# Advancing Human Reliability Analysis Methods for External Events with a Focus on Seismic

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**Abstract:** The reliability of operator actions following an external initiating event is a topic that has increased importance following the 2011 seismic-induced tsunami at the Fukushima Daiichi site in Japan. This event has prompted licensees in the U.S.A., and internationally, to reexamine their plant's risk profile and the plant's ability to prevent and/or mitigate damage following external initiating events (external hazards). In support of the industry initiatives to evaluate and prepare for external initiating events, the Electric Power Research Institute and Scientech have developed a preliminary approach to analyze the reliability of operator actions following external initiating events, with a specific focus on seismic events. The preliminary approach has been published in EPRI 1025294, A Preliminary Approach to Human Reliability Analysis for External Events with a Focus on Seismic, in December 2012. Since the development of the 2012 report, the approach and methods suggested in the report have been applied in the development and in the review of seismic PRAs that are currently in development. This paper summarizes the development of the current external events human reliability analysis (HRA) methods and guidance, and summarizes recent insights from applying this approach to seismic PRAs.

**Keywords:** HRA, Seismic HRA, External Events, External Hazards

## 1. INTRODUCTION

The purpose of EPRI report 1025294 [1] is to provide methods and guidance for the human reliability analysis of external events PRAs based on the current state-of-the-art in both PRA and in HRA modeling. Prior to the development of this report, substantial research has been performed to develop and improve Human Reliability Analysis (HRA) methods in support of Probabilistic Risk Assessment (PRA). The development of existing HRA methods, however, was limited primarily to internal events PRA, specifically to initiating events that did not involve spatial impact. These methods often contain underlying assumptions that may or may not be applicable to area/spatial impacts, especially those affecting the plant site such as the regional impact following a seismic event, external flood or hurricane (external initiating event or external hazard). Recent HRA advances that culminated in the publication of Fire HRA methods and guidance in NUREG-1921 [2] were considered in the development of EPRI report 1025294.

Additionally, the state-of-the-art in seismic and external events PRA models and issues was surveyed in order to understand existing external events HRA guidance [3, 4]. The results of this review were not surprising. As is common in HRA, there was a wide variation in existing methods for external events HRA. Variation existed between methods used for different hazard types as well as plant-to-plant variation for evaluation of a given hazard type. In addition to reviewing current external events PRA models and methods, a review of historical operating experience was conducted. The relevant insights from the review of operational experience were incorporated into the development of the various steps of the 2012 external events HRA process. The operating experience review task primarily built upon previous, published work conducted by EPRI (Post-Earthquake Investigation Program from 1985 to 2012), as well as a review of utility presentations and LERs. Additionally, interviews were conducted with personnel from nuclear plants impacted by recent seismic events. The review of historical data focused on real-world seismic events at nuclear power plants and other industrial facilities, and it was performed in order to identify potential failure modes and performance shaping factors (PSFs) that should be considered when developing external events HRA

EPRI report 1025294 provides a framework for external events HRA, a general screening approach, and a detailed quantification approach which can be applied consistently across a variety of external events were developed. The report was written to provide methods and guidance for all external events, but included specific guidance for HRA in a seismic PRA, including operator actions to recovery from relay chatter. The detailed quantification approach provided in EPRI report 1025294 is an adaptation of the "EPRI HRA Methodology", also known as the "EPRI HRA Approach" for internal events [5, 6, 7, and 8]. The specific objectives of EPRI report 1025294 are listed below.

- Provide a consistent framework for analysts to perform HRA for all external hazards.
- Provide hazard-specific guidance for consideration of relevant performance shaping factors (PSFs) based on operational experience and existing research.
- Provide a general screening approach and detailed quantification method that can be applied consistently to a variety of external events.
- Provide seismic-specific guidance that reflects, to the extent possible, current research and relevant operational experience.

Paper organization. Section 2 of this paper describes the HRA process as it supports external hazards PRA. Sections 3 through 8 summarize the treatment of external events HRA in EPRI report 1025294. Additional information on the external events HRA approach of EPRI report 1025294 has been described in earlier conference papers [9, 10, and 11]. Section 9 summarizes insights, including areas of potential future research, and conclusions.

## 2. HRA PROCESS

As with recent HRA guidance, such as NUREG 1921 [2], the external events HRA process is often appears as a linear process with the following elements.

