RESEARCH NEEDS IN FIRE RISK ASSESSMENT

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Abstract

This paper identifies and discusses a number of fire risk assessment areas where research appears to be needed to: a) provide a better understanding of the risk contribution due to fires in nuclear power plants, b) provide improved support of ongoing and anticipated activities regarding nuclear power plant fire protection, and c) develop improved methods and tools to support the previous two objectives. An analytical representation of the current fire risk assessment process, augmented by information from a variety of sources, is employed to systematically identify potential need areas. The results of this process are expected to play a major role in the development of a fire research program.

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1. BACKGROUND AND OBJECTIVE

Since being prompted by the Browns Ferry fire of 1975, a number of nuclear power plant fire risk assessments (FRAs) have shown that fires can be significant contributors to plant risk. The most important scenarios identified in these analyses tend to involve the occurrence of relatively infrequent fires whose location and severity are such that critical sets of plant equipment are likely to be damaged by such a fire, if it occurs. These general conclusions regarding the potential magnitude and character of nuclear power plant fire risk appear to be consistent with empirical evidence, where serious fire-induced challenges to reactor core cooling are not common events but have occurred.

While there is little argument about the potential importance of fires, the magnitude of the fire risk and the specific measures needed to efficiently manage this risk are not as clear when considering individual plants. Table 1 summarizes the results from a sample of FRAs performed on U.S. nuclear power plants. The variability in the estimated fire risk and risk contributors is due not only to plant-specific variations in design and operation, but also to variations in the methods and data used in the studies. Uncertainties in the current state of knowledge concerning the initiation, growth, suppression, and plant impacts of fire-induced nuclear power plant accident scenarios all contribute to this latter category of variability; they have raised significant concerns regarding the usefulness of current FRA tools in supporting proposed plant changes and the development of a risk-informed, performance-based rule for nuclear power plant fire protection.

The objective of this paper is to discuss a number of FRA methods and data areas where improvements appear to be needed. The discussion is based on the authors' experience in FRA methods development, the performance of FRAs, and the review of these studies; insights from the US. Nuclear Regulatory Commission's (NRC) ongoing review of Individual Plant Examinations of External Events (IPEEEs); experiences from the NRC's current efforts regarding the development of a risk-informed, performance-based fire protection rule; the results of a recent NRC-sponsored review of fire research issues [1]; a review of other recent papers and reports on current issues in FRA (e.g., [2,3]); feedback from the NRC's Advisory Committee on Reactor Safeguards (ACRS); and informal discussions with researchers from universities, industry, government, and international organizations. The paper presents work in progress and does not represent a final NRC consensus position on research need areas, let alone a prioritization of needs. However, it is expected that the issues presented in this paper will factor strongly in the development of the NRC's fire research program. We note that, because of limited resources, this fire research program will probably focus on a limited number of issues. Collaboration with industry and international organizations is needed to ensure broad coverage of potential concerns.

It should be cautioned that the technical issues raised in this paper do not necessarily prevent the use of FRA as a decision support tool. While they are imperfect tools, FRAs have led to a better understanding of fire risk. This paper simply identifies areas where additional improvements in FRA tools and in fire risk understanding could be useful to NRC's fire protection activities.

Table 1 - A Partial List of Fire PRAs for U.S. Nuclear Plants (Not Including IPEEEs)

Plant	Sponsor	Date	Fire CDF (/yr)	Total CDF (/yr)	Important Contributors[a]
HTGR (design)	USDOE	1979	1.1E-5[b]	4.1E-5[b]	CSR (only the CSR was analyzed)
Zion 1/2	Utility	1981	4.6E-6	4.9E-5	Electrical equipment room, CSR
Big Rock Point	Utility	1981	2.3E-4	9.8E-4	Station power room, cable penetration area
Indian Point 2	Utility	1982	2.0E-4[c]	4.7E-4	Electrical tunnels, swgr room
Indian Point 3	Utility	1982	6.3E-5[c]	2.3E-4	Swgr room, electrical tunnel, CSR
Limerick	Utility	1983	2.3E-5	1.5-5[d]	Equip. rooms, swgr room, access area, MCR, CSR
Millstone 3	Utility	1983	4.8E-6	7.2E-5	MCR, instrument rack room, CSR
Seabrook	Utility	1983	1.7E-5	2.3E-4	MCR, CSR
Midland	Utility	1984	2.0E-5	3.1E-4	Swgr room
Oconee	Utility	1984	1.0E-5	2.5E-4	
TMI-1	Utility	1987	8.6E-5	5.5E-4	MCC area, swgr room, cabinet area
Sav. River K Rx	USDOE	1989	1.4E-7[e]	3.1E-4[e]	MCR, maint. area, cable shaft, DG rooms
S. Texas Project	Utility	1989	< 1.2E-6[f]	1.7E-4	MCR
Diablo Canyon 1/2	Utility	1990	2.9E-5	2.0E-4	CSR, MCR
Peach Bottom 2	USNRC	1990	2.0E-5	2.8E-5[g]	MCR, swgr rooms, CSR
Surry 1	USNRC	1990	1.1E-5	7.6E-5[g]	Swgr room, MCR, aux bldg, cable vault/tunnel
La Salle 2	USNRC	1993	3.2E-5	1.0E-4	MCR, swgr rooms, equip rooms, turbine bldg, cable shaft
Grand Gulf 1	USNRC	1994	< 1.0E-8[h]	6.7E-5[g,b]	No areas found to contribute
Surry 1	USNRC	1994	2.7E-4[h]	4.3E-4[g,b]	Swgr room, cable vault/tunnel, containment, MCR

a) Area contribution > 1% total fire CDF; contributing areas prioritized by contribution (most important first); MCR = main control room, CSR = cable spreading room
b) Frequency of core heatup
c) Prior to plant modifications identified by risk study
d) Internal events only
e) Frequency of severe core damage
f) Total contribution from external events
g) Seismic contribution calculated using EPRI seismicity curve
h) Midloop conditions; instantaneous CDF is presented

2. APPROACH

In order to systematically identify FRA areas where research is needed, it must be first recognized that the intended research has the following three general technical objectives:

1) The research should lead to an improved understanding of the risk contribution due to fires in nuclear power plants. This understanding covers both quantitative aspects (e.g., the magnitude of the overall fire risk) and qualitative aspects (e.g., the scenarios that tend to dominate fire risk).

2) The research should provide support for ongoing or anticipated NRC program office activities. Examples include the development of a risk-informed, performance-based fire protection rule; fire protection inspections; and review of proposals to change a plant's current licensing basis. The last should include an evaluation of the impact of the proposed changes on risk (including fire risk).

3) The research should lead to the development of improved FRA methods and tools (including data), where such improvements are needed to support the first two objectives. Improvements are needed not only enable the assessment of situations not covered by current FRA, but also to improve the analysts' and decision makers' confidence in the results of an FRA.

