Curtiss-Wright/Scientech Seismic HRA Insights and Lessons Learned from the Application of EPRI Report TR-1025294

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In 2014 and 2015 Curtiss-Wright Scientech performed two seismic Human Reliability Analysis (HRAs) on nuclear power plants in the United States, using the seismic HRA guideline presented in EPRI Report 1025294. The purpose of this paper is to identify HRA insights gained by the application of this guidance and to identify areas of future improvements in the guidance and seismic HRA. The HRA approach followed the seismic HRA guideline as closely as possible. At the start of these projects, EPRI-TR_105294 had just been published and the seismic HRAs performed were two of the first applications of this guidance.

I. INTRODUCTION

In 2014 and 2015 Curtiss Wright Scientech (CW/Scientech) performed two seismic PRAs (SPRAs) at nuclear power plants in the United States. As part of each SPRA, a seismic Human Reliability Analysis (HRA) was also performed. The starting point for both seismic HRAs was the existing internal events HRA, which was fully developed in the HRA Calculator[2] for each power plant. The seismic HRA approach followed the guidance in EPRI report 1025294: A Preliminary Approach to Human Reliability Analysis for External Events with a Focus on Seismic[1]. This guidance document was developed by CW/Scientech in conjunction with EPRI in 2012. Both seismic PRAs have undergone peer reviewed, and this paper presents the insights on seismic HRA using the EPRI 1025294 (Ref. 1). guidance based on experience and peer review results.

II. METHODOLOGY

The full methodology of the approach used for these two seismic HRAs is documented in EPRI 1025294[1]. Figure 1 presents the seismic HRA process in flowchart format, and the high level steps are summarized in this section.