1. Identification and Definition
2. Qualitative Analysis
3. Quantification
4. Model Integration:
    a. Cut set Review and HEP Reasonableness Check
    b. Recovery
    c. Dependency
    d. Uncertainty

Although this process is often depicted as sequential steps, in the practical application to developing an HRA these steps are iterative. EPRI 1025294 [1] presents the guidance in the order which an HRA analyst is likely to use the various elements of the guidance, accounting for the iteration between screening and detailed assessments. Figure 1 provides a mapping between the external events HRA process and the sections of EPRI 1025294. This figure shows the iterative relationship between the PRA process, the HRA process and allows both tasks to proceed in parallel.

EPRI report 1025294 provides two approaches for quantification, first a screening quantification and then a detailed quantification. The screening approach is intended to require fewer resources and be more conservative than the detailed quantification.

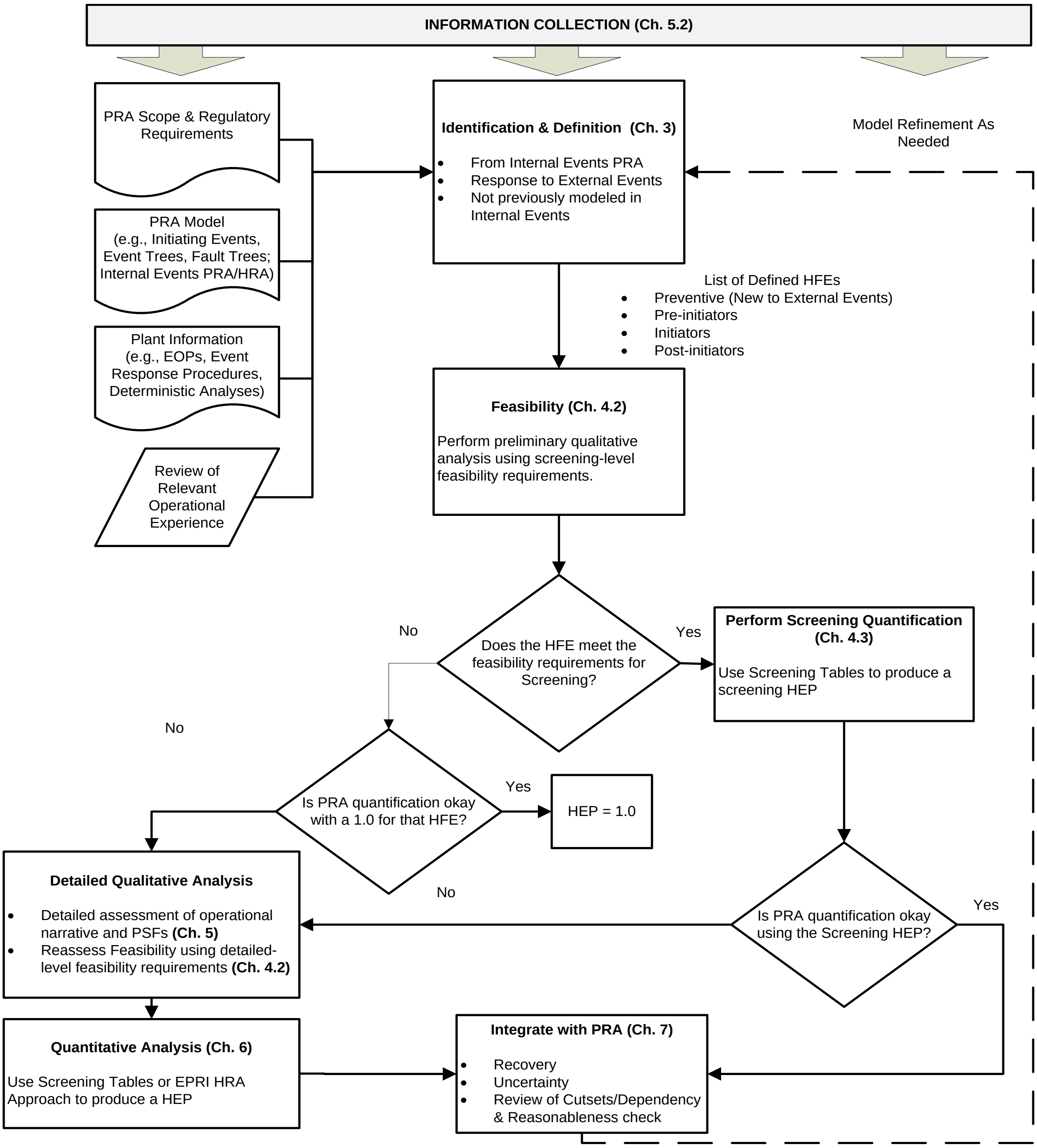


**Figure 1.**
**Mapping of HRA Steps To Sections Within EPRI 1025294 [1]**

## 3. IDENTIFICATION AND CLASSIFICATION

The identification process in an external events PRA follows the same approach as in an internal events PRA – to understand the plant response (including the procedures to be implemented) and to understand how the plant response is captured in the PRA model. Within the PRA, operator actions typically come from one of two sources: 1) HFEs already existing in the PRA (usually from the internal events PRA); or 2) procedure review in conjunction with modeled accident sequence review to identify new operator actions.

In general the following  groups of procedures are reviewed for applicability to external events.

- Preventive procedures –procedures for preparing for high winds, hurricane or other external events where the onset of the event is known beforehand, typically when the hazard is imminent.

- Response procedures – Those procedures used in response to an initiating event.  Response procedures include: Emergency Operating Procedures (EOP), Abnormal Operating Procedures (AOPs), Alarm Response Procedures (ARP), Severe Accident Management Guidelines (SAMGs), fire procedures, and seismic or other external event procedures (including FLEX procedures).

- Normal operating procedures (NOP, also known as operating procedures). Those procedures used in day to day plant operation. These procedures include normal shutdown and start up procedures, system alignment procedures, and test and maintenance procedures.  These plant specific procedures are well trained on and the wording is standardized across the complete procedure set.

For external events HRA, there are three types of post-initiating event operator actions.

- Internal events operator actions

- Preventive operator actions

- External event response operator actions