These three objectives imply a broad range of research needs. In order to ensure that the identification of research needs is reasonably complete, an augmented analytical approach is employed. This approach first involves a systematic examination of the current FRA process and methodology, and the identification of areas where the current state of knowledge is weak and/or controversial. Next, to help ensure that the list of identified needs is not too heavily dependent on a particular view of fire risk and that it is not exclusively focused on methodological issues, the list is then supplemented using a information from a variety of sources, as discussed later in this section.

2.1 Fire Risk Assessment Process

Fire risk assessment for commercial nuclear power plants, as it is performed today, is little changed from the analytical process described in Refs. 4 and 5 and used in the Zion and Indian Point studies some 15 years ago [6,7]. Weaknesses in the elements of the approach, i.e., the data and tools for specific portions of the analysis, have been identified and progressively addressed in a number of studies (e.g., [8,9]). Furthermore, a number of remaining weaknesses in these elements, e.g., in the treatment of fire phenomenology, are the subject of discussion and ongoing research, as discussed below. However, the basic structure of the analysis has remained relatively constant.

In a typical FRA, the core damage frequency contribution due to a given fire scenario (where, in this discussion, a fire scenario is defined by the location and burning characteristics of the initiating fire) can be decomposed into three components: the frequency of the fire scenario, the conditional probability of fire-induced damage to critical equipment given the fire, and the conditional probability of core damage given the specified equipment damage. Formally accounting for the possibility of different levels of equipment damage and different plant responses following fire initiation,

$$CDF = \sum_i \lambda_i \left(\sum_j p_{ed,j|i} \left(\sum_k p_{CD,k|i,j} \right) \right) \quad (1)$$

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 the occurrence of fire scenario i, and $p_{CD,k|i,j}$ is the conditional probability of core damage due to plant response scenario k given fire scenario i and damage to critical equipment set j. Note that the second term addresses the issues of fire growth, detection, suppression, and component damageability, and that the third term addresses the unavailability of equipment unaffected by the fire and/or operator failures.

The three-term decomposition of fire risk presented in Eq. (1) is not unique; alternate decompositions (often involving more terms) can be found in the literature. From the standpoint of this paper, however, it is useful because each of the three terms tend to be addressed differently in current FRAs. In particular, the fire frequencies are generally estimated using simple statistical models for fire occurrences, the likelihood of fire damage is estimated using combinations of deterministic and probabilistic models for the physical processes involved, and the likelihood of core damage is estimated using conventional probabilistic risk assessment systems models. These different analytical approaches imply different methods and tool development needs.

2.2 Additional Sources of Information

The use of Eq. (1) in the identification of research issues is both a strength and a weakness. Clearly, it provides a framework for systematically identifying FRA issues especially relevant to Objective #1 listed above. This helps to ensure completeness. On the other hand, being model based, it provides a particular view of fire risk. If it is not carefully exercised, issues not explicitly addressed or even emphasized by the model may not be identified. For example, current FRAs are focused on the possibility of thermal damage to plant equipment. Although the general framework of Eq. (1) also applies to alternate damage mechanisms, e.g., smoke damage and damage due to suppression activities, specific issues relevant to these mechanisms, e.g., the frequency-magnitude relationship for smoke, can easily be overlooked.

Another weakness with the use of Eq. (1) in identifying research issues is that such an approach tends to focus on methodological and data issues. It does not necessarily address the users' needs implied by Objective #2; these needs may be satisfied by the performance of technical assessments using the current state of the art.

A variety of information sources are used to supplement the list of issues identified using Eq. (1). Formal sources include a recent NRC-sponsored review of fire research issues [1]; recent papers and reports on current issues in FRA (e.g., [2,3]); and feedback from the NRC's Advisory Committee on Reactor Safeguards. Informal sources include the authors' participation in the review of IPEEE studies and in NRC's current efforts to develop a risk-informed, performance-based fire protection rule; as well as informal discussions with researchers from universities, industry, government, and international organizations.

An important example of users' needs input is provided by Table 2. This table contains a list of 13 potential safety issues recommended for further study by the NRC staff. Twelve of

these issues were identified as part of the NRC's fire protection rulemaking planning process [10]; the thirteenth issue (availability of safe shutdown equipment) was identified following the staff's review of the Quad Cities Individual Plant Examination of External Events (IPEEE) study [11]. Examination of these issues shows that a number of them (e.g., availability of safe shutdown equipment) can probably be addressed without additional methodological developments. However, they remain as potential research issues because their generic risk significance is not completely understood.

Table 2 - Supplemented List of Fire Protection Issues Identified in the Fire Protection Task Action Plan

Fire Impact on Reactor Safety
Availability of Safe Shutdown Equipment
Hot Shorts Resulting in Spurious Operations or Component Damage
Control Room/Cable Spreading Room Interaction with Remote Shutdown Capability
Smoke Effects on Personnel/Equipment
Explosive Electrical Faults
Compensatory Measures for Fire Protection Deficiencies
Seismic Fire Interactions
Fires During Non-Power Operations
Broken/Leaking Flammable Gas Lines
Reliability of Fire Barriers
Equipment Protection from Fire Suppression System Actuation
Fire Detection Methods

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3. POTENTIAL RESEARCH NEEDS

Table 3 presents a list of the potential fire research issues identified using the approach described above. As indicated by the note at the bottom of the table, most of these issues are grouped according to the general FRA area of analysis (e.g., fire initiation analysis). The remainder of the issues deal with either: a) problem-specific, integrated treatments of fire initiation, equipment damage, and plant response, or b) issues not directly derived from the FRA analysis process. Table 4 groups these issues into topic areas, where topic areas can be distinguished by the general type of analysis (e.g., statistical vs. phenomenological) as well as subject matter. Note that the orderings of the potential issues and topics are not based on any notion of relative importance. Discussions within the NRC regarding issue and topic prioritization are ongoing.

The remainder of this section provides background information relevant to the issues listed in Tables 3 and 4.

Table 3 - Potential Research Issues

Issue ID	Issue Title
I1	Adequacy of fire events database
I2	Scenario frequencies
I3	Effect of plant operations, including compensatory measures
I4	Likelihood of severe fires
E1	Source fire modeling
E2	Compartment fire modeling
E3	Multi-compartment fire modeling
E4	Smoke generation and transport modeling
H1	Circuit failure mode and likelihood
H2	Thermal fragilities
H3	Smoke fragilities
H4	Suppressant-related fragilities
B1	Adequacy of data for active and passive barriers
B2	Barrier performance analysis tools
B3	Barrier qualification
B4	Penetration seals
S1	Adequacy of detection time data
S2	Fire protection system reliability/availability
S3	Suppression effectiveness (automatic, manual)
S4	Effect of compensatory measures on suppression
S5	Scenario-specific detection and suppression analysis
P1	Circuit interactions
P2	Availability of safe shutdown equipment
P3	Fire scenario cognitive impact
P4	Impact of fire induced environment on operators
P5	Role of fire brigade in plant response

Table 3 - Potential Research Issues (continued)

Issue ID	Issue Title
R1	Main control room fires
R2	Turbine building fires
R3	Containment fires
R4	Seismic/fire interactions
R5	Multiple unit interactions
R6	Non-power and degraded conditions
R7	Decommissioning and decontamination
R8	Fire-induced non-reactor radiological releases
R9	Flammable gas lines
R10	Scenario dynamics
R11	Precursor analysis methods
R12	Uncertainty analysis
O1	Learning from experience
O2	Learning from others
O3	Comparison of methodologies
O4	Standardization of methods

Note: The first character in the issue IDs refers to the type of issue. I = fire initiation, E = fire-induced environment, H = hardware impact, B = fire barrier, S = fire detection and suppression, P = plant response, R = integrated fire risk, O = other.

