FIRE PRA MATURITY AND REALISM: A DISCUSSION AND SUGGESTIONS FOR IMPROVEMENT

Nathan Siu, Kevin Coyne, Selim Sancaktar, and Nicholas Melly

U.S. Nuclear Regulatory Commission: MS CSB 4A07M, Washington, DC, 20555, Nathan.Siu@nrc.gov

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. In this paper, we address the issue of technical maturity through the identification of a number of key indicators and the issue of realism through quantitative and qualitative comparisons of fire PRA results with operational event data. Based on our analysis, we judge that fire PRA is in an intermediate-to-late stage of maturity (albeit less mature than internal events analysis) and that fire PRAs, as performed using current guidance, may be providing conservative quantitative results. However, our results cannot confidently support estimates of the degree of conservatism. We also observe that the qualitative results of fire PRAs are generally consistent with operational experience. We conclude with a number of suggestions for activities to enhance fire PRA realism.

I. BACKGROUND AND OBJECTIVE

I.A. Estimated Risk Importance of Fire

Since the earliest industry-sponsored full-scope probabilistic risk assessments (PRAs) (e.g., the 1982 Indian Point Probabilistic Safety Study, reviewed for the U.S. Nuclear Regulatory Commission – NRC – by Kolb, et al.[1]), and continuing through the NRC's NUREG-1150 (Ref. 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. 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.[7] This rule change endorsed the National Fire Protection Association (NFPA) Standard 805 (commonly referred to as "NFPA 805").[8] Several licensees have submitted Licensing Amendment Requests (LARs) to make use of this change. The LAR submittals received to date[a] largely employ the fire PRA guidance documented in the joint Electric Power Research Institute (EPRI)/NRC Office of Nuclear Regulatory Research report EPRI 1011989/NUREG/CR-6850 (henceforth referred to as "NUREG/CR-6850"),[10] and a supplement to that report capturing lessons learned from pilot submittals.[11] The LAR submittals indicate that the estimated fire core damage frequencies (CDFs) remain significant.[b]

I.B. The Problem

Fire PRA has often been characterized as being less mature and less realistic than internal events PRA. (See, for example, the NRC Advisory Committee on Reactor Safeguards – ACRS – 1998 review of NRC's safety research program,[12] a 2008 Nuclear Energy Institute – NEI – report on early lessons from the implementation of NFPA 805,[13] a 2010 NEI report on an approach to improve fire PRA realism,[14] a 2011 ACRS report on the current state of NFPA 805 implementation,[15] and a 2014 paper on the implications of fire PRA modeling conservatisms.[16]) Gallucci analyzes a number of public statements and identifies different points of view within the PRA community.[17]

The two related (but separate, as discussed in the following section) issues of fire PRA maturity and realism are important practical matters. PRA results and insights are being increasingly used in regulatory applications. These applications range from plant-specific (e.g., 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

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[a] As of the writing of this paper, 27 LARs have been submitted for NRC review, and two more are expected.[9]

[b] The NFPA 805 LARs for 20 units, submitted over the period 2008-2013, have an average reported fire CDF of about 4E-5/reactor-year (ry) and an average contribution to total CDF of about 70%.

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." 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 debated weaknesses.

I.C. Purpose

In an earlier paper, we have provided some initial ideas and questions relevant to an assessment of fire PRA maturity and realism.[18] In this paper, we provide refinements on our earlier analysis (in response to comments) and further discussion on the state of ongoing research activities. Our intent is not to further inflame passions in a still-heated discussion, but to document our understanding of the current situation. Recognizing that fire PRA concerns continue to shape industry and NRC discussions aimed at improving risk-informed regulation,[19,20] and that fire PRA is likely to play a major role in NRC's ongoing Level 3 PRA project,[21] we believe that our effort is timely.

II. MATURITY AND REALISM IN A PRA CONTEXT

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 technical and organizational system relevant to the decision problem. 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. Of course, the practitioners of a less mature discipline might consciously use conservative (and potentially unrealistic) assumptions in an attempt to compensate for weaknesses in the current state of knowledge – the extent and appropriateness of this practice is a key controversy in ongoing U.S. fire PRA applications – but this only shows that the issues are coupled, not identical.)

III. ON THE MATURITY OF FIRE PRA

Judging the maturity of a technical field is a subjective matter. Different authors have identified a number of characteristics they consider to be indicators of maturity. Stetkar et al. 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).[15] 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, 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).[22] Budnitz emphasizes the use of the technology in support of practical decision making as an important indicator of maturity. Finally, in an 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.[23] Cornell's situations can be grouped into one of three categories of indicators involving the field's practitioners, research agenda, and applications.[18] In addition to the above indicators, Cornell observes that in a mature field, an analytical framework exists, the limitations of available methods are understood, methods can be adapted to new situations, and research activities are driven by the needs of practice.

Applying the preceding ideas, it appears to us, for the reasons provided below, that nuclear power plant fire PRA is in an intermediate-to-late stage of maturity, but is 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,[24] continuing with plant changes identified in the IPEEE program[4] and more recently with staff approvals of licensee-requested fire protection program transitions as per NFPA 805. These show that the technology is being used in practical applications. Further, it appears that the field has many of the characteristics identified by Cornell.

Key factors in the second part of our assessment are the relatively small number of fire PRA practitioners (as compared with internal events), the current controversy with a number of the consensus models and data as provided by NUREG/CR-6850 and associated guidance, and the lack of consensus regarding the realism of the overall fire PRA results. We recognize that, as pointed out by Stetkar et al.,[15] the ongoing licensee and staff activities related to NFPA 805 will increase the fire PRA experience base, and should, over time, reduce the maturity gap with internal events.

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 and therefore both resources and desire to address weaknesses, perhaps such differences of opinion shouldn't matter very much. However, should discussion be desired, or, more practically, should there be a need 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.[15] and others (see, for example, the quotes provided by Gallucci[17]), that substantial changes in fire PRA maturity are likely to take many years.

IV. 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 indicated by past and current guidance, is iterative.[25,9] 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 the summary and detailed outputs of past and recent fire PRAs. In the following section, we briefly discuss the technology (i.e., the methods, models, tools, and data) of fire PRA.

IV.A. 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. Of course, since there has been no fire-induced core damage event, [c] such a comparison is not entirely straightforward. However, there have been a number of "close calls" worldwide, including, but not limited to, the 1975 Browns Ferry fire.[28]

IV.A.1 Total Fire CDF

To explore what the fire-related operational experience can tell us about fire CDF, we follow the approach of Gallucci,[29] who used event precursor CCDPs developed by the NRC's ASP program as data points.[d] Based on nine precursor events covering the period 1969-2004,[e] Gallucci estimated that the average fire CDF for U.S. plants is 7.1E-5/ry.

In the years following Gallucci's 2006 analysis, there have been two "important" (CCDP ≥ 1E-4) fire-related precursor events. These were a March 28, 2010 fire at the H.B. Robinson 2 plant, and a June 7, 2011 fire at the Fort Calhoun plant. Neither was a "significant" (CCDP ≥ 1E-3) precursor.

To update Gallucci's analysis to: (a) incorporate the new evidence from the Robinson fire (but not the Fort Calhoun fire since that event occurred during cold shutdown), and (b) address uncertainties (Gallucci focuses on point estimates), we perform two Bayesian

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[c] In the period 1980-2012, only around 80 Licensee Event Reports have been initiated by (or later involved) fires. The vast majority of these did not represent major challenges to nuclear safety: none were classified by the NRC's Accident Sequence Precursor (ASP) Program as "significant" (with Conditional Core Damage Probabilities – CCDPs – greater than 1E-3) and only two had CCDPs between 1E-4 and 1E-3.[26] Out of the 1695 reviewed fire events for the period 1990-2009 included in the EPRI Fire Events Data Base,[27] only 28 were classified as "challenging," and this designation is based on a judgment that the fire had a substantive effect on the environment outside the initiating source, not the nature or significance of the components actually affected.

[d] This approach involves using the sum of CCDPs, a non-integer value, in place of the number of events in a standard statistical estimation process. This approach is similar to early analyses using operational experience when estimating CDF and to current PRA treatments of "impact vectors" in common cause failure analysis.[30,31]

[e] Save for the Browns Ferry fire, all of the events occurred after the promulgation of Appendix R in late 1980. A notable 1968 electrical cable fire at San Onofre 1, which affected a number of important systems, is not included. The event pre-dated the earliest PRA studies and no CCDP was estimated. Further, as discussed in NUREG/CR-6738, the plant was constructed prior to the development of current cable flammability standards.[28]

case studies. Both case studies use Gallucci's evidence to develop an intentionally broad prior distribution. (In particular, we use the CCDPs reported by Gallucci to estimate the mean value of a constrained non-informative prior distribution.[32]) Case 1 includes the evidence from Browns Ferry (both the event CCDP and the industry operating years up to the promulgation of Appendix R). Case 2 excludes this evidence.

As with all statistical analyses, our two cases rely on the strong assumption of "exchangeability," i.e., the assumption that the plants in the analysis group are nominally identical and that they do not change over time.[33] This assumption is especially arguable for Case 1, as 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 in late 1980) and analyses (e.g., the IPEEEs). Additional limitations of our analysis are noted later in this section.

On the other hand, given the sparseness of accident data, we must always be cautious about discarding data. For example, although one of the prime lessons from the Browns Ferry fire was that water should be used to promptly extinguish electrical fires, the reluctance to use water contributed to delayed fire suppression in a 1995 fire event.[28] Recently, such reluctance was echoed in remarks made during a Commission hearing on fire protection.[34] Our two cases cover the range of views on the applicability of the Browns Ferry event and the CCDP of that event.[f]

Figure 1 compares the results of the two cases with fire CDF estimates from NFPA 805 LAR submittals. The comparison is done on an industry-wide basis – the figure shows the total U.S. fire CDF (i.e., the sum of all the individual plant fire CDFs) estimated using the precursor CCDPs and using the NFPA 805 LAR estimates. We denote this metric by F-$\mathrm{CDF}_{\mathrm{US}}$. We use the industry-wide approach to support an "apples to apples" comparison (the precursor-based estimate addresses an "average plant," whereas the LAR estimates are plant-specific) and to facilitate comparisons with total U.S. operating experience. The details of our analytical methodology, and an illustration of the relatively small impact due to uncertainties in the LAR estimates, are provided in our earlier paper.[18]

Figure 1 shows that the CCDP-based estimates are extremely uncertain. (The "reverse-J" shaped distributions indicate that very small values cannot be ruled out.) This is not surprising since the evidence consists only of CCDPs and not actual events, and all of the non-Browns Ferry CCDPs are very small (on the order of 1E-4 or less);[17,18] their sum (including the Robinson event) is approximately 1E-3.

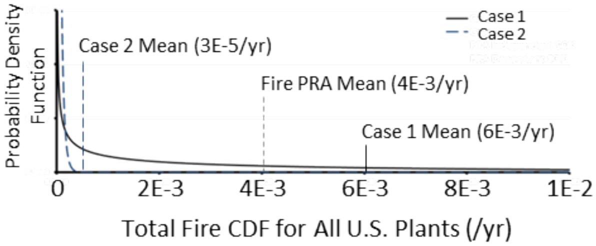

Fig. 1. Comparison of distributions for F-$\mathrm{CDF}_{\mathrm{US}}$

Figure 1 also shows that the inclusion of Browns Ferry appears to make a qualitative difference in our comparison. The mean value for Case 1 is somewhat greater than the fire-PRA based mean value, whereas the mean value for Case 2 is significantly less. Because the Browns Ferry fire is the only event with a significant CCDP, this observation is also not surprising.

In comments on our earlier paper, we have been reminded that a number of the fire PRA estimates reported in the NFPA 805 LARs take credit for planned changes aimed at significantly reducing fire CDF. We do not have the pre-change CDF estimates, but recognize that these could be higher. This would move the fire-PRA based estimate of F-$\mathrm{CDF}_{\mathrm{US}}$ to the right in Figure 1.

To explore the potential significance of the different states of knowledge on F-$\mathrm{CDF}_{\mathrm{US}}$ shown in Figure 1, we investigate 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-$\mathrm{CDF}_{\mathrm{US}}$.)

