Comparing Various HRA Methods to Evaluate their Impact on the results of a Shutdown Risk Analysis during PWR Reduced Inventory

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Abstract: Shutdown risk analyses of commercial pressurized water reactors (PWRs) in the United States have been performed in the past. The dominant sequences are driven by human failure events. This paper compares the impact on the results from various Human Reliability Analysis (HRA) methods against the SPAR-H methodology [1]. The analysis was performed on a 4-loop PWR commonly operated in the US as part of the US Nuclear Regulatory Commission's (NRC) Significance Determination Process (SDP) during reduced inventory operations. Potential initiators were evaluated for the plant during the reduced inventory operational states. The analysis was performed using the Standardized Plant Analysis Risk (SPAR) Model used by the NRC and developed and maintained by the Idaho National Laboratory (INL) [2]. The existing at-power SPAR model was modified to develop the shutdown model used for this analysis. This paper presents the results observed and performs sensitivity analysis using various HRA methods to evaluate the impact on the core damage frequency. The results show that the change in core damage frequency using other HRA methods was not significant and would not impact the results of the SDP conclusions.

Keywords: HRA, Shutdown, SPAR-H, CBDT/THERP

1. INTRODUCTION

As part of the NRC Reactor Oversight Process (ROP), inspection findings are evaluated using the significance determination process (SDP) in accordance with Inspection Manual Chapter (IMC) 0609, "Significance Determination Process." For issues that occur during shutdown (SD), these evaluations are performed using IMC 0609 Appendix G "Shutdown Operations Significance Determination Process" [3].

In the past five years, numerous shutdown analyses have been performed to assess the significance of findings during shutdown operations. The major insight from many of these assessments is that most of the dominant accident sequences are driven by operator actions, as expected. The existence of multiple systems and equipment that lack automatic initiation of some kind highlights the importance of the operating crew and its ability to mitigate the event or condition. This of course has focused increased attention on the HRA conducted by both the NRC's and utility risk analysts.

For this paper, we will analyze a shutdown issue and present the results. In addition, we will use the SPAR-H methodology and compare those results to those obtained using the Electric Power Research Institute (EPRI) Cause-Based Decision Tree (CBDT) method [4] and the Technique for Human Error Rate Prediction (THERP) [5] method.

2. ANALYSIS AND METHODOLOGY

2.1. Description

This paper will analyze the risk of going to mid-loop conditions while making repairs. Mid-loop is the condition where water level is reduced to the middle of the hotleg, thus allowing work on the hotleg or other components. The applicable plant mode was Mode 5 (i.e., cold shutdown), reduced inventory, both pressurizer power operated relief valves (PORVs) open, and steam generator loops open and filled. Figure 1 depicts the relative reactor coolant system (RCS) levels for a typical PWR and shows reduced inventory and mid-loop levels relative to the reactor core and the associated instrumentation.

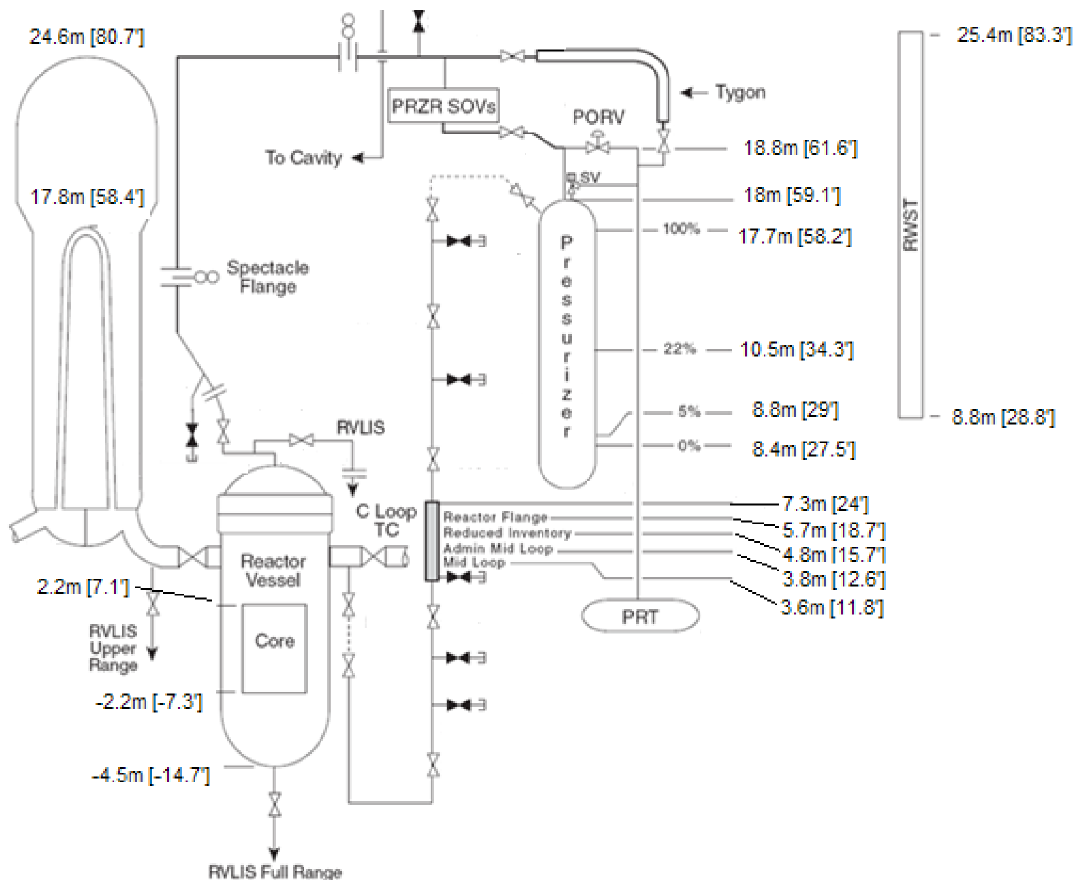

Figure 1. Reactor Coolant System Level Schematic

2.2. Model Development

No appropriate shutdown model existed for the PWR in this evaluation. Therefore, the applicable at-power PWR SPAR model was modified to allow analysis of the risk profile of the site due to the evolution and time in reduced inventory. Since the repairs resulted in time spent in Mode 5 with reduced inventory, potential initiating events for this plant operational state (POS) were evaluated.

Event trees were created to analyze the condition for Loss of Inventory (LOI), Loss of Offsite Power (LOOP), Loss of Shutdown Cooling (LORHR), and Overdrain (OD).

These event trees are shown in Figures 2 – 5. The event trees were linked to existing at-power system models using the appropriate fault trees from the SPAR model. In addition, new fault trees were developed as required to fill in any missing system models. The existing fault trees were modified as necessary to appropriately describe system dependencies during applicable conditions and the different success criteria found during shutdown.

Initiating event data for all initiators except OD were obtained from the EPRI TR-1003113 Table 7-2 “PWR Initiating Event Updated Uniform Distributions (Based on a One-Step Bayesian Update with 1994-2000 Data)” [6]. In the absence of EPRI data on OD, the initiating event value was obtained from NUREG-6144 [7] and was then Bayesian updated using plant-specific data.

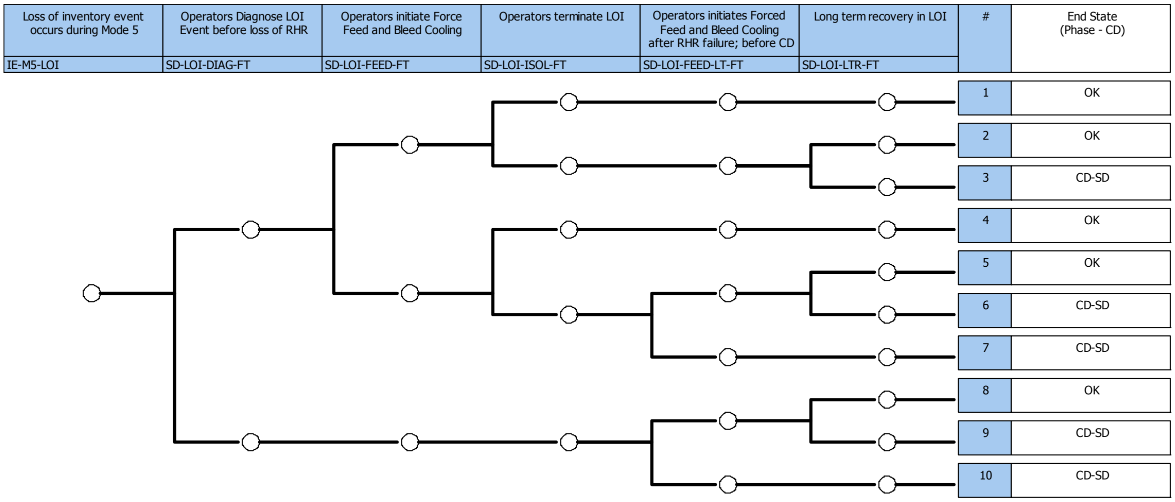

Figure 2. Loss of Inventory Event Tree

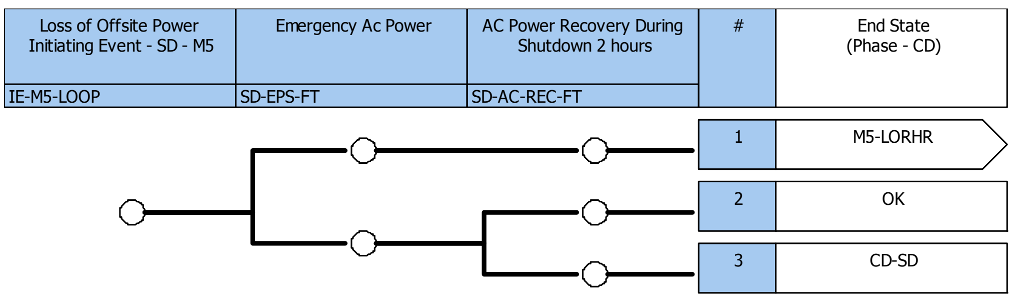

Figure 3. Loss of Offsite Power Event Tree

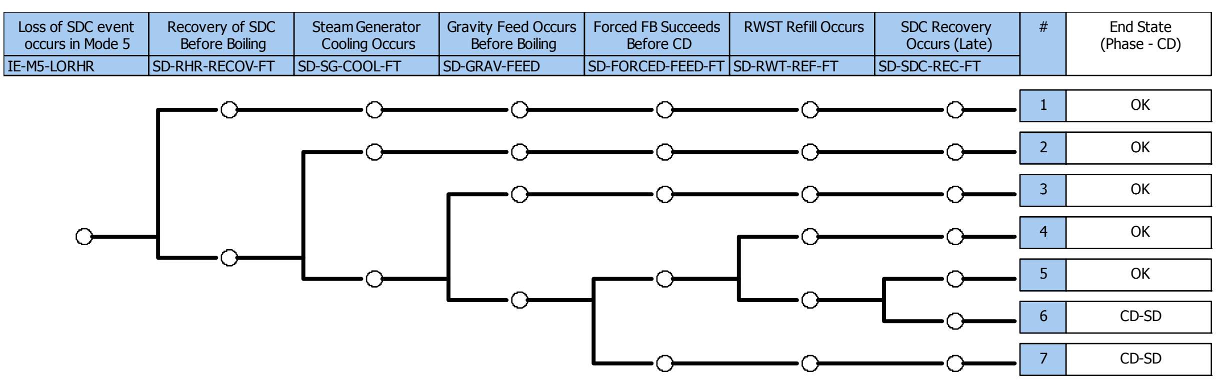

Figure 4. Loss of Residual Hear Removal Event Tree

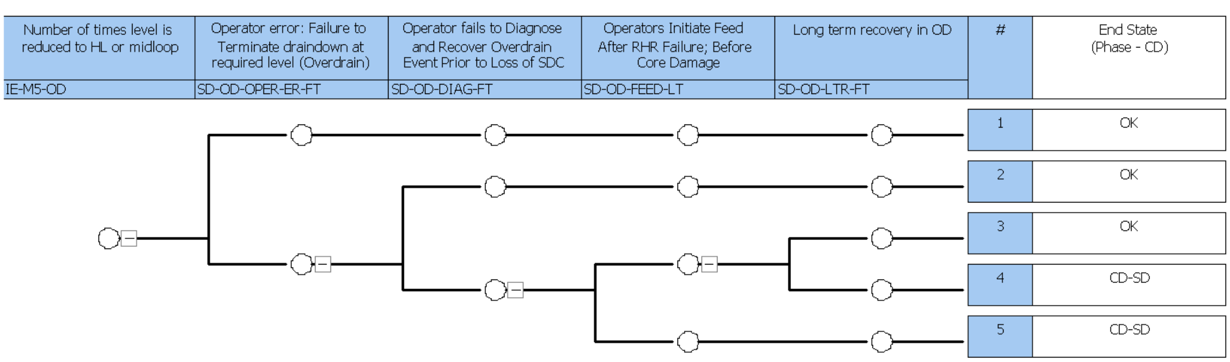

Figure 5. Overdrain Event Tree

2.3. Human Reliability Analysis (HRA)

As mentioned above, operator actions often drive shutdown PRA results, as there are few automatic equipment actions during shutdown. These actions are analyzed by calculating human error probabilities (HEPs) for each human failure event (HFE). The HEPs were calculated using the Low Power Shutdown (LPSD) SPAR-H worksheets from NUREG/CR-6883 [1]. Consideration was given to the available time to perform the action, stress levels of the crew during the event, complexity of the action, crew experience and applicable and relevant training, quality and thoroughness of procedures, ergonomics, fitness of duty issues, and available work processes. Table 1 shows a summary of the HEPs.

Table 1. Summary of Human Reliability Analysis

Human Error Event	Description	Controlled by Ops Crew	Time Available	Mean Diagnosis HEP	Mean Action HEP	Total Mean HEP
SD-LOI-DIAG-XHE	Operator fails to diagnose LOI outside of containment before loss of shutdown cooling (SDC)	One	20 mins	2.0E-3	NA	2.0E-3
SD-LOI-FEED-XHE	Operator fails to initiate feed before loss of SDC	One	20 mins	2.0E-3	2.0E-2	2.2E-2
SD-LOI-FEED-LT-XHE	Operator fails to initiate feed after loss of SDC, before core damage	One	60 mins	2.0E-3	2.0E-3	4.0E-3
SD-LOI-ISOL-AFD-XHE	Operator fail to terminate SLOI leak before is depleted	Two	>12 hrs.	1.0E-4	2.0E-5	1.2E-4
SD-LOI-ISOL-BRF-XHE	Operator fails to terminate SLOI leak before SDC fails	One	15 mins	2.0E-2	2.9E-1	3.1E-1
SD-LOI-LTR1-XHE	Operators fail to refill RWST as part of long-term recovery	Two	>12 hrs.	1.0E-4	2.0E-5	1.2E-4
SD-LOI-LTR2-XHE	Operators fail to restart SDC as part of long-term recovery	Two	>12 hrs.	2.0E-4	2.0E-4	4.0E-4
SD-OD-DIAG-XHE	Operator fails to diagnose overdrain event prior to loss of SDC	One	58 mins	4.0E-3	2.0E-4	4.2E-3
SD-OD-FEED-XHE	Operator fails to initiate feed before core damage during OD	One	60 mins	2.0E-3	2.0E-3	4.0E-3
SD-OD-LTR2-XHE	Operators fail to restart SDC as part of long-term recovery	Two	>12 hrs.	2.0E-4	2.0E-4	4.0E-4
SD-XHE-RHR-RECOV	Operators fail to recover failed RHR train before RCS boiling	One	15-20 mins	2.0E-1	2.0E-2	2.2E-1
SD-RHR-FEED-XHE	Operator fails to initiate feed during shutdown before core damage after SDC failure	One	60 mins	2.0E-3	2.0E-3	4.0E-3
SD-XHE-RHR-LT	Operators fail to restart SDC as part of long-term recovery	Two	>12 hrs.	NA	4.0E-4	4.0E-4
SD-XHE-XM-RWST	Operators fail to refill RWST as part of long-term recovery large leak	Two	>12 hrs.	1.0E-5	2.0E-5	3.0E-5

Notes: Estimated time to boil is 15-20 minutes
Estimated time to core damage is 60 minutes after loss of SDC

In addition to the calculation of specific HEPs for each HFE, sequences or cutsets, which involved multiple operator actions, were examined for human action dependency. Such dependency can occur due to a common cue or short/limited time separation between different cues, or other factors. An event tree with appropriate dependency-causing factors was used to determine the dependency of an operator action on a failed preceding action. The method of identifying dependent operator actions involved reviewing the cutsets that were generated following quantification of the accident sequences. Once those HFEs that were dependent on previously occurring HFEs were identified, SPAR-H was used to perform the initial dependency analysis to calculate the dependent HEP values. Those dependent HEPs and their corresponding values are reported in Table 2. Using the SPAR-H/THERP dependency model, the HEP combinations identified in Table 2 were both determined to have "low" dependency [8,9].

Table 2. Summary of Dependent HEP Results

Dependent HEP Name	Description	Applicable Operator Action Failures	Independent HEP	Final Dependent HEP
SD-LOI-FEED-LT-XHE-D1	Operator fails to diagnose LOI before loss of SDC and feed RCS late before core damage	SD_LOI_DIAG_XHE * SD_LOI_FEED_LT_XHE	4.0E-03	5.4E-02
SD-OD-DIAG-XHE-D8	Operators fail to recognize and recover overdrain before failure of SDC	SD-OVERDRAIN * SD-OD-DIAG-XHE	4.2E-03	5.4E-02

3. RESULTS

The detailed SDP risk analysis was performed using a PWR SPAR Model. The analysis calculated the conditional core damage probability (CCDP) of the two additional overdrains and the time in the high-risk evolution, reduced inventory. The analysis was performed using the SAPHIRE code version 8.07.17 [10].

As stated earlier, this analysis evaluates the risk during Mode 5. The initiators evaluated were loss of LOI, LORHR, LOOP, and OD. With the exception of OD, all of the initiators were multiplied by the duration to obtain the CCDP. The OD initiator is a demand-based initiator that is based on the number of times the plant drained down to reduced inventory.

For this analysis, the POS evaluated was Mode 5 (cold shutdown, before refueling, reduced inventory, and RCS vented).

The POS duration was assumed to be about 40 hours. This duration covers the period of time the plant was in reduced inventory. This analysis only evaluates the time period where RCS level was in reduced inventory or lower. Table 3 delineates the results for the POS and each initiating event. It provides the description and duration of the POS, the evaluated initiators, the initiator frequency, the conditional core damage frequency (CDF) and the CCDP. The result of the CCDP analysis is 2.4E-6.

Table 3. CCDP Results

POS Description	Duration (Hours)	Initiator	Conditional CDF/Year	CCDP
Plant is in Mode 5, reduced inventory, pressurizer PORVS open, and steam generator (SG) loops open and filled.	40.00	IE-LOI	1.4E-05	6.5E-08
		IE-LORHR	6.9E-05	3.2E-07
		IE-LOOP	9.4E-05	4.3E-07
Plant is in Mode 5, reduced inventory, pressurizer PORVS open, and SG loops open and filled.	NA	IE-OD	1.6E-06	1.6E-06
* Overdrain is a demand-based initiator.			Total	2.4E-06

The top five cutsets for all initiators are shown in Table 4. The cutsets are ranked from highest failure probability to lowest. Each cutset probability is listed along with the basic event names and descriptions. Lastly, the table delineates the event tree and sequence number associated with the cutset. It is important to note that 99% of the total risk contribution is from the five cutsets listed in the table below. In addition, as mentioned earlier and as evident by a review of the cutsets, all the failures are attributed to operator error. The unavailability of equipment contributes <1% to the overall core damage frequency.

4. HRA SENSITIVITY ANALYSIS

Given the importance of the HRA for this analysis, a sensitivity study was conducted on the HEPs. The original HRA analysis was performed using the SPAR-H Methodology [1] that focused on adjusting the performance-shaping factors (PSFs) found in the Low Power and Shutdown worksheets. The information to inform the PSFs was gathered through operator interviews, reviews conducted on appropriate procedures, and the thermal hydraulics calculations used to develop the accident progression for each initiator event tree. The information developed the bases for the context of each HFE, and the SPAR-H worksheets were used to quantify the HEPs. The sensitivity analysis utilized the same information and was performed by the same analyst, but the CBDTM [4] and the THERP [5] methods were used to quantify the HEPs. Specifically, the CBDT and THERP methods were used to develop the diagnosis and action portions of the HFE, respectively. To eliminate variability from the analysis, the time windows and other factors discussed above for the diagnosis and action were addressed similarly to the way they were addressed using SPAR-H. In addition, the SPAR model used for the initial assessment was also used for the sensitivity analysis. The new HEPs were entered into the model and re-quantified using the same rules, fault trees, event trees, and basic events used in the original analysis. In addition, the dependency analysis was not changed and was used for both assessments. The resultant HEPs from the HRA sensitivity analysis are shown in Table 5. And Table 6 delineates the overall results of the sensitivity analysis to the CCDP.

Table 4. Top 5 Accident Sequence Cutsets (All Initiators) Using SPAR-H HEPs

Cutset#	Cutset Probability		Basic Event Name	Basic Event Description
1	9.24E-05	9.24E-05	M5-LOOP :1-7	
		1.050E-1	IE-M5-LOOP	Loss of Offsite Power initiating event - Shutdown - M5
		4.000E-3	SD-RHR-FEED-XHE	Operator fails to initiate feed during shutdown before core damage after RHR failure
		2.200E-1	SD-XHE-RHR-RECOV	Operators fail to recover failed RHR before RCS boiling
2	6.93E-05	6.93E-05	M5-LORHR :7	
		7.880E-2	IE-M5-LORHR	Loss of SDC event occurs in Mode 5
		4.000E-3	SD-RHR-FEED-XHE	Operator fails to initiate feed during shutdown before core damage after RHR failure
		2.200E-1	SD-XHE-RHR-RECOV	Operators fail to recover failed RHR before RCS boiling
3	1.41E-05	1.41E-05	M5-LOI :10	
		1.310E-1	IE-M5-LOI	Loss of inventory event occurs during Mode 5
		2.000E-3	SD-LOI-DIAG-XHE	Operator fails to diagnose LOI outside of containment before loss of SDC
		5.400E-2	SD-LOI-FEED-LT-XHE-D1	Operators fail to initiate feed after loss of SDC; before core damage
4	1.43E-06	1.43E-06	M5-OD :5	
		1.000E+0	IE-M5-OD	Number of times level is reduced to HL or mid-loop
		5.400E-2	SD-OD-DIAG-XHE-D8	Operators fail to recognize and recover overdrain before failure of SDC
		4.000E-3	SD-OD-FEED-XHE	Operator Fails to Initiate Feed Before Core Damage During OD
		6.600E-3	SD-OVERDRAIN	OVERDRAIN EVENT
5	1.43E-07	1.43E-07	M5-OD :4	
		1.00E+00	IE-M5-OD	Number of times level is reduced to hotleg or mid-loop
		5.400E-2	SD-OD-DIAG-XHE-D8	Operators fail to recognize and recover overdrain before failure of SDC
		4.000E-4	SD-OD-LTR2-XHE	Operators fail to restart SDC as part of long-term recovery
		6.600E-3	SD-OVERDRAIN	OVERDRAIN EVENT

Table 5 Modified HEPs Using CBDT and THERP

Human Error Event	Description	SPAR-H Mean Diagnosis HEP	SPAR-H Mean Action HEP	SPAR-H Total Mean HEP	CBDT Mean Diagnosis HEP	THERP Mean Action HEP	CBDT / THERP Total Mean HEP
SD-LOI-DIAG-XHE	Operator fails to diagnose LOI outside of containment before loss of SDC	2.0E-3	0	2.0E-3	3.2E-3	0	3.2E-3
SD-LOI-FEED-XHE	Operator fails to initiate feed before loss of SDC	2.0E-3	2.0E-2	2.2E-2	1.5E-3	6.6E-3	8.1E-3
SD-LOI-FEED-LT-XHE	Operator fails to initiate feed after loss of SDC, before core damage	2.0E-3	2.0E-3	4.0E-3	1.5E-3	4.6E-3	6.1E-3
SD-LOI-ISOL-AFD-XHE	Operator fail to terminate SLOI leak before RWST is depleted	1.0E-4	2.0E-5	1.2E-4	2.3E-4	4.2E-5	2.7E-4
SD-LOI-ISOL-BRF-XHE	Operator fails to terminate SLOI leak before SDC fails	2.0E-2	2.9E-1	3.1E-1	1.8E-2	3.3E-3	2.1E-2
SD-LOI-LTR1-XHE	Operators fail to refill RWST as part of long-term recovery	1.0E-4	2.0E-5	1.2E-4	4.5E-6	4.2E-5	4.7E-5
SD-LOI-LTR2-XHE	Operators fail to restart SDC as part of long-term recovery	2.0E-4	2.0E-4	4.0E-4	4.5E-6	1.2E-4	1.2E-4
SD-OD-DIAG-XHE	Operator fails to diagnose and recover overdrain event prior to loss of SDC	4.0E-3	2.0E-4	4.2E-3	4.1E-3	2.3E-3	6.4E-3
SD-OD-FEED-XHE	Operator fails to initiate feed before core damage during OD	2.0E-3	2.0E-3	4.0E-3	1.5E-3	4.6E-3	6.1E-3
SD-OD-LTR2-XHE	Operators fail to restart SDC as part of long-term recovery	2.0E-4	2.0E-4	4.0E-4	4.5E-6	1.2E-4	1.2E-4
SD-XHE-RHR-RECOV	Operators fail to recover failed RHR train before RCS boiling	2.0E-1	2.0E-2	2.2E-1	1.7E-3	2.6E-2	2.8E-2
SD-RHR-FEED-XHE	Operator fails to initiate feed during shutdown before core damage after SDC failure	2.0E-3	2.0E-3	4.0E-3	1.5E-3	1.3E-2	1.5E-2
SD-XHE-RHR-LT	Operators fail to restart SDC as part of long-term recovery	0	4.0E-4	4.0E-4		1.2E-4	1.2E-4
SD-XHE-XM-RWT	Operators fail to cross-tie Unit 1 RWST as part of long-term recovery	1.0E-5	2.0E-5	3.0E-5	4.5E-6	2.2E-3	2.2E-3

Table 6 PWR CCDP Results with HRA Sensitivity

POS Description	Duration (Hours)	Initiator	SPAR-H Conditional CDF/Year	CCDP	CBDT/THERP Conditional CDF/Year	CCDP
Plant is in Mode 5, reduced inventory, pressurizer PORVS open, and SG loops open and filled.	40.00	IE-LOI	2.3E-05	1.0E-07	1.4E-05	6.5E-08
		IE-LORHR	3.3E-05	1.5E-07	6.9E-05	3.2E-07
		IE-LOOP	4.6E-05	2.1E-07	9.4E-05	4.3E-07
Plant is in Mode 5, reduced inventory, pressurizer PORVS open, and SG loops open and filled.	NA	IE-OD	2.3E-06	2.3E-06	1.6E-06	1.6E-06
* Overdrain is a demand-based initiator, obtained from the NUREG/CR-6144.			Total	2.7E-06	Total	2.4E-06

5. CONCLUSION

LPSD issues are important to safety and are different than at-power issues in that their significance is often driven by human error. As shown in Table 6, the HRA sensitivity analysis using the CBDT and THERP methods resulted in a CCDP that was very close to the original analysis.

One insight gained by performing the analysis using the CBDT/THERP methods was the importance of reviewing the procedurals cues and steps that would drive the operators to perform the required diagnosis and subsequent action. The analysis drove the analyst to focus on the accident progression and the operator's actions as they followed the plant procedures. In contrast to THERP, the SPAR-H methodology is much coarser and is most often used to evaluate the overall HFE considered in the analysis. Seldom will an analyst quantify HEPs on a procedural step-by-step basis. It is analogous to modeling a super-component. In this way, the SPAR-H methodology provides the analyst with a standard tool that can be easily used to support the SDP process and to assist in the regulatory decision-making process by providing a best-estimate value while also balancing time and resource considerations.

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