Table 4 - Potential Fire Research Issues Grouped By Topic Area

Topic ID	Topic Title	Issue ID	Issue Description
T1	Fire events database	I1	Adequacy of fire events database
T2	Fire initiation analysis	I2	Scenario frequencies
		I3	Effect of plant operations, incl. compensatory measures
		I4	Likelihood of severe fires
T3	Fire modeling toolbox: assessment and development	E1	Source fire modeling
		E2	Compartment fire modeling
		E3	Multi-compartment fire modeling
		E4	Smoke generation and transport modeling
		H2	Thermal fragilities
		H3	Smoke fragilities
		H4	Suppressant-related fragilities
		R12	Uncertainty analysis
T4	Fire barrier reliability analysis	B1	Penetration seals
T5	Fire barrier qualification and thermal analysis	B2	Adequacy of data for active and passive barriers
		B3	Barrier performance analysis tools
		B4	Barrier qualification
T6	Detection and suppression analysis	S1	Adequacy of detection time data
		S2	Fire protection system reliability/availability
		S3	Suppression effectiveness (automatic, manual)
		S4	Effect of compensatory measures on suppression
		S5	Scenario-specific detection and suppression analysis
T7	Circuit failure mode and likelihood	H1	Circuit failure mode and likelihood
T8	Impact of fires on operator performance	P3	Fire scenario cognitive impact
		P4	Impact of fire induced environment on operators
		P5	Role of fire brigade in plant response
		R10	Scenario dynamics
T9	Risk significance of main control room fires	P1	Circuit interactions
		R1	Main control room fires
T10	Risk significance of turbine building fires	R2	Turbine building fires
T11	Risk significance of containment fires	R3	Containment fires

Table 4 - Potential Fire Research Issues Grouped By Topic Area (continued)

Topic ID	Topic Title	Issue ID	Issue Description
T12	Fire PRA applications issues	P2	Availability of safe shutdown equipment
		R4	Seismic/fire interactions
		R5	Multiple unit interactions
		R6	Non-power and degraded conditions
		R9	Flammable gas lines
		O3	Comparison of methodologies
T13	Non-core damage issues in fire risk assessment	R7	Decommissioning and decontamination
		R8	Fire-induced non-reactor radiological releases
T14	Precursor analysis methods	R11	Precursor analysis methods
T15	Experience from major fires	O1	Learning from experience
T16	International cooperation	O2	Learning from others
T17	Fire PRA guidance and standardization	O4	Standardization of methods

3.1 Fire Initiation

According to a recent NRC study, the frequencies of fires in key U.S. nuclear power plant compartments have not changed dramatically when comparing the periods 1965-1985 and 1986-1994 [12]. The computed reductions (in most cases) and increases (in the case of the turbine building) are generally not large when considering: a) the uncertainties in the estimated frequencies, and b) variability in reporting practices. Other than addressing the need for a maintained database, therefore, it may appear that little methodological work needs to be done in this area. However, a closer examination of the way in which empirical fire frequencies are employed in FRAs reveals some issues that need to be addressed.

First, and most obvious to FRA practitioners and reviewers, is the reduction of fire frequencies performed in most detailed FRAs to accommodate the fact that not all fires are risk significant, i.e., that a fire must have the proper location and severity characteristics to be a potentially important cause of critical equipment damage. In a number of FRAs, "location fractions" are employed to reduce plant area-based fire frequencies to account for geometrical factors; other FRAs use plant component-based fire frequencies for this same purpose. Regarding fire severity, "severity fractions" are widely used to address the fraction of fires (in a given compartment or involving a given component) that have the potential to cause significant damage in a relatively short amount of time.

Current reduction factors used to address location and severity considerations can reduce the compartment fire frequencies (the λ_i) by one or more orders of magnitude. However, the basis for these reduction factors is not strong. Early studies relied heavily on analyst judgment. Attempts to reduce the influence of judgment have led to: a) the component-based approach to fire frequency, employed in the Electric Power Research Institute (EPRI) Fire-Induced Vulnerability Evaluation (FIVE) methodology [13], and b) event-based estimation of severity fractions (e.g., [14-16]). However, these approaches are not without problems. Regarding the location issue, the FIVE approach requires an assumption

that the total frequency of fires involving a specific class of equipment is constant from plant to plant. (Note that relaxation of this assumption will require an estimate of the population base, including non-safety as well as safety equipment.) This assumption neglects differences in the effectiveness of fire prevention programs, but is not, in general, expected to have a major impact on fire frequency estimates.

The concerns with the event-based treatment of the severity issue are potentially more significant. These include: ambiguity in the data (qualitative event narratives are used to determine if a given fire was severe); possible double-counting of the impact of suppression in the data (effective suppression may be the reason why a particular fire was not reported as being severe, but fire suppression is modeled separately in the FRA -- see Section 3.2.4); neglect of possibly significant differences between conditions (e.g., fuel bed geometry) of the event and those of the situation being analyzed in the FRA which can affect the severity of the fire; and scarcity of data for the large, transient-fueled fires that have been predicted to dominate fire risk in a number of studies.

Other issues related to the estimation of fire frequencies include: the effect of plant operations on fire frequency, the frequency of self-initiated cable fires, and the potential significance of unreported fires. Regarding the first issue, current analyses are unable to quantitatively predict the impact of such measures as the use of fire watches or the existence of administrative controls on the storage of transient combustibles on the frequency of fires, let alone the frequency of severe fires. This is an important problem from a fire risk management point of view, e.g., in situations where such compensatory measures as fire watches are proposed to account for temporary fire protection deficiencies. Regarding the second issue, tests have shown that electrical ignition of fires involving IEEE-383 rated cables is difficult (e.g., see Ref. 17). A practical FRA question is, for compartments containing only rated cables, what is the frequency of cable fires? Is it sufficiently low that the analysis only need consider transient-fueled fires? The third issue is related to the severity factor issue: many fires in U.S. nuclear power plants do not cause sufficient damage to meet reporting criteria. The fire frequencies used in FRAs, therefore, are based solely on reported fires. While it has been argued in past FRAs that only the reported fires are potentially risk significant and should be considered when estimating the λ_i, a detailed technical basis to support this argument has not been developed.

