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THE NRC'S SPAR MODELS: CURRENT STATUS, FUTURE DEVELOPMENT, AND MODELING ISSUES

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ABSTRACT

Probabilistic risk assessments (PRAs) play an increasingly important role in the regulatory framework of the U.S. nuclear power industry. The Nuclear Regulatory Commission (NRC) relies on a set of plant-specific Standardized Plant Analysis Risk (SPAR) models to provide critical risk-based input to the regulatory process. The Significance Determination Process (SDP), Management Directive 8.3 - NRC Incident Investigation Program, Accident Sequence Precursor (ASP) and Mitigating Systems Performance Index (MSPI) programs are among the regulatory initiatives that receive significant input from the SPAR models. Other uses of the SPAR models include: Screening & Resolution of Generic Safety Issues, License Amendment reviews and Notice of Enforcement Discretion (NOEDs). This paper presents the current status of SPAR model development activities, future development objectives, and issues related to the development, verification and maintenance of the SPAR models.

Key Words: SPAR, SAPHIRE, ASP, MD 8.3, MSPI, SDP

1 INTRODUCTION

The Standardized Plant Analysis Risk (SPAR) models are a set of 76 linked fault tree/event tree probabilistic risk models used by the Nuclear Regulatory Commission (NRC) to evaluate the risk of operations at all 104 U.S. nuclear power plants. The SPAR model development program was originated in 1995 primarily to support NRC's Accident Sequence Precursor (ASP) program. The models, quantification code (SAPHIRE [1]), primary data source [2] and the human reliability analysis (HRA) methodology [3] were all developed at the Idaho National Laboratory (INL).

NRC's transition to risk informed decision making, as well as advances in probabilistic risk assessment (PRA) methods, has necessitated many enhancements to the SPAR models. These models have evolved from crude order of magnitude approximations to detailed models yielding results comparable with utility PRA models. Figure 1 illustrates the history of the SPAR model development as well as the feedback mechanisms used to facilitate ongoing model modifications.

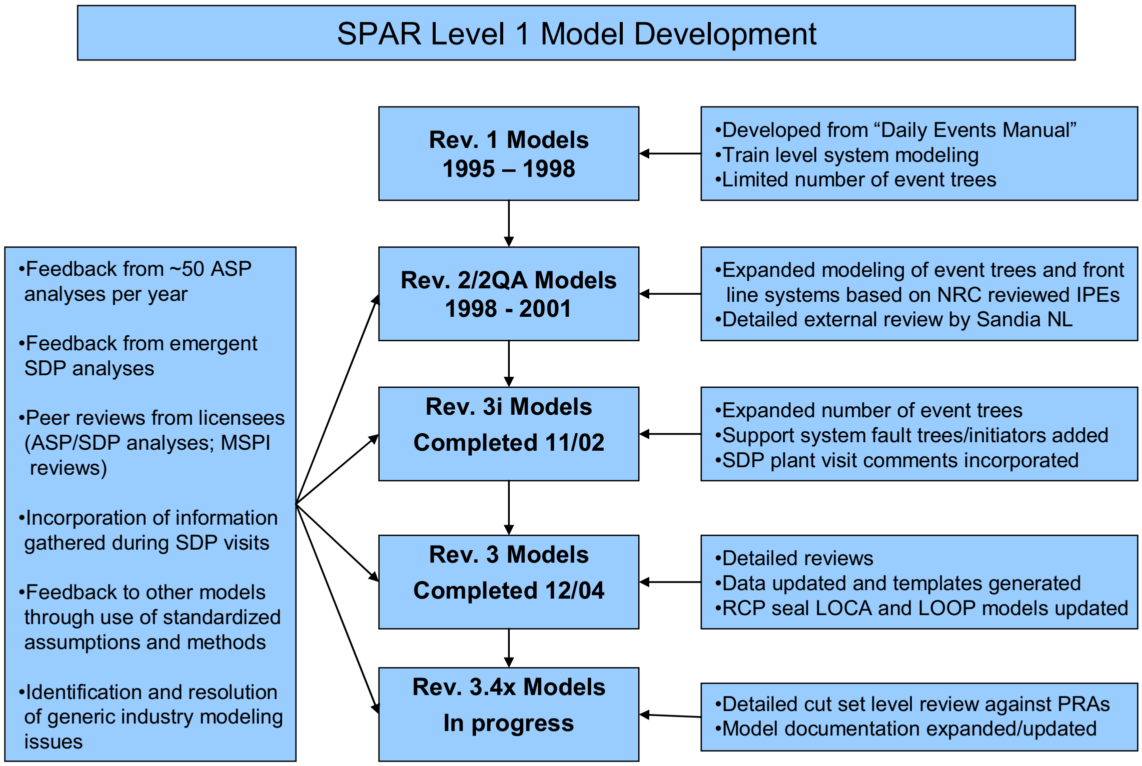

Figure 1. SPAR models - development history and feedback mechanisms

The SPAR model development program has expanded to include the following model types:

Level 1 – Internal Events, full power operation

Level 1 – Internal Events, shutdown operation

Level 1 – External Events, (fires, floods, seismic, etc)

Level 2 – Full spectrum, not limited to Large Early Release Frequency (LERF)

Level 3 – Pending further evaluation

The current objective of the SPAR model development program is to produce detailed plant-specific probabilistic risk assessment tools that can be used by NRC staff analysts in the performance of their risk-informed regulatory activities. The current status of the SPAR model development activities, future development objectives and issues related to the development, verification and maintenance of the SPAR models are described in more detail in the following sections.

2 CURRENT STATUS

The SPAR models are nearing completion of a detailed review process comparing SPAR model results, at the individual cut set level, with current utility PRA results. Of the 76 active SPAR models, 73 have had the comparison process completed (Revision 3.4+). The remaining three models will be compared upon receipt of updated plant PRA results. This comparison effort consists of comparing the importance of analogous components (basic events) found in both the SPAR and PRA models. Those events found to have significant differences in their importance are examined to determine the reason for the difference. Once the origins of the differences are understood the SPAR models are modified if appropriate, or a basis for the difference enumerated in the SPAR model documentation. Incorporation of current data (NUREG/CR-6928 [2]) is also performed as part of the comparison process. A typical plot of basic event importances from a Revision 3.4+ SPAR model compared with those from a utility PRA model is shown in Figure 1.

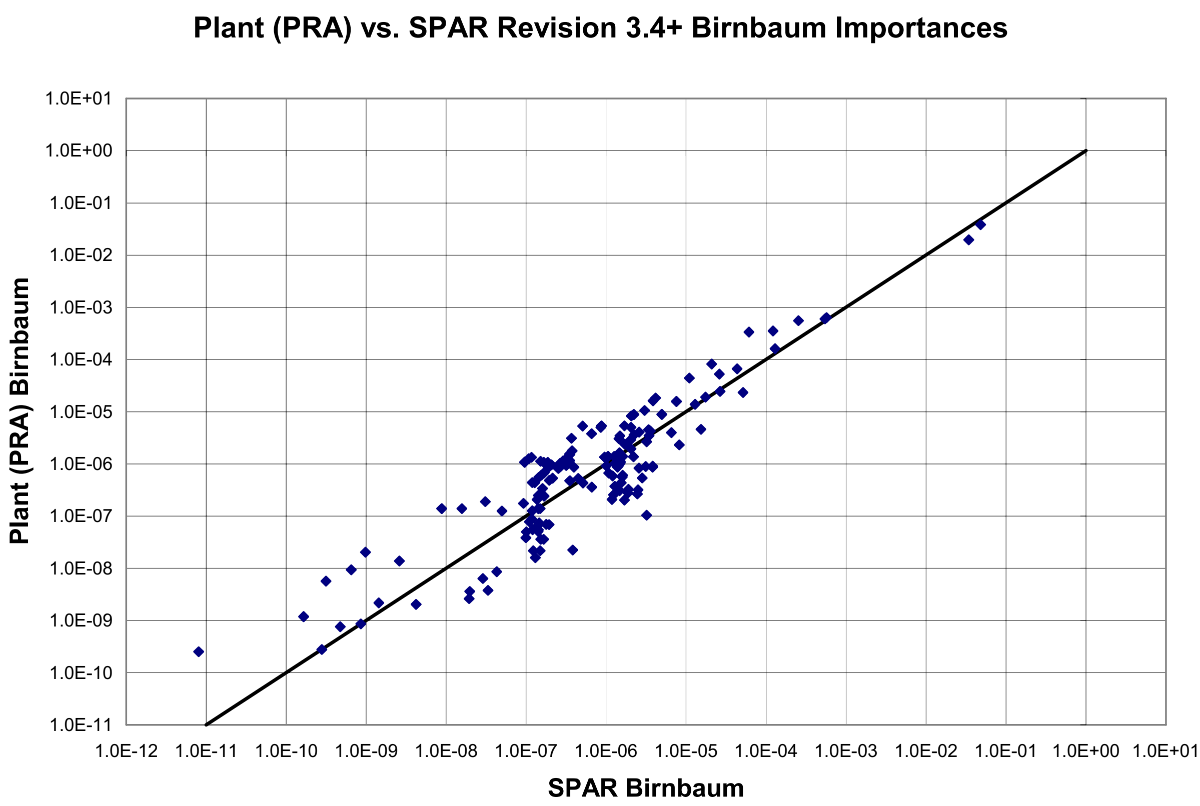

Figure 2. Scatter plot of basic event importances for a Revision 3.4+ SPAR model

The coverage and detail of the SPAR models increase with each major revision. In addition to the 76 internal events full power models there are now thirteen models having some degree of modeling for external events (internal and external fires, severe weather, seismic and flooding). Six of the SPAR models include low power/shutdown logic. Five SPAR models also include

Level 2/LERF logic. With the exception of the Level 2 logic, all of the various analysis types associated with each plant are contained within a single integrated SPAR model.

The detail of a SPAR model now approaches that of a typical utility PRA with approximately 1200 basic events, 150 fault trees and 15 event trees. At the nominal SPAR truncation of 1E-13/year a typical SPAR model generates in the range of 50,000 cut sets. The core damage frequencies (CDF) calculated in the current SPAR models average 4.1E-6/year for the boiling water reactors (BWRs) and 1.8E-5/year for the pressurized water reactors (PWRs). These values correlate closely with utility generated values of 5.3E-6/year for BWRs and 1.4E-5/year for PWRs [4].

3 ONGOING AND FUTURE DEVELOPMENT EFFORTS

The SPAR Model Development Program continues to develop and improve risk analysis tools and capabilities to support the use of PRAs in the NRC's risk-informed regulatory activities. The SPAR program is nearing completion of a major effort to perform detailed comparisons between the SPAR model results and the PRA results. NRC and INL staff are working with industry representatives to resolve key outstanding technical issues common to both SPAR and utility PRA models. Resolution of these issues and incorporation of the resolutions into the SPAR models is expected to span the next 2-3 years.

The SAPHIRE code is the platform for development and quantification of the SPAR models. A major revision of the SAPHIRE code (8.0) is scheduled for release late this year. Among the more significant SAPHIRE code enhancements incorporated into the new version are streamlined and highly automated interfaces to support the significance determination process (SDP) and event assessments. Specific analyses modules to support the revised Level 2/LERF SPAR model development effort are planned as well. Improved quantification algorithms are being explored to support the analysis of the integrated SPAR models.

3.1 Level 1 Models

As previously noted the NRC and INL are working with industry representatives to develop practicable and technically sound guidance for PRA methodology applications for several key technical issues. This involves working with Electric Power Research Institute (EPRI) on a cooperative research and development program. These key issues account for much of the differences between the SPAR model results and those of utility PRAs. The three principal issues currently being addressed in this cooperative program are:

1. Estimation of Support System Initiating Event (SSIE) frequencies using fault trees - In addition to addressing specific construction methodologies, environmental considerations relating to water quality of suction sources in open cycle cooling systems (i.e., service water) is also being addressed as part of this issue.
2. Treatment of Loss of Offsite Power (LOOP) events – Resolution of this issue will address multi unit effects, mission times (e.g., diesel generators), extended station blackout events, conditional LOOP modeling, operation of steam-driven and diesel-driven equipment, etc.

3. Standard approaches for crediting injection following overpressure induced failures of containments in BWRs - Issues being addressed include containment depressurization rate assumptions, break locations and equipment susceptibilities, long-term injection with diesel-driven pumps, etc.

Once a consensus resolution to these issues is achieved, the resolutions will be incorporated into the SPAR models. Peer review against ASME standards is then expected to follow incorporation of the consensus resolution approaches.

3.2 Shutdown Models

Operating experience and various studies show that the risk from shutdown operation can be important. To broaden their understanding of this risk, NRC is pursuing a program to model the risk of shutdown operations. The current shutdown models are based on SPAR at power system fault tree logic that is modified as necessary and then combined with shutdown specific event trees. Currently there are five PWR and one BWR shutdown models. These models are integrated with the corresponding at power SPAR models.

The shutdown model logic is structured around plant technical specification operational modes. Risk from shutdown operations arising from Mode 4 (hot shutdown), Mode 5 (cold shutdown), and Mode 6 (refueling) for PWRs and Mode 4 (cold shutdown) and Mode 5 (refueling) for BWRs is explicitly modeled. These operational modes are further delineated into plant operational states (POSs) based on factors such as time since shutdown; reactor coolant system (RCS) inventory and RCS pressure/pressure boundary status. Consideration of these additional factors yields plant operational states with similar mitigating system applicability. The end result of this assemblage is the definition and explicit modeling of nine POSs for PWRs and six POSs for BWRs.

The results of these models indicate the risk of operation while shutdown, on a per hour basis, is comparable to operation at power. Operator actions are found to dominate the shutdown risk. During shutdown, many of the automatic initiations are secured and many of the systems are in atypical alignments. Ongoing maintenance activities also reduce the redundancy of many of the mitigating systems. Operator understanding of and response to, the atypical alignments and equipment status are critical during a shutdown.

3.3 External Event Models

The SPAR suite of models also includes thirteen external events models (internal & external fires, severe weather, seismic and flooding). As with the other types of SPAR models, the external events models are integrated with, and build on, the at power Level 1 models. One notable difference between the external events models and all other SPAR model types is that the external events models are truly not independent analyses. The scenarios and related equipment failures found in the PRAs are extracted and assimilated into the SPAR models. This information is incorporated into the SPAR models via impact vectors in existing fault tree/event tree logic. No independent analyses are performed when generating the external events models.

In excess of 40 nuclear plants are currently transitioning to the performance based regulatory basis of National Fire Protection Association (NFPA) standard 805. The SPAR model development program, in conjunction with the SAPHIRE development program, is currently evaluating the methods and potential SAPHIRE code changes necessary to incorporate this information into the SPAR models.

3.4 Level 2/Large early Release Frequency (LERF) SPAR Models

The current Level 2/LERF modeling efforts are focused on developing SPAR models for the full spectrum of Level 2 outputs, not just large early release (LER). This enhanced modeling effort will provide support for:

- New reactor design assessments
- The State of the Art Consequence Assessment (SOARCA)
- Estimates of societal risk (latent cancers, land contamination, etc.) as well as individual early fatality risk
- Incorporation of Severe Accident Management Guidelines (SAMG)/Extensive Damage Mitigation Guidelines (EDMG) into SPAR models
- Assessment of effectiveness of SAMG and EDMG measures
- The assessment of advanced computation methods (Bayesian networks, data fusion techniques) in support of real time accident management

There are two parts to the Level 2/LERF models: 1) Extension of the Level 1 models to include containment systems and 2) development of containment event trees to model containment phenomenology and accident progression. Modifications to the SAPHIRE 8 code have been introduced to support Level 2/LERF SPAR Model Development. Figure 2 illustrates the Level 2/LERF SPAR model development approach.

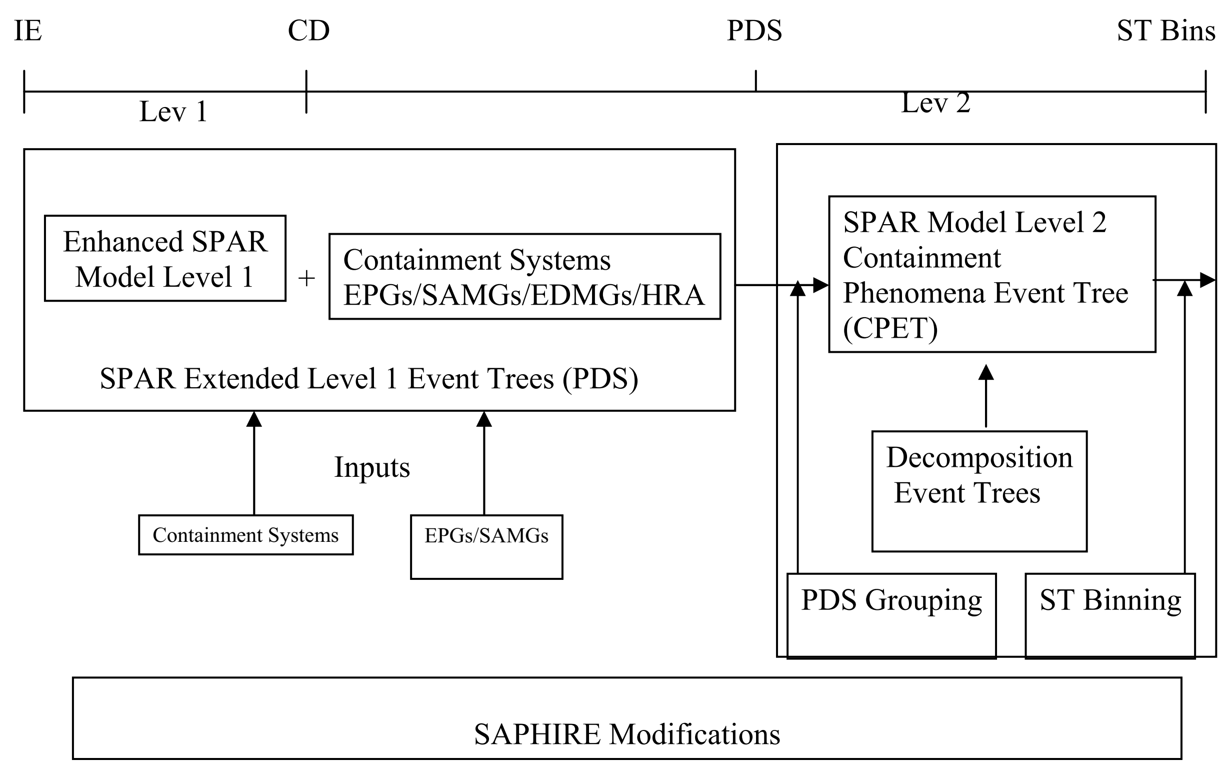

Figure 2 – Overview of Level 2/LERF SPAR Model Development Process

3.4.1 Extended Level 1 SPAR Model Development

The approach taken to modeling the systems and human actions that are important to accident progression following core damage (e.g., containment systems, support systems) that are important to defining the accident progression beyond core damage (i.e. containment accident progression) for assessing containment performance and radionuclide transport and release but are not considered significant to the determination of core damage (and hence are not included in the Level 1 core damage SPAR model) was to modify and/or extend the Level 1 model to include these systems and human actions.

For the extended Level 1 models new events were added as required (either event tree events or fault tree events) to support Level 2 accident progression analysis. These new events include those for containment systems such as containment sprays, Emergency Operating Procedures (EOPs) and SAMG operator actions, and systems utilized for severe accident management actions (e.g. firewater system). Additional branches were also added under current existing (Level 1 core damage) event headings which are important to the Level 2 accident progression but were considered irrelevant for core damage determination. Comparison of the success criteria for existing events in the Level 1 core damage event tree and with success criteria required for the Level 2 accident progression modeling needs was performed and events were added or modified as necessary to reflect different success criteria.

Extending the Level 1 event trees to include containment systems and human actions provides the following advantages compared to other approaches (such as the use of “bridge event trees”). This approach allows all system dependencies to be considered in a uniform, integral manner and facilitates maintenance and updating of the Level 1 and Level 2 models in a consistent manner. Any plant modification that impacts any system or human action are simultaneously updated in both the Level 1 core damage models and Level 2 models

3.4.2 Containment Event Tree (CET)/Decomposition Event Trees (DET)

The containment event tree models generally consider the phenomenological aspects of accident progression. System status and human actions are only considered to the extent that the accident phenomena impact system availability or the need for, or probability of success of, human actions. Hence, these event branching probabilities generally represent epistemic uncertainty rather than aleatory uncertainty as in the systems event trees. In this approach CETs are constructed with a limited number of event headings representing the most important phenomena that impact accident progression, containment failure and fission product release. Subsidiary event trees (DETs) are developed to support the quantification of each of the CET events, with the last event in the DET being the event of interest (CET event) and prior events in the DET representing events or other factors that have a causal influence on the likelihood of a particular state (branch) of the end event. The range of uncertainty in the individual events in the DET are represented in the form of a discrete probability distribution over the states (value ranges) of the event. In addition to probabilistic events, the DETs generally include deterministic events which represent dependencies on plant damage state conditions and on prior event branch decisions in the CET. Quantification of the CET/DETs involves marginalization of the joint probability distribution represented by the DET to obtain the branch probabilities for the end event in the DET and propagation (multiplication) of the DET end event (CET event) marginal probabilities.

3.4.3 SAPHIRE 8 Modifications to Support Level 2/LERF SPAR Model development

A substantial number of enhancements have been introduced into the SAPHIRE 8 code version to support the development and quantification of Level 2/LERF SPAR models. These include model changes to support the extended Level 1 modeling and to support the Containment Event Tree/Decomposition Event Tree approach for modeling containment phenomenology and accident progression.

Modifications have been introduced that allow the flagging of identification of top event headings that have been added to support Level 2/LERF accident sequence progression and were not included in the Level 1 core damage model. Similarly, the capability of flagging and identification of new branches that have been added to existing Level 1 core damage events to support the Level 2 accident progression modeling is now supported.

SAPHIRE 8 allows the graphical display of either the core damage (Level 1) event tree structure or the full extended Level 1 event tree structure with the additional top event headings and branching structure. The code also supports linking in fault trees as appropriate for core damage analyses or for quantification of the sequences through the extended Level 1 event tree.

SAPHIRE 8 supports the use of graphical decision trees (logic diagrams) supported by if-then-else inference rules for defining distinct plant damage states (PDS) groups and for assigning sequences to PDS groups. Similarly, the use of decision trees and rules are supported for defining distinct Source Term Bins and for assigning containment accident progression sequences to Source Term Bins.

Code modifications have been introduced to support modeling Level 2 phenomena that impact accident progression using event trees (CETs) supported by subsidiary (decomposition) event trees (DETs) for detailed modeling and quantification. Two approaches to quantification of the CET/DETs are available: End-to-end (CET/DET) sequence quantification (multiplication of sequence branch probabilities) or marginalization for each end state probability in the DETs and quantification of the CET using the event marginal probabilities (multiplication of CET marginals).

Five extended Level 1 SPAR models have been developed to date as well as three Level 2/LERF (CET/DET SPAR) models.

4 MODELING ISSUES

Current SPAR modeling issues are both practical and technical. With the large number and varied model types, in conjunction with the numerous analysts involved in modeling, day-to-day modeling issues such as configuration control, consistency and efficiency in modeling are challenges to the SPAR program. The lack of regular and systematic feedback from the utilities regarding plant modifications is also problematic. Technical issues include those previously mentioned modeling topics being cooperatively worked with the industry and specific SAPHIRE code limitations.

Configuration control is difficult due to numerous and often concurrent modifications/updates being performed on the models. The configuration control issue is exacerbated by assorted groups and organizations working concurrently on the models. The SAPHIRE website is the repository for current status information as well as the latest models. The SPAR model program also relies heavily on the date and version number stamping features contained in SAPHIRE to ensure and implement configuration control. Use of version control software that limits access to the model of record and provides a formal checkout procedure is being studied for future use.

The inclusion of varied analysis types within a single SPAR model frequently leads to multiple success criteria for the same function. For example, injection flow requirements for shutdown logic may be less restrictive than for at power logic. Modularizing fault tree logic at the train level provides the necessary flexibility to model these varying success criteria and remains an ongoing effort.

Evolving SPAR model needs and advancements in the state of the art of the PRA industry occasionally out pace existing SAPHIRE features. One current SAPHIRE limitation is the allowance of only one set of rules (modifications that set house events and/or perform substitutions in sequence logic) per event tree sequence. This constraint necessitates extensive writing of unique/explicit rules for each sequence. Soon to be released SAPHIRE version 8 will eliminate this restriction by allowing the use of inclusive overlapping sequence rules. This improvement will greatly reduce the effort to construct external events models. The pending incorporation of support system initiating event fault trees has necessitated research into additional algorithms to calculate importance measures for components found in both mitigating as well as support system initiating event fault trees.

5 CONCLUSIONS

The SPAR models in their current configuration and breadth are valuable tools used by the NRC to understand and evaluate risk associated with operation of nuclear power plants. They are robust tools useful to the NRC for most PRA applications. The standardized construction of these models (SAPHIRE quantification platform, failure and unavailability data, HRA methodology, modeling assumptions, level of detail, etc) provide a consistent platform from which to evaluate individual plant risk impacts as well as industry-wide issues. The SPAR models are continuously improving in detail, accuracy and breadth of coverage. These tools will continue to evolve to meet the emerging needs of the NRC and to reflect advancements in the state of the art of the PRA industry (PRA standards, analysis types, PRA quality, etc.).

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