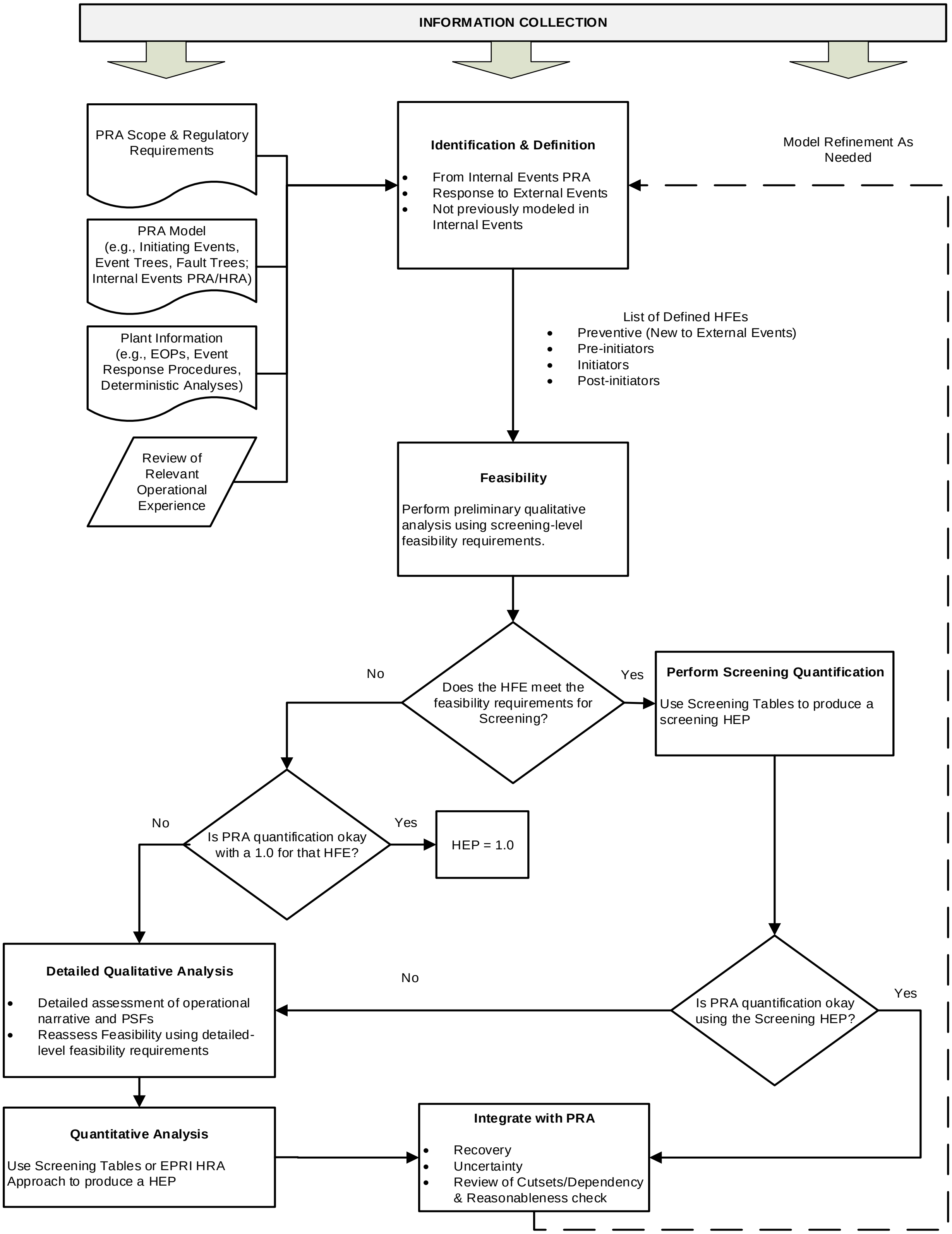

Fig. 1. Seismic HRA Process Flowchart[1]

II.A. HFE Identification

Operator actions, also known as Human Failure Events (HFEs) to be included in the seismic PRA are first identified from several different sources. The starting point is the internal events HRA notebook and corresponding HRA Calculator[2] database. The internal events HFEs are reviewed and either screened in or out for inclusion in the seismic PRA. HFEs that support plant response to initiating events included in the seismic PRA are screened in, and HFEs support plant response to initiating events not included in the seismic PRA are screened out. This was accomplished by reviewing the event trees included in the seismic PRA and the supporting fault tree logic. The HFEs that are screened out are not included in the seismic PRA model, and no further analysis of them is performed.

In addition to HFEs from internal events, seismic recovery actions new to the seismic PRA are identified and defined in this step. This process is done iteratively in parallel with the seismic PRA model development, and actions are added on an as-needed basis. New seismic recovery actions are necessary, for example, to supplement existing internal events actions that are no longer feasible, or in response to a scenario new to the seismic PRA.

II.B. HFE Definition

The basic requirements of HFE definition include:

- Accident sequences, the initiating event, and subsequent system and operator action successes and failures leading to the HFE
- Accident sequence specific procedural guidance
- The availability of cues and indications for detection and evaluation errors
- Accident sequence specific timing of cues and the time available for successful completion
- The high level tasks required to achieve the goal of the operator action

For HFEs taken from internal events, the information above is collected from the internal events HRA documentation. Subsequent steps in the seismic HRA process will update this information for the seismic scenario context. New seismic recovery HFEs must be defined by gathering the information above from procedures, thermal hydraulic analysis, operator interviews, walkdowns, and other applicable sources.

II.C. Damage State Bin Definition

EPRI 1025294[1] provides generic damage state bin definition guidelines presented in the table below. These must be mapped to the plant specific seismic hazard bins, which are defined in terms of peak ground acceleration (PGA), measured in standard units of gravity (g).