The internal events operator actions associated with these HFEs are actions required in response to a plant initiating event and/or reactor trip, typically directed by the EOPs, ARPs, AOPs, and/or NOPs. Because internal events operator actions have been identified, their HFEs defined, and their HEPs quantified as part of the internal events HRA, it is not necessary to repeat the internal events HRA identification process. All that is required for the external events PRA identification process is to determine which of these HFEs could occur in external events scenarios.

Preventive actions would be plant and external event specific, and the identification of these actions would be performed by a review of procedures and discussions with plant operations.  These actions would typically be included in the external events PRA on as-needed bases.  Preventive operator actions are an area of ongoing study, and while they are not explicitly within the scope of EPRI 1025294 [1], they are subject to the same feasibility criteria described in that report.  Example of preventive actions could include:

- Closing doors or placing flood barriers, such as sand bags or drain plugs, prior to flood damage

- Transporting additional diesel fuel on site prior to an expected prolonged loss of offsite power such as a hurricane.

- Staging portable equipment (e.g., preparing to implement FLEX options)

External events response actions are new post-initiating event operator actions used to mitigate the effects of an external event.  This category of HFEs is typically not included in the EOP/AOP network of procedures. These operator actions are identified by review of the external event response procedures in conjunction with the modeled PRA functions and sequences.

Response actions are sometimes called *recovery actions,* and may appear in event trees or the fault tree portions of the PRA. Response actions consist of the following types of actions.

- Terminating the impact of the external initiating event – actions taken to identify and protect components that are operating in an undesired state or are threatened after the external event has occurred. These are somewhat analogous to preventive actions described above, but often have a shorter time window. For example, if a power-operated relief valve spuriously opens due the initiating event, the failure may be able to be recovered by de-energizing the valve.

- Mitigation of external initiating event consequences using the affected SSC – actions taken to recover failed SSCs by providing an alternate success path. For example, actions taken in response to a seismically-induced LOSP and SBO due to relay chatter preventing load sequencers from loading EDGs and equipment loads onto vital AC buses. The HFE models operators resetting circuits/relays from the control room or in the switchgear rooms, restarting the EDGs and loading equipment manually if the load sequencer remains unavailable. Note – human reliability analysis does not address repair of failed components.

- Mitigation of external initiating event consequences using alternate components – actions taken to recover failed SSCs by providing an alternate success path. For example, restoration of power to an electrical bus by aligning an alternate component such as a standby rectifier/inverter or a source (such as a skid-mounted diesel generator used for FLEX). Note – human reliability analysis does not address repair of failed components.