Figure 2 shows the results obtained for an exposure period of 10 years. It can be seen that the differences between the Case 1 and fire-PRA based estimates are

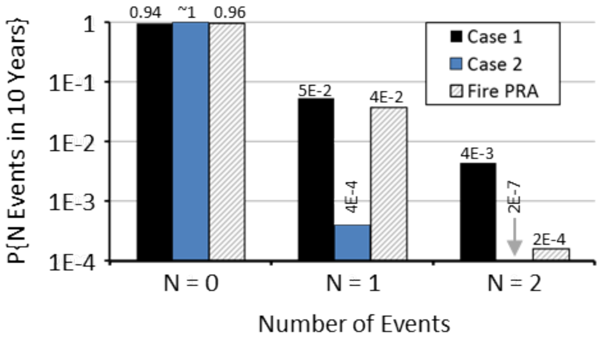

Fig. 2. Comparison of fire-induced core damage probabilities (all U.S. plants, 10 year exposure)

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[f] Gallucci uses a CCDP of 0.20 but notes other estimates range from 0.03 to 0.40.

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-$\mathrm{CDF}_{\mathrm{US}}$, will almost certainly result.) On the other hand, the differences between Case 2 and the fire PRA estimate are large. Similar conclusions result when the exposure period is increased to 50 years.

Altogether, although we remain concerned with the practice of discarding empirical data based on the notion that underlying problems have been fixed, because of the many changes in fire protection after Browns Ferry (including the plant changes in response to Appendix R and those made due to IPEEE results), we judge that Case 2 is probably closer to representing our state of knowledge than Case 1. Recognizing the point that the LAR CDFs represent post-change configurations, it appears that even the weak statistical evidence available provides mild support to the contention that fire PRAs, as currently practiced, are leading to conservative results.

We have already noted concerns with the assumption of exchangeability required by a statistical analysis, and with the lack of quantitative information for the pre-change fire CDFs of plants transitioning to NFPA 805. Additional cautions with our analysis are as follows:

- Our statistical analysis:
    - is limited to precursors that involved initiating events – it does not address the CDF implications of precursors involving degraded conditions;
    - uses event CCDPs as objective data, whereas a) the approach for estimating CCDPs has evolved over time, and b) such use represents an engineering approximation to a more rigorous treatment of data uncertainty;[31] and
    - is based on precursor results that utilize a "failure memory" assumption where observed successes are modeled at their nominal failure probability and failure events are modeled as they occurred during the event. This may limit the applicability of these results for a more general PRA analysis (e.g., the full spectrum of potential fire-related damage is not considered).
- Our fire-PRA based estimate of F-$\mathrm{CDF}_{\mathrm{US}}$ is based on the assumption that the fire CDFs reported in the as-submitted NFPA 805 LARs are representative of those that would be generated for plants who have not yet updated their fire PRAs

These limitations, as well as the extremely large computed uncertainties in our results, limit on our ability to draw strong conclusions from our comparison of statistical and fire-PRA based estimates. (For example, we cannot use our analysis to confidently quantify the potential degree of conservatism associated with current fire PRA technology and practices.) They also strengthen the need to assess the realism of fire PRA from a variety of perspectives, as we do in the following sections.

IV.A.2 Relative Contributions to Total CDF

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

Figure 3 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).

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, which do not account for the last 20 years of fire PRA research and experience, underestimated the importance of key issues addressed in the recent studies (we discuss changes in fire PRA technology later in this paper), c) the total CDF estimates consider a different range of hazards, or d) the recent fire PRA results are indeed conservative (as compared with the results for internal events and other hazards).

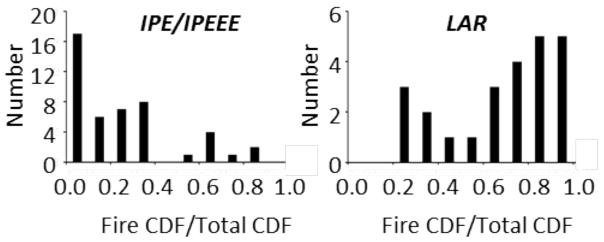

Fig. 3. Comparison of fire contribution to CDF

IV.A.3 Industry Analyses

In 2010, Canavan et al. performed an analysis that compared fire PRAs with operational experience.[14] (The results of this analysis have been more recently discussed by Chapman.[36]) The analysis did not attempt to perform a CDF-level statistical analysis, but looked at some of the constituent parts (including intermediate outputs) of a fire PRA, illustrating key points using a number of fire PRAs performed to support fire protection program changes per NFPA 805. The analysis raised concerns regarding model input (fire frequencies and severities, as represented by heat release rates), and calculated consequences (the frequency of spurious operations and the frequency of severe safety challenges as represented by high CCDPs).

Canavan et al. raise a number of good points regarding the cumulative effect of multiple modeling conservatisms (each of which may not have a major impact individually). However, as a counterpoint to these points, we note that:

- the analysis' concern with the overestimation of the frequency of fires, recently echoed by Saunders and Burns,[16] is based on a since-disproven hypothesis of a systematic downward trend in fire occurrences (which leads to a discounting of older events in the fire database);
- some of the concerns address fire PRA outcomes that are not the focus of the analysis, and are typically not, by themselves, measures that analysts would normally consider when deciding if further iteration is needed; and
- it is unclear whether addressing the conservatisms identified would be cost-beneficial. (For example, EDGs were apparently unimportant for six of the seven plants considered in the analysis. It is conceivable that the resources required to perform more realistic analysis would not result in significantly different results.[g])

These observations aside, we find the authors' argument regarding the over-prediction of events with high CCDPs to be compelling,[h] and only observe that their results could be due to conservatisms in the estimation of the CCDPs (e.g., due to scoping-level assessments of the plant impact of fire damage or to the neglect of recovery actions) as well as conservatisms in the estimation of the frequencies of scenario-specific fire damage zones.

IV.B Important Scenarios

The results of a PRA include qualitative information (particularly, the nature and characteristics of risk-significant scenarios) as well as quantitative information (e.g., fire CDF). It's therefore useful to compare important 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 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 have been observed in major fire events, and,
2) major fire events have involved scenarios not typically addressed by fire PRAs.

IV.B.1 Fire PRA Scenarios

Past U.S. 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.[1-4,37,38] 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.[i] The risk-significant accident sequences triggered by fires are generally dominated by some form of transient (e.g., loss of feedwater, loss of offsite power – 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 analyzed).

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 Standardized Plant Analysis Risk – All Hazard (SPAR-AHZ) models.[26,39] 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

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[g] We recognize that under conditions (e.g., arising during the Reactor Oversight Process), previously unimportant modeling details can become more important. However, developing a model suitable for addressing all possible applications would be cost-prohibitive and counter to the current, application focus of PRA activities.

[h] Such an analysis would likely be useful when reviewing PRA models for other hazards.

[i] Interestingly, many international fire PRAs assume that a severe fire will cause the loss of the entire room and emphasize the analysis of multi-compartment scenarios.

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 most fire PRAs, it is assumed that every modeled fire scenario results in a trip.)
- The total frequency of scenarios involving fire-induced LOOP (modelled as being unrecoverable) ranges from 8E-3/ry to 1.5E-2/ry.
- Scenarios involving main control room (MCR) abandonment are not major contributors, ranging from 0.1% to 2% of total fire CDF. The CCDPs for these scenarios range 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 External Events – 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.

IV.B.2 Observed Fire Scenarios

A review of notable U.S. fire precursor events occurring in the period 1969-2012 shows that, other than the 1975 Browns Ferry fire, none of these events involved multiple safety system losses and serious challenges to core cooling.[18] Regarding international fires, there have been five events involving multiple safety system losses and serious challenges to core cooling.[28] 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 1993 Narora fire in India.

These events represent a very small fraction of the fire events that have occurred. For the U.S. alone, the current EPRI Fire Events Database includes reviewed records for nearly 1700 fire events occurring over the period 1990 through 2009.[27] 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.)

IV.B.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 potentially significant 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 – our review of LERs identifies 50 relevant events in the 1985-2012 time period – but none have been assessed to be significant precursors. We observe that yard fires appear to be visible CDF contributors in two of the seven fire PRAs reviewed by Canavan et al.,[14] but do not know if the potentially anomalous estimated importance of such fires is due to fire PRA technology limitations, analyst-driven simplifications, or aspects of the NFPA 805 licensing process.

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 seven 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, even less-than-order of magnitude mismatches between the model estimates and empirical experience can erode confidence in the models.[j]

Regarding our second point of comparison, it appears that most of the significant historical events identified represent, at a high level, scenarios involving fire sources

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[j] Whether such a difference *should* affect user confidence, given the uncertainties in PRA modeling and results, is a point for discussion within the broader PRA community.

and induced transients typically included in fire PRAs. (A 1989 precursor at Oconee, which led to an overcooling transient with a potential challenge to reactor pressure vessel integrity, may be an exception.) 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., a 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.[28] NUREG/CR-6738, which was specifically intended to identify 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.

V. IMPROVING FIRE PRA TECHNOLOGY

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

The current fire PRA framework and approach remains largely as described by Apostolakis et al.[40] and the PRA Procedures Guide, NUREG/CR-2300 (Ref. 25). 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, NRC/RES initiated a fire PRA research program whose efforts were guided by a structured identification and evaluation of potential problem areas.[41] Using results from that program and parallel industry activities, RES and EPRI jointly developed NUREG/CR-6850 (EPRI 1011989) and Supplement 1 to that document.[10,11] These documents provide the principal technical guidance available for current U.S. fire PRAs.

Summary evaluations of the status of fire PRA technology based on NFPA 805 applications have been provided in by Canavan et al.,[14] Stetkar et al.,[15] Gallucci,[17] and, most recently, NEI.[19] The list technical topics of concern identified by NEI, include:

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

All of these topics, as well as most of the topics identified by earlier authors, are being addressed by ongoing work. Thus, it seems clear that progress towards improved realism is being made. Furthermore, it is important to recognize that the topics represent specific aspects of fire PRA; the overall framework and approach is not being challenged. Of course, as with any technical field regardless of its state of maturity, there are areas for improvement. Potential research topics include a number of the important (but admittedly extremely difficult) operational experience issues identified in NUREG/CR-6738, particularly multiple fires, multiple hazards, and non-proceduralized actions. We also note that none of the current work appears to be explicitly aimed at developing screening tools to address what appear to be anomalous qualitative results (e.g., the risk importance of yard fires).

VI. CONCLUSIONS

Based on the results of our analysis of available information, we judge that fire PRA is in an intermediate-to-late stage of maturity (albeit less mature than internal events), and that the quantitative results of current fire PRAs, as performed using current guidance, may be conservative (to an uncertain degree). Some of the observed conservatisms may arise from practical modeling choices made to reduce analysis effort, and others are likely due to limitations in current fire PRA technology and guidance. We are unable to support with any confidence statements regarding the overall magnitude of conservatism.

From a qualitative standpoint, we observe that current fire PRAs compare well with operating experience. Most of the important scenarios identified by the fire PRAs appear to have a basis in past precursor events (U.S. and international), and most of the precursor events represent, at a high level, scenarios involving fire sources and induced plant transients typically included in fire PRAs. As a potential realism concern, we note that some fire PRAs identify yard fires as being important risk contributors – this result does not seem to be consistent with operational experience. We also note that current fire PRA technology does not address some notable features of a number of precursor events, including multiple fires, multiple hazards, and non-proceduralized recovery actions. At this point, we cannot assess the quantitative impact of addressing these features.

Work is underway to develop improvements in several key areas. Operational experience reviews, such as those discussed in this paper, should be used to identify and prioritize remaining gaps. It is particularly important to work on enabling efficient analysis of situations where current, qualitative results (e.g., scenario rankings) appear to be inconsistent with operating experience. Such work may require improvements in the estimation of CCDPs , as well as in the estimation of fire-induced damage.

We recognize that a number of our conclusions may appear to be obvious to some in the PRA community. Nevertheless, given the state of controversy within the field, we have found it useful to perform an independent examination of past arguments using information available to the staff. We believe that both quantitative and qualitative comparisons of fire PRA results with operational experience are extremely valuable, and expect that similar comparisons would also be useful for PRA treatments of internal events and other hazards.

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This discussion will focus almost entirely on gameplay and features of the alliance war as a whole (i.e. the aspects managed by @ZOS_BrianWheeler and team) rather than combat and combat mechanics, although this will be touched on. I would therefore ask that people do not use this discussion as a QQ thread about skills and discuss the points that are made and indeed, any additional points that they believe may be valid.Â The buff to siege is excessive and undoubtedly discourages smaller scale play. If you have any better suggestions for changes please feel free to post them and I will add them here.