TABLE I. Damage State Bin Definition – Recommended Guidance

Bin #	Damage State Description	Recommendation for Seismic Risk Assessment
1	No damage to the plant safety-related SSCs or non-safety SSCs required for operation. Limited damage to non-safety, non-seismic designed SSCs like residences and office buildings	< SSE
2	No expected damage to the plant safety-related SSCs or to rugged industrial type non-safety SSCs required for operations. Damage may be expected to non-safety SSCs not important to plant operations and to the switchyard. Some falling of suspended ceiling panels.	> SSE up to HCLPF of most fragile safety related SSC.
3	Widespread damage to non-safety related SSCs and/or some damage expected to safety related SSCs. Significant number of vibration trips and alarms.	> HCLPF of most fragile safety related SSC to HCLPF of critical instrumentation or HCLPF level of 25th percentile component, whichever is lower.

Bin #	Damage State Description	Recommendation for Seismic Risk Assessment
4	Substantial damage to safety related and non-safety related SSCs. This is particularly applicable to external events susceptible to a cliff edge effect.	> HCLPF of critical instrumentation or HCLPF level of 25th percentile component, whichever is lower

The seismic fragility analysis is used to obtain fragility information on instrumentation and SSCs for damage state bin definitions.

II.D. HFE Feasibility Analysis

After operator actions are identified and the HFEs defined, the feasibility of each action is determined for all seismic event damage state bins. This feasibility check ensures the seismic HRA only credits operator actions which are possible. The feasibility assessment uses the HFE definitions, as well as information gathered from the seismic operator interviews and walkdowns, and accounts for seismic effects on performance shaping factors (PSFs) when applicable. If an HFE is determined to not be feasible for a damage state bin, it is set to 1.0 for that bin. The following PSFs dominate feasibility assessment:

- Time Available
- Manpower Requirements
- Cues
- Procedures and Training
- Accessible Location & Environmental Factors
- Equipment and Tools Available
- Equipment Operability

II.E. Screening HEP Quantification

HFEs carried in to the seismic PRA from internal events are first quantified with a screening approach that assigns a multiplier to each feasible HFE for each damage state bin. The internal events Human Error Probability (HEP) is multiplied by this factor to determine the initial bin specific seismic HEP. The screening tree for existing operator actions in EPRI 1025294 is used, and presented in the figure below.