Regardless of how the operator action is identified, the corresponding HFE must be defined for use in the external events PRA. The human failures are defined to represent the impact of the human failures at the function, system, train, or component level as appropriate.

For new actions, the definition should start with the collection of information from PRA and engineering analyses. For actions carried over from the internal events, the existing definition should be reviewed and modified as-needed to account for the new context of the external event.

## 4. FEASIBILITY

The HRA for most spatial analyses is typically performed in conjunction with the PRA development. Because tasks of the PRA are typically developed concurrently, not all of the information required to perform a detailed HFE quantification will be known initially and the PRA will need screening HEP values initially to develop and quantify the risk model.

For a screening analysis, the HFE definition and feasibility assessment are conducted simultaneously as part of the initial qualitative analysis. If a more detailed analysis is needed, then the initial qualitative analysis should be further developed. Prior to performing the qualitative analysis, if the operator action did not pass the screening-level feasibility assessment, the feasibility should be reassessed after gathering more details.

Regardless of when the feasibility assessment is conducted or the level of detail of the current PRA, the feasibly assessment needs to consider the following, at a minimum.

- Timing

- Manpower

- Cues

- Procedures and training
- Accessible Location & Environmental Factors
- Tools and equipment operability.

If the operator action is feasible, the analyst can proceed to perform either a screening or a detailed quantification. If the analyst finds the screening to be too conservative or limiting, the analyst is encouraged to apply the detailed HRA method. EPRI 1025294 [1] provides additional detail on considerations for each of these feasibility criteria.

## 5. SCREENING ANALYSIS & QUANTIFICATION

The screening process is optional, but it provides a set of HEPs for the initial PRA model quantification and helps identify the important sequences. The ranking can be used to determine which sequences might be further analyzed to reduce the calculated risk by detailed modeling.

The screening method provided was initially developed specifically for application in developing a seismic risk assessment. However, with the current state-of-knowledge, it is reasonable to use the described screening approach in EPRI 1025294 [1] as a screening method for other external events, with the caveat that future research on other external events may require this approach to be modified to incorporate relevant operating experience.

### 5.1 Step 1- Identify Damage State of the Plant Following the External Initiating Event

Both the screening HRA method and the detailed HRA method start by asking the analysts to identify the damage state of the plant following the external initiating event. The damage state is intended to account for the overall context resulting from the external event beyond the specific failures dictated by the cut set, including impact to local infrastructure and non-safety related systems, level of heightened stress, general increase in level of coordination and workload, and quality of working environment. These damage states, described in Table 1, were selected based on the definitions provided in EPRI NP-6695 and its update EPRI 1025288 [4], but have been adjusted here to correlate more closely with the impact of the context on operator performance. Because the design basis for the range of external events can vary substantially from plant to plant, the bins selected here reflect the effect of the external event on the plant rather than providing absolute values (e.g., PGA values). Bin definition is generic for seismic because the seismic hazard is not straightforward, and there is not a direct correlation between hazard level and damage state. Recommendations for seismic HRA provided in Table 1 may not fit the damage state definition appropriately for every plant, and is provided only as a starting place when no other information is available; it is expected that the HRA analyst will have to interface with the PRA analyst to correlate the damage states provided here with the hazard bins (e.g., ground motion intervals) used in the PRA. Note: The SSE is a convenient, but generally very conservative value; higher values could be justified. HCLPF recommendations here may also be overly conservative.

**Table 1**
**Damage State Definitions For Screening**

| Bin # | External Event Damage State Description | Recommended Link to Seismic Hazard |
|---|---|---|
| 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. | Below the SSE. |
| 2 | No expected damage to the plant safety-related SSCs or to rugged industrial type non-safety SSCs required for operation. Damage may be expected to non-safety SSCs not important to plant operations and to the switchyard (e.g., LOOP expected). Falling of suspended ceiling panels. | At or above the SSE, up to HCLPF of most fragile safety-related SSC.<br>(e.g., 2011 North Anna event) |
| 3 | Widespread damage to non-safety related SSCs and/or some damage expected to safety related SSCs. Significant number of vibration trips and alarms requiring resetting. | Above the HCLPF of most fragile safety-related SSC to HCLPF of critical instrumentation or HCLPF level of 25th percentile component, whichever is lower.<br>(e.g., 2007 Kashiwazaki-Kariwa,<br>2011 Onagawa events) |
| 4 | Substantial damage to safety related and non-safety SSCs. The threshold of this damage state is such that it produces a cliff-edge effect in the likelihood of operator response. | Wide-spread damage to critical instrumentation.<br>(2011 Fukushima Daiichi and Daini events) |

