2. In ten of the 11 challenging fires, multiple safety systems were impacted. Conversely, none of the other 14 fires involved multiple safety systems.
3. Nine of the 16 severe fires were deemed challenging fires; only two (Browns Ferry and Oconee) of the nine non-severe fires were judged to be challenging.
4. Seven fires were multiple (simultaneous) fires, six of which were electrically induced. Two of these six electrically induced fires resulted in a challenging fire and three were severe fires.
5. Secondary fires were experienced in five of the incidents; four of these secondary fires became challenging fires and three were severe.
6. Seven of the fire incidents involved self-ignited cable, two in the U.S. and five in the former USSR. In one incident, a self-ignited cable fire in a low flame spread cable (cable qualified to IEEE-383) did not self-extinguish. All self-ignited cable fires involved power cables due to low cable fire rating, mechanical damage, or excessive current due to electrical faults.
7. There were no transient fuel fires: neither challenging, severe, nor interesting fires.
8. Room-to-room fire propagation occurred in seven of these fire incidents, primarily due to doors left open or cable penetrations not sealed. Only one such incident occurred in the U.S. (Browns Ferry)

9. A majority (13) of the 25 fire incidents involved the turbine building. Four of these became challenging fires.

10. Smoke propagated to other compartments in 11 or more of the fires and was in the control room in at least 10 of the fires; eight of these combined cases involved severe fires; seven of the 10 fires that created smoke in the control room were deemed challenging.

B.1.2 Lessons Learned about the Initial Phase of Challenging Fires from the Study, "Special Study: Fire Events – Feedback of U.S. Operating Experience"

This report on fire events covering operating experience from 1965 through 1994, characterizes the frequency and nature of fire event data from U.S. operating plants and examines the potential impact that this updated data could have on fire risk assessments.

In particular, the database contains summary information on over 350 fire events that occurred in U.S. nuclear power plants between 1986 and 1994. For each event, the data table listed the following information: docket/plant, source of information, date/time, location, fire duration, affected plant system(s), cause, initiating combustible, component effect of fire, train effect of fire, plant power level at time of fire, effect on plant power level, detection means, and suppression means. Not all information was available for all events.

The information in this table came from a variety of sources. One source was LERs for those fires that were reportable to the USNRC. These LERs are publicly available and 22% of the events came from this source. Another source was Nuclear Energy Insurers Limited (NEIL), a proprietary database made available to the USNRC under special agreement. This source captured many fires that were not reportable, and thus were not described by LERs, and made up about 30% of the events in the database. The Electric Power Research Institute (EPRI) provided information on about 29% of the events. Finally, about 19% of the event information came from either the Nuclear Plant Reliability Data System (NPRDS), or its recent replacement, EPIX. Both of these are proprietary databases maintained by the Institute for Nuclear Plant Operations (INPO). The USNRC has access to this information through an agreement with INPO.

In order to build this database, interpretations or assumptions had to be made, in some cases. While attempts were made to be as accurate as possible, this needs to be recognized as an inherent part of building any fire database, given the state of current fire event reporting. It is not possible to know how complete this database is relative to all the fires that occurred in nuclear power plants from 1986 to 1994. We suspect that use of these varied sources provides confidence that no "substantial" fires have been missed. It is possible that very small fires may not have shown up in any of these sources and thus are not in the database. The extent of such omissions is unknown. Hence users of the database and the results in this report must be aware that this possibility exists, and represents a source of uncertainty.

The information was provided from the USNRC in the form of a WordPerfect table that was converted to an Excel spreadsheet for ease of analysis. The only information available to the authors of this report was that provided in the table. Because of the proprietary nature of some of the information and since the database was undergoing an internal quality review, the authors of this report had no means of verifying it or of obtaining more detailed information (i.e., we did not have access to the raw data).

An attempt was made to structure the database into forms that would ease the analysis. Hence the database was sorted on six categories. Based on what we intuitively judged would yield the most useful information, ten different sorts were performed as indicated in Table B.2.

Table B.2 – Sorts of Special Study Database

Sort	Order of Fields Sorted
1	Location/Power Level/Fire Cause/Duration/Detection/Suppression
2	Location/Power Level/Component/Fire Cause/Duration/Detection
3	Location/Power Level/Duration/Detection/Suppression/Fire Cause
4	Location/Power Level/Duration/Suppression/Detection/Fire Cause
5	Detection/Suppression/Power Level/Duration/Fire Cause/Component
6	Duration/Detection/Suppression/Power Level/Fire Cause/Component
7	Power Level/Fire Cause/Initial Combustible/Duration/Detection/Suppression
8	Power Level/Component/Location/Detection/Suppression/Duration
9	Location/Component/Fire Cause/Initial Combustible/Power Level/Duration
10	Fire Cause/Initial Combustible/Component/Detection/Suppression/Duration

In performing the data sorts, three categories in the (Houghton 1997) database were deemed not to be relevant information for our task and were "dropped" from our sorts to better focus our attention on the elements we anticipated would yield the most useful information. These categories included: plant system, power effect and train affected. One shortcoming in the database became readily apparent, namely that there is too much variability within certain groups, which hinders data analysis. As an example, power level is reported as either power or shutdown, thus readily enabling the fire data to be sorted into two categories. On the other hand, the database lists 177 electrical failures (as the fire cause) involving 78 "different" initial combustibles, many of which are single or double entries. This limits the usefulness of the database in supporting the development of mechanistic FIPS. It would be helpful if fire data could be collected and reported in a more systematic way, and if the initial combustible could be grouped into fewer and more meaningful categories (with possible subcategories). As examples, all transient fuel initiated fires should be so reported (Transient fuel – "*xxx*"), with the subcategory "*xxx*" allowing for combustibles such as rags, trash, wood, and solvents. Also, while the database includes numerous "electrical wiring entries," knowing which were in power cables would be of interest. In addition, "motor internals" as the initial combustible, most likely involve wiring. In summary, a well-planned, formalized approach to fire incident reporting could yield a database more useful in FIPS development.

Despite the shortcomings identified above in the database, we were able to gain some qualitative and semi-quantitative insights into NPP fires. These are summarized below.

Power Level – A majority of the fire incidents in the database occurred during shutdown (199). Not surprisingly 85 percent of the welding fires occurred during shutdown. When the 81 welding initiated fires are removed from the database, the percentage of fires initiated by electrical failure (≈ 60 percent) or overheated material (≈ 35 percent) is essentially the same whether during power or shutdown.

Detection – Where the detection means was identified (360 total), five of every six fires were detected by a human (fire watch, plant personnel, security personnel, workers).

Suppression – Of the 347 fire incidents where the suppression means is identified, only13 fires were suppressed automatically. Five of these were detected by plant personnel and eight were detected automatically. The database does not allow one to assess whether or not detection was prior to or after suppression.

Cable Spreading Room – Only three fire incidents took place in the CSR, all occurred during power operation, and all were categorized as small (15 minutes or less in duration). Interestingly two of these fires were extinguished by an automatic suppression system; the other was detected by plant personnel and suppressed by a portable fire extinguisher. Note that FRAs generally find CSR fires to be among the most risk-significant.

Control Room – Eight of the 374 fires occurred in the control room, six while the plant was at power, and all were of short duration (5 minutes or less). Four were suppressed with portable extinguishers, two were self-extinguished, one was suppressed automatically, and for one the suppression means was not listed.

Switchgear Room – Eighteen fires occurred in switchgear, 11 while the plant was at power, and all but one (overheated material) were electrical. Two of the switchgear fires at power resulted in a fire categorized as medium size, with durations of 50 minutes and 20 minutes. These fires should be analyzed in greater detail to extract the circumstances [e.g., pre-existing fire condition, delay in detection (if a factor), presence of secondary fuels].

Turbine Building – By far the greatest number of fire incidents (109) occurred in the turbine building, and five of the 12 large fires (duration greater than one hour) in the database were the result of fires in turbine buildings.

Offsite – The highest percentage of fires that grew to be categorized as medium or large occurred offsite. Of thirteen offsite fires in the database, only two resulted in a small fire (duration less than 10 minutes).

Large Fire/Explosions – Fifteen fires or explosions in the database resulted in large fires (durations ranging from 1 to 17 hours). Six of these fires occurred in the turbine building, and the remaining nine fires occurred offsite.

Explosions – There are 20 explosions in the database and seven of these resulted in medium or large fires. FRAs do not explicitly address explosions.

B.1.3 Lessons Learned about the Initial Phase of Challenging Fires from the NRC Fire Protection Engineers Meeting

A meeting was held with several NRC fire protection engineers regarding transient fuels, transient ignition sources, oil fires, and other areas of concerns. The discussions were spirited and candid. These engineers expressed concerns regarding some aspects of the current FRA approach. These are discussed below.

Transient Fuels

Control of flammable liquids is maintained by limiting the quantity allowed in the plant at any one time, e.g., <1 gal. However, flammable liquids are not controlled by location; this is a concern of some fire protection engineers. It is very common to have flammable liquids (small quantities, <1 gal.) in plastic containers. During a shift, however, containers are frequently left open during breaks. Otherwise, flammable liquids are in safety cans, in storage lockers.

Safety (storage) cabinets are designed to contain fire within the cabinet or to contain a spill or leak. They are not designed to prevent flammable liquids from participating in a major fire within the area. Frequently doors to storage cabinets are left ajar; it must be recognized that safety cans are designed to vent in a fire, which would accelerate the rate of heat release (RHR). Finally the engineers expressed concern that there are no rules governing the location of these storage cabinets.

Substantial quantities of combustibles are assembled in one location during staging prior to shutdown for maintenance (e.g., hundreds of gallons of oil, O_2/acetylene for cutting). This is a relatively recent phenomenon; consequently fire experience data on this practice does not yet exist. In the past, NPPs operated for 12 mouths followed by three months downtime. Now plants are competing for the lowest ratio of downtime/operating time. A particular concern is that the designated area for transient fuel storage has often been near off-site power cables and switchgear. It would not be uncommon that welding gases, reels of cable and hundreds of pounds of dress-out gear would be stored in close proximity, creating a sizable fuel load.

Other transient fuel concerns expressed by the NRC fire protection engineers included:

- There is a lot of protective clothing discharged around step-off pads placed in plastic bins scattered throughout the plant.
- Substantial quantities of wood (some fire treated) are used throughout the plant for scaffolding. Sometimes a plastic covering ("tent") is placed over a wooden frame to isolate a piece of equipment, e.g., pump, that is being worked on.
- Fifty-five gallon drums filled with rags (many oil contaminated) and paper wastes are located throughout the plant during outages.
- Transient fuels, e.g., oily rags, have been seen in electrical cabinets and a lot of combustibles, e.g., wood, rags, are left in cable trays.

Of note, the engineers strongly disagreed with the finding in the EPRI Fire Events Database that transient ignition sources ignite transient combustibles, while fixed ignition sources do not. As an example, they cited the ignition of wood scaffolding around a diesel-generator by the hot diesel exhaust.

Transient Ignition Sources

The engineers identified four classes of transient ignition sources.

- Hot Work, e.g., cutting, grinding – The vast majority of fires started from these sources are small, quickly extinguished, and in the opinion of the engineers not reported.
- Temporary Heating Sources (e.g., salamanders) – The engineers believed that there is a high incidence of fires from temporary heating sources. Interestingly, the NPP fire experience database does not support this belief.
- Welding - particularly when welding up high. Fires start in cable trays, frequently from the transient combustibles left in the tray, and in scaffolding.
- Temporary Electrical Installations – These installations are built for outages and typically powered up prior to the outage to check them out. They are frequently built on wood bases, utilized for high amperage equipment, connected to temporary lighting, e.g., halogen lights, and not protected with fuses and breakers.

Oil Fires

The major concern is leaks/breaks in pressurized oil systems, e.g., diesel-generators. There are many exposed exterior pipes, lines, and fittings in close proximity to heated surfaces. Pressurized leaks are not readily contained and constant vibration causes leaks and sometimes failure in oil delivery systems. Hence there is always the potential for a widespread, rapidly developing fire. Of a lesser concern is that in the dynamic plant environment, repairs of oil leaks are not always made promptly. It is common that an oil leak, e.g., an air compressor, will be "managed", i.e., rags will be placed down to absorb the oil, and the oil refilled daily. This creates a potentially significant fuel source as the leak increases and if the oily rags remain within the plant.

Major Concerns

The NRC engineers identified six areas of concern:

- Cable Tray Fires – Four concerns regarding cable tray fires were expressed: breaker/fuse coordination; ring cuts; multiple fires; and in older plants the practice that instrumentation/control/power cables were installed in the same tray.
- Large Motors/Pumps
- High voltage switchgear
- Auxiliary Boiler in Turbine Building
- Seal-Oil Pump Room (H_2/oil) – The concern is that if the turbine-generator trips due to a fire and if off-site power runs through~~t~~out the building the off-site power may be lost. Then the on-site emergency power would be challenged.
- Explosions – Three areas of concern were identified: H_2 generators; battery charging room (H_2 build-up); and high voltage explosions.

B.2 Non-Nuclear Power Sources

Data were gathered and reviewed from various sources, e.g., NTSB, NFPA to expand our database on the critical elements in challenging fire scenarios and to support development of fire initial phase scenarios (FIPS). Analysis of real fire events in complex engineered systems can help to improve our understanding of key elements to be included in our FIPSs. Results of our findings and analysis follow.

B.2.1 Lessons Learned about the Initial Phase of Challenging Fires from the National Transportation Safety Board

The National Transportation Safety Board (NTSB), among its various charges, investigates aviation and marine transportation accidents. The NTSB publishes its findings, actions and decisions through accident reports. We met with the NTSB and were guided to reports that were deemed relevant and readily available. These reports were reviewed and analyzed.

Aircraft Accidents

The NTSB publishes an annual review of accident data involving U.S. registered aircraft that were not conducting air carrier revenue operations, e.g., personal, business, instructional. The data for 1996 (published May 1999) indicated a low number (8) of fire, explosion, fire/explosion accidents as “first occurrence” (i.e., initiating event in the accident sequence) of the total of 1,935 general aviation aircraft accidents. The potential relevance of these data to NPP FIPS is considered low and it was decided not to pursue this avenue of inquiry further at this time. However, one separate NTSB report involving a commercial carrier offered important lessons and is described below.

ValuJet Airlines Flight 592. On May 11, 1996, a ValuJet Douglas DC-9-32 crashed into the Florida Everglades about 10 minutes after takeoff from Miami International Airport. The crew of flight 592 became aware of a fire in the passenger cabin about 6 minutes after takeoff. The wreckage that was recovered provided evidence of fire damage throughout the majority of the forward cargo compartment and areas of the airplane above it. The NTSB determined that the probable cause of the fire was activation of one or more chemical oxygen generators being carried in the forward cargo compartment of the airplane.

Because the cargo compartment where the fire occurred was a class D cargo compartment and was not equipped (nor was it required to be equipped) with a smoke detection system, the cockpit crew of ValuJet flight 592 had no way of detecting the threat to the safety of the airplane from the in-flight fire until smoke and fumes reached the passenger cabin. Furthermore, because the cargo compartment was not equipped (nor was it required to be equipped) with a fire suppression system, the cockpit crew had no means available to extinguish or even suppress the fire in the cargo compartment.

If the fire started before takeoff, and if a smoke/fire detection-warning device had activated, the flightcrew most likely would not have taken off. However, the Safety Board concluded that even if the fire had not started until the airplane took off, a smoke/fire warning device would have more quickly alerted the pilots to the fire and would have allowed them more time to land the airplane. Further, the Safety Board concluded that if the plane had been equipped with a fire suppression system, it might have suppressed the spread of the fire (although the intensity of the fire might have been so great that a suppression system might not have been sufficient to fully extinguish the fire) and it would have delayed the spread of the fire, and in conjunction with an early warning, it would likely have provided time to land the airplane safely.

Fires in cargo compartments had been experienced previously. On August 19, 1980, a Lockheed L-1011 operated by Saudi Arabian Airlines was forced to return shortly after departure from Riyadh, Saudia Arabia, because of an in-flight fire in the aft section of the airplane. Even though the airplane landed successfully, the fire continued and spread throughout the cabin, killing all 301 occupants. The subsequent accident investigation concluded that the fire probably originated in the aft cargo compartment from an undetermined source. In June 1983, the FAA Technical Center completed a study of the effectiveness of transport-category aircraft class D cargo compartments in containing fires by oxygen starvation. The FAA study concluded that the Federal regulations did not ensure adequate burn-through resistance of class D cargo liners subjected to realistic fires. The study also noted that the cargo compartment liner was the initial fire barrier for the protection of aircraft components, structure, passengers, and crew members from a fire inside the cargo compartment.

On February 3, 1988, American Airlines flight 132, a McDonnell Douglas DC-9-83, experienced an in-flight fire while en route to Nashville Metropolitan airport, Tennessee, from Dallas-Ft. Worth, Texas. As the airplane was on a final approach, a flight attendant and a deadheading first officer (passenger) notified the cockpit crew of smoke in the passenger cabin. The fire eventually breached the cargo compartment, and the passenger cabin floor over the mid cargo compartment became hot and soft. The fire did not extinguish in-flight. After landing, the 120 passengers and six crewmembers safely evacuated the airplane. The Safety Board found that hydrogen peroxide solution (an oxidizer) and a sodium orthosilicate-based mixture had been shipped and loaded into the mid (class D) cargo compartment of the airplane. The investigation determined that the chemicals were improperly packaged and were not identified as hazardous materials. After the hydrogen peroxide leaked from its container, a fire started in the cargo compartment.

Lessons Learned

1. The presence of oxygen (oxidizer) source can greatly enhance the rate of fire growth and compromise fire containment designs based on oxygen starvation.

2. The absence of smoke/fire warning devices can enable fires to grow to an unmanageable size prior to detection.

3. Suppression systems may be unable to extinguish a high intensity fire supported by an oxygen source; however, they can delay the spread of the fire.

B.2.2 Lessons Learned about the Initial Phase of Challenging Fires from Marine Accidents

Tankship Seal Island. On October 8, 1994, the Liberian tankship Seal Island was moored at the Hess Oil Refinery in St. Croix, U.S. Virgin Islands. While engineering personnel were changing the lubricating oil strainer on the ship's service turbogenerator, lubricating oil sprayed onto the hot turbine casing and a fire erupted. The fire burned about 6 hours before it was extinguished. Three crew members were killed and 6 other crew members sustained serious injuries.

About 4 months before the accident, while at sea, the chief engineer had directed a temporary repair to the lubricating oil duplex strainer for the ship's service turbogenerator. The strainer was leaking about 6 gallons per day past the lower O-ring on the directional valve. The permanent repair was never made despite numerous opportunities over the four months. The fire seriously damaged the tankship's engineroom; smoke, water and soot badly damaged the accommodations and pilothouse. The tankship was declared "no longer a useful carrier" and was sold as scrap for $12 million.

Lesson Learned

1. Lubricating oil sprayed on hot surfaces can result in a very rapidly developing fire, which is difficult to extinguish even when detected immediately. Lubricating oil can serve as a readily available fuel supply to sustain, and accelerate the growth of, the fire.

MS Ecstasy Fire. On July 20, 1998, at approximately 1642, the Liberian passenger ship Ecstasy was departing to Port of Miami, Florida bound from Key West. At 1710 an alarm sounded on the fire control panel on the bridge deck and shortly thereafter flames and large volumes of black smoke were seen issuing from the stern of the vessel. Almost 45 minutes later, while fighting the fire, carrying out damage control, and manuvering the ship toward a safe anchorage, the ship lost all propulsion power and steering and began to drift. The fire was brought under control and extinguished about 2109.

The fire started in the laundry room as a result of a welding repair to an ironing/folding machine and immediately spread to a ventilation duct. A hot work permit is required for all welding done on-board the ship; the welders did not have the permit and apparently failed to use a fire blanket. There were sprinklers in the laundry room but none in the ventilation ducts. Unable to extinguish the fire, the welders left the area. Other personnel activated manual pull stations.

The fire spread to a ventilation duct above the ironing/folding machine and fueled by lint (and wax used in the ironing process) quickly spread through the ductwork, exiting out onto the aft mooring deck plenum, an area where exhaust ventilation ducts exit the ship. The fire exiting on the aft mooring deck ignited large diameter polypropylene rope with lint embedded in its fibers. Next the fire spread back into additional ductwork along the rope, which had been run temporarily through those ducts. Cables and equipment adjacent to the ducts ignited and burned and, finally, smoke from these fires fouled a nearby propulsion control computer, causing irreversible damage and subsequent loss of propulsion power and control.

Lessons Learned

1. Combustible material deposited in ventilation ducts can rapidly propagate a fire from the room of origin to numerous areas, involving fuel in other locations.
2. Running temporary ropes or cables through ventilation ducts or doors can enhance fire propagation through existing pathways.
3. High temperatures transferred through duct walls or other barriers can ignite multiple fires adjacent to them.
4. Smoke can cause failure of sensitive electronic equipment.

B.2.3 Lessons Learned about the Initial Phase of Challenging Fires from the National Fire Protection Association

The National Fire Protection Association's (NFPA) Fire Analysis and Research Division provides customized services on fire-related issues for a fee. In particular, they can develop Customized Reports gleaned from their extensive databases on the size, characteristics, or trends of a specific fire problem of interest. These reports contain statistical tables and explanatory text when needed. Such data, while of some interest, were deemed to be of insufficient value to actively pursue. However NFPA does conduct Incident Searches – searches of individual fire incident files, specifically their Fire Incident Data Organization (FIDO) database. FIDO keywords and codes cover many topics not coded in the database used for statistical analysis; even when NFPA cannot provide precise statistics on a specific topic, they often can provide illustrative fire incidents. We requested such an Incident Search.

The search covered the years 1980-1998 and limited the fires selected from the NFPA database to fires that we judged would be relevant to nuclear power plants. Thus, we included use codes for nuclear energy plants, steam plants, electric generating plants, electrical/electronic laboratories, electrical/electronic communications centers, and electric distribution equipment. We specifically excluded heats of ignition from blasting, fireworks and rocketry; ignition factors for incendiaries, sabotage, thawing, controlled burns, and children's play; and buildings of wood construction. The search generated limited information on only several dozen fires. Unfortunately, it yielded little useful information beyond what we already had (e.g., Browns Ferry fire). One other incident of relevance from the NFPA search is described below.

Newark Cogeneration Facility. A rapidly developing fire in the Newark Cogeneration Facility in Newark, New Jersey on December 25, 1992 claimed the lives of all three workers who were in the plant at the time. The fire in the recently built electrical power plant broke out at about 8:30 AM. The early-morning fire occurred just after a shift change at the plant. It appears that the lubrication (lube) oil piping failed on the discharge side of the lube oil pump for the plant's steam turbine. This resulted in a rapid release of preheated, 190°F oil discharging at an estimated 170 to 180 psi. Materials safety data sheet information indicated a flash point of 385°F for this oil.

Since the pump was positive displacement, high discharge pressures existed for much of the time during release of the fluid. Most of the 2,000 gallons of combustible lube oil was missing from the lube oil tank. It appears to have contributed to the fire by escaping through a break at a flange connection in the 6-inch-diameter lube oil piping.

This break probably resulted in a fine spray of lube oil throughout the immediate area and a quick buildup of oil beneath the turbine. Physical evidence indicates that ignition was probably delayed, but an unknown ignition source soon ignited the fuel-air mixture, causing a low-order explosion in the building. The ignition also resulted in a fire at the failed piping flange and a hot, running pool fire under the steam turbine's concrete support pedestal. During this initial period of fire growth, the automatic sprinkler system that protected most of the plant area did not operate because of a closed valve; thus no notification (automatic or manual) was made to the fire department.

Lessons Learned

1. Breaches in the integrity of high-pressure oil piping create conditions, e.g., sprays and pools that can quickly develop into a challenging fire.

2. Automatic sprinkler systems can be rendered inoperative by improper human actions.

B.2.4 Lessons Learned about the Initial Phase of Challenging Fires from Other Serious Fire Events

In our review of other documents on fire risk two other serious fire events were discovered. These are described below.

Piper Alpha

Shortly after 2200 on the evening of July 6, 1988, a series of gas explosions occurred that ultimately destroyed the Piper Alpha gas production platform in the North Sea. One hundred and sixty-five out of 226 people on the platform were killed, together with two rescuers.

A gas safety valve was removed for recertification from condensate injection loop A, and the blind flanges covering the pipework openings were only screwed down thumb-tight. When a duty pump in loop B failed, operators inappropriately started condensate injection pump A, thereby creating a fuel vapor cloud in the equipment space via the partially sealed relief valve opening. The vapor cloud then ignited in the closed area.

The automatic fire-suppression pumps were routinely left in “manual” to prevent divers being inadvertently sucked towards the pumps’ seawater intakes if the pumps should start without warning. Reaching the fire-pump controls to start them manually involved accessing the area of the explosion.

The primary cause of the initial gas leak was the failure of the operators to be aware that the compressor should not be started, which was blamed on failure of the “permit-to-work” (tagging) system. Once the fire started and operators could not reach the emergency fire-fighting diesel pumps to start them, the fire raged unabated, destroying the rig structure.

Lesson Learned

1. Major fires can result from simple omission errors such as overlooking the tagged-out status of equipment.

Phillips 66

The fire and explosion at the Phillips 66 Company Houston Chemical Complex on October 23, 1989, resulted from a massive release (85,000 pounds) of a process gas used in making high-density polyethylene. The gas was a mixture of four flammable chemicals: isobutante, ethylene, hexene, and hydrogen. The gas cloud exploded with a force calculated to be 2.4 tons of TNT. Twenty-three workers were killed, over 130 were injured, and the property losses exceeded $750 million.

The accident occurred during routine maintenance operations that involved unblocking a (chemical) reactor leg in which particles of ethylene settle after they are created by interaction of the process gas at an elevated temperature and pressure. The leg is connected to the main reactor via a special air operated globe valve, called a DEMCO® valve. Once the valve is closed, the leg can be detached from the reactor and the polyethylene removed. If the valve is open when the leg is detached, the process gas inventory will be discharged almost immediately. In the post-explosion analysis, one of the valves was found open. Despite a corporate requirement by Phillips to have “double isolation” for such a hazardous connection, local plant procedures no longer called for this standard. Further, the DEMCO valve involved in the accident did not have its lockout mechanism in place.

Lesson Learned

1. A major fire can occur from a simple error during routine operations or maintenance when organizational safety standards, i.e., removing the need for double isolation, are not practiced.

B.2.5 Information from the FAA Technical Center

A visit was made to the FAA Technical Center, Atlantic City International Airport, NJ to discuss with the Manager, Fire Safety Section and the Program Manager Aircraft Fire Safety/Aircraft Cabin Safety the FAA research directed towards fire safety.

The mission of the Fire Safety Section is to set minimum standards for survivability from fire. Their fire concerns are grouped into two broad areas: post-crash and in-flight. The data indicates that there are a couple of thousand in-flight fires per year. Numerous fires occur in the galley, but these have never developed to be a challenging fire. Three major areas of concern have been identified.

- Material/ignition sources carried on by passengers – FAA's approach is to provide materials, e.g., luggage compartment, to confine the fire and to ensure rapid detection and suppression.
- Fuel tanks – The approach is to eliminate ignition sources (not 100% effective); also have looked at using an inerting system for critical times, e.g., during take-off and early in the flight.
- Hidden areas – Fires in areas where the crew cannot "see", e.g., lavatory, cargo hold, have the greatest potential for catastrophic failure due to an in-flight fire.

The FAA tried a few years ago to initiate some PRA work with NIST. The effort was unsuccessful; hence much of the FAA analysis is subjective. Each major fire accident is "new", since most of the research has been directed towards solving previous major fire incidents.

B.3 References

(Nowlen 2001) Nowlen, S.P., M. Kazarians, and F. Wyant, "Risk Method Insights Gained from Fire Incidents, NUREG/CR-6738, Sandia National Laboratories, prepared for U.S. Nuclear Regulatory Commission, Washington, DC, September 2001.

(Houghton 1997) Houghton, J.R., "Special Study: Fire Events - Feedback of U.S. Operating Experience," AEOD/S97-03, U.S. Nuclear Regulatory Commission, June 1997.