Fire PRA Maturity and Realism: A Technical Evaluation and Questions

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Fire PRA has often been characterized as being less mature and less realistic than internal events PRA. Perceptions of immaturity can affect stakeholders' use of fire PRA information. Unrealistic fire PRA results could affect fire-safety related decisions and improperly skew comparisons of risk contributions from different hazards. This paper addresses the issue of technical maturity through the identification of a number of key indicators. It addresses the issue of realism primarily through a number of quantitative and qualitative comparisons of fire PRA results with operational event data. Rather than attempting to resolve the ongoing debate on the maturity and realism of fire PRA, this paper offers a few current thoughts from a work in progress to clarify some of the terms of the debate, brings some additional evidence to the discussion, and raises pertinent questions.

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Fire PRA has often been characterized as being less mature and less realistic than internal events PRA. Perceptions of immaturity can affect stakeholders' use of fire PRA information. Unrealistic fire PRA results could affect fire-safety related decisions and improperly skew comparisons of risk contributions from different hazards. This paper addresses the issue of technical maturity through the identification of a number of key indicators. It addresses the issue of realism primarily through a number of quantitative and qualitative comparisons of fire PRA results with operational event data. Rather than attempting to resolve the ongoing debate on the maturity and realism of fire PRA, this paper offers a few current thoughts from a work in progress to clarify some of the terms of the debate, brings some additional evidence to the discussion, and raises pertinent questions.

1. Background

1.1 Estimated Risk Importance of Fire

Since the earliest industry-sponsored full-scope probabilistic risk assessments (PRAs) (e.g., the Indian Point Probabilistic Safety Study, reviewed for the U.S. Nuclear Regulatory Commission – NRC – in Ref. 1), and continuing through the NRC's NUREG-1150 [2] and Risk Methods Integration and Evaluation Program (RMIEP) studies [3] and the industry's Individual Plant Examinations of External Events (IPEEEs) [4], fire has been shown to be a significant risk contributor for U.S. plants.[1] This finding, which is illustrated by the core damage frequency – CDF – metrics provided in Table 1, is not unique to the U.S.; international studies also recognize the risk importance of fire [5, 6].

In 2004, the NRC modified its fire protection rule (10 CFR 50.48) to provide licensees with a voluntary, risk-informed option for meeting the NRC's fire protection requirements. This rule change endorsed the National Fire Protection Association (NFPA) Standard 805 "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2001 Edition" (commonly referred to as "NFPA 805") [7]. Several licensees have submitted Licensing Amendment Requests (LARs) to take advantage of this change. The LAR submittals largely employ the fire PRA guidance documented in the joint report EPRI 1011989/NUREG/CR-6850 (henceforth referred to as "NUREG/CR-6850") [8], and a supplement to that report capturing lessons learned from pilot submittals [9]. The LAR submittals indicate that the estimated fire CDFs remain significant (see Table 2). The last line in Table 2 is noteworthy, particularly in comparison with the last line in Table 1. We will return to this point later.

[1] *This finding applies to the general population of plants. Whether fire is an important contributor for a particular plant (and what are the dominant risk scenarios) is very much a function of plant-specific details.*

Table 1. **CDF estimates from early U.S. fire PRAs**

Study	Plant(s)	Mean Fire CDF (/ry)	% Fire Contribution to Total CDF[a]
Indian Point (1982)	Indian Point 2 Indian Point 3	2.0E-4 9.9E-5	38 50
NUREG-1150 (1990)	Surry 1 Peach Bottom 2	1.1E-5 2.0E-5	14[b] 72[b]
RMIEP (1992)	LaSalle 2	3.2E-5	32
IPEEE (mid-late 1990s)	99 units	3.7E-5[d]	26[c,d]

[a]Computed as the ratio mean fire CDF/mean total (all hazard) CDF; both CDFs are for at-power conditions
[b]Total CDF computed using seismic CDF based on Electric Power Research Institute (EPRI) seismic hazard curves
[c]Population average
[d]Computed for plants performing seismic PRAs (not seismic margins assessments)

Table 2. **Summary statistics from a representative sample of NFPA 805 LARs**

Sample size	15 units
Submittal dates	2011-2013
Average reported fire CDF	3.9E-5/ry
Minimum reported fire CDF	6.5E-6/ry
Maximum reported fire CDF	6.5E-5/ry
% fire contribution to total CDF	68

1.2 The Problem

Despite a history nearly as long as that for internal events analysis, fire PRA has often been characterized as being less mature and less realistic than internal events PRA [10-13]. Gallucci [14] provides in-depth documentation and analysis of on-the-record statements (many from public meeting transcripts) regarding the issue of fire PRA maturity and conservatism. Some of these statements assert (as above) that fire PRA methods are relatively immature and produce conservative results, while others provide a moderating or even contrary point of view.

The two related (but non-identical, as discussed in the following section) issues of fire PRA maturity and realism are important practical matters. Following the NRC's 1995 PRA Policy Statement [15], PRA results and insights are being increasingly used in regulatory applications to the extent supported by the PRA state of the art. These applications range from plant-specific (e.g., the management of plant maintenance activities, the approval of changes to a plant's licensing basis, the assessment of the significance of inspection findings) to industry-generic (e.g., the assessment of potential safety issues affecting more than one plant, the determination as to whether new regulatory requirements should be imposed on the industry). Depending on the particular application, a variety of PRA outputs, including importance measures, accident frequencies (both CDF and large early release frequency – LERF), changes in accident frequencies, and relative contributions to risk may be called for. Clearly, if the analysis of a risk-significant hazard (or hazard group) is unrealistic, the PRA could be providing faulty information to the decision making process. Moreover, an unrealistic analysis could skew comparisons of risk contributions from different hazards, thereby distorting our understanding of risk and degrading one of the major benefits of PRA, which is to help focus attention on areas of "true safety significance" [15]. Even further, if the PRA analysis of a hazard is viewed as immature (or less mature than analyses of other important hazards), stakeholders might be tempted to overly discount even useful information from the PRA in lieu of evidence from other sources (e.g., global statistical estimates, worst case analyses) that may have their own, if less thoroughly examined weaknesses.

In this paper, we will not attempt to resolve the ongoing debate on the maturity and realism of fire PRA. Rather, we offer a few current thoughts from a work in progress to clarify some of the terms of the debate, bring some additional evidence to the discussion, and raise pertinent questions.