## 5.2 Step 2 - Plant Damage Assessment

Another consideration that appears in the screening trees is based on the plant damage assessment. Following an external initiating event often times the entire site is affected and the effects (such as flood water obstructing access, high radiation areas, and/or damaged equipment) can impact human performance far after the event is over. Thus the external initiating event can have impacts on both cognition and execution that last a considerable amount of time. There is expected to be an overall reduction in workload and complexity once the site has been assessed and the extent of the damage understood.

The damage assessment has been defined in the external events HRA as a break-point for both cognition where not only is the damage to the plant known (after the break-point), but also the workload and distractions associated with determining the impact of the event are reduced. The cognitive load on the operators is reduced because they have a clearer picture of the damage inflicted on the plant due to the initiating event, including an understanding of what equipment is damaged but may not have failed yet. By this point in the scenario it is also expected that the crew have had the opportunity to implement basic “working solutions” to compensate for issues caused by the external event (e.g., determining usable pathways, establishing alternate means of communication, etc.). For seismic events, a detailed plant damage assessment consists of a post-event walkdown and is usually performed within 4 to 8 hours of the event. This initial walkdown should not be confused with the more involved, formal damage assessment required prior to restart to identify issues which might degrade long-term reliability of components, typically called “post-shutdown inspections and tests”.

## 5.3 Step 3 – Assessment of Time Margin

A review of the operating experience suggests that the PSFs associated with seismic events manifest themselves most often as a delay, rather than direct failure, of the operator action. Therefore, the level of credit assigned at the screening level is dependent upon the amount of time margin – or tolerance for unexpected delays – available.

## 5.4 Step 4a - Quantify Screening HEP For HFEs From Internal Events PRA

For operator actions carried over from the internal events PRA into the external events PRA, the internal events qualitative and quantitative analysis can be used as the starting point for the external events PRA quantification. A simple decision tree has been developed to show how to determine a multiplier to apply to the internal events HEP. The event tree considers the following headings in the development of the HEP. The end state of the decision tree branches are either a screening HEP or a multiplier for the internal events HEP. Multipliers range from 2 to 50, and screening HEPs range from the internal events HEP value to 1.

- Immediate, memorized action (or not)
- Action location
- Damage state
- Time margin consideration
- Cue before or after plant damage assessment

## 5.5 Step 4b - Quantify Screening HEP For New External Events HFEs

For new operator response actions that were not carried over from the internal events PRA into the external events PRA, multipliers are not applicable, but the same factors are used to determine a screening HEP. Screening HEPs were developed by selecting a base human error probability (BHEP) then applying the same multipliers used in the internal events HFEs described above; the screening values were given no more credit than 1.0E-2.

# 6. DETAILED ANALYSIS & QUANTIFICATION

By the time the analyst has reached the stage requiring a detailed analysis of the HFE, the HFE has been defined and the basic feasibility has been assessed. The HFE definition and feasibility comprise the foundation of the qualitative analysis. The feasibility criteria for screening is more stringent than that required for detailed analysis (e.g., the screening requirement for an action to be considered feasibility is that the *primary* cue must be available, whereas the detailed analysis stipulates that either the *primary* or *secondary* cues must be available). Therefore, additional data gathering and analysis may need to be performed to satisfy the feasibility criteria for a detailed analysis if the feasibility criteria for the screening analysis were not met.

Qualitative analysis is an essential part of an HRA. The objectives of qualitative analysis are to:
understand the modeled PRA context for the HFE, understand the actual "as-built, as-operated" response of the operators and plant, and translate this information into factors, data, and elements used in the quantification of human error probabilities.

Recent experimental studies have shown that the quality of the quantitative analysis is strongly impacted by the quality of the qualitative analysis, even for fairly prescriptive methods such as the EPRI HRA Methodology. ERPI 1025294 [1] provides detailed guidance on performing a thorough qualitative analysis, using insights from seismic operating experience.

The EPRI HRA Methodology (also known as the EPRI HRA Approach) is based on EