RISK-INFORMED RESOLUTION OF GENERIC SAFETY ISSUE 191

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ABSTRACT

The United States Nuclear Regulatory Commission (USNRC) relies on Probabilistic Risk Assessment (PRA) as one of the main pillars of its risk-informed regulatory and oversight functions. In 2011, the South Texas Project Nuclear Operating Company (STPNOC) initiated a risk-informed project to resolve Generic Safety Issue 191 (GSI-191), which is related to the performance of the emergency core cooling system (ECCS) following a loss of coolant accident (LOCA). This paper summarizes the results of collaborative work on this project by teams of experts from industry and academia. The progress of the research and its implementation have also significantly benefitted from the discussions and feedback received from regulatory representatives. An integrative framework was developed to explicitly provide failure probabilities for the post-LOCA PRA basic events associated with the concerns raised in GSI-191. These basic event probabilities are estimated using the CASA Grande program, which was developed as part of the project. This program encompasses the time-dependent modeling of the underlying physical phenomena of the basic events and the propagation of the uncertainties in the physical models. This paper summarizes the elements of the integrative framework including PRA and the CASA Grande program, as well as the input parameters, assumptions, methodology, and results of the STPNOC analysis. The results show that the risk of core damage or large early release related to the concerns raised in GSI-191 in the as-built, as-operated design for STPNOC is very small (as defined in Regulatory Guide 1.174).

Key Words: Probabilistic Risk Assessment (PRA), Generic Safety Issue 191 (GSI-191), Safety, Risk

1 INTRODUCTION

Since 2002, Generic Safety Issue number 191 (GSI-191), has eluded resolution despite significant efforts by industry and the Nuclear Regulatory Commission (NRC). The basic issue is related to hypothesized LOCA scenarios that would result in the generation of debris, including insulation materials, failed coatings, chemical products, and latent dust and dirt. GSI-191 presents two major questions: (a) would the debris that is carried with the coolant to the containment sump plug up the suction strainers of the ECCS pumps, and (b) would the debris

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that penetrates through the strainers cause blockage of the fuel channels within the reactor core. Although recent thought has been given to risk quantification [1], and early recognition of the need for risk evaluation was identified [2], serious investigation into risk quantification had not been undertaken. Instead, resolution followed a classical deterministic approach. As challenges continued to frustrate resolution of GSI-191 using a deterministic approach, in 2010, the NRC commissioners directed the staff to consider new and innovative approaches for resolution. One of the options in the staff requirements memorandum (SRM) [3] was the use of a risk-informed approach. Therefore, STPNOC initiated a three-year undertaking as a pilot plant to define and implement a risk-informed methodology to resolve GSI-191.

This required an extension of existing models, uncertainty quantification, PRA evaluation, and development of new models to evaluate the physical phenomena associated with ECCS strainer blockage and core blockage. The scope of the phenomena modeled in the project is extensive, and includes location-specific LOCA frequency estimation, jet formation physics, debris generation, debris transport, effects of chemicals on head loss in debris beds, strainer head loss, degasification, downstream effects, and reactor thermal-hydraulics. The risk-informed framework can benefit and significantly improve the analysis required to address GSI-191 issues in multiple ways. First, it enables us to analyze the full spectrum of postulated LOCA events. Second, it ensures that physical processes are characterized as comprehensively and as realistically as possible. Additionally, the probabilities and frequencies are appropriately quantified. Moreover, the uncertainties are quantified using uncertainties in experimental and operational data to directly include the possibility of extreme events, which had not been contemplated in traditional deterministic analysis.

2 METHOD OF ANALYSIS; THE INTEGRATED FRAMEWORK

An integrative framework was developed to explicitly provide failure probabilities for the post-LOCA PRA basic events associated with the concerns raised in GSI-191. Figure 1 depicts the two components of this integrated framework at a high level of abstraction. The first component (module 1 in Figure 1), illustrates the plant-specific LOCA branches of the PRA and includes risk scenarios and their associated fault trees. The second component (module 2 in Figure 1) contains models of the underlying physical phenomena associated with the basic events in module 1. In other words, module 2 (CASA Grande) provides estimated probabilities and the associated uncertainties to the basic events of the LOCA-PRA in module 1, based on the physical models that have been developed for these basic events.

The output from CASA Grande is used to feed directly into the plant-specific PRA. The PRA results are then compared to a hypothetically perfect plant configuration with respect to the concerns raised in GSI-191 to calculate the change in core damage frequency (CDF) and large early release frequency (LERF). If the \{CDF, ΔCDF\} and \{LERF, ΔLERF\} values are within Region 3 (Figure 2), as defined in Regulatory Guide 1.174 [4], the risk associated with GSI-191 is considered to be very small.
Module 1 STPNOC PRA with added features to capture details of concerns associated with GSI-191

- ECCS: Emergency core cooling system
- FA DP: Fuel assembly differential pressure
- LLOCA: Large LOCA
- LOCA: Loss of coolant accident
- LTC: Long term cooling
- MLOCA: Medium LOCA
- RCP: Reactor coolant pump
- RHR: Residual heat removal
- SLOCA: Small LOCA

Module 2 Engineering models of physical phenomena provide added input to the STPNOC PRA for concerns associated with GSI-191

Major inputs to module 2:
- Containment CAD model
- LOCA frequency data
- Thermo hydraulic data
- Chemical effects data
- Debris transport data
- Strainer and core geometry
2.1 Module 1: PRA

The purpose of the PRA quantification in this study (module 1 in Figure 1) is to quantify the risk and uncertainty in the as-built, as-operated plant associated with the concerns raised in GSI-191. The PRA quantification forms the basis for “mitigative measures and alternative method approach” that the NRC staff identified as a GSI-191 closure path in 2012 (Nuclear Regulatory Commission, 2012 [5]). In the integrated risk-informed framework proposed in this study, distributions associated with the PRA basic events are provided by the CASA Grande module (module 2 in Figure 1) discussed in Section 2.2. The basic event probabilities provided to the PRA are shown in Figure 1 with dotted arrows.

2.2. Module 2: CASA Grande

The goal of the CASA Grande module (module 2 in Figure 1) is to propagate uncertainty in physical parameters from the break initiation to potential core damage precursors: (a) strainer head loss, (b) core blockage, (c) boron precipitation, and (d) air ingestion. In other words, CASA Grande folds phenomenological uncertainties into plant performance metrics to support risk-informed decision making which creates a platform for parametric studies, sensitivity analysis, and comparison of physical approximations. Uncertainty propagation is accomplished by assuming that the input parameters are random variables with distributions derived from historical data, experimental data, expert elicitation, physics, or a combination of these sources. Random observations from multivariate distributions that govern these parameters are generated with sampling schemes. Finally, these values are propagated [6] through CASA Grande to yield as output, an estimator of a key performance measure, such as the probability of a subsystem failure, which is passed to the PRA model. In this section, a brief description of various analyses within CASA Grande (i.e. elements of Module 2 in Figure 1) is provided.

2.2.1. LOCA Frequency

Determining the initiating event frequency (number of breaks per year) is a key requirement in performing a risk-informed evaluation. Estimating the frequencies for LOCA pipe breaks,
particularly larger breaks, is challenging since there is limited data from operating experience (due to the very low frequencies of these breaks). The best generic estimates for LOCA frequencies are based on an expert elicitation process that was documented in NUREG-1829 [7]. NUREG-1829 provides LOCA frequencies as a function of break size for both BWR and PWR plants. These values are total frequencies that include all potential primary-side break locations. However, since two equivalent-size breaks in different locations may have a significantly different likelihood of occurrence as well as a significantly different effect on GSI-191 related phenomena (e.g., quantity of debris generated, transport fractions, in-vessel flow paths, etc.), the total frequencies for all possible break locations must be broken down into the specific frequencies for each break location. The LOCA frequencies must then be appropriately sampled to evaluate the full range of potential LOCA scenarios. This was done utilizing the following steps:

