INSIGHTS FROM THE APPLICATION OF CURRENT FIRE PRA METHODS FOR NFPA-805

1.0 BACKGROUND

The original plant-specific fire risk analyses were developed for most plants during the late 1990s as part of the Individual Plant Examination for External Events (IPEEEs). As more demanding risk-informed applications have been pursued, the NRC and EPRI identified the desirability of enhanced fire PRA methods. A joint NRC and EPRI effort developed a new set of guidelines and methods for fire PRAs, now documented in NUREG/CR-6850/EPRI TR-1011989 [Ref. 1] (henceforth referred to as NUREG/CR-6850). This document was intended to establish a new state of practice for fire PRA.

NUREG/CR-6850 is currently being used by licensees to develop fire risk studies to support implementation of NFPA-805 [Ref. 2] under 10 CFR 50.48(c), and other PRA applications. Due to regulatory deadlines, a large number of concurrent "first-of-a-kind" applications of NUREG/CR-6850 are being undertaken for more than 30 nuclear sites. In effect, these studies all represent the first implementation of these recently developed methods. As a result, technical details associated with implementing NUREG/CR-6850 are being resolved in near real time.

A number of utilities are now reaching the point where insights regarding the degree of realism can be developed. Furthermore, as specific and overall risk results begin to be developed, insights on the relative usability of these studies are becoming clear.

2.0 PURPOSE

The purpose of this paper is to summarize some of the insights from applying these recently developed fire PRA methods and to propose a path forward for further development.

3.0 SUMMARY

The EPRI/NRC effort to develop NUREG/CR-6850/EPRI TR-1011989 [Ref. 1] has changed several aspects of the state of practice in fire PRAs. Some specific technical areas where NUREG/CR-6850 has provided methodology enhancements are as follows:

- Task 2 – Component Selection: Improved guidance is provided on the development of new fire-induced accident sequences, including the treatment of fire induced spurious actuations.

- Task 6 – Fire Ignition Frequency: Changes in "counting" method and underlying data address previous 'Generic RAIs' from Fire IPEEEs related to addressing fire severity and fire suppression. Restructuring of ignition source bins and treatment of those bins has resulted in further improvement.

- Tasks 8 and 11 – Scoping and Detailed Fire Modeling: For Task 8, the approach to establishing "severity factors" has changed significantly, where there is much greater resolution in the fire severity distribution function. Instead of simplistically modeling severe and non-severe fires, an almost continuous spectrum can now be treated. In addition, fire suppression can also be applied when previously considered 'double crediting' as noted in the 'Generic RAIs' for the Fire IPEEEs. Significant improvement in the treatment of Main Control Board in-cabinet fires is included. In addition, substantial guidance is provided for establishing and treating fire modeling input parameters, including guidance for treating manual suppression reliability.

- Tasks 9 and 10 – Circuit Analysis: Significant changes are included for the treatment of fire induced spurious actuations and the associated conditional probability.

- Task 15 – Sensitivity and Uncertainty: Guidance is provided for formally addressing this element.

While these changes have enhanced the overall fire PRA framework, it is clear that the methods were not previously tested in an integrated manner and the current efforts are, in effect, the pilots for the methods. As a result these first-time applications of NUREG/CR-6850 have resulted in a large number of frequently asked questions (FAQs) which have led to near-real-time changes in the methods. The quantitative assessment of fire risks brings to light a spectrum of uncertainties that are not present, or relevant, in a traditional bounding approach. For example, the precise consequences of a postulated fire are difficult to assess quantitatively due to modeling uncertainties in fire development, and plant, human, and SSC response to fire conditions. A typical response to uncertainty is to adopt a conservative approach, in order to bound the uncertainties. However, PRA is to tool that must be based on realism and an accounting of uncertainties, if the results are to be useful and comparable.

As the first plants begin to reach the point of model integration and quantification, several areas have been identified that skew the results of the fire PRA, obscure the insights, and could adversely impact decision-making. Specifically, the following inter-related areas have been identified:

- Task 6 – Fire Ignition Frequency: Treatment of fire event data and fire frequency estimation appear to have a conservative bias.

- Tasks 8 and 11 – Scoping and Detailed Fire Modeling: Fire intensity (growth and propagation) correlations and associated "severity factors" appear to reflect a conservative application of insights from fire experiments that were designed to ensure ignition, propagation, and produce upper end of the fire intensity. In addition, non-suppression probabilities, based on actual fire events, conservatively estimate the time to suppression and do not account for fire brigade control fire damage and spread. For example, a large fire entered into the Fire database as lasting 45 minutes, may have been controlled by the brigade at 15 minutes resulting in no further damage beyond 15 minutes. This conservative input results in a very conservative estimate for non-suppression probabilities.

- Tasks 9 and 10 – Circuit Analysis: Circuit failure analysis, particularly hot short susceptibility, and the associated likelihood analysis appear to contain conservatisms.
- Task 12 – Post-Fire Human Reliability Analysis: Applying assumptions for severe fire conditions when modeling the detection and suppression for manual fire fighting; thus, reducing credit for the expected crew performance.

PRA is intended to be a realistic assessment of the risk and risk contributors, and to account for uncertainties potentially important to the application. As such, any conservative assumptions must be treated with appropriate caution. In fact, the general approach taken in the development of consensus standards for PRA is to encourage the use of realism. That is, a more realistic PRA is characterized as having a higher capability. Likewise, PRAs that pervasively contain conservative biases are considered to have less capability.

Caution must also be used when separate, but inter-related, elements are combined (integrated), as the impact of multiple individual conservatisms can be significant and inappropriate. That is, an individual conservative assumption may not adversely impact the results and insights of a PRA. However, when combined with multiple conservative assumptions, the impact can be significant and inappropriate.

A simple example: when an individual conservatism impacts a single contributor by increasing its likelihood by a factor of 2 or 3, this may not be a “significant” impact on the PRA. However, when several inter-related conservatisms are combined for that contributor, the impact of the conservatism is much greater, and the risk results may be affected by an order of magnitude or more (e.g., a scenario/cutset containing 3 contributors with a factor of 2 conservatism, increases by a factor of 8; a scenario/cutset with three factors of 3 increases by a factor of 27).

The inappropriate inclusion and use of conservatism can be even more influential in areas such as fire modeling, where a near binary decision on failure or success is made. For example, when addressing fire intensity, a decision on a conservative characterization of a fire may be the difference between success and failure for particular scenarios. In such cases, the impact of the decision can lead to a significantly different perception of the risk.

Moving forward towards completion of new fire PRAs, implementation of NFPA-805, and use of the fire PRAs in other risk-informed applications, it is important that we develop sufficiently realistic results, so as to not skew decision-making. While current limitations in technology may preclude comprehensive realism, there are several areas where additional realism is achievable. Cooperation between Industry and NRC is viewed as important to continuing the evolution and improvement of fire PRA methods. Several opportunities for such cooperation are identified at the end of this paper.

4.0 TECHNICAL CONSIDERATIONS

We are approaching the time at which the fire PRAs using NUREG-6850/EPRI TR-1011989 are to be completed. In order to support effective risk-informed decisions, it is important that a realistic characterization of the risk contributors be developed. To date, no Fire PRAs have been completed using NUREG/CR-6850/EPRI TR-1011989. While these new methods represent a change to previous methods, the degree of realism in the analysis can only be gauged by indications from the on-going plant-specific applications and a review of the guidance that drives those indications.

There are strong indications that individual conservatisms in the methods and data may result in a substantial conservative bias when the individual analysis elements are aggregated and propagated through a complete analysis. These indications are based on an understanding of the important contributors arising in some of the initial fire PRAs and a review of the operating experience risk significance and trends in fire events as depicted in the NRC's Accident Sequence Precursor Program [Ref. 3] and industry fire event trends as documented on the NRC's Operating Experience web site [Ref. 4].

The following subsections summarize the fire PRA topics where current guidance introduces conservative modeling and analysis assumptions that may significantly overestimate fire impacts.

4.1 Initiating Events

Fire frequency estimates and their severity are generally conservatively overestimated. As a result, the fire ignition frequencies may be conservative by a factor of 2 to 10. The basis is discussed below.

<u>Fire frequency Trends Show Decline</u>

Fire event data used to develop NUREG/CR-6850 fire ignition frequencies includes events that occurred many years before current fire protection practices and data collection practices were implemented and before or during the early stages of Appendix R initial implementation. For instance, the basis has fire events as early as 1968. A more current NRC analysis of fire events [Ref. 4] indicates the trend toward lower frequency and less severe fires in comparison to past history. This trend reflects the improved data collection, improved housekeeping, reduction in transient fire hazards, and other improved fire protection steps; but the analyzed data continues to be biased by data drawn from a time period with fewer controls and less awareness of fire protection actions needed in nuclear power plants. The data therefore lags current plant configuration and operational practices.

Many fire events with low impact potential conservatively classified as "challenging" in the fire event count used to estimate fire frequencies

NUREG/CR-6850 data includes many low severity events, or indeterminate events, in the "challenging" or potentially challenging categories. Their inclusion conservatively impacts the generic fire ignition frequency estimates. The inclusion of certain lower severity events in the "challenging" or potentially challenging categories does not appear to be consistent with the fundamental assumptions and guidance regarding their damage potential as fire ignition events. A limited review of the EPRI Fire Events Data Base (FEDB) [Ref. 5] for electrical cabinets and cutting and welding bins indicates that the data count includes many events that are not likely to pose the kind of impact assumed in the ignition source characterization, and thus, results in conservative fire frequency estimates. This includes many events that occurred during shutdown conditions including refueling events where plant personnel were nearby and easily suppressed the event, events where the intensity of the fire and/or damage was very small for fires lasting up to 15 minutes after discovery, and events where staff were easily able to disrupt low fire intensity initiators by removing electrical current from circuits or use drop cloths to smother small hot work fires. A final point involves the consideration and treatment of high energy arcing faults on all 480V switchgear. There appear to be conservatism in this approach that are inordinately impacting risk results, despite the paucity of real events.

4.2 Fire Intensity of Ignition Events

Heat release rates (HRR) and associated severity factors are used to characterize variability in fire intensity for a given ignition source. These are reported to be based on an expert panel's judgments in consideration of the fire experimental data developed as part of the project. The "panel" factored in the results of fire testing of various ignition sources conducted in support of the project. Many, if not most, of the tests were conducted using configurations and ignition sources to ensure fire propagation of the test ignition source. Use of the heat release rate (HRR) at the 75% of peak value to represent typical fire intensity for fire propagation and damage assessments also adds to conservative bias in the evaluation of fire impact associated with a given fire ignition source. The severity factors and "the recommended HRR distribution profiles were developed based on expert judgment during a non-facilitated meeting" [Appendix G, reference 1]. It is not clear that such an approach is consistent with the technical requirements for the use of expert judgment in PRAs as outlined in the ASME PRA Standard, Section 4.3 (soon to be Section 1-4.3 of the Combined PRA Standard)

A potentially more extreme conservative bias occurs in the treatment of combustible liquid fires. In cases involving large lubricating oil volumes, the combination of the severity factor recommendations and the existing state of the art methods for fire modeling can show that all postulated oil fires will overwhelm an automatic fire suppression system. While the eventual actuation of the system may control the fire, the calculated time delay in the response of the system is such that nearby overhead targets are damaged even when offset from the fire source. The NUREG/CR-6850 treatment of oil fire scenario uses 10% of the total oil inventory as the smallest fire size. For example, in the case of a turbine driven Main Feedwater pump, that would require all postulated pump fires to involve a substantial oil inventory which is inconsistent with industry experience. This leads to a substantial overstatement of the impact and likelihood of oil fires, as compared to industry experience.

Given the over 800 fire events classified as “challenging” or potentially challenging in the FEDB, it seems that the fire growth and propagation characteristics associated with the HRR distributions in NUREG/CR-6850 would be characteristic of a much larger number of these events than has been reported in the past 10-15 years. This observation is supported by the fact that there were only three fire initiated accident sequence precursors identified in the NRC’s Accident Sequence Precursor Program during the past 15 years. These involved high voltage, preferred power source fire events that caused loss of offsite power (LOOP) to the affected plants. However, these events are accounted for in the LOOP data used in PRAs. Even though these were significant fires, there were no reported effects on safety systems or complications to plant shut down activities.

The NRC routinely evaluates significant events at nuclear plants as part of the Accident Sequence Precursor (ASP) program. However, no accident sequence precursors associated with actual fires in plant internal compartments could be found. Three precursor events were found that involved fire protection inadequacies that were detected by licensee and/or NRC inspections. In general, there have been a few fires per year of significance that caused either a plant shutdown due to faults in BOP power conversion equipment or, more rarely, a safety train failure, as tallied in NRC’s Operating Experience web site. None of these observed events, other than LOOP events were identified as accident sequence precursors. This indicates that the intensity of real fires do not comport with the likelihood and assumptions proposed in NUREG/CR-6850.

4.3 Circuit Failure Analysis

The circuit failure analysis approach provides both a level of detail for safe shutdown system circuit operability determination and consideration of spurious actuations that were not typically incorporated in prior fire PRAs. Its application per NUREG/CR-6850 guidance incorporates additional conservatism to those scenarios that pass the conservative screening. In particular, conservative treatment is applied to component initial states, and the possibility for hot shorts that result in undesirable equipment operation. Two methods for estimating circuit failure mode probabilities are provided: use of failure mode probability estimate tables, or a computational probability approach. The table approach is recommended where applicable (i.e. in most, if not all cases of interest) and is noted as providing “more conservative” results. The report also recognizes that there are mismatches between the needs of fire PRA and current estimates of spurious actuation probability. There is cited a broad consensus that the spurious actuation probability values are generally conservative.

The table approach indicates that on the order of half the susceptible multi-conductor cables will exhibit hot short conditions that will lead to spurious operations including multiple spurious operations (MSO) that could complicate the attainment of a safe shutdown state. The combinations and consequences of MSO (given that it occurs) on equipment configuration are not well defined in the report. The MSO could lead to momentary or permanent effects on equipment; this distinction has not been effectively addressed in the report, leading to the conservatively biased assumption of worst case system configuration.

Hot shorts were found in the tests to be a relatively short duration event (e.g., on the order of 11 minutes or less). As the fire burns, a ground fault eventually occurs. Thus, there is potential conservatism in that some spurious operations will again change state to their fail safe conditions. The current guidance does not specifically address modeling this situation.

The specific tests that were performed used configurations that arranged conductors and circuits that would tend to maximize the likelihood of hot shorts and therefore do not necessarily reflect a typical installation. More recent tests conducted by NRC [Ref. 6] indicate lower probability of hot shorts and lesser durations.

Moreover, the modeling and quantification of spurious operations in the report has not been compared to the results of the more than 800 “challenging” and potentially challenging fire events to determine if the limited testing cited and the analytic modeling guidance is realistic and representative. In the operating experience, one fire event was identified in the past 15 years that “may” have involved a spurious operation. Also, one accident sequence precursor event was found involving a discovered condition that could have resulted in loss of shutdown capability, if a fire had occurred at specific plant location with that vulnerability. However, the event did not involve identification of vulnerability to hot short related spurious actuations. Again, the assumptions proposed in NUREG/CR-6850 do not align with the events observed in actual events.

4.4 Non-Suppression Probabilities

NUREG/CR- 6850 endorses the use of “generic” non-suppression curves. These curves reflect conservative estimates for when fires where put out and more importantly, the failure to account for control of the fire versus extinguishment. The net impact is a conservative bias on the non-suppression factor input into the PRA. Some enhancement is needed in this area to appropriately reflect the reality of fire protection strategies. Two suggestions include (1) either the control times need to be estimated and used as non-suppression factors, or (2) control times need to be estimated and the control methods used in the modeling. As an example; the Oconee switchgear fire lasted 45 minutes, but the control was established at around 15 minutes. If this event were to be modeled as a large switchgear fire lasting 45 minutes, it would have damaged half of the turbine building. In fact, the fire didn’t even damage its own feeder cables (hence the fire didn’t put itself out).

4.5 Plant Staff Response and Control Room Crew Credit

Current generation LWRs depend on crew actions to complete many of the tasks required for plant safe shutdown. Since most fires of interest in a fire PRA are assumed to have characteristics that could provide a major challenge, the capability and reliability of plant staff from fire brigade to control room crew are assumed in the analyses to be significantly diminished in a fire scenario. As there is little industry experience on the types of fires modeled in fire PRAs, NUREG/CR-6850 recommends a quite conservative characterization of crew actions in fire PRAs. This conservatism can have a significant influence on the calculated fire PRA results.

In addition, many fire events that have been captured in the FEDB indicate prompt detection and suppression actions have been taken by crews in close proximity to the fire at its onset. While NUREG/CR-6850 implies this could be an important factor in the risk model in Chapter 11, it also significantly limits such considerations in Appendix P. This again raises the question of counting so many insignificant fire events in the challenging category where normal operational considerations do not meet the modeling premise for growth, propagation, and ultimately damage to other important equipment.

Crediting plant staff response, especially as it relates to the fire brigade, is interrelated with methodology and technology capabilities in the area of fire modeling. From a practical perspective, the time available for fire brigade response is dictated by the thermal behavior of the fire. However, the current guidance for fire modeling essentially treats all fires as rapidly progressing to a fully involved fire with little or no treatment of the incipient phase. Additionally, there is no means to credit incipient detection systems that could be used to preclude initiation of a fire. As a consequence, the actual industry experience associated with successful plant fire alarm response and brigade actions to limit damage to the fire source itself is largely inconsistent with the current guidance which predicts a much more pessimistic response.

4.6 Overall Technical Implications

The goal of a PRA is to provide a realistic representation of the risks, and an assessment of the uncertainties which can influence an application of the fire PRA. In fact, the term of a "conservative PRA" is, in effect, an oxymoron. A number of the conservative biases cited above may be due to concerns on limitations in our state of knowledge. While this may be true in certain instances, caution must be exercised to prevent these concerns from obscuring the resulting risk results. In other instances, it appears the additional refinement of the methods, driven by the insights from these initial applications, could be beneficial in eliminating undue conservatisms. While individual conservative judgments may seem to be unimportant in isolation, the combined, synergistic effect of multiple conservatisms presents an unnecessary and inappropriate challenge to the usefulness of the insights and conclusions of a study. This could lead to poor decision-making on the appropriate course of action for implementing NFPA-805, and have implications for other risk-informed applications that use the fire PRA.

The current fire PRAs being developed consistent with NUREG/CR-6850 and the additional clarifications provided in reponse to industry FAQs have more systematic modeling conservatism than the more mature internal events PRA evaluations. The fire PRA results cannot be simply compared with internal events PRAs because of the interaction of conservatisms that have been included in the fire PRA guidance. Therefore, the use of the fire PRA figure of merit as a reflection of CDF (or LERF) may be inappropriate. This disparity will also have impact on risk informed prioritization between fire and other safety issues. The conservatisms may mask or distort fire and non-fire risk insights, impacting even the NFPA-805 implementation for which they are initially intended to be used.

Another set of considerations presented by the development and application of these new methods involves the role of these risk results in the regulatory process. In many respects, implementation of the risk-informed processes of NFPA-805 represents a new era for risk-informed applications. Some of the key regulatory/licensing issues include:

- Introduction of numerical PRA results into the plant licensing basis,
- The trade-off between achieving realism in PRA results and concerns over increasing the scope of systems, structures, and components included in the regulatory scope under NFPA-805,
- Implications of conservative fire PRA methods for on-going PRA applications, and
- Requirement to assure regulatory compliance using PRA results

Each of these considerations creates new challenges for risk-informed regulatory decision-making.

This leads to another concern of how NRC inspection and regulatory applications reviews will deal with conservative simplifications embodied in the screening analysis results and other conservatisms in the more detailed fire risk modeling discussed above. It will likely be a costly, burdensome, and debatable process to address those fire PRA matters where regulatory applications guidance is not available and must be developed on a case by case basis. Given the widespread use of PRAs now and the anticipated increase expected in the future, creeping conservatisms may compound the regulatory interpretations in the future.

Lastly there is the concern that others will not appreciate the conservative nature of the fire PRA performed to support NFPA-805 compliance and will see the conservative risk results as an unwarranted safety concern that has not been addressed. (See for instance, the NRC's SOARCA project [7, 8] developed to update the siting consequence study, NUREG/CR-2239 [9].)

Therefore, it is important to address the issues that have significant potential to conservatively affect the fire PRA results as soon as possible. We also propose that regulatory guidance be developed to address the consideration of these factors in risk-informed decision-making and other regulatory applications in a timely manner. The NRC's draft NUREG-1855 and the conforming changes that will be made in Reg. Guide 1.174 are logical places to address this issue. The combined PRA standard will provide limited guidance in this regard. Prior to finalization of application guidance, caution in considering conservatism should be used in applying the fire PRA results.

5.0 PROPOSED PATH FORWARD

The initial applications of the new state of practice in fire PRA reflected in NUREG/CR-6850 have been completed. As is often the case with new methods, application is yielding insights that can assist in improving the methods. This is the situation with NUREG/CR-6850. Ideally, these initial applications would be included in a feedback process to assist EPRI and NRC in further enhancing these methods. Unfortunately, the connection of NUREG/CR-6850 with the on-going effort to implement NFPA-805 in order to establish a new licensing basis has schedule pressures that make such a feedback process more challenging. In recognition of this situation, the following recommendations are made:

1. Based on the insights gleaned to date, select one or two of the topics identified in Section 4 for further development. For example, some initial EPRI work on fire initiating events indicates that there may be benefit in augmenting the FEDB with an impact vector-based approach similar to that used in common cause failure analysis. In addition, fire event frequency trends over the last 15-20 years should be factored into the fire ignition frequency estimates. Another example involves the treatment of hot shorts. A more realistic approach could be developed for estimating hot short likelihood that takes into consideration the most recent experimental data and applicable operating experience.

2. As the NFPA-805 pilots and other early implementers identify conservatisms in dominant contributors to fire risk that may be unduly influencing decision-making, use the FAQ process to document appropriate approaches to attain a more realistic result. The on-going FAQ effort to enhance the treatment of human reliability appears to be a good example of a coordinated industry/NRC response on one such issue. It is expected that there may be many specific areas requiring such interactions as plants finalize their NFPA-805 plans. The FAQ process must be sufficiently expeditious to support these resolutions without impeding NFPA-805 implementation.

3. EPRI and NRC should initiate an effort to formally update NUREG/CR-6850/EPRI TR-1011989 as quickly as feasible in order to document consensus approaches and integrate the enhancements identified in the FAQ process and the other efforts identified above.

4. Caution should be used in applying fire PRA results, and in particular in quantitatively combining those results with internal event results, until fire PRA methods have matured to the point where the residual conservatisms are minimal. The NUREG-1855 and the conforming changes to Reg. Guide 1.174 are logical places for this caution to be identified.

REFERENCES

1. NUREG/CR-6850/EPRI TR-1011989
2. NFPA 805
3. Accident Sequence Precursor Program Annual SECYs
4. NRC's Operating Experience web site http://nrcoe.inel.gov/results/
5. EPRI Fire Events Data Base TR-1003111
6. CAROLFIRE NUREG/CR-6931
7. NRC Announces First Phase Of State-Of-The-Art Reactor Consequence Analysis, Press Release, May 7, 2007
8. State-Of-The-Art Reactor Consequence Analysis Work Plan, NRC web site, http://www.nrc.gov ADAMS number ML072200450
9. 1982 NUREG/CR-2239, "Technical Guidance for Siting Criteria Development"