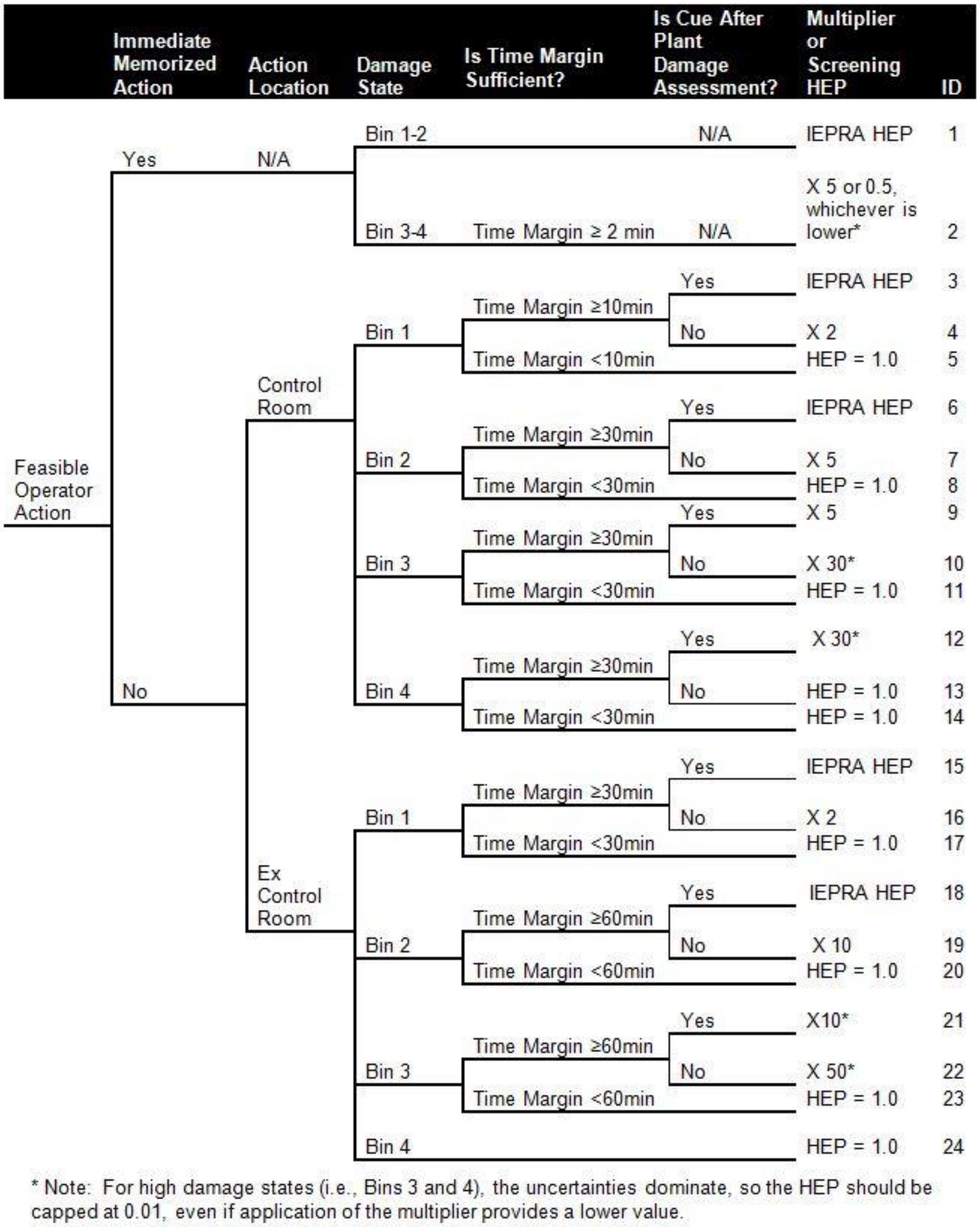

Fig. 2. Seismic Screening Tree for Existing Operator Actions from Internal Events[1]

The nodes of the Screening Tree are discussed below:

<u>Feasibility:</u> If the operator action is not feasible given the external event context then the HEP is 1.0

<u>Immediate Memorized Action:</u> This node treats a special case of operator actions that are performed immediately following a plant trip, without requiring the guidance of procedures. For the purpose of this assessment, immediate memorized operator actions are defined as highly trained (e.g., memorized action or skill-based), time-critical control room actions that occur in the first 5-10 minutes after the reactor trip. Typically, these are plant-specific, are annotated as described in a plant policy and/or procedures, and should be defined by the plant operators.

Action Location: The action location node differentiates between actions that are performed in the control room and those performed outside the control room. The external event will have a greater impact on the physical environment outside the control room. The assumption is that the control room will likely not be physically impacted (e.g., environment, access to panels, etc.) in such a way as to significantly degrade the operator's performance. If control room habitability issues are identified, this challenges that assumption and the action should be considered unfeasible (HEP = 1.0) for screening analysis.

Damage State: This node defines the level of damage and activity to be expected during the plant response. The level and type of damage to safety-related SSCs and also to non-safety related SSCs caused by the external event effects both cognition and execution through workload, tasks, timing, physically challenging environment, stress and distractions. Note: damage state bin 4 represents an extreme plant damage state, and for the purpose of these analyses was treated as a cliff edge, above which no operator actions are credited and therefore all HEPs are set to 1.0 for this bin.

Time Available for Recovery: As part of the definition step, the timeline of the internal events HFE was confirmed as generally applicable to the external event. This initial timeline, however, is not expected to account for, in detail, every potential delay caused by the impact of the external event. Actions can be delayed due to access issues, increased cognition time, delays due to inter-organization/multi-unit coordination and a host of other factors that are not explicitly accounted for in a timeline built for a screening-level analysis. This node asks whether the action is still feasible from a timing perspective accounting for the impact of some of these uncertainties. In other words, is there sufficient time available for recovery, where recovery time is expressed as the difference between the time available and the time required ($T_{avail} - T_{reqd}$)? To apply the screening values, the recovery time must be greater than the requirements defined; these factors are included in the decision tree for ease of use.

II.F. Detailed Analysis HEP Quantification

The screening HEPs generated in the previous step are used for initial quantification of the SPRA model. The results of initial quantification are used to determine risk significant HFEs, and these HFEs along with newly defined seismic recovery actions are quantified using detailed analysis. EPRI 1025294 (Ref. 1) directs the detailed analysis of HFEs to be done in two parts: qualitative and quantitative analysis. In practice these are done in tandem for each HFE using the internal events detailed analysis as the starting point if available.

Detailed qualitative analysis is accomplished through information collection, development of an HFE narrative, PSFs, review of relevant experience, and reviews with plant operations. The impact of seismic events on each of these steps, and changes from the IEPRA HRA are discussed individually below.

Information Collection and the HFE Narrative: The information and narrative that was developed for the IEPRA HFEs remains applicable and unchanged for seismic HRA. For new seismic recovery actions, information collection and HFE narrative definition is performed through review of the scenario, timing information, procedures, and operator interviews.

Performance Shaping Factors: Given that an HFE remains feasible for seismic scenarios, the following PSFs are considered

- Cues and Indications
- Timing
- Procedures and Training
- Complexity
- Workload, Pressure, and Stress
- Human-Machine Interface
- Special Fitness Needs
- Crew Communications, Staffing, Dynamics
- Review of relevant experience
- Reviews with Plant Operations

The HRA Calculator[2] is used to quantify each detailed analysis HEP, using the max of CBDTM[3] and HCR/ORE[3] for the cognitive portion of the HEP, and THERP[4] for the execution portion.

II.G. Dependency Analysis

After the two phases of quantification the final HEPs are implemented in the model. A dependency analysis is performed on the cutset results. The same methodology employed for internal events is used for seismic HRA, and the HFE combinations are analyzed using the HRA Calculator[2] dependency module.

III. INSIGHTS

III.A. Insights on Identification and Definition

Having a complete and fully developed internal events HRA and corresponding documentation greatly facilitates identification of HFEs for the SPRA. Existing detailed analysis for internal events HFEs is practically essential in order to perform the initial feasibility analysis for the SPRA, therefore if the internal events HRA is not complete, needs to be updated, or is currently being updated, activity on the seismic HRA should be postponed until after this is complete. Generally, for U.S. plants the internal events HRA is an effective and fully developed starting point. However, the Level 2 actions from internal events that are carried into the SPRA may not be fully developed or they may be documented outside of the HRA notebook. A thorough review of the model is necessary to identify all such actions.

For these two seismic HRAs, very few new seismic-specific operator actions were added to the model. They were added iteratively as needed based on model development and initial results. The two cases where a new operator action were necessary were: 1) isolating CCW upstream of a location that was not accessible given the seismic initiator, and 2) failure to shutdown remotely given a seismic event which causes MCR un-inhabitability due to ceiling panel failure. Note that for these two plants relay chatter was not an issue, therefore undesired actions in response to spurious alarms were not considered.

Some HFEs which were screened in to the seismic PRA did not require any further analysis beyond what exists for internal events, i.e. they were not adjusted and the HEP values remained the same for all seismic bins (except above the "cliff edge" bin when all post initiators were deemed unfeasible as discussed above). Pre-initiators and errors of commission were such types of actions.

"Type B" operator actions which cause the initiating event in the PRA required special consideration for seismic. They may be screened out of the SPRA if a seismic event cannot cause the plant conditions that would require the action, for example screen plugging due to debris buildup over time. Conversely, they may require complete reanalysis of the scenario timing if they are in response to a flood and have negative timing parameters (i.e. occurring before reactor trip). For these SPRAs the reactor trip and flood are assumed to both occur at time T=0. These actions, in which the timing or success criteria must be reanalyzed, should be set to 1.0 until that is accomplished.

III.B. Insights Damage State Bin Definitions

The mapping of the plant specific hazard bins (based on PGA level) to the seismic HRA damage state bins is a crucial step. The current guidance in EPRI 1025294 (Ref. 1) has recommendations for this mapping using plant specific fragility information, shown in Table 1 above, however not all required information is known in the early stages of the seismic HRA therefore some assumptions may be necessary. The plant specific Safe Shutdown Earthquake (SSE) level was known at the beginning of the two SPRAs performed by CW/Scientech but other fragility info such as the HCLPFs of safety related SSCs (bin 2 upper bound) and instrumentation (bin 3 upper bound) was not. Assumptions were made for these parameters, and were later verified as the Seismic Equipment List (SEL), which contains the fragilities of the components, was refined. Bin mapping was refined in parallel.

The table below expands on the recommended damage state bin definitions with the plant specific mapping for one of the seismic HRAs performed. For the Bin 1 upper bound the plant SSE was initially known, and correspondingly set to 0.18 g. For Bin 2 0.5 g was initially assumed as the HCLPF for the most fragile safety related SSC. This was later verified as all safety related SSCs had HCLPFs above 0.5 g (but not above the next hazard bin therefore 0.5 g was kept as the Bin 2 upper bound). For Bin 3 0.8 g was assumed as the upper bound, above which instrumentation could not be credited. After refinement of the SEL and initial model quantification results this was determined to be too conservative, therefore actual instrumentation failure probabilities for each hazard bin were calculated and included alongside the HFEs in the model. This was done up to hazard bin 6 which had an instrumentation failure probability of 0.42, but not done above that as the failure probabilities increased above 0.9 for Bin 7 and 8.

TABLE II. Damage State Bin Definition – Mapping to Plant Specific Fragility Information

EPRI Bin #	Damage State Description	Seismic Recommendation	Plant Hazard Bins		Plant Specific Criteria Used
			Bin	PGA Range (g)	
1	No expected damage to safety and non-safety related SSCs	< SSE	1	0.09-0.18	Plant SSE = 0.18 g
2	No expected damage to safety-related SSCs or to rugged industrial type non-safety SSCs. Damage may be expected to unimportant non-safety SSCs and to switchyard.	> SSE up to HCLPF of most fragile safety related SSC.	2	0.18-0.3	0.5 g is the lowest HCLPF of any safety-related SSC on the SEL. This was initially an assumption that was then verified.
			3	0.3-0.5	
3	Widespread damage expected to non-safety related SSCs and/or some damage expected to safety related SSCs. Lots of alarms and vibration trips.	> HCLPF of most fragile safety related SSC to HCLPF of critical instrumentation or HCLPF level of 25th percentile component, whichever is lower.	4	0.5-0.8	2.0 g is the threshold at which instrumentation is no longer credible. For hazard bin 6 instrumentation failure probability was 0.42, for bin 7 it was 0.9. Initially 0.8 g was assumed to be the instrumentation failure point – this was increased after SEL refinements
			5	0.8-1.2	
			6	1.2-2.0	
4	Substantial damage to safety related and non-safety related SSCs.	> HCLPF of critical instrumentation or HCLPF level of 25th percentile component, whichever is lower	7	2.0-3.0	Defined as guaranteed failure for all HFEs.
			8	>3.0	

III.C. Insights on Feasibility and Qualitative Analysis

For the HFEs carried into the SPRA from internal events, typical post-initiator Level 1 actions were fully defined in the HRA Calculator[2], and the necessary information for a seismic feasibility analysis could be extracted directly from there, including PSFs such as timing information, location and required equipment, cues, procedures, etc. This information is gathered and analyzed in the context of the seismic Damage State Bins, and documented. Screening HEPs and Level 2 actions from internal events are not always fully developed, defined, or documented and therefore the necessary feasibility information may not be available. For these cases the feasibility information and assessment must be generated directly based on procedure review, walkdowns, operator interviews, etc., or the action must be set to 1.0 as unfeasible.

In general, the plant response for Damage State Bin 1 remained very similar or identical to internal events by definition. For Bins 2 and 3 the feasibility considerations were impacted by seismic events, such as instrumentation availability, time available to perform the action, location accessibility and equipment availability for local actions.

Operator interviews were useful for verifying feasibility of actions in Damage State Bins 2 and 3, especially cue availability for all actions, and pathway accessibility/ equipment availability for local actions. Because interviews are required for all risk significant actions it is useful to perform two sets of interviews – an initial one to understand general plant response to a seismic event and discuss feasibility issues, and then a second one following initial model quantification when risk metrics of HFEs are known in order to discuss the specific scenario of risk significant actions. New actions added to the model should also be discussed during the second interview when they are known.

III.D. Insights on Instrumentation Availability

To account for instrumentation availability a total list of instrumentation credited in the SPRA was generated from the HRA Calculator[2] using the primary and secondary cues listed for each action. This list was included on the SEL and fragilities were generated for each component on the entire instrument loop, including mounting structures (racks, panels, etc.), as well as the MCR ceiling. A bounding fragility was then applied using the most conservative component on the instrumentation list. The panel fragilities were all explicitly calculated using exact locations and elevations, but the rack fragilities were calculated using the roof of the tallest building for conservatism. For one plant the conservative fragility was panel, and for the other plant it was an instrumentation component itself.

Instrumentation power supplies were considered separately from the instrument loop components, and a bounding power supply fragility was calculated. Figure 3 below shows how the bounding instrumentation fragility and power supply fragility were added to the fault tree logic for each HFE in the SPRA model.