1. Calculate the relative probability of breaks for specific weld categories (i.e., an analysis of calculating damage mechanism dependent weld failure rates based on service data, a Bayes method for uncertainty treatment developed in the EPRI RI-ISI program, and estimates of conditional probability vs. break size. The details are available in [8].)
2. Identify applicable weld category and spatial coordinates for each weld location
3. Statistically fit the NUREG-1829 frequencies (5th, Median, and 95th) using a bounded Johnson distribution for each size category. These fits represent the epistemic uncertainty associated with LOCA frequencies as a function of break size.
4. Sample epistemic uncertainty (e.g., 62nd percentile) and determine the corresponding total frequency curve based on the bounded Johnson fits (assuming linear interpolation between size categories).
5. Distribute total LOCA frequency to each weld location based on the relative probability.
6. Sample break sizes at each weld location and proceed with the GSI-191 analysis carrying the appropriate initiating event frequencies.
7. Repeat steps 4-6 to build failure probabilities for each plant performance metric and quantify uncertainties in these estimates.

2.2.2. Debris Generation, Transport and Accumulation

Analysis of debris generation, transport, and accumulation in CASA Grande adapts a deterministic GSI-191 methodology to the risk-informed approach. In this phase, CAD data are imported into CASA Grande and insulation-specific ZOI size is determined based on an NRC-approved deterministic method in NEI-04-07. The break jet ZOI is modeled as a sphere (fully offset DEGB) or as a randomly-directed hemisphere (any other break). The ZOI radius depends on the insulation destruction pressure and break size [9, 10]. Then, insulation debris quantities are automatically calculated for thousands of break scenarios in CASA Grande. Additionally coatings (qualified/unqualified), latent debris quantities, and debris size characteristics, as well as blow-down, wash-down, pool fill, recirculation, and erosion transport fractions are provided as input to CASA Grande [11-13]. The total transport to the ECCS strainers was determined based on the logic tree method described in NEI 04-07 [9]. To analyze time-dependent arrival of debris at the strainer several time-dependent transport sources (cavity fill, initial wash-down, unqualified coating failure, wash-down transport by recirculated spray/break flow, fiberglass erosion recirculation, etc.) are taken into consideration [13]. Time-dependent accumulation of suspended debris is modeled assuming homogenous mixing in the pool and time-dependent flow rates at each sump.
2.2.3. Chemical Effects

The analysis of chemical effects was performed to support the risk-informed resolution of GSI-191 and improve understanding of how corrosion processes contribute to head loss. The objective of this analysis is to develop data and models for input to CASA Grande to calculate time-dependent chemical concentrations, solubility limits, precipitate formation, and precipitate contribution to head loss at the strainer and in the core, to use bench-top testing to investigate potential variations in plant-specific conditions.

Two main hypotheses were subjects of this analysis; A) constituents in solution (phosphate, silicon) can lead to passivation of metal surfaces, reducing corrosion and; B) the pre-formed precipitates used in the WCAP-16530-NP protocol [14] can cause higher head loss than when metal ions are slowly released into solution via corrosion. Continued testing over increasingly wider parameter ranges fails to refute either hypothesis, with the result that few adverse chemical effects have been observed under typical STPNOC plant conditions. Conditional probability distributions of chemical-induced head loss increase were introduced to account for potential adverse effects that have not yet been observed or fully characterized.

2.2.4. Strainer Head Losses

Overall head losses across the strainer include the clean strainer head loss as well as the debris bed head loss from both conventional debris (fiber, particulate, RMI, paint chips, etc.) and chemical precipitates. If the strainer head loss exceeds the NPSH margin of the pumps, the pumps are presumed to fail. Similarly, if the head loss exceeds the structural margin of the strainers, the strainers are presumed to fail, potentially allowing large quantities of debris to be ingested into the ECCS. If either of these conditions is observed during assessment of a given scenario, the accident scenario is assigned as a failure.

The clean strainer head loss (CSHL) function in CASA is described using an equation with two empirically derived coefficients, one for viscous and one for inertial losses. A curve fit to the measured CSHL for a prototype strainer module [15] showed the dominancy of the inertial term for STP conditions [16].

The NUREG/CR-6224 correlation was selected for the CASA computation of conventional (fiber and particulate) debris head loss across the strainer. The head loss correlation requires the following debris parameters: material density, bulk density, and characteristic size, which are the quantities needed to compute THE surface-to-volume ratio. Based on the debris characteristics provided in [18-21], these parameters were estimated and used for the head loss calculations in CASA Grande. Although, the head loss correlation has been validated over a large range of approach velocities and debris types, there were specific STP conditions (e.g., low approach velocities prototypical of the STP strainers and buffered borated demineralized water) where the NUREG/CR-6224 head loss correlation had not been compared to experimental data. To ascertain the applicability of the correlation to STP conditions, STP performed confirmatory head loss testing [21]. The NUREG/CR-6224 head loss correlation generated reasonable estimates of the head loss experiments conducted with ground acrylic paint and extended the approach velocity down to the STP strainer approach velocity of 0.0086 ft/s. However, the experiments showed that the measured head losses at lower temperatures were lower than the head losses calculated by the NUREG/CR-6224 head loss correlation. To account for additional
uncertainties in the applicability of the correlation in parameter ranges that have not been tested, an additional inflation of ~5 was applied to all predicted head-loss calculations; hence the CASA calculated head losses are judged to be conservative with respect to the NUREG/CR-6224 head-loss correlation.

In CASA Grande, head losses due to chemical effects are implemented as a set of probability distributions for chemical effects bump-up factors applied to all breaks [16]. To account for the presence of the extreme conditions in the scenario sample space, exponential probability distributions were applied as direct multipliers to the estimated conventional head loss. The probability distributions were developed based on the current results from the CHLE testing [22, 23], WCAP-16530-NP calculations [24], and reasonable engineering judgment.

2.2.5. Air Ingestion

Pressure drop across a strainer may release air bubbles from the solution. The assumption made in the analysis is that the dissolved gas in the containment pool is at equilibrium conditions based on Henry’s Law (function of containment pressure and temperature). The objective is to calculate the quantity of air released based on the difference in pressure downstream of the strainer and the pool surface (if strainer head loss is greater than strainer submergence, air will be released) [16]. CASA explicitly calculates the quantity of air released in proportion to the time-dependent pressure drop occurring on each strainer independently and compares these quantities to the respective acceptable void fractions of each pump.

2.2.6. Debris Penetration

Debris penetration is a function of two mechanisms. The first mechanism is direct passage of debris as it arrives on the strainer. A portion of the debris that initially arrives at the strainer will pass through, and the remainder will be captured by the strainers. The direct passage penetration is inversely proportional to the combined filtration efficiency of the strainer and the initial debris bed that forms. A second mechanism by which debris may penetrate the strainer is by shedding, which is the process of debris working its way through an existing bed and passing through the strainer. The fraction of debris that passes through the strainer by direct penetration will drop to zero after the strainer has been fully covered with a fiberglass debris bed. Shedding, however, is a longer-term phenomenon since particulate and small fiber debris may continue to work through the debris bed for the duration of the event [25].

Debris that penetrates the strainer can cause both ex-vessel and in-vessel problems. The most significant downstream effects concern the quantity of fiberglass debris that accumulates in the core. This is a highly time-dependent process due to several time-dependent parameters including initiation of recirculation with cold leg injection, arrival of debris at the strainer, accumulation of debris on the strainer, debris shedding, direct passage, flow changes when pumps are secured, decay heat removal through coolant boil-off, and switchover to hot leg recirculation.

Debris that passes through the strainer will not necessarily end up on the core. A portion of the debris could pass through the containment spray pumps, and a portion could either bypass or pass directly through the core and spill out the break. The debris that does not accumulate in the core is assumed to arrive back in the pool where it can transport and potentially pass through the strainer again.
2.2.7. In-core Debris Accumulation

The potential for core blockage to occur is largely dependent on (a) the size of the break, (b) the location of the break, and (c) the ECCS injection path. Medium and large breaks are similar in terms of core blockage. However, for a small break (either the hot or cold leg side) the break size is small enough to allow the RCS to fill with water. For medium and large breaks, however, the flow path through the core strongly depends on the location of the break (cold leg or hot leg side breaks) and the injection path (cold leg or hot leg injection).

Following a LOCA at STP, water would initially be injected from the RWST to three out of four of the cold legs. Since the water from the RWST is free of debris, there would be no potential for core clogging during this phase. After the RWST has been drained, the SI and CS pumps would be realigned to take suction from the ECCS sumps. Due to potential issues with boron precipitation, two of the three trains would be realigned from cold leg injection to hot leg injection approximately 6.5 hours after the start of the accident.

For a medium or large hot leg break, the SI flow would initially be injected in the cold legs, forcing the flow to pass through the core and then spill out the break. After the start of recirculation, but before hot leg switchover, debris that penetrates the strainer would transport with the flow and accumulate in the core. The head loss due to the debris would result in a compensating rise in the steam generator water level. Eventually, given sufficient head loss, a portion of the SI flow could pass over the steam generator tubes reducing the flow through the core.

There are two potential concerns that have been raised with the hot leg break/cold leg injection scenario: (a) if flow starts spilling over the steam generator tubes, it may cause a siphon to form that would suck all of the SI flow over the tubes and directly out the break [26], and (b) core blockage may be large enough to prevent sufficient decay heat removal from entering the bottom of the core and the remaining SI flow may preferentially spill over the steam generator on the broken loop where it could pass directly out the break.

Under standard conditions, the maximum possible height of a siphon (neglecting frictional losses) is approximately 33 ft. Since the temperature in the steam generator tubes would be significantly higher than standard conditions, the siphon would break at an elevation less than 33 ft. Elevated containment pressure could increase the maximum height of a siphon, but elevated pressure generally trends with elevated temperature, and the containment pressure drops quickly during the RWST injection phase [27]. At STP, the lowest steam generator tubes are over 40 ft above the bottom of the hot legs [28]. Therefore, flow over the steam generator tubes would not result in a siphon effect that would raise concern. This conclusion is further supported by the results of thermal-hydraulic simulations [29]. After switchover to the hot leg injection, it is not likely that the debris would cause any significant blockage issues during hot leg injection [16].

For a medium or large cold leg break, the SI flow would initially be injected in the cold legs, and the majority of the flow would bypass the core, spilling directly out of the break. However, a portion of the injected water would flow into the core to make up the water lost due to boil-off. The debris that penetrates the strainer after the start of recirculation would transport with the flow, and a portion of the debris could accumulate in the core. Unlike the hot leg break scenario,
however, the head loss due to the debris would result in a decrease in the core water level rather than a rise in the steam generator water level.

There are two potential concerns that have been raised with the cold leg break/cold leg injection scenario: (a) core blockage may be large enough so that the water level cannot be maintained above the top of the core, and (b) debris buildup at the bottom of the core may prevent mixing with the lower plenum volume resulting in a more rapid onset of boron precipitation. After switchover to the hot leg injection, full blockage at the top of the core would be prevented by countercurrent flow due to thermal buoyancy. Also, the amount of debris available at this time is much lower than that of the cold leg injection phase due to the debris bed filtration.

The acceptance criteria for debris loads on the core were defined based on the break location, injection flow path, and fiberglass debris loads that could potentially cause issues for debris blockage. Based on the thermal-hydraulic modeling, which showed that full blockage at the bottom of the core would not result in core damage for hot leg breaks, the acceptance criterion was essentially set to an infinite fiber quantity. For cold leg breaks, an acceptance criterion of 15 g/FA was used based on the conservative results of testing by the PWROG.

2.2.8. Boron Precipitation

Boron precipitation is primarily a concern for large cold leg breaks during cold leg injection. In this scenario, the water in the core would be boiling and the net flow entering the core would be equivalent to the decay heat boil-off rate. To prevent boron precipitation in these scenarios, the SI flow is switched from cold leg injection to hot leg injection. The required switchover timing depends on the concentration of boron in the RCS/RWST/accumulators, the decay heat level, and natural mixing processes within the reactor vessel based on temperature and/or density gradients. Previous deterministic analyses have shown that if the hot leg switchover occurs within seven hours following a cold-leg break, boron would not precipitate. However, debris blockage could invalidate or challenge these analyses. The core blockage acceptance criteria are bounded by the boron precipitation acceptance criteria. For medium and large cold leg breaks, the acceptance criterion for boron precipitation was assumed to be 7.5 g/FA of fiber debris on the core [16].

2.3. CASA Grande Input Parameters

There are large numbers of input parameters that are used in the risk-informed GSI-191 evaluation (as shown in Figure 1), and many of these input parameters are described by probability distributions, characterizing the associated level of uncertainty. One of the key inputs is provided by thermo-hydraulic analysis as explained in Section 2.3.1.

For some input variables, a best-estimate value may be adequate for a realistic analysis (this could be true for parameters that have a tight range between the minimum and maximum values or for parameters where the results of the analysis are relatively insensitive to large variations in the parameter values). However, other input variables require probability distributions to accurately describe the relative proportion of values across their range. Figure 3 shows an illustration of a probability density function for total water volume in containment (from the RWST, RCS, and accumulators). Depending on the specific analysis, either the calculated minimum or calculated maximum, water volume would be used as an input for a deterministic
evaluation. For a risk-informed evaluation, the input probability distribution is sampled to determine the actual impact on the results with an appropriate probability weight carried through the analysis for the extreme conditions associated with the minimum and maximum values.

2.3.1 Thermal-hydraulic Analysis and Input Data

The analysis of the reactor system and containment response during LOCA scenarios was performed using system codes. RELAP5-3D [30], a thermal-hydraulic system code used for best estimate simulations of normal operation and postulated transients (including LOCA) in LWRs, was selected to perform the simulations of the reactor system. A MELCOR [312] model of the reactor containment was prepared to simulate the containment response, in conjunction with the RELAP5 model. The reactor behavior was simulated under different LOCA scenarios and plant conditions such as: (1) small, medium, and large break sizes; (2) cold and hot leg breaks; and, (3) diverse operating conditions (RHR, fan coolers, containment sprays availability).

Thermal-hydraulic calculation results were also provided as boundary conditions (sump water temperature profile) for the chemical effects tests, and as input parameters for CASA Grande.

3. RESULTS

One of the primary functions served by CASA Grande in the risk-informed resolution process is quantifying conditional failure probabilities related to GSI-191 phenomena for various states of plant operability. Failure probabilities are passed to the plant-wide PRA, which determines the incremental risk associated with GSI-191 failure modes. In this role, CASA serves very much like an elaborate fault tree that informs top-event branch fractions that are built in to the event tree.

CASA compiles the failure probabilities for basic events needed for the PRA by testing the outcome of every postulated break scenario against seven performance thresholds:
1. Strainer $\Delta P \geq NPSH_{\text{margin}}$ (i.e., loss of ECCS pump net positive suction head (NPSH) due to head loss across the strainer debris bed),
2. Strainer $\Delta P \geq P_{\text{buckle}}$ (i.e., strainer mechanical collapse due to head loss across the strainer debris bed),
3. Strainer $F_{\text{void}} \geq 0.02$ (i.e., ECCS pump failure due to air ingestion through the sump strainer),
4. Core fiber load $\geq$ cold leg break fiber limit for boron precipitation (i.e., accelerated boric acid accumulation and subsequent precipitation due to debris buildup in the core),
5. Core fiber load $\geq$ hot leg break fiber limit for boron precipitation (i.e., accelerated boric acid accumulation and subsequent precipitation due to debris buildup in the core),
6. Core fiber load $\geq$ cold leg break fiber limit for flow blockage (i.e., core blockage due to debris buildup in the core), and
7. Core fiber load $\geq$ hot leg break fiber limit for flow blockage (i.e., core blockage due to debris buildup in the core).

Modes 1-3 are counted as failures if any single operable strainer exceeds the thresholds at any time during the 36-hr. calculation. Modes 4-7 are assessed against the accumulated fiber penetration from all operable strainers, and they must exceed the threshold before switchover to hot leg injection to be counted as failures. For the present quantification, thresholds for modes 5-7 were set infinitely high so that only exceedance of the cold leg break boron precipitation loading (Mode 4) was recorded as failure.

STP has a configuration of three trains with one sump per train. Each train has 3 pumps, an LHSI pump, an HHSI pump, and a CS pump. Variations in the pump flow rates affect several important areas of the overall GSI-191 evaluation, so pump failure scenarios must be carefully evaluated. The primary areas affected by pump flow rates include: washdown transport, recirculation transport, debris accumulation, approach velocity, strainer head loss, etc. Any combination of pumps could fail due to mechanical problems, giving a total of 512 possible permutations for the STP configuration. However, the number of cases that need to be analyzed are reduced by certain assumptions [16] to five plant states: case 1 (full train operation), case 22 (single train failure), case 43 (dual train failure), case 9 (two LHSI pump failures), and case 26 (single train failure with failure of one additional LHSI pump). Here, these case numbers correspond to those in [16].

After a suite of scenarios for each plant state is evaluated, the sum of the probability weights for failed scenarios within each LOCA category is divided by the sum of probability weights for all scenarios within each LOCA category to generate the conditional failure probabilities needed for the PRA. Table 1 reports the mean conditional failure probability associated with each composite failure mode for each of five plant operation states. No failures were recorded for small or medium-break events, and later discussion will explain that only the higher range of large-break events contributed to failure. In addition to the composite PRA failure modes, the total failure probability conditioned on the LOCA category is also provided [16].
The results of Table 1 can be interpreted in the following ways: A design basis accident response with three trains operable (Case 1) is estimated to incur a total failure probability of 0.09% given that an LLOCA occurs (9 failures in every 10,000 large-break events). If only one train is operable (Case 43), this estimate increases to 0.45% (45 failures in every 10,000 large-break events). The primary reason for the increase is the additional head loss incurred at the single strainer by collecting all of the debris that is distributed in proportion to flow across three strainers under Case 1. Conversely, failures incurred by exceeding the boron fiber load are reduced (compare first and last columns), because less cumulative fiber is penetrating the single, highly loaded strainer. Blockage failure is reported as zero probability because the thresholds were set very high, partly to avoid double counting blockage failures for events that first exceed the bounding low value for fiber load thresholds related to boron precipitation.

The PRA quantification shows that the incremental risk associated with the concerns raised in GSI-191 are very small. Changes in core damage frequency (CDF) and large early release frequency (LERF) that are derived by comparing the results from the GSI-191 PRA modeling an ideal plant (i.e., a plant with no fibers) to the GSI-191 PRA modeling the current plant configuration are $1.09 \times 10^{-8}$ per year and $8.6 \times 10^{-12}$ per year, respectively. When these incremental changes are compared to the baseline values in accordance with Regulatory Guide 1.174, these changes fall in Region III, i.e., “very small changes” [32].

4. CONCLUSION

This paper summarizes the results of collaborative academia-industry work begun in 2011 in response to the USNRC’s call for innovative approaches for resolution of Generic Safety Issue 191 (GSI-191). The method of analysis develops a new risk-informed approach in an integrative framework to explicitly provide failure probabilities for the post-LOCA PRA basic events associated with the concerns raised in GSI-191. These basic event probabilities are estimated using a program called CASA Grande, developed as part of the project. This program encompasses the time-dependent modeling of the underlying physical phenomena of the basic events and the propagation of the uncertainties in the physical models.

In this paper the elements of the integrative framework including PRA and the CASA Grande program, as well as the input parameters, assumptions, methodology, and results of the STPNOC

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1 Case 1 = Full three-train operation; Case 9 = Dual LHSI pump failures; Case 22 = Single train failure; Case 26 = Single train failure with an additional LHSI pump failure; Case 43 = Dual train failure.
analysis have been summarized. The results show that the risk of core damage or large early release related to the concerns raised in GSI-191 in the as-built, as-operated design for STPNOC is very small (as defined in Regulatory Guide 1.174). The authors believe the work described here represents an incremental step in commercial reactor risk analysis that could help form the foundation for further development of reactor regulation settings [33].

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6. REFERENCES