2. Maturity and Realism in a PRA Context

As seen from the previous section, the issues of fire PRA maturity and realism are often raised in concert. We believe that although related, they are actually separate. The concept of maturity addresses the relative state of development of a technical discipline. On the other hand, in a PRA context, the concept of realism addresses the degree to which an analysis represents the current state of knowledge relevant to the decision problem.[2] The analytical technology (i.e., methods, models, tools, and data) of a less mature discipline could, but need not, produce unrealistic analysis results. Conversely, a more mature discipline could, for practical reasons, employ technology with known weaknesses, only requiring that the weaknesses be understood and appropriately addressed in the decision making process.[3] Of course, the practitioners of a less mature discipline might consciously use conservative (and unrealistic) assumptions in an attempt to compensate for weaknesses in the current state of knowledge – the extent and appropriateness of this practice is the key controversy in ongoing U.S. fire PRA applications[4] – but this observation only shows that the issues are coupled, not identical.

3. On the Maturity of Fire PRA

Judging the maturity of a technical field is a subjective matter, being dependent on the judgment of the assessor. To add some structure to the debate, we note that Stetkar and his co-authors are careful to distinguish between the maturity of the fire PRA technology (which dictates what level of analysis is possible) from the maturity of the application of that technology (which indicates what is happening in the field) [12]. They also tie the notion of maturity to the number of experienced analysts performing fire PRAs. Budnitz provides similar indicators in a discussion of the state of seismic PRA [19], referring to the number of practitioners (or groups of practitioners), the degree of practice, and the state of technical development of the field (including the availability of detailed guidance for new practitioners). Budnitz emphasizes the use of the technology in support of practical decision making as an important indicator of maturity. This emphasis is echoed in a Technical Opinion Paper issued by the Nuclear Energy Agency's Committee on the Safety of Nuclear Installations (NEA/CSNI) [20]. Finally, in a thoughtful exposition on the state of structural safety engineering, Cornell describes characteristic situations associated with the different stages of development of a technical field based on his observations from a number of fields (including geotechnical engineering, structural dynamics, and finite element analysis) [21].

Table 3 provides a summary of Cornell's discussion, grouping his situations into one of three categories of indicators involving the field's practitioners, research agenda, and applications.

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[2] *In his 2003 speech "Realism and Conservatism," then-NRC Chairman Diaz defines the term "realistic" as "being anchored in the real world of physics, technology and experience" [16]. In a PRA context, because a) the PRA needs to deal with rare (and hopefully unobserved) events, and b) the purpose of the PRA is to support decision making, we think it appropriate to tie the notion of "realism" to the needs of decision making.*

[3] *For example, NUREG-1855 [17] advocates the use of consensus models coupled with sensitivity analyses to address key model uncertainties.*

[4] *Interestingly, the Lewis Commission's 1978 review of the seminal 1975 Reactor Safety Study (WASH-1400) also raised a concern with "a pervasive regulatory influence in the choice of uncertain parameters" [18].*

Table 3. **Indicators of Stages of Technical Maturity (adapted from Cornell [21])**

	Developmental Stage		
	Early (Infancy, Emerging)	Intermediate (Adolescent, Developing)	Late (Mature, Stable)

Practitioners	• Small research community
	• Small number of practitioners
	• Strong personality influences, competing schools of thought
		• Larger number of practitioners
		• Larger number of experienced researchers
			• Many well-trained and experienced practitioners
			  • Recognize limits of applicability of methods
			  • Can adapt methods to new situations
			  • Can work with researchers to identify important issues

Research Agenda	• Driven by perceived needs • Problem selection affected by personal choice (e.g., due to ease of formulation or solution)	• New practice-driven research problems • Some consensus positions for some broadly defined problem areas • Some unproductive research lines abandoned • Incomplete coverage of topics	• Most research driven by needs of practice • More abstract research addresses needs clearly identifiable by all concerned
Applications	• Local applications (addressing small parts of larger problems) • No broader framework	• Fast growth • Developing vocabulary • Optimistic views on new methods; limitations not well understood	• Vocabulary has evolved • General framework exists • Little "selling" of area

Applying the preceding ideas to our experience in developing and applying fire PRA methods, models, tools, and guidance, it appears to us that nuclear power plant fire PRA is: a) in an intermediate stage of development (but well past the early stage), and b) less developed than internal events PRA. A key factor in the first part of our assessment is the acceptance of fire PRA results in supporting major decisions, starting with the Commission's 1985 decision to allow continued operation of the Indian Point Plants [22] as informed by findings and recommendations of the NRC's Atomic Safety and Licensing Board (ASLB) [23],[5] continuing with plant changes identified in the IPEEE program[6] [4] and more recently with staff approvals of licensee-requested fire protection program transitions as per NFPA 805.[7] Key factors in the second part of our assessment are the relatively small number of fire PRA practitioners (as compared with internal events) and the lack of consensus models and data for a number of important issues. We recognize that, as pointed out by Stetkar et al. [12], the ongoing licensee and staff activities related to NFPA 805 will increase the fire PRA experience base, and will likely, over time, reduce the maturity gap with internal events.

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[5] *In the Indian Point PRA, which played a major role in the ASLB hearing, fire was shown to be a major contributor to CDF (see Table 1). The ASLB, in its remarks on PRA areas needing modelling improvement, mentioned fire as one of a number of areas needing improvement (the others were the treatment of operator diagnosis of accidents in progress, DC power supply failures, common mode failures due to plant maintenance, seismic hazard, and hurricane and tornado hazard), but did not place special emphasis on this point [23].*

[6] *Although the NRC has not tracked changes identified in the IPEEE studies, a number of IPEEE submittals indicated that changes had actually been made [4].*

[7] *As of this writing, the staff has approved five NFPA LARs and an additional 22 LARs are under review [24].*

Of course our assessment is subjective; others can review the available information and reach a different conclusion. Given that the issue of maturity tends to be self-resolving as long as there are practical application needs, perhaps such differences of opinion shouldn't matter very much. However, should discussion be needed, or, more practically, should we wish to accelerate the maturation process, we suggest that a structured consideration of indicators such as those we've identified above is useful. We note that these indicators suggest several possible actions one could take to increase the maturity of a field – research and development aimed at improving the analytical technology is only one such action. The indicators also support the point made by Stetkar et al. [12] and others (see, for example, the quotes provided by Gallucci [14]), that substantial changes in fire PRA maturity are likely to take many years; there is no "quick fix."

4. On the Realism of Fire PRA

Fire PRA, as with PRA in general, is aimed at identifying risk-significant scenarios and quantifying their likelihoods and consequences. In principle, it can address scenarios with a wide range of consequences (e.g., various states of plant damage). In practice, the analytical resources of U.S. fire PRAs are typically focused on scenarios leading to core damage and (in recent times) large, early release. To accomplish this, the analysis, as originally formulated and currently practiced, is iterative [25-27]. Potentially important scenarios are identified, conservatively assessed, and passed on to more detailed analysis stages if they meet certain screening criteria. The intent is that the overall results of the analysis be sufficiently realistic for the purposes of the study; there is no guarantee that the analyses of non-contributing scenarios, some of which may be important contributors to intermediate end states (e.g., loss of specified safety functions but not core damage), are realistic.

The strong tie of the analysis results to the specific purpose of the analysis complicates our assessment of realism. In this section, we look at this topic from a number of angles: the summary and detailed outputs of past and recent fire PRAs, and the technology (i.e., the methods, models, tools, and data) of fire PRA.

4.1 Fire CDF Estimates

One natural approach to assess the realism of fire PRA is to compare its summary output measures (notably, fire CDF) against appropriate empirical benchmarks, e.g., statistical estimates derived from operational experience. However, such a comparison is not straightforward.

4.1.1 Challenges in Comparing Fire PRA CDF Estimates with Statistical Estimates

From a practical standpoint, data for severe fire events are sparse. A review of international operating experience documented in NUREG/CR-6738 [28] shows that although there have been some "close calls" to core damage,[8] there have been no actual core damage events caused by fires of interest to U.S. fire PRAs.[9] A review of operational events reported to the NRC via Licensee Event Reports (LERs) and analysed under the NRC's Accident Sequence Precursor (ASP) program [29] indicates that in the period 1980-2012, only around 80 have been initiated by (or

8 *In addition to the well-known 1975 Browns Ferry cable fire, NUREG/CR-6738 identifies five fire events that seriously challenged nuclear safety: Greifswald 1 (1975), Beloyarsk 2 (1978), Armenia 1&2 (1982), Chernobyl 2 (1991), and Narora 1 (1993). As discussed later in this paper, all of these events involved fire-induced loss of multiple safety systems; three (Greifswald, Armenia, and Narora) involved station blackout conditions either caused by the fire or by fire-fighting actions.*

9 *The 1957 Windscale accident involved a fire in the reactor's graphite-moderated core. The 1979 Chernobyl 4 accident also involved a graphite fire – this fire was the result rather than the cause of the reactor power excursion which damaged the core.*

later involved) fires.[10] The vast majority of these did not represent major challenges to nuclear safety: none were classified as "significant" (with Conditional Core Damage Probabilities – CCDPs – greater than 1E-3) and only two had CCDPs between 1E-4 and 1E-3.[11] Out of the 1695 reviewed fire events for the period 1990-2009 included in the EPRI Fire Events Data Base, only 28 were classified as "challenging," and this designation is based on the severity of the fire severity, i.e., its ability to damage components, but not the nature or significance of the components actually affected [30].

From a theoretical standpoint, simple statistical analyses for CDF of the sort seen in the literature following the March 11, 2011 Fukushima Dai-ichi reactor accidents (e.g., [31-33]), which involve dividing the number of observed core damage events by the number of reactor years, are based on two underlying assumptions: a) the plants in the analysis group are nominally identical, and b) the plants do not change over time. Apostolakis [34], who refers to these assumptions under the unifying title of "exchangeability," argues that from a regulatory decision maker's perspective, both assumptions are questionable. Regarding the first, one of the early, fundamental lessons from PRAs over the years is that risk is plant specific [35]. Regarding the second, U.S. plants have made numerous fire-safety related improvements in response to events and associated regulatory actions (e.g., the promulgation of Appendix R to 10 CFR 50.48 following the Browns Ferry fire) and analyses (e.g., the IPEEEs). More sophisticated statistical analysis techniques are available to address heterogeneity within a group and time dependence. However, such methods require even more data than the simple approach described above.

To provide a general indication of the potential magnitude of variability across plants and over time, we plot recent point estimates of total CDF (i.e., the CDF from all contributors) obtained from 41 risk-informed LARs (covering 61 units) submitted over the period 2002 through 2013 (over 75% were submitted after 2007) in Figure 2. Figure 3 shows how recent estimates for total CDF compare against estimates derived from the IPE and IPEEE studies.[12]

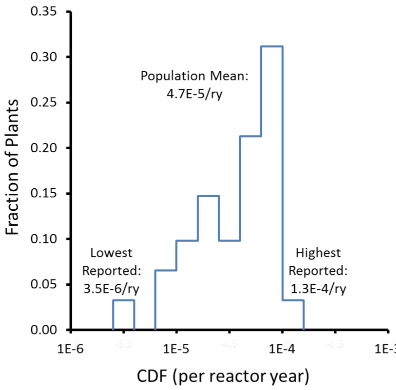


Figure 2. **Recent total CDF estimates**

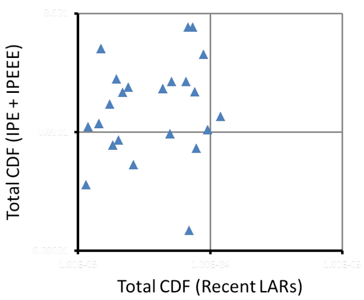


Figure 3. **Comparison of recent and past CDFs**

10 *The NRC's LER database can be accessed via https://nrcoe.inel.gov/secure/lersearch/index.cfm.*

11 *The statuses of the ASP program and the Standardized Plant Analysis Risk – SPAR – models used to estimate event CCDPs are described in annual NRC staff papers, e.g., SECY-13-0107 [33]. The ASP program considers all events and degraded plant conditions reported in LERs per the requirements of 10 CFR 50.73. Currently an event is classified as a precursor if the CCDP for that event is greater than a set criterion (the greater of 1E-6 and the plant-specific CCDP for a non-recoverable loss of balance-of-plant systems).*

12 *Figure 3 is based on the results from plants that: a) recently submitted a risk-informed LAR that addresses CDF contributions from all initiators, and b) performed a seismic PRA as part of their IPEEE analysis.*

Figure 2 shows that most of the total CDF estimates fall between 1E-5/ry and 1E-4/ry. Figure 3 shows that most (but not all) of the total CDFs have decreased, some by a substantial amount. Based on a review of some of the LAR submittals, it appears that these changes can be attributed to both modeling changes and the incorporation of actual improvements in plant design and operation.

We caution both figures and our following analysis are provided only for the purpose of a rough comparison. The LAR estimates were developed for varying purposes and are of varying vintage, and may therefore embed different differences in modelling assumptions, level of detail, and perhaps even scope.

4.1.2 Empirical and Fire PRA CDF Estimates

Without challenging decision maker concerns regarding the exchangeability of events across the U.S. fleet and over time, we think that, for the purpose of discussing the realism of fire PRA, it's useful to explore how the predictions of current fire PRAs compare against available, plant-level statistical evidence. In particular, does the statistical evidence support or deny assertions of fire PRA conservatism?

To perform this comparison in the presence of sparse data, we follow the approach of Gallucci, who uses event precursor CCDPs developed by the ASP program as data points [36]. Based on precursor events covering the period 1969-2004 (see Table 4), Gallucci estimates that the average fire CDF for a U.S. plant is 7.1E-5/ry.

Table 4. **Precursor events included in Gallucci's analysis [37]**[13]

Plant	Date	CCDP	Event Notes*
Browns Ferry 1 & 2	3/22/75	0.20**	Multi-unit cable fire; multiple systems lost, spurious component and system operations; makeup from control rod drive pump (non-proceduralized action)
Rancho Seco	3/19/84	2.2E-6	Main generator explosion and fire; damage to non-nuclear instrumentation power supply complicated shutdown
Oconee 1	1/3/89	3.3E-6	Reactor coolant pump (RCP) switchgear fire during power escalation; operators exceeded allowed cooldown rate
Waterford 3	6/10/95	9.1E-5	Non-safety 4 kV switchgear fire; partial loss of offsite power (LOOP)
Surry 1 & 2	10/9/99	1.2E-6 (each)	4 kV bus bar connection fire (small); loss of two emergency buses due to electrical fault
Diablo Canyon	5/15/00	9.6E-5	12 kV bus fire damaged nearby 4 kV bus; loss of offsite power to all 4 kV loads
San Onofre 3	2/3/01	1.4E-4	Switchgear fire following outage; loss of non-safety power
Quad Cities 2	8/2/01	6.6E-5	Main transformer fire following lightning strike; loss of normal offsite power
Watts Bar 1	9/27/02	3.3E-4	Offsite (hydroelectric station) fire; LOOP, fire brigade dispatched offsite, reduced onsite staffing

*See NUREG/KM-0002 [37] for a recent compilation of information on the Browns Ferry fire and NUREG/CR-6738 for a fire-PRA oriented discussion of that event. The notes on the remaining events are based on their LER Summaries.
**Consistent with SECY-10-0125 [38]. Gallucci notes other estimates range from 0.03 to 0.40.

[13] *A number of the listed CCDP estimates differ from those provided in Refs. 39 and 40. Also, the Watts Bar Hydroelectric Station fire is not relevant for our discussion. However, as pointed out by Gallucci, the analysis results are dominated by the CCDP value assigned to the Browns Ferry fire; the values of the other CCDPS have negligible effect.*

Table 5. **Post-2004 fire precursors with CCDP > 1E-4**

Plant	Date	CCDP [29]	Event Notes
H.B. Robinson 2	3/28/10	4E-4	4 kV cable fire, loss of RCP seal cooling and additional equipment failures; operators fail to diagnose plant conditions and control plant; operator actions cause a second fire
Fort Calhoun	6/7/11	4E-4	480V switchgear fire during cold shutdown; loss of multiple safety buses (combustion products migrated to non-segregated bus duct)

In the years following Gallucci's analysis, two important fire-related precursor events (but no significant fire-related precursor events) have occurred in the U.S. These involved a March 28, 2010 fire at the H.B. Robinson 2 plant, and a June 7, 2011 fire at the Fort Calhoun plant (see Table 5).

To update and extend Gallucci's analysis, we:

(1) incorporate the post-2004 operating experience, including the Robinson fire[14] (but not the Fort Calhoun fire since our analysis addresses at-power conditions);

(2) perform a Bayesian analysis to develop a distribution for the average plant fire CDF to quantify the uncertainty in the estimate;

(3) use the result of the Bayesian analysis to estimate the distribution of F-CDF_{US}, the total U.S. fire CDF (i.e., the sum of all of the individual plant fire CDFs)[15]; and

(4) compare this precursor-based distribution for F-CDF_{US} against a distribution for F-CDF_{US} derived from recent NFPA 805 LAR submittals.

Our Bayesian assessment in Step (2) uses Gallucci's point value estimate as the mean value of a constrained non-informative prior distribution [41]. We compare precursor- and PRA-based sums rather than averages in Step (4) to ensure an "apples to apples" comparison (the precursor-based estimate addresses an "average plant," whereas the PRA estimates are plant-specific) and to facilitate comparisons with total U.S. operating experience.

Based on our analysis, the mean value of F-CDF_{US} is about 6E-3/yr. (This is slightly lower than Gallucci's result because no significant fire precursors have occurred since his analysis.) Comparing this result with the mean value of F-CDF_{US} derived from the NFPA 805 LAR submittals (about 4E-3/yr), it can be seen that the fire PRAs would appear to provide a smaller estimate than the precursor-based analysis. However, when we plot the distributions of F-CDF_{US} (see Figure 4), we see this comparison of the mean values can be misleading. The uncertainties in the precursor-based estimate are extremely large (due to the weakness of the operational evidence), and so the comparison of F-CDF_{US} estimates actually does not provide a definitive statement regarding the conservatism (or non-conservatism) of current fire PRA results.[16]

[14] *We do not include the Fort Calhoun event since the expressed concerns with fire PRA (and hence our analysis) are centered with PRA for at-power conditions. From a strictly numerical perspective, the inclusion of the Fort Calhoun event would not significantly affect our results.*

[15] *Conceptually, this step involves the multiplication of the Bayesian result for a single plant by the number of operating U.S. plants (roughly 100).*

[16] *The PRA-based distribution treats the uncertainties in the plant PRA estimates. However, the distribution is quite narrow because it represents the sum of these estimates.*

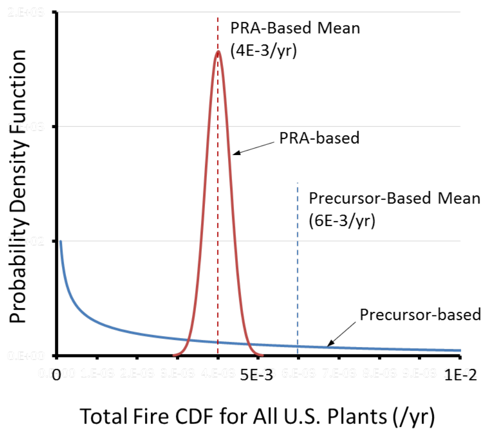


Figure 4. **Comparison of precursor- and PRA-based distributions for F-CDF_{US}**

Figure 4 shows quite different states of knowledge resulting from the two different sources of evidence. To explore the significance of this difference, consider the probability of observing N fire-induced core damage accidents (anywhere in the U.S.) over a time period T (where N = 0, 1, 2, etc.). This probability is the Poisson distribution averaged over all possible values of F-CDF_{US}:

$$P(N|T)=\int_0^{\infty}\frac{(f\cdot T)^N}{N!}e^{-f\cdot T}\pi(f)df \qquad (1)$$

In this equation, which substitutes the symbol "f" for F-CDF_{US} for simplicity, $\pi(f)$ is the probability density function for F-CDF_{US}.

Figure 5 shows the results of Eq. (1) for both the precursor- and PRA-based cases when T is set to 10 years. It can be seen that the differences between the precursor- and PRA-based estimates are negligible. (The difference is most noticeable for N = 2, an unrealistic situation since should a core damage event actually occur, major changes to plants, the regulatory system, etc., and thereby F-CDF_{US}, will almost certainly result.) Similar conclusions result even when T is set to 50 years.

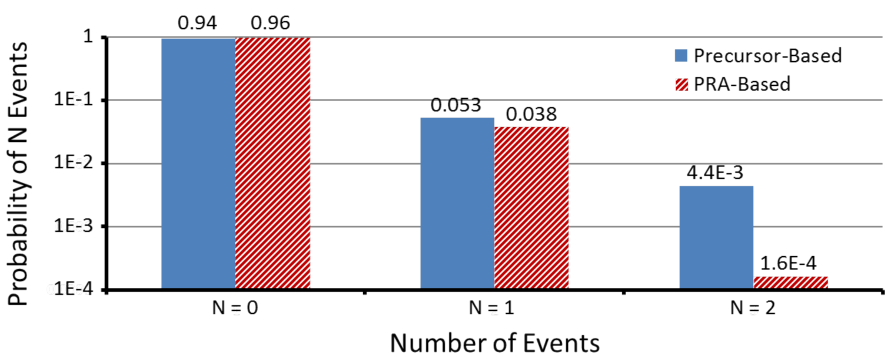


Figure 5. **Comparison of precursor- and PRA-based estimates of U.S. fire-induced core damage event probabilities**

We caution that our analysis:

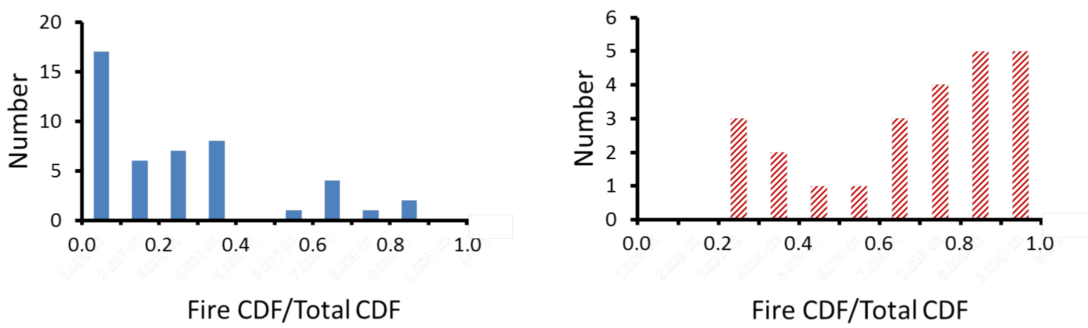
- relies on the questionable assumption of exchangeability;
- is limited to precursors that involved initiating events (e.g., a plant trip or LOOP) – it does not address the CDF implications of precursors involving degraded conditions;[17]
- uses event CCDPs that quantify the possibility of "what-ifs" associated with plant response to an initiating event (e.g., additional independent hardware failures) but do not address different possibilities associated with the triggering fire (e.g., different locations or severities) – the observed fire-induced damage is a "given;" and
- produces results that are somewhat sensitive to the assessed CCDP for the Browns Ferry fire. (For example, the precursor-based probability of N = 1 changes to 0.011 if the CCDP is 0.03, and to 0.083 if the CCDP is 0.40.)

With these caveats, our results do not provide a "smoking gun" supporting assertions of fire PRA conservatism.

4.1.3 Relative Contributions to Total Plant CDF

The preceding analysis uses available operational experience but requires a number of assumptions, the most important one being that of event exchangeability. To provide a second, but still CDF-based perspective on the realism of current fire PRAs, we look at past and current estimates for the relative contribution of fires to the overall CDF.

Figure 6 compares the relative contribution of fire to total CDF from the IPE/IPEEE studies (mainly performed in the mid-late 1990's) and from recent (post-2007) risk-informed LAR submittals. The IPE/IPEEE results come from the 46 plants which either completely screened seismic events or developed seismic CDF estimates. The 24 LAR estimates primarily involve NFPA 805 plants, but a few involve other risk-informed applications (e.g., plant Technical Specification modifications). Figure 7 compares the ratio of fire CDF to internal events CDF for the IPE/IPEEE studies (98 plants) and for the same set of LAR submittals addressed in Figure 6b.



(a) IPE/IPEEE **(b) Recent LAR**

Figure 6. **Fire contribution to CDF: comparison of IPE/IPEEE and recent LAR results**

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[17] *SECY-13-0107 uses an "integrated ASP index" to address both initiating events and plant conditions but notes the difficulty in estimating CDF from this information.*

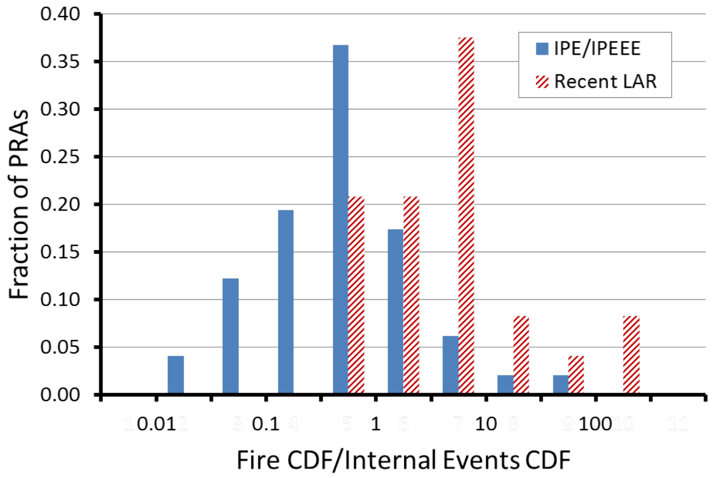

Figure 7. **Ratio of fire CDF to internal events CDF: comparison of IPE/IPEEE and recent LAR results**

Recognizing that the recent LAR submittals represent a smaller sample, nevertheless the difference between the two sets of results is striking. In the IPE/IPEEE studies, fire is an important contributor for many plants. In the recent LAR submittals, fire is a major or even dominant contributor for most plants. Possible explanations for this change include: a) the numerous plant changes made since the IPE/IPEEE studies were preferentially effective for non-fire related initiators (a difficult proposition, given the importance of plant response to fire risk), b) the IPEEE studies underestimated the importance of key issues addressed in the recent studies (we discuss changes in fire PRA technology later in this paper), or c) the recent fire PRA results are indeed conservative.

4.2 Important Scenarios

Similar to our analysis of fire CDF, it's interesting to compare fire PRA scenarios with scenarios from actual operational experience. Such a comparison cannot provide definitive conclusions because: the empirical data are sparse (and many of the potentially relevant events are quite old, pre-dating many important plant improvements), the fire PRA identifies a myriad of possibilities, and even low-likelihood events can occur. Nevertheless, we qualitatively explore whether:

1) important fire PRA scenarios been observed in major fire events, and,

2) major fire events have involved scenarios not typically addressed by fire PRAs.

4.2.1 Fire PRA Scenarios

Past studies (including the IPEEEs), taken as a whole, have consistently found that fires involving electrical cables and/or cabinets in key plant areas (e.g., main control rooms, emergency switchgear rooms, cable spreading rooms, cable vaults and tunnels) are the dominant contributors to fire risk [1-4, 42, 43]. In a number of these areas, the risk-significant scenarios can involve fires that start in electrical cabinets but propagate to cables outside. Typically, the fire effects are relatively localized (i.e., not room-encompassing) – the fire is important because it affects a local concentration of important cables. However, the IPEEEs have shown that for some plants, large turbine building fires and fires inducing main control room abandonment could be important. The risk-significant accident sequences triggered by fires are generally dominated by some form of transient (e.g., loss of feedwater, LOOP, loss of various support systems) but loss of coolant

accidents (LOCAs), including reactor coolant pump (RCP) seal LOCAs and transient-induced LOCAs involving stuck open relief valves are important for some plants. Scenarios involving non-fire related failures can be visible contributors to risk, but the risk tends to be dominated by scenarios in which the initiating fire causes enough damage to cause core damage directly (if such scenarios exist for the plant being analysed) [42, 44].

The technical lessons stemming from recent fire PRA studies have not yet been synthesized as most of the NFPA 805 submittals are undergoing NRC review. To shed some light on important scenarios, we consider the results of NRC's SPAR-AHZ models[18] [29, 45]. The three most recent models (all for PWRs) address fire scenarios using information from NFPA 805 submittals. These models are benchmarked against the licensee models; the differences are not important for the purposes of this paper.

The important scenarios identified by the three SPAR-AHZ fire models are, for the most part, consistent with those identified in past studies. Electrical fires in the usual important areas (e.g., main control rooms, cable rooms, switchgear rooms) and turbine building fires are important contributors at some or all of the plants. The plant response scenarios triggered by these fires typically involve some form of transient (including LOOP scenarios), sometimes involving the spurious opening of a power-operated relief valve (PORV). Fire-induced RCP seal LOCAs are not important contributors at these plants.

The greatest difference between the SPAR-AHZ models and older studies concerns yard fires. In the SPAR-AHZ models, these fires (which include fires involving large station transformers), are either the top or the number two contributor for the three plants.

Some additional observations concerning the three SPAR-AHZ fire model scenarios are as follows.

- The total frequency of scenarios involving reactor trip (automatic or manual) ranges from 0.06/ry to 0.30/ry. (As with past fire PRAs, it is assumed that every unscreened fire scenario results in a reactor trip.)
- The total frequency of scenarios involving fire-induced LOOP ranges from 8E-3/ry to 1.5E-2/ry. These LOOPs are modelled as being unrecoverable.
- Scenarios involving main control room abandonment are not major contributors, ranging from 0.1% to 2% of total fire CDF. The CCDPs for these scenarios span a large range, going from 0.06 up to 1.0. For plants with higher CCDPs, it can be seen that the low CDF contribution is due to the estimated low frequency of fires spurring evacuation, not the modeled robustness of the plant response.
- The fire PRA models generate thousands of detailed event sequences that need to be quantified. (By comparison, the older SPAR-EE models generate on the order of 50 sequences to be quantified, more for models if MCR scenarios are divided into cabinet-level sub-scenarios.) This creates challenges not only for the software quantification tools, but also more subtle challenges for model checking during model development and after quantification.

[18] *The NRC's SPAR models are used to support a number of staff activities, notably the assessment of the significance of operational events and of inspection findings. The SPAR-AHZ – "All Hazard" – models, similar to the older SPAR-EE ("External Event") models developed over the period 2005-2010, are intended to enable integrated, plant-specific analyses of internal hazards (including equipment failures, human errors, and internal floods) and external hazards using a single SPAR model.Currently, 20 SPAR-AHZ models have been developed.*

4.2.2 Observed Fire Scenarios

Tables 4 and 5 list notable U.S. fire precursor events occurring in the period 1969-2012. Other than the 1975 Browns Ferry fire, none of these involved multiple safety system losses and serious challenges to core cooling.

Table 6 provides summaries of the five non-U.S. fire events involving multiple safety system losses and serious challenges to core cooling identified and analysed in NUREG/CR-6738. It is important to recognize that none of these events involved plants of U.S. design, and that the latest event occurred in 1993; we are unaware of any severely challenging fires since the Narora fire.

Table 6. International Fires Involving Severe Challenges to Core Cooling

Plant	Type	Date	Summary Description (based on narratives provided in Ref. 28)
Greifswald 1	VVER-440	12/7/75	92 min cable fire in or near 6 kV switchgear started by electrical fault; caused station blackout (SBO), loss of all normal core cooling for 5 hours, loss of coolant through pressurizer safety (failed to reclose); recovered through low pressure pumps and cross-tie with Unit 2 to power one AFW pump (non-proceduralized actions).
Beloyarsk 2	LWGR-1000	12/31/78	Lube oil fire in turbine building collapsed turbine building roof, propagated into several elevations of control building (open penetrations, cable shafts); damaged main control room (MCR) panels; secondary fire from oil-filled transformer; extreme cold weather, fire under control in 17 hours, extinguished in 22 hours; damage to multiple safety systems and instrumentation, reactor control was "extremely difficult."
Armenia 1 & 2	VVER-440	10/15/82	Short circuit in a 6 kV cable led to 7 fires (ignition points) in 2 different cable galleries; fire spread to other cables, smoke spread to several areas including Unit 1 MCR; Unit 2 had some lesser fire effects; automatic foam system in manual and not actuated, fire brigade did not start attack for 20 minutes because power was on; fire under control in 6 hours, extinguished 1 hour later; Unit 1 SBO caused by hose streams about 2 hours into fire, loss of instrumentation and reactor control about 1 hour later; event also involved secondary H_2 explosion, lube oil fire and transformer explosion; recovered via temporary cable from emergency diesel generator (EDG) to high pressure pump (non-proceduralized action), recovery of Unit 1 MCR power from Unit 2 sources.
Chernobyl 2	RBMK-1000	10/11/91	Turbine failure, H_2 and oil release, large turbine building fire, turbine building roof collapsed causing loss of generators, eventual loss of all feedwater (direct damage from falling debris or de-energization to aid local fire fighting; feedwater supply intermittent, operators use seal water supply system for makeup; reactor control regained in 3.5 hours, recovery actions well outside written and practiced procedures; fire put under control also in 3.5 hours, fire extinguished 2.5 hours later.
Narora 1	PHWR	3/31/93	Turbine blade failure, H_2 explosion and fire, large turbine building fire; fire propagated along cable trays, smoke forced abandonment of MCR (shared between units) for 13 hours, fire caused loss of power to Unit 1 shutdown panel but not Unit 2 shutdown panel; major part of fire put out in 1.5 hours, fire fully extinguished 7.5 hours later; SBO 10 minutes into event, diesel-driven fire pumps used to feed steam generators, tripped by apparent common-cause (but not fire-related) failure 3.5 hours later, one pump restarted 1.75 hours later; operators "flying blind" for 4.5 hours (until staff entered containment to read instruments); EDG started and loaded 5.5 hours into event but shutdown cooling pump not energized until 17 hours – this led to declared end of SBO conditions.

Tables 4 thru 6 represent a very small fraction of the fire events that have occurred. For the U.S. alone, the EPRI Fire Events Database includes reviewed records for nearly 1700 fire events occurring over the period 1990 through 2009 [30]. However, the vast majority of these events have posed minor challenges to nuclear safety and are not addressed in our current, high-level analysis. (An integrated review of these events similar in spirit to that done in NUREG/CR-6738 would likely be useful in an analysis of fire PRA modeling of intermediate, pre-core damage plant states.)

4.2.3 Comparison of Fire PRA and Observed Scenarios

Qualitatively comparing the U.S. and international precursor descriptions with the fire PRA results, it appears that the fire PRAs are doing reasonably well with respect to our first point of comparison: most of the important scenarios identified by the fire PRAs appear to have a basis in operating experience.

The one major potential concern arises from the high risk importance given to yard fires by the three SPAR-AHZ models (and the associated licensee NFPA 805 models). Yard fires (including large station transformer fires, have been reported – a recent review identifies 50 relevant events in the 1985-2012 time period – but none have been assessed to be significant precursors. At this point, we do not know if this concern applies to a broader set of current fire PRAs.

A somewhat lesser potential concern is revealed by a more quantitative look at the intermediate results of the three SPAR-AHZ models. As indicated earlier, these results suggest a high rate of fire-induced reactor trips (on the order of 0.1/ry) and fire-induced LOOPs (on the order of 0.01/ry). Reviewing the LERs for 1980-2012, it appears that the U.S. average rates (based on around 80 fire-related trips and 7 fire-related LOOP events in that time period) are on the order of 0.03/ry and 2E-3/ry, respectively. At this point, we do not know if this apparent conservatism applies to a broader set of current fire PRAs. Also, as discussed earlier in this paper, conservatism in estimated intermediate state frequencies does not necessarily imply conservatism in CDF estimates. However, order-of-magnitude mismatches between the model estimates and empirical experience can erode confidence in the models.

Regarding our second point of comparison, it appears that most of the events listed in Tables 4 thru 6 represent, at a high level, scenarios involving fire sources and induced transients typically included in fire PRAs. (The 1989 Oconee fire, which led to an overcooling transient with a potential challenge to reactor pressure vessel integrity, may be an exception.[19]) However, it also appears that the U.S. precursors have involved a number of features not addressed in current fire PRAs:

- multiple fires (e.g., the 2010 Robinson event);
- multiple hazards (e.g., the 1984 Rancho Seco fire where debris from the hydrogen explosion appears to have been the principal cause of damage);
- fires as consequences rather than initiators of a scenario (e.g., the second fire during the 2010 Robinson event).

These observations echo a number of points made by NUREG/CR-6738 in its detailed review of 30 notable fire events (including the Browns Ferry fire and the non-U.S., severely challenging events summarized in Table 6). NUREG/CR-6738, which was specifically intended to identify

[19] *Following normal PRA modeling practices, the 2002 Watts Bar fire, in which the plant's response to an offsite fire degraded the plant's capability to tackle onsite fires, is outside the scope of the fire PRA (which is limited to internal fires). However, the authors are unaware of any PRA that has explicitly modeled such a situation in its analysis of LOOP or external fire events.*

potential areas for fire PRA technology improvement based on lessons from operational events, states that "the overall structure of a typical fire PRA can appropriately capture the dominant factors involved in a fire incident" but also notes several modeling challenges. These include the treatment of:

- factors underlying long-duration fires (including delays in initiating fire fighting, use of ineffective media in initial attacks, initial fire severity, and fire inaccessibility);
- the effect of smoke propagation on fire fighting and operations;
- personnel actions taken to facilitate fire fighting (including equipment de-energization);
- turbine building fires and fires in non-safety areas;
- fire-induced spurious operation of equipment;
- the effects of fire-induced failures of major structures;
- multiple fires (including multiple fires caused by the same root cause and secondary fires); and
- multiple hazards (including explosions, missiles, and flooding).

NUREG/CR-6738 also indicates that the lack of credit for non-proceduralized operator actions in typical fire PRAs is a source of conservatism, but does not emphasize this point.

Some, but not all of these challenges are being addressed in more recent fire PRAs and ongoing research and development activities.

4.3 Fire PRA Analysis Technology

The preceding section focuses on the results of current fire PRAs. This section briefly discusses the status of methods, models, tools, and data available for fire PRA.

As pointed out by numerous papers (see Ref. 27 for a recent overview), the basic fire PRA framework and approach remains largely as described by Apostolakis et al. [25, 44] and the PRA Procedures Guide, NUREG/CR-2300 [26]. However, in the years since the initial applications of this methodology (e.g., the early 1980's Indian Point PRA), considerable work has been performed to improve the realism of specific modeling elements. In the late 1990's, the NRC's Office of Nuclear Regulatory Research (RES) initiated a fire PRA research program whose efforts were guided by a structured identification and evaluation of potential problem areas [46]. Using the results of that program and parallel industry activities, RES and EPRI jointly developed NUREG/CR-6850 (EPRI 1011989) [8] and Supplement 1 to that document [9]. These documents provide the principal technical guidance available for current U.S. fire PRAs.

Recent evaluations of the status of fire PRA technology based on NFPA 805 applications have been provided in 2011 by Stetkar et al. [12] and Gallucci [14], and in 2013 by the Nuclear Energy Institute (NEI) [13]. The fire PRA technical issues identified by NEI include:

- the probability of fire-induced short circuits ("hot shorts");
- the duration of fire-induced hot shorts in direct current (DC) circuits;
- the effectiveness of incipient detection systems; and
- the frequency-magnitude relationship for the heat release rates associated with actual plant fires.

Work is ongoing by RES and industry to address this list of issues, which is shorter than earlier lists (e.g., see [12, 14]). Thus, it seems clear that progress towards improved realism is being made. However, it should be recognized that a number of the important (but admittedly extremely difficult) issues identified in NUREG/CR-6738, namely multiple fires, multiple hazards, and non-proceduralized actions, are not yet being addressed.

5. Summary Observations and Questions

Our discussion on fire PRA maturity is heavily influenced by one expert's views on the characteristics of a mature technical field. Our discussion on fire PRA realism relies heavily on: (1) sparse operational data (the number of fire-related precursor events is small; the number of challenging events is even smaller) and the key assumption of exchangeability; (2) summary information provided in recent risk-informed LARs; and (3) detailed information from a very small set of SPAR-AHZ fire models. Furthermore, our review of issues raised by other authors (e.g., potential reasons for differences between fire PRA technology and applications [12], cultural drivers for potential conservatisms [13]) is ongoing. We therefore refrain from drawing definitive conclusions, offering only a number of summary observations from our work to date.

- As a field, fire PRA has been judged sufficiently mature to support important regulatory decisions, but lags internal events analyses in a number of key indicators of technical maturity.
- Comparisons of precursor- and fire PRA-based estimates of the likelihood of a fire-induced core damage event in the U.S. do not show a large numerical difference.
- Comparisons of past and current fire PRAs show that the estimated relative contribution of fire to total CDF has increased significantly.[20]
- With one potentially major exception, most of the important scenarios identified by a number of current fire PRAs appear to have a basis in operating experience. The exception involves yard fires: the high importance ascribed to these fires by the PRAs does not seem to be consistent with actual fire events.
- A number of past fire-related precursor events (U.S. and international) exhibit some important characteristics not reflected in current fire PRAs. Treatment of some of these characteristics (i.e., multiple fires, multiple hazards) would likely increase fire CDF estimates. Treatment of others (particularly non-proceduralized operator recovery actions) would likely decrease fire CDF estimates.
- Recent and ongoing research and development efforts are reducing concerns about the realism of fire PRA's treatment of a number of key issues.
- NUREG/CR-6738 [28] and the report by Stetkar et al. [12] are extremely valuable resources, the former for its in-depth, fire-PRA oriented review of notable fire events, and the latter for its coverage of current issues with the practice of fire PRA and the use of fire PRA results.

Our review also suggests a number of questions whose answers will likely be useful in planning future activities.

[20] *We emphasize that this is an observation. As discussed in Section 4.1.3, the implications may be troubling from a realism perspective and deserving of further investigation.*

- Does the issue of fire PRA maturity warrant additional activity beyond what's being done to improve realism?
- Have there been any recent international important, fire-related precursor events? Do these show the same characteristics as exhibited by U.S. events?
- How do the quantitative and qualitative results of international fire PRAs compare with U.S. results?
- Over the years, have there been any major changes in international perceptions regarding the key contributors to fire risk?
- Does the international PRA community have concerns regarding the realism of fire PRA? If so, do these concerns affect the use of fire PRA results in practical applications?
- What are the key outstanding technical issues in international fire PRAs? Do these need to be resolved to alter the use of fire PRA results?

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