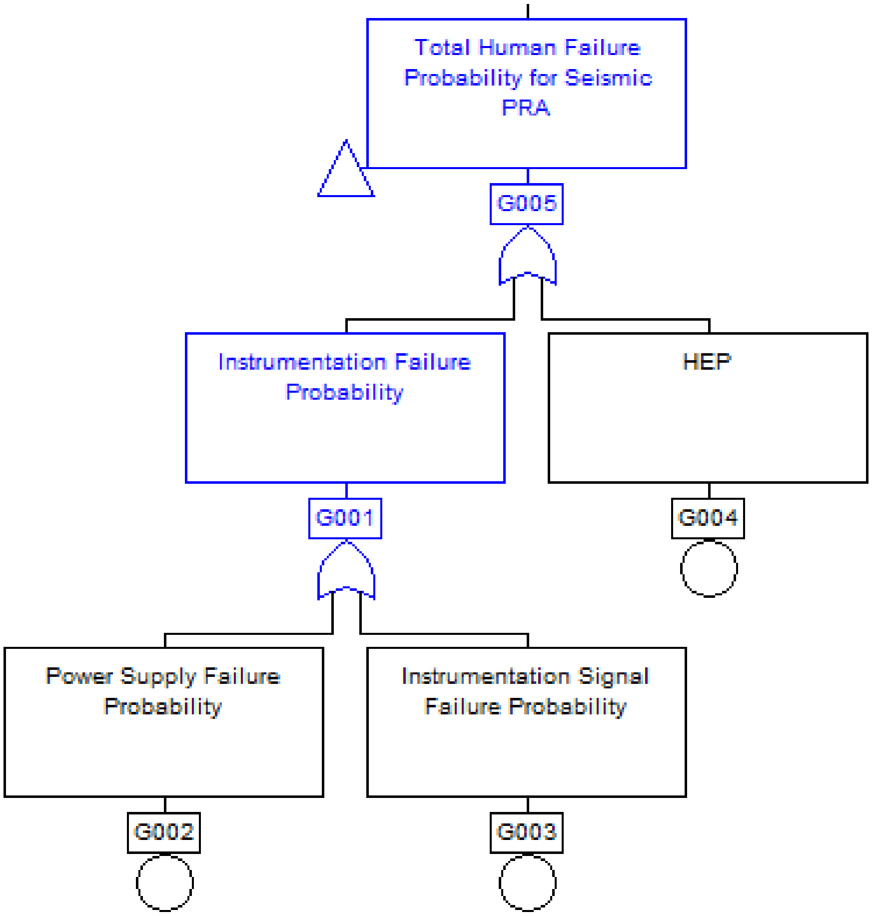

Fig. 3. Instrumentation Availability Logic Modeling

III.E. Insights on Quantification

For the initial screening analysis, the Level 1 post initiator HFEs carried into the SPRA from internal events were assigned a multiplier using the screening tree shown in Figure 2 for Damage State Bins 1-3. For Damage State Bin 4, all HFEs are assumed unfeasible. Level 2 HFEs were only credited in Damage State Bin 1 initially for conservatism, and the HEPs used were generated using multipliers from the screening tree in Figure 2 as well. This was done using Microsoft Excel[5] macros in order to facilitate the process and ensure reviewability and reproducibility. The FRANX[6] seismic HRA editor was not used because it does not match the criteria and decision nodes in the screening tree shown in Figure 2. These initial HEPs for both Level 1 and Level 2 were used in the initial model quantification to determine the risk significant HFEs, which were then quantified using detailed analysis.

Less than 10 HFEs per SPRA turned out to be risk significant, and none in Damage State Bin 4 where all HEPs were set to 1.0 ended up being risk significant. No time critical actions were risk significant, however the risk significant HFEs did include some Level 2 actions. Detailed analysis was straightforward for the EOP driven actions (i.e. Level 1), and a re-analysis of the CBDTM[3] trees was done in addition to adjusting the timing information and THERP[4] stress levels. New actions were also straightforward to quantify with these methods after operator interviews and procedure review.

Level 2 actions were more difficult, as the guidance for quantification of Level 2 actions for seismic events is limited in EPRI 1025294[1]. The PRA scenarios for these were, in general, broadly defined. The seismic initiator is expected to have the most impact on actions occurring shortly afterwards and significantly less impact on long term actions. Therefore, the Level 2 actions occurring long after the seismic initiator (i.e. > 12 hours) were left at their internal events values for Damage State Bins 1-3. Short term Level 2 actions were set to 1.0 as unfeasible for all Bins.

III.F. Insights on Model Integration

Incorporation of the hazard bin specific HEPs was done manually, in order to map the Damage State Bin specific HEPs to their corresponding hazard bin specific HFE names in the SPRA model.

EPRI 1025294 (Ref. 1) lists error factors that are larger than those typically used for internal events. These resulted in calculated HEPs greater than 1.0 when uncertainty analysis was performed, therefore the error factors given by the HRA Calculator[2] were used instead. Analysts should ensure that no error factors generate HEPs greater than 1.0 during uncertainty analysis.

IV. CONCLUSIONS

In conclusion, during the seismic HRA portion of the SPRA few new actions were added to the model, and for these particular SPRAs relay chatter was not an issue. Definition of the EPRI Damage State Bins required some initial assumptions which later needed to be verified, and the definitions refined if necessary. Collecting the necessary feasibility information early during qualitative analysis is crucial, especially instrumentation credited in the model, and a complete internal events HRA documentation greatly helps. The screening quantification process from EPRI 1025294 was done for the initial model quantification to identify risk significant HFEs, and this should be done early. If information needed for the screening quantification is not available, the HFE should be set to 1.0 for all Damage State Bins. Detailed analysis was performed for the risk significant HFEs and was straightforward for Level 1 post initiators (i.e. EOP driven actions). The level of effort between detailed vs screening quantification is not as great as initially anticipated, because a proper feasibility analysis for all HFEs credited in the SPRA accounts for much of the effort needed for detailed analysis. Guidance is needed for quantification of Level 2 seismic HFEs, as results show these actions are important.

ACKNOWLEDGMENTS

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