The preceding issues deal with the problem of quantifying the likelihood of fire occurrence. A related issue concerns the establishment of conditions for the next stage of the FRA, the estimation of the likelihood of equipment damage (see Section 3.2). Current methods for performing this next stage generally rely upon fire environment simulation models, and these models require the specification of the initial conditions for a given simulation. The problem is that current fire frequency analyses provide, at most, the frequency of “small” and “large” fires in a specified compartment or involving a specified component. They do not provide the physical characteristics associated with these “small” and “large” fires needed by the simulation models. This ambiguous interface between the fire frequency and equipment damage analyses allows significant analyst discretion. For example, the Indian Point study [7] assumes that “large” fires have a severity equivalent to a 2-foot diameter oil fire, while the Surry NUREG-1150 study [18] assumes that this is the equivalent severity of “small” fires. In the Quad Cities IPEEE [11], all main feed pump fires are analyzed as if they involve the release of a pump’s entire lube oil inventory into a diked sump area and subsequent ignition of the oil; there is no distinction between large and small fires.

Fire frequencies have, to date, been treated as empirical parameters which can be directly estimated from data. The issues discussed above show that this treatment may need to be re-examined, especially if FRA is to play a stronger role in risk management. As argued in Ref. 19, a more mechanistic, systems modeling approach which specifically addresses the possible scenarios leading to fire ignition and the different outcomes of these scenarios, and does so within the constraint of available data, appears to be needed.

3.2 Equipment Damage

Given a fire in a nuclear power plant compartment, the conditional probability of damage to key equipment needs to be determined. In a detailed FRA, the assessment typically involves a prediction of the fire-induced environmental conditions, an assessment of the likelihood of equipment damage under these conditions, and an assessment of the likelihood that the fire will not be detected and suppressed before equipment damage occurs. The analysis may also consider the effectiveness of fire barriers in preventing fire damage to protected equipment and in preventing fire growth to neighboring compartments.

3.2.1 Fire Environment

Characterization of the fire-induced thermal environment for the purposes of probabilistic risk assessment (PRA) requires the estimation of the time-dependent temperature and heat fluxes in the neighborhood of the safety equipment of interest (i.e., the "targets"). This requires the treatment of a variety of phenomena as the fire grows in size and severity, including the spread of fire over the initiating component (or fuel bed), the characteristics of the fire plume and ceiling jet, the spread of the fire to non-contiguous components, the development of a hot gas layer, and the propagation of the hot gas layer or fire to neighboring compartments. It also requires an appropriate treatment of uncertainties in the structure and parameters of the models used to perform the analysis.

It is well recognized in the fire sciences community that there are limitations in our current ability to model fire behavior (e.g., see [20]). Even current "field models" (numerical computational fluid dynamics simulation models) adapted to fire applications do not address all of these limitations as they deal with fluid flow and heat transfer but not with fundamental combustion processes. The development of a detailed level understanding of fire phenomenology is a long term prospect. Given the risk assessment perspective that near term decisions must be supported with the best information presently available, the question is if the tools available are "good enough." More precisely, are there tools to treat all fire scenarios of interest, are the limitations of these tools known, and are the biases and uncertainties in their predictions understood?

A fire scenario involves the development of a specified source fire over time. Three source fires of special interest in nuclear power plant FRAs are cable tray fires, electrical cabinet fires, and very large oil fires. The risk significance of cable tray fires and electrical cabinet fires, has long been recognized. More recently, very large oil fires have been found to be important in situations where severe turbine building fires can significantly impact efforts to achieve safe shutdown (e.g., see Refs. 11 and 21). As discussed below, there are considerable uncertainties in key parameter values characterizing cable and cabinet fires. On the other hand, while the physical properties of oil are reasonably well understood, the ability of current FRA models to accurately predict the behavior of very large oil fires under realistic

plant conditions is of concern, due to such complications as flame obstructions and oxygen starvation (both local and global).

Given a source fire, the next questions to be answered by the thermal environment analysis involve fire growth within the compartment and spread to neighboring compartments (neglecting for the moment the effect of fire suppression activities). Characteristics that can affect these processes include the compartment geometry and ventilation, location of the source fire, and, in the case of the multi-compartment fires, the effectiveness of barriers (see Section 3.2.3). As will now be discussed, these characteristics are not completely addressed by the models currently used in FRA.

To date, U.S. nuclear power plant FRAs have used quite simple zone model-based tools, e.g., the correlations provided as part of the EPRI FIVE methodology [13] and the COMPBRN computer code [22,23], to predict the thermal environment due to a variety of fire sources, including cable tray, electrical cabinet, and oil pool fires. However, it is not always recognized in FRAs that these tools have been developed to address specific classes of fire problems and are not applicable to all situations. For example, the inherent zone modeling assumptions in both FIVE and COMPBRN do not address many practical complexities (e.g., obstructions in the fire plume, complex compartment geometry, complexities in forced ventilation flow, physical movement of fuel, room flashover) which can be important in some analyses. Further, the correlations employed implicitly or explicitly by these models are not appropriate for all situations. Some scenarios of potential concern include very small fires (e.g., single wire electrical insulation fires), very large fires (e.g., very large oil spill fires), or elevated fires. Unfortunately, the limitations of these simple models have not been succinctly characterized to inform FRA analysts, many of whom may not have strong background in fire science, when they should be wary of the model predictions.

Even in cases where the models are appropriate, the uncertainties in their predictions have not been completely characterized. These uncertainties stem from two sources: the uncertainties in model input parameters, and the uncertainties in the fire models themselves.

Regarding the first source of uncertainty, all compartment fire models require, as input, information concerning the burning characteristics of the fire and the physical characteristics of the compartment. The latter can usually be specified with relatively low uncertainty. However, this is not typically the case with the former. Whether the fire model requires a time-dependent heat release rate, as is the case with many widely available zone models (e.g., CFAST [24]), or more detailed information such as mass pyrolysis rates per unit fuel area and radiation feedback coefficients, as is the case with COMPBRN, the data available to estimate the required parameters are often sparse, especially in the case of cable fires and electrical cabinet fires. Further, the data may be sufficiently ambiguous that their applicability to a particular FRA scenario is uncertain. This problem has led to a controversy in the treatment of heat release rate data for electrical cabinet fires in recent IPEEEs [3].

In the relatively small number of FRAs where parameter uncertainties have been formally propagated through a fire model, the probability distributions used to quantify the uncertainties in these parameters are relatively broad. It should be noted, however, that even these broad distributions do not necessarily reflect possible biases resulting from differences between the manner in which experimental measurements are made (e.g., using bare thermocouples above cable jackets) and the manner in which they are used in the FRA (e.g.,

as cable surface temperatures). Because of the data sparseness, near term efforts are needed to ensure that all relevant information is readily available for use in FRA. Because of the possible biases, efforts are also needed to ensure that this information is properly used. Formal Bayesian techniques for quantifying uncertainty may be required (e.g., see Ref. 25). Longer term efforts to increase the amount of quality data may also be needed.

Regarding the second source of uncertainty, it has already been pointed out that current fire models are highly approximate. Furthermore, benchmarking calculations of direct relevance to nuclear power plant FRA have been extremely limited. Consequently, there are significant uncertainties in the model predictions even in situations where the model input parameters are known quite well. (Note that the uncertainties in the input parameters complicate the assessment of the models' predictive capabilities [26].) The problem is that the issue of model uncertainty, which was considered in a preliminary fashion in early FRAs (e.g., [6,7]), has not been seriously addressed in more recent studies. This is partially due to the fact that the risk assessment community has not reached a consensus on how to treat model uncertainty (see Ref. 27). Another reason is that the data needed to quantify uncertainty in fire model predictions, regardless of approach, are limited. (Note that, as pointed out by Ref. 1, not all of these data are currently available to analysts.) Consequently, the uncertainties in FRA fire model predictions, even for such widely used variables as the average hot gas layer temperature, are not well known for most situations of interest. There is a clear near term need to characterize these uncertainties, making the best possible use of available (and potentially available) information in this process. As in the case of input parameter uncertainties, longer term efforts to generate more benchmarking data may also be needed.

The above discussion has focused on the prediction of the thermal environment induced by a fire. Predictions of non-thermal environmental characteristics due to the fire (e.g., smoke) or efforts to put the fire out (e.g., humidity) have historically received far less scrutiny in nuclear power plant FRAs. However, with the increasing use of sensitive electronic components in advanced instrumentation and control systems, and with increasing concern of the environmental impacts of fires on operator performance, these issues are gaining increased attention. Models such as CFAST are capable of predicting the buildup of smoke within a room and the transport of smoke to other rooms. However, research efforts generating the basic data needed to estimate smoke generation rates characteristic of nuclear power plant fires and to quantify the uncertainties in these rates are still in their early stages (e.g., see [28]). Also, as in the case of the thermal environment models, the uncertainties in the smoke buildup and transport models need to be assessed.

In summary, there appears to be a short term need to: define the limitations of the fire models used (or proposed for use) to treat fire scenarios of interest in FRA, improve the characterization of uncertainties in the input parameters for these models, and improve the characterization of uncertainties in the models themselves. Possible longer term needs include: additional data for input parameter and model uncertainty quantification, and improved fire models to address key limitations in current models (again with respect to the scenarios of interest in FRA).

3.2.2 Hardware Performance

Given a predicted environment for a piece of equipment, the FRA needs to determine the likelihood of equipment failure and the mode of failure. Because of the common cause failure potential of cable fires, the key concern is the fragility of electrical cables. However, the fragilities of other potentially vulnerable equipment, e.g., electro-mechanical and electronic components in electrical cabinets, are also of interest. In principle, the multiple threats posed by heat, smoke, and fire suppressants may need to be addressed. In practice, only the effects of heat have been treated in mechanistic analyses.

Current FRA treatments of equipment failure due to heat are very simple; it is generally assumed that damage will occur if a representative temperature (e.g., the surface temperature of a cable) exceeds a threshold value. In some analyses, component damage is also assumed if the incident heat flux exceeds a critical value. When component temperature criteria are used, conservative approaches (e.g., assuming the component is at the local environment temperature) or simple heat transfer models (e.g., lumped capacitance models or one-dimensional transient heat conduction models in the case of cables) are employed.

Similar to predictions of the fire-induced environment, predictions of thermal damage are subject to uncertainties and biases in both parameters (e.g., the cable damage temperature) and models. Potentially important biases include neglect of the difference between the cable surface temperature and its temperature in the vicinity of the conductors and the neglect of possible phase changes. The material properties of key equipment, especially electrical cables, and the potential effect of improved modeling (e.g., to determine the temperature of equipment in electrical cabinets) need to be better understood.

Current FRAs do not explicitly address the issue of smoke damage. (It can be argued that smoke damage is partially addressed in scoping analyses which assume that any fire within a given plant area damages all equipment in that area. Such an approach, of course, does not cover smoke-induced damage in neighboring areas.) A number of studies have been performed or are being performed to investigate the impact of smoke on electronics (e.g., [28,29]). However, the effect of smoke on the reliability of other types of potentially vulnerable equipment (e.g., switchgear) is not currently being studied and may need to be addressed.

Regarding the failure of equipment due to the application (or misapplication) of suppression agents, an analysis of the potential risk significance of this issue has been performed [30]. This analysis employs historical information on suppression system actuations and equipment failures to estimate generic equipment fragility. It is not clear how much of the uncertainty in equipment response is due to variations in equipment layout (with respect to the suppression system), how much is due to variations in equipment design, and how much is due to other factors (e.g., room ventilation, duration of exposure). A more detailed investigation of suppressant-related equipment fragility may be required, especially for the seismic-fire interactions scenarios determined to be potentially important by Ref. 30.

Besides determining the likelihood of equipment failure , the FRA needs to specify the failure mode, i.e., how the failure occurs. Of particular interest when dealing with electrical control or power cables are circuit failures that lead to loss of function and those that can lead to spurious actuation of plant equipment. The latter failure mode, typically referred to as “hot

shorts" in FRAs, has been shown to be an important and sometimes even dominant contributor to risk. In such cases, the scenarios often involve the spurious opening of one or more valves in the primary system boundary and a subsequent loss of coolant accident (LOCA).

From an FRA methods standpoint, the concern is that hot short analyses are generally simplistic. The probability of a single hot short is commonly based on a generic probability distribution derived subjectively in 1981 from a limited amount of information [31]. (The distribution, assumed to be lognormal, has a 5th percentile of 0.01 and a 95th percentile of 0.20; its mean value is 0.07.) The probability of multiple hot shorts is typically obtained by multiplying this probability an appropriate number of times. The latter procedure ignores the potentially significant impact of state-of-knowledge dependencies. More importantly, both it and the original single hot short distribution do not reflect such presumably important issues as the circuit design, the function of the cable, and the characteristics of other cables in the vicinity.

Given the reported risk significance of hot short scenarios, there is a clear need for improved models and data for estimating the likelihood of fire-induced spurious actuations. It should be noted that the importance of analyzing different circuit failure modes will probably increase when the effects of fire on instrumentation, which are generally not treated in current FRAs, are addressed.

3.2.3 Fire Containment

As part of determining the immediate environment of equipment potentially affected by a fire, the FRA needs to consider the effectiveness of fire barriers.[1] The question is, from an FRA perspective, the degree to which the barrier reduces the likelihood of damage to protected equipment.

Current FRAs treat barriers fairly simply and sometimes simplistically. For barriers separating fire areas, many FRAs neglect the possibility of barrier failure. Others that treat this possibility use generic failure probabilities reported in a number of NRC FRAs (e.g., Ref. 9). We note that the data used to estimate the failure probabilities have not undergone extensive review, and, further, that they have been widely misinterpreted. In the original analysis of "barrier failure rates," the total number of observed barrier failures[2] is divided by an estimated exposure time. These failure rates have been quoted and used as failure probabilities. We also note that the original analysis is of limited scope and does not incorporate recent data. It appears that for scenarios where barrier reliability plays an important role, there is a need to establish a firmer basis for quantifying this reliability.

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[1]Note that the often-quoted fire duration ratings of fire barriers (e.g., as determined by the ASTM E-119 furnace test) should be taken as relative indications of barrier effectiveness. The fire sciences community has agreed that the quantitative model relating fire loads and fire severity that underlies these ratings is obsolete [32]. This means, for example, that a 3-hour barrier will not necessarily prevent the spread of fires with an "equivalent severity" (as computed from the fire load) of less than 3 hours.

[2]The analysis considers fire doors, dampers, and penetrations, but does not explicitly define what is meant by "barrier failure."

For barriers separating equipment within compartments, the barriers are usually either assumed to be 100% reliable or are entirely neglected. Even when physical models for barrier performance are employed (e.g., COMPBRN provides a one-dimensional steady state heat conduction model), these models do not address such behaviors as gross distortion and mechanical failure of the barrier system. Fire tests have shown that such behaviors are strongly affected by installation practices (e.g., the method of sealing joints). Furthermore, the physical properties of the barriers needed to address such complex issues are not readily available.

For both inter- and intra-compartment barriers, it appears that a probabilistic model which combines deterministic modeling with empirical evidence (from both field observations and qualitative tests) is needed. A particular issue that may need to be addressed is that of penetration seals; questions have been raised concerning the effectiveness of these seals in preventing fire spread.

3.2.4 Fire Detection and Suppression

Within the context of an FRA, the objective of a detection and suppression analysis is to determine the likelihood that a fire will be detected and suppressed before the fire can damage critical equipment. This requires an assessment of the performance of automatic systems and of the effectiveness of manual fire fighting efforts.

Ref. 33 describes a methodology which assesses the likelihood of various detection/suppression scenarios and their associated suppression times using generic fire protection system reliability estimates and detection/suppression time data obtained from nuclear power plant fire events. The results obtained using this methodology are presented in Ref. 34 and have been used in a few FRAs (e.g., [35]). An alternate methodology which: a) does not explicitly identify different detection and suppression scenarios, b) uses physical models included in FPETOOL [36] to estimate detector and sprinkler actuation times, and c) uses expert judgment to estimate other characteristic delay times in the fire detection/suppression process, has been used in the LaSalle FRA [9].

Most FRAs have used a simpler model in which automatic systems, if they are credited and actuate, are assumed to be immediately effective. (See the guidance provided in Ref. 16.) The results of calculations for equipment damage times are sometimes compared with the results of FIVE worksheet calculations for fire detector and sprinkler actuation times to determine if automatic systems should be credited. If automatic suppression is unsuccessful, the likelihood that manual suppression efforts will be effective before equipment damage is then determined. A possible weakness with this simpler model is its neglect of delays in fire suppression following fixed system actuation observed in real events (e.g., the Browns Ferry fire). However, because the fire growth models used in FRAs do not account for the retarding effects of suppression activities, the risk impact of this neglect is not clear.

Regardless of the methodology employed, detection and suppression analyses require estimates of the reliability of automatic detection and suppression systems. Current FRAs use generic industry (non-nuclear as well as nuclear) estimates which can account for plant practices (e.g., installation and maintenance) in only an average manner. For example, in the case of detection systems, the estimates cannot account for such plant- and scenario-specific factors as detector actuation logic, detector location, detector spacing, room congestion, and

the behavior of the fire. Similar concerns hold for automatic suppression systems. It is important to note that the suppression system reliability estimates are generally based upon data for system actuation. Because they do not address the issue of suppression system effectiveness, they are not direct measures of the likelihood of successful suppression (prior to damage). It is also important to note that, even if it can be assumed that suppression system actuation is equivalent to fire suppression prior to damage, the use of generic suppression system reliability estimates may be optimistic in studies where severity factors are used in the fire initiation analysis (see Section 3.1). This is because the reliability estimates are not conditioned on the fire severity.

In addition to fire protection system reliability estimates, detailed detection and suppression analyses also require estimates of the delay times (e.g., the detection time, the time to initiate fire suppression, the time to final suppression) characteristic of the fire suppression process. More precisely, since these times should be modeled as random variables, estimates of the parameters of the aleatory distributions for these times are required. As indicated above, currently available methods for estimating these parameters involve the use of empirical event data, simple physical models, or expert judgment.

Regarding event data, two key issues are the availability of data and the applicability of the data to the scenario being analyzed. Objective data for detection times (i.e., the time intervals between fire initiation and detection) are, almost by definition, quite rare. Generally, the first indication of the fire is when the fire is detected either by automatic detectors or by plant personnel. (Occasionally, the fire initiation time can be inferred from detailed event narratives.) Suppression time data are more available, but are not reported for all fire events. The data are generally insufficient to show how the suppression time distribution varies as a function of such issues as the location, severity, and accessibility of the fire. (Note that Ref. 34 presents different distributions for “high” and “low” severity fires, but this categorization depends on a somewhat subjective interpretation of event narratives.)

Regarding model-based approaches for estimating event timing, the same concerns discussed in Section 3.2.1 apply here as well. In particular, the accuracy, limitations, and uncertainties in FRA physical models with respect to predicting smoke and temperature levels for realistic power plant scenarios are unclear. It is important to observe that fire models which are conservative with respect to fire damage predictions may be non-conservative with respect to fire suppression. Furthermore, the use of one fire model in the damage analysis and a different fire model in the suppression analysis can lead to significant errors in the prediction of damage likelihood.

Expert judgment, often supported by the results of plant fire brigade drills, has been used in many FRAs to estimate the time to manual suppression. The analyses typically assume that the manual suppression time equals the brigade arrival time and often do not account for delays associated with detection (prior to brigade activation) or actual fire suppression (following brigade arrival). They also typically do not address aleatory uncertainties associated with the suppression process, e.g., variations in response time due to the time of day. The LaSalle FRA [9] addresses these concerns to some extent by using expert judgment to estimate the minimum, maximum and average times to detection, suppressant application, and suppression (or substantial control) for a variety of scenarios. However, the LaSalle FRA has the same basic problem as other FRAs using expert judgment in the detection and suppression analysis; it does not reflect actual delay times from

previous events.

The preceding discussion addresses estimation issues in detection and suppression analysis. Refs. 2, 8, and 19 raise a number of modeling issues which are not quantitatively addressed by most FRAs. These include the impact of smoke and loss of lighting on the effectiveness of manual fire fighting, the effectiveness of compensatory measures (e.g., fire watches) for temporary fire protection deficiencies, and the effect of interactions between the fire growth and suppression processes on the likelihood of suppression before damage. The first issue includes the possibility of misdirected suppression efforts which can damage sensitive plant equipment; as indicated in Section 3.2.2, some but not all of the information needed to address this issue is presented in Ref. 29. The first issue also includes the possibility that scenario-specific smoke and loss of lighting effects will require modifications to the generic suppression time distributions used in many FRAs. The second issue stems from the observation that a number of FRAs assume that fire watches are as reliable as automatic systems in suppressing fires regardless of the fire characteristics. There currently is no technical basis to confirm or refute this assumption. The third issue arises from the fact that current FRAs do not account for the inhibiting effects of suppression activities on fire growth and often do not account for the reduction in fire suppression probability as fire severity increases.

The general modeling framework described in Ref. 33 appears to contain all scenarios addressed by other FRA detection and suppression analyses, and also appears to be capable of incorporating treatments of most of the issues discussed above. (The main exception is the interaction of the fire growth and suppression processes.) The implementation of this framework, however, does not yet address many of these issues. It appears that improvements on the implementation, including the use of information employed by other approaches (e.g., the predictions of physical models for detection and suppression, the results of fire brigade drills), are needed. Note that this framework is not suitable for dealing with detailed fire growth and suppression interactions; if these must be treated (e.g., in non-FRA applications), a more simulation-based approach will be needed.

3.3 Plant System Response Analysis

For each fire scenario involving damage to a set of equipment, the FRA must assess the conditional core damage probability (CCDP). This analysis must address the response of plant hardware and staff under fire conditions. It should be noted that FRAs which use internal events analyses without modification to assess the CCDP do not address many of the issues raised in this section.

Regarding the hardware response, a potential concern is the independence of those systems and components which are not directly affected by the fire. For example, will the fire cause cascading electrical faults which will disable other equipment and safety functions? While many plants have considered this issue deterministically, it is not clear that a system reliability analysis (which allows for failures of components with some probability) would dismiss the importance of such a scenario.[3] This concern, as well as related concerns

[3]Note that many of the deterministic circuit analyses have apparently not been done to a sufficient level of detail to assure correct functioning in the event of a fire, even if no random

regarding main control room fires [e.g., the loss of control power before the transfer of control from the main control room to the remote shutdown panel(s)] and spurious actuation of equipment leading to component damage or LOCAs, have been discussed under the general title of “control systems interactions” by Ref. 8 and have been classified as Generic Safety Issue 147 (GSI 147): “Fire-Induced Alternate Shutdown/Control Room Panel Interactions.” Reviews of recent IPEEEs indicate that the risk associated with this concern is still not well understood [37].

A second concern is with the likelihood that safe shutdown equipment not directly affected by the fire will actually be available when called upon. Appendix R to 10 CFR 50 requires that “one train of equipment necessary to achieve hot shutdown from either the control room or emergency control station(s) must be maintained free of fire damage by a single fire, including an exposure fire.” However, it does not provide any requirements concerning the availability (or, for that matter, the reliability) of this equipment. As shown by the Quad Cities IPEEE [11], situations where the equipment unavailability is significantly higher than the generic values typically used in PRAs can be important contributors to risk.

Regarding the response of plant operations staff to fire events,[4] current FRAs treat the effect of fires in relatively crude ways. Some FRAs increase human error probabilities to account for the additional “stress” induced by the fire and some do not take credit for ex-main control room actions in the affected fire area (due to heat and smoke). However, these adjustments may not adequately address such plant-specific issues as the role of fire brigade members in accident response or the complexity of fire response procedures,[5] nor are they universally agreed upon. Moreover, they are quite judgmental; there currently is no strong technical basis for the magnitude (or even direction) of the adjustments.

Another concern with the treatment of operator response involves “errors of commission.” As is true with PRAs in general, FRAs do not address these errors very well. In particular, they do not address possible effects of fire (including fire-induced faulty instrumentation readings and spurious equipment actuations) on operator situation assessment and decision making, nor do they address incorrect operator actions stemming from incorrect decisions. Using the terms of Ref. 38, FRAs do not address the likelihood of “error forcing conditions” being caused by a fire or the likelihood of “human failure events,” given these error forcing conditions.

From the standpoint of research needs identification, neither of the hardware concerns appears to require any methods development; some analysis is required to determine their risk significance with respect to the industry, as well as with respect to individual plants. On the other hand, methods development is required to improve the treatment of operator behavior

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failures are considered [37].

[4]Note that human performance issues concerning fire detection and suppression are discussed in Section 3.2.4.

[5]Work on self-induced station blackout (SISBO) and a number of recent IPEEE studies appear to indicate that complexities in procedures designed to mitigate possible fire-induced hot shorts can be significant contributors to risk.

under fire conditions. An empirical basis for adjusting the results of conventional human reliability analyses and a practical approach for assessing the significance of fire-induced errors of commission are required. Research relevant to the latter area is ongoing (e.g., [38,39]); the results of these efforts need to be applied in an FRA context.

3.4 Scenario Risk Assessment Issues

The first six sets of issues listed in Table 3 (Issues I1-I4, E1-E4, H1-H4, B1-B4, S1-S5, and P1-P5) have been identified largely through an examination of the current FRA paradigm [as represented by Eq. (1)]. The next set of issues listed in Table 3 (Issues R1-R12) have been identified through a variety of other means, including reviews of FRA treatments of specific scenarios, the results of previous investigations of fire risk assessment issues (e.g., [8]), and input from NRC staff concerning scenarios not currently addressed by FRAs. Most of these issues are associated with integrated assessments of risk for particular scenarios. They are briefly discussed in this section.

Main control room fires. Main control room (MCR) fires have been shown to be dominant contributors to risk in some FRAs and negligible contributors in others. Unfortunately, much of this difference in predicted risk significance appears to be due to modeling assumptions about the likelihood of severe fires in the MCR, the time available to suppress a severe fire before MCR evacuation is required, and the likelihood of successful operator actions given a severe fire. There currently is insufficient information available to specify how MCR fires should be modeled; improved methods and data are needed to reduce the degree of analyst-to-analyst variation in the results.

Turbine building fires. Historical turbine building fires (e.g., the Narora fire [21]) and the Quad Cities IPEEE [11] show that severe turbine building fires can be important contributors to risk. Potential concerns with the adequacy of FRA tools for these fires have been mentioned earlier. They include the lack of knowledge concerning the frequency-magnitude relationship for turbine building fires (see Section 3.1) and the adequacy of current FRA tools for predicting the environment induced by a severe turbine building fire (see Section 3.2.1). Partly because of these concerns, the overall risk contribution from turbine building fires at any given plant is uncertain.

Containment fires. The containment contains safety-related equipment (e.g., cables for redundant instrumentation) which might be vulnerable to a severe fire. However, most FRAs have assumed that containment fires are negligible contributors to risk (even for non-inerted containments) per the arguments stated in Ref. 13, i.e., containment fires are infrequent and previous FRAs have shown that containment fires are not risk significant. Noting that most previous FRAs have not explicitly addressed fire-induced instrumentation failures and many have not addressed spurious equipment operation, the latter argument may be questionable. An improved assessment of the potential risk contribution of containment fires is needed. If a detailed analysis is required, improvements in the state-of-knowledge concerning the frequency-magnitude relationship for containment fires and improved tools for predicting fire environment within containments will be needed.

Seismic/fire interactions. Ref. 8 identifies a number of issues associated with the effect of seismic events on fire protection and fire risk. These include seismically-induced fires (e.g., fires involving the tipping of improperly anchored electrical cabinets) and seismically-induced

suppression system actuations. A recent investigation of the effects of the January 17, 1994 Northridge earthquake on industrial facilities (including conventional power plants) appears to indicate that suppression system actuations are more likely than fires [40]. (Fires only appear to be a significant concern when the earthquake causes the failure of flammable gas lines.) Note that according to Ref. 40, the peak ground accelerations associated with the Northridge earthquake were much larger than the design values of many of the facilities examined. Ref. 8 indicates that the risk associated with seismic/fire interactions can be addressed via dedicated walkdowns; however, it does not provide a methodology for quantifying the risk associated with walkdown findings.

Multiple units. The results of a number of FRAs have shown that some multi-unit sites have areas where a single severe fire can initiate transients and damage mitigating equipment for multiple units. Another, more subtle multi-unit interaction involves situations where safe shutdown of one unit requires equipment from another unit. Besides depriving the “non-affected unit” of the services of that equipment, errors in performing the actions required to make the equipment available to the “affected unit” could lead to further unavailabilities of the non-affected unit’s equipment. It appears that most (if not all) FRAs to date have focused on the fire risk associated with a single unit; the frequency of multiple unit core damage due to a single fire has not generally been explicitly calculated. The detailed results of the Quad Cities IPEEE [11] indicate that, at least for some plants, this frequency may not be negligible. The current FRA framework is capable of dealing with this issue. However, detailed examinations of the overall plant response and modifications in the plant response analysis models are needed to assess its risk significance.

Non-power and degraded conditions. Most current FRAs have focused on the fire risk associated with at-power operation. The fire risk associated with low power and shutdown operation has received limited attention (e.g., [35]). The fire risk associated with scenarios involving: a) damage to equipment required to achieve and maintain cold shutdown, or b) degraded conditions (i.e., fires following a non-fire initiating event) has apparently not been addressed. The issue of degraded conditions is potentially a concern for consequential fires, e.g., fires caused by the same chain of events which leads to a loss of offsite power. The current FRA framework appears to be capable of dealing with non-power and degraded conditions. Analyses which reflect possible changes in fire frequencies (and in the frequencies of severe fires), as well as changes in plant response, may need to be performed. Note that Ref. 12 presents information useful for the quantification of fire frequencies during low power and shutdown operation.

Decommissioning and decontamination. FRAs have not been performed to assess the risk associated with the decommissioning and decontamination phases of a plant’s life cycle. If fire-induced direct releases of radioactive material to the environment or occupational risks need to be analyzed, additional FRA methods and data may be needed.

Fire-induced non-reactor radiological releases. As shown by Eq. (1), current FRAs are focused on evaluating scenarios involving core damage. The risk associated with direct radiological releases to the environment has not yet been evaluated. Note also that the impact on core damage frequency due to direct radiological releases (which can affect operator performance) is not evaluated in current FRAs.

Flammable gas lines. Potential problems with the leakage and ignition of combustible gases within plant compartments are addressed under Generic Safety Issue 106: "Piping and the Use of Highly Combustible Gases in Vital Areas." As analyzed in Ref. 41, this is a medium priority generic issue. Based upon the IPEEE reviews to date [37], it is not known if this issue is highly risk significant for any single plant.

Scenario Dynamics. As pointed out in Ref. 42, the timing of fire-induced equipment failures (which can be on the order of tens of minutes for some scenarios) is not treated in current FRAs. Instead, the FRAs treat fire-induced equipment failures as occurring at the beginning of the scenario. Furthermore, they effectively assume that the operators know exactly what has been lost due to the fire. In an actual fire, of course, equipment can be lost progressively over the course of the scenario, and the operators will not necessarily know exactly what has been lost (or what indications to mistrust) at any point in time, let alone what will be lost in the future. The current FRA approach can be conservative in situations where the equipment is lost well after it is truly needed. It can be non-conservative in situations where the scenario dynamics introduce considerable confusion. In general, the scenario dynamics could present a very different context to the operator than the one assumed in FRAs. The effect of this different context on operator performance and predicted risk could be significant [38,39].

Precursor analysis methods. The NRC's accident sequence precursor program, which evaluates the risk significance of reported events and plant conditions as precursors to core damage accidents, currently lacks tools for evaluating fire events or conditions involving fire protection deficiencies. Tools for performing such evaluations have been proposed (e.g., [43]) but not yet rigorously tested.

Uncertainty analysis. A meaningful uncertainty analysis requires a careful consideration of uncertainties in models, as well as in model parameters. The issue of model uncertainty is discussed in Section 3.2.1. It is worth noting that a proper treatment of uncertainties can significantly affect perceptions concerning the credibility of current FRAs. Ref. 19 uses the results of a formal uncertainty analysis to show that, from the perspective of FRA, the need for extremely accurate fire growth models may be significantly less than implied by the results of sensitivity calculations of the kind discussed in Ref. 8.

3.5 Other Issues

The last four issues listed in Table 3 (Issues O1-O4) concern general means to improve FRA and fire risk management. The first two involve the need to collect information from past events and from other fire research efforts. Regarding past events (Issue O1), serious fires have occurred in U.S. and international nuclear power plants, as well as in other industrial facilities. Current FRAs tend to make limited use of the information obtained from these events. For example, they use counts of events to estimate fire frequencies, but do not use event descriptions to determine if changes in the basic FRA structure are warranted. Regarding other fire research efforts (Issue O2), a substantial amount of work is being conducted outside the nuclear industry. For example, Ref. 44 reports on an international effort to validate current fire simulation software. The results of these validation efforts, or other non-nuclear fire modeling activities (e.g., [24,45]) have not yet been generally reflected in current FRAs. While issues O1 and O2 do not imply specific research needs, they indicate elements that need to be incorporated in a viable fire research program.

The second two issues in Table 3 concern the use of FRAs in risk-informed, performance-based regulation. Issue O3, "Comparison of methodologies," refers to the fact that a number of different methodologies are used by current FRAs. The degree to which the differences in FRA results are due to these methodological differences (which affect analysis level of detail, modeling assumptions, and data) is unclear. Clearly, this source of variability needs to be better understood when the FRAs are used to support regulatory decision making. Issue O4, "Standardization of methods," is a natural follow-on to Issue O3. It concerns the degree to which FRA methods and data can be or should be standardized.

4. CONCLUDING REMARKS

Improvements in the NRC staff's ability to thoroughly understand and accurately evaluate nuclear power plant fire risk require efforts in a number of areas. In order to initiate improvements in these areas, this paper has developed and discussed a list of potential research issues which involve: research on material properties and scenario phenomenology, the development of methods and tools based on the results of this research, and the application of these methods and tools to actual plants. The next steps in the improvement process are the development of a prioritized list of research topics (where one topic may include a number of related research issues) and the development of a research program to address these topics. Work on these steps is ongoing.

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