Standardized Plant Analysis Risk Model and Other Probabilistic Risk Assessment Lessons Learned from Mitigating Systems Performance Index Development and Implementation

1.0 Introduction

The Standardized Plant Analysis Risk (SPAR) Model Development Program has played an integral role in the Accident Sequence Precursor (ASP) Program analysis of operating events. In a complementary fashion, one of the objectives of the ASP Program is to use plant operating experience results and insights for feedback to the SPAR models, as well as to licensee probabilistic risk assessment (PRA) models. In addition, the use of SPAR models as part of the ASP Program and the significance determination process (SDP) Phase 3 evaluations also provides the opportunity for review and benchmarking of the SPAR models against the licensee PRA models in cases where the licensee also provides risk-related input to the ASP and SDP evaluations.

In a similar manner, over the past year, as part of the NRC's efforts to implement the Mitigating Systems Performance Index (MSPI), the staff used SPAR models as a tool to help determine and verify the quality of PRAs needed for MSPI implementation. This MSPI PRA quality task provided many lessons learned in terms of modeling and data found in the SPAR models and in licensee PRA models. This enclosure summarizes these lessons learned.

2.0 Background

The MSPI is formulated as a simplified linear approximation of the change in core damage frequency (CDF) attributable to changes in the reliability and availability of risk-significant elements of a plant system in response to internal initiating events with the reactor operating at power. The Birnbaum *importance* of a basic event is the partial derivative of the CDF with respect to the basic event probability in a PRA model and provides a measure of the risk sensitivity of a plant component to CDF.

The Birnbaum importance measures of the monitored components are critical inputs to the MSPI calculation, and each licensee determines its measures by using its PRA model. An important aspect of PRA quality for MSPI implementation is the comparison of Birnbaum values within different classes of plant design. The Birnbaum values for like components modeled in the PRAs for two plants of similar design should be relatively close. For example, two four-loop pressurized-water reactors (PWRs) of the same thermal rating, with similar numbers and ratings of emergency diesel generators, auxiliary feedwater system pumps, and emergency core cooling system components, should generally have Birnbaum values for like components that agree to within about a factor of 3 based on previous staff reviews. Greater differences can be attributable to the following:

- Important differences in balance-of-plant design, particularly electrical power and cooling water dependencies, or plant backfits can result in two otherwise similar plant designs having divergent values.

- Differences in operating procedures and plant equipment performance may occur because some plants may have implemented off-normal or emergency operating procedures to address risk-significant scenarios. In other cases, the plant equipment performances might differ, and these are reflected in differing PRA model inputs and outputs.

- Finally, PRA modeling assumptions and methods may differ. Two different organizations may have prepared the PRA models for two sister plants and used different software and databases and/or different levels of detail in their modeling.

In this regard, the SPAR models representing all 103 operating plants have proven useful in establishing a benchmark for this effort. Because the SPAR models use identical industry-average failure rates and similar modeling techniques, two of the three elements contributing to differences in plant Birnbaum values can be eliminated. Theoretically, any differences that exist for Birnbaum values for like components in a group of sister plants would arise from differences in plant design. In many cases, very subtle differences such as the direct current (DC) power dependencies or the installation of a nonsafety pump can account for an order of magnitude or more difference in Birnbaum values.

3.0 Use of SPAR Models to Address PRA Quality in MSPI

The staff used the SPAR models as part of its review of the technical adequacy of the licensee PRA models for implementation of the MSPI in FY 2006. The staff obtained PRA information from the industry in the form of Birnbaum importance measures at the basic-event level from the draft MSPI basis documents provided by the licensees in September 2005. The staff assigned plants to SPAR groups based on specific design characteristics. Plant PRA model Birnbaums were then compared to the Birnbaums of the SPAR group. If the Birnbaums were comparable, the staff eliminated the plant PRA model component as a possible outlier. If not comparable, the staff then reevaluated each candidate outlier to determine if the basic event was in the appropriate group. Basic event Birnbaums were reassigned to different groups as appropriate and the process repeated. The staff then evaluated the remaining plant components that could not be eliminated by the above screening against the following three criteria:

- Was the Birnbaum different because of an identifiable design feature?
- Was the Birnbaum different because of an identifiable operations feature (data, procedure)?
- Was the Birnbaum different because of an identifiable modeling method difference?

The review encompassed design features, operations features, or modeling method, as appropriate. If the modeling or method was acceptable to the staff, it eliminated the basic event as a possible outlier. In addition, the staff used the industry's own PRA cross-comparison efforts, in the form of Westinghouse Owners Group (WOG) and Boiling Water Reactors Owners Group (BWROG) reports (References 2 and 3), to attempt to address candidate outliers. If the information available to the NRC reviewers was not adequate to explain the outlier issue, the staff usually contacted the licensee in an effort to resolve the issue. Those candidate outliers that could not be resolved by this review effort were then characterized as final outliers.

For each final outlier, the staff contacted the licensee and explained why the staff believed the plant PRA value was an outlier. Each licensee had an opportunity to resolve the concern. Often, this involved performing PRA model sensitivity studies, providing relevant procedures and data, or providing relevant PRA model calculations. The staff continued to work with the industry until all MSPI outlier concerns were resolved, either by the staff's acceptance of the reason for the Birnbaum value difference, or by the licensee changing its PRA model. Various plants made over one dozen PRA model changes as a result of this comprehensive review effort. In addition, the SPAR models were changed, in part to address needed enhancements identified in the outlier review process.

4.0 SPAR Model Changes

A number of changes to the SPAR models have been or are being implemented as a result of the MSPI PRA outlier identification and resolution process. In most cases, these same issues had been identified as part of the overall SPAR model enhancement effort, and were being implemented one plant model at a time consistent with previously planned model updates. The following describes some of the more significant SPAR modeling issues that arose during the PRA outlier resolution process.

Loss of vital alternating current (AC) bus frequency. During the review of a number of candidate outliers for auxiliary/emergency feedwater pumps for PWRs, the staff found that the loss of AC bus (with no recovery) frequency used in the SPAR model was significantly higher than that used by most of the industry. This manifested itself in Birnbaum importance values for such pumps being much higher in the SPAR model than in the licensees' PRAs. In its review of the operating events database used for SPAR, the staff found that 75 percent of the original events listed were not applicable and should be eliminated from the data, and that the loss of vital AC bus frequency should decrease by about a half order of magnitude. The staff is incorporating these changes into the SPAR models as it updates each model.

Loss of vital DC bus frequency. Similar to the preceding issue regarding the loss of vital AC bus frequency, staff reviews identified that the loss of vital DC bus (with no recovery) frequency in the SPAR models was significantly higher than that used by most of the industry. Review of the operating events database used for SPAR found that two out of three of the original events listed should be eliminated from the data, and that the loss of vital DC bus frequency should decrease by about a half order of magnitude. The staff is incorporating these changes into the SPAR models as it updates each model.

Loss of vital electrical bus event modeling. During the process of addressing PRA candidate outliers, the staff identified asymmetries in the Birnbaum values for some pumps both within the SPAR models and within the licensees' PRA models. For example, the Birnbaum value for the emergency feedwater pump on one safety train might be high, while the value for the opposite train was low. In some cases, the asymmetry represented real plant design asymmetry regarding power supply dependencies. In other cases, this asymmetry was an artifact of the method the licensee used to model test and maintenance unavailability. In still other cases, the SPAR model used the simplifying approach of modeling the loss of only one electrical division, usually the more important division, while doubling the frequency as appropriate. This modeling assumption manifested itself in incorrect Birnbaum values for some key components in the SPAR models. The staff is changing the SPAR models to explicitly treat the loss of each risk-significant electrical bus separately, as appropriate.

Single loss-of-service-water frequency value for all sites. The SPAR models use a single, operating experience-based value for the total loss-of-service- water frequency at all plants irrespective of plant design and site characteristics, e.g., ocean site versus inland river location with cooling towers. However, during its reviews, the staff noted significant site-to-site variations for loss-of-service- water frequency used in licensee PRAs. As a consequence, the staff has initiated a task to identify the feasibility and data needs for developing site-specific frequencies for loss of service water. If successful, this effort may lead to the development of plant-specific initiator fault trees for events such as loss of service water, loss of component cooling water, and loss of instrument air.

In addition to the above anticipated model changes, the SPAR Model Development Program will address a number of long outstanding issues. Many of these issues became evident during the MSPI PRA outlier identification and resolution process. Examples include the following:

- the need to perform confirmatory thermal-hydraulic (T-H) analyses in support of system success criteria that differ from the standard set in the SPAR models, e.g., number of pressurizer power-operated relief valves (PORVs) needed for bleed and feed success in PWRs

- development of a standard approach for recovery from station blackout after battery depletion

- development of a standard approach for modeling BWR reactor vessel injection following gradual containment overpressurization owing to loss of suppression pool cooling

The staff has identified the need for extensive T-H analyses in a number of areas to provide more solid technical bases for success criteria and operator action timing, consistent with requirements set forth in the American Society of Mechanical Engineers (ASME) PRA standard (Reference 1), for example. As part of the Risk Assessment Standardization Project (refer to Enclosure 1 for details about RASP), the staff is developing a multiyear plan and schedule. This work plan will be completed in FY 2007.

5.0 Licensee PRA Model Issues

During the MSPI PRA outlier resolution process, the staff identified a number of common issues in some of the licensees' PRA models. In conjunction with the licensees, the staff ultimately resolved most of these issues. The following describes several of the more important issues that were frequently observed.

Loss of offsite power (LOOP) issues. The PRA outlier screening process identified a number of emergency diesel generator (EDG) Birnbaum values from the licensees' PRAs that appeared low compared to those within the industry plant group, or compared to the SPAR model values. Most of these issues related in some form to one or more of the following:

- the application of convolution integrals for assessing more accurately the timing of equipment failures and the impact on offsite power recovery

- low contribution from one or two components to the total LOOP frequency, e.g., weather-related or grid-related

- the treatment of alternate power supplies as partially or totally independent from the LOOP events in the data, e.g., 161-kV or 69-kV emergency power source

The staff obtained and reviewed several detailed offsite power recovery calculations using convolution integrals. In most cases, the net effect of these analyses is to reduce the contribution of LOOP/station blackout sequences to CDF. The reduction is a function of the degree of redundancy of emergency power supplies, the number and diversity of equipment available for coping with the station blackout event, and critical timing issues such as core uncovery and battery depletion. The staff found the analyses to be acceptable and was able to resolve several PRA outlier issues.

The LOOP frequency comprises several elements. While there are plant-to-plant variations in the modeling of LOOP events, generally the elements consist of grid-related, plant-centeredrelated, and severe weather-related components. In several cases, the staff determined that the licensee's model had not included the weather-related component as is accepted practice for most PRAs, and the licensee agreed to incorporate that component. In several other cases, the licensee used a grid-related component lower than the norm because that plant's geographic location makes it less susceptible to grid-related events, as most grid-related events tend to occur in the Northeast. The staff generally found the analyses to be reasonable in this regard. In at least one case, the PRA model for a plant in the Northeast revised its PRA model to reflect a higher contribution of grid-related events, based on regional operating experience data.

Finally, a number of plant PRA models had LOOP frequencies substantially lower than the norm based on quantitative credit taken for alternate or emergency offsite power supplies from 161-kV or 69-kV lines, for example. The staff agreed that such alternate power supplies provided a safety benefit. However, the staff's concern was with how the LOOP data were being applied within the PRA model in question. The LOOP data compiled by Idaho National Laboratory are for *total* losses. The data already include the loss of primary and secondary sources of offsite power at plant sites. No data had been collected on *partial* LOOP events which might prove useful to licensees in their plant-specific analyses. Rather, several licensees used the total LOOP data in effect as partial LOOP data, then credited plant-specific features such as an emergency reserve auxiliary transformer to effectively reduce the probability of sequences leading to core damage. In the absence of reliable data for partial LOOP events, the licensees' methods were not appropriate. Licensees agreed to revise their LOOP analyses after the staff expressed these concerns.

Loss-of-service-water frequency. As discussed above, the SPAR models use a value based an operating experience for the total loss of service/raw water (LOSW) frequency. The value is an estimate based on the number of applicable reactor-years in the United States with no observed, sustained total loss during power operation. Aware of the wide variability of site characteristics and service water system design, the staff generally had minimal concerns about plant-specific frequencies that differed from the SPAR value. However, in several instances, the staff observed LOSW frequencies that were as much as two orders of magnitude below the SPAR value and most generally accepted values used in the industry PRA models. The staff was particularly concerned when the site in question had experienced precursors to LOSW events such as frazil ice, sea grass clogging of screens, debris infiltration, and other events. The staff requested the licensees to reconsider their initiator frequencies in light of operating experience, and most licensees agreed to increase the LOSW frequencies to varying degrees and as much as an order of magnitude in two cases.

Credit for reactor pressure vessel (RPV) injection following BWR containment overpressure. The staff observed a number of instances in which Birnbaum values for EDGs, residual heat removal pumps, and/or emergency service water (ESW) pumps in the licensees' PRAs were lower than expected. Closer review revealed that the amount of credit taken for RPV injection following BWR overpressure could have a significant impact on CDF and Birnbaum values. In two cases, sensitivity studies performed by the licensees indicated that this credit reduced the internal events CDF by factors of about 2 to 3. Additionally, Birnbaum values for important components such as EDGs and ESW pumps would increase by an order of magnitude without such credit.

The staff conducted extensive reviews for several plants where this credit appeared to be a factor in the PRA outlier status. Information useful to the staff in its reviews included:

- potential containment failure modes, pressures, and locations
- location of piping penetrations
- systems credited for injection
- location and environmental qualification of mitigating equipment
- reactor/auxiliary building room heatup calculations from steam ingress
- dependencies and location of equipment necessary to depressurize the reactor and keep the safety relief valves open
- location of backup nitrogen supplies
- time available for operator action
- containment event trees to address the phenomena
- sensitivity studies of the potential impact of various key assumptions.

The staff reviewed all relevant information in detail and found the information provided by the licensee to be acceptable for MSPI implementation. The staff plans a number of additional studies associated with these issues as part of RASP.

Station blackout mitigation after battery depletion. A number of licensees took significant credit for station blackout mitigation following station battery depletion. The staff's primary concern is with the ability to monitor critical process variables, control important equipment, and operate high-voltage circuit breakers in the absence of DC power. In several instances, the licensee informed the staff of the availability of batteries dedicated to switchyard operation. Additionally, licensees provided information on relevant procedures and training for the mitigation measures in question. The staff reviewed the information on an individual basis. Where the licensees provided sufficient bases for the credit, the staff accepted the modeling for the purpose of MSPI implementation. In one case, the licensee agreed to not credit operator recovery actions for certain sequences.

6.0 Generic Industry PRA Issues

The staff identified several PRA issues generic to the industry during the MSPI PRA outlier resolution process. The following describes three of the more significant examples.

Model truncation and convergence. The ASME PRA standard provides specific guidance and instruction regarding appropriate PRA model truncation levels and CDF convergence. During its reviews, the staff identified several concerns about the truncation levels in some of the preliminary PRA model quantifications performed by licensees. In several instances, the licensees did not demonstrate an adequate degree of convergence of the CDF in the PRA model. In other cases, while the analysis showed the CDF to be adequately converged, the licensees did not demonstrate adequate convergence of the Birnbaum values (derived from the CDF and Fussell-Vesely values). Sensitivity studies performed by the staff, as well as those published in the open literature, have identified that in many instances truncation levels need to be an order of magnitude or more lower for Birnbaum values to be converged to the same precision as CDF, especially for low Fussell-Vesely and Birnbaum values. In one instance, the licensee demonstrated by way of sensitivity study that reduction of the truncation level from 3×10^{-11} to 1×10^{-12} resulted in a 17 percent increase in CDF and a 30 percent increase in the Birnbaum value for the component in question.

As a result, the MSPI working group specified several options for the licensees to use in their PRA model quantification. The default option is to use a truncation level seven orders of magnitude lower than the baseline CDF. Thus, if the baseline CDF is, for example, 1×10^{-5}/yr, a truncation limit of 1×10^{-12}/yr would be acceptable. However, for a number of licensees, their PRA models were too large or the number of cut-sets generated too great to allow quantification in a reasonable amount of time. Therefore, the working group provided two alternative approaches. One alternative allowed for the derivation of Birnbaum importance measures for monitored components based on first principles, i.e., by requantification of the model with basic event probability set to 1.0 (failed). The second alternative approach allowed for use of higher truncation limits by demonstrating adequate convergence of the Birnbaum value for the monitored component(s) in question. The staff was satisfied that the licensees ultimately demonstrated adequate levels of truncation and convergence for MSPI implementation.

Small loss-of-coolant accident (LOCA) frequency. During the PRA outlier resolution process, the staff identified a systematic bias in the Birnbaum values for the high-pressure safety injection (HPSI) pumps in the SPAR models. Overlaying the plots of the distribution of Birnbaum values from the SPAR models and from industry PRAs for PWRs demonstrated that, on average, SPAR HPSI pump values were significantly lower than industry values. Review of the underlying data from industry and SPAR clearly showed that the industry's small LOCA-initiating event frequencies were significantly higher than the mean value of 4×10^{-4}/yr used in the SPAR models. For example, WCAP-16464-NP (Reference 2) provides the small LOCA initiator frequencies for Westinghouse/Combustion Engineering plants. The median initiator frequency for this group of plants is approximately 3×10^{-3}/yr, or nearly an order of magnitude higher than the SPAR value. The data also indicate a range of plant-specific frequencies spanning a factor of about 40 from a low of 2.5×10^{-4}/yr to a high of 1×10^{-2}/yr. While the definition of "small" LOCAs can vary from plant to plant, this variation would appear to exceed reasonable expectations. For example, plant-specific LOCA analyses may define "small-break" LOCAs to be between 1/2-inch and 2-inch equivalent diameter sizes at one plant, while another plant might have used 3/8-inch as the lower bound and 1.9-inch as the upper bound. Regardless, these small differences in the definition of break size can hardly account for the large variation in initiator frequencies.

While there generally is good consistency across the industry as to what constitutes medium-break and large-break LOCAs, such is not the case with small LOCAs. Some licensees include mechanical failure of reactor coolant pump seals in the small LOCA category, while others have split off the low end of the small LOCA spectrum and created small-small or very small LOCA categories, which have altogether different success criteria than small LOCAs. A consequence of this inconsistency in small LOCA definition and variation in small LOCA frequency is the difficulty of making direct comparisons between the SPAR models and the industry PRA models as a whole. The industry could significantly enhance PRA modeling by standardizing the process for defining LOCAs and for apportioning the total LOCA frequency in those cases where some plant-to-plant variation is necessary because of design differences.

PORV success criteria for bleed and feed. In a few cases, the PRA outlier resolution process identified major differences in the Birnbaum values for auxiliary feedwater (AFW) pumps that were attributable to variation in success criteria for pressurizer PORVs for bleed and feed. For example, a number of plants have used 2-of-2 PORVs in their success criteria, while other plants have specified 1-of-2. Still other plants have used a combination of 2-of-2 and 1-of-2 based on sequence specific circumstances. While there are design and procedural reasons for such variation (specifically, reactor thermal power rating and PORV relief capacity), often the success criterion is the result of the degree of analysis undertaken by the licensee. In one case, the staff reviewed nearly a thousand pages of analysis prepared, in part, to establish plant-specific success criteria. The staff's review of WCAP-16464-NP (Reference 1), which summarizes bleed-and-feed success criteria as well as PORV relief capacity, identified some lack of consistency within the industry in this regard.

For some plants with a high degree of redundancy and diversity of power supplies for AFW, for example, the calculated CDF and overall risk profile may not be sensitive to this criterion. For still other plants, it has been demonstrated that the CDF can vary by as much as a factor of 2 or 3 depending on this criterion. One objective of the SPAR Model Development Project is to account for plant-specific variation in design, and hence success criteria, for the use of such mitigation strategies as bleed and feed. However, it is not possible to duplicate the wide variation in success criteria while still maintaining the degree of standardization desired in the SPAR models, especially if the industry has different success criteria. As discussed above, the staff is initiating a study to perform confirmatory analyses in support of system success criteria that differ from the standard set in the SPAR models (e.g., the number of pressurizer PORVs needed for bleed-and-feed success in PWRs). This study is being performed as part of RASP.

7.0 Comparison of Licensee PRA Model CDF with SPAR Model CDF

The staff compared the April 1, 2006, licensee CDF values to the most current SPAR values. Although only about half of the SPAR models have undergone the latest phase of enhancement, 80 percent of the SPAR model CDFs are presently within a factor of 2 of licensees' internal events model CDFs. The average SPAR model CDF is approximately 8 percent higher than the average licensee CDF, so no significant systematic bias in the SPAR models is evident. The staff considers this a strong validation of SPAR model fidelity.

8.0 Summary of Results

Implementation of the MSPI represents a major step forward for risk-informed performance indicators. It is widely perceived as the first industrywide application using a structured process to address PRA quality.

Before MSPI implementation, the staff established a systematic process to understand PRA modeling differences. This process examined differences both within the industry, by comparing PRA values for classes of similar plants, and between plant PRA models and the NRC's own SPAR models.

The process identified PRA differences with the potential to impact the MSPI, then set out to identify whether those differences originated in bona fide design differences, differences in plant operating procedures and performance, or PRA modeling methods and assumptions. In the process, the staff screened in over 260 candidate PRA outliers, which eventually consolidated to several dozen plant-specific issues. The staff then addressed these issues in detail and resolved all PRA outliers before MSPI implementation on April 1, 2006. From these PRA reviews, the staff gained important insights into potential enhancements to both the NRC's

SPAR models and the industry PRA models. As part of RASP, the staff is now planning to address the most important remaining issues affecting SPAR model fidelity.

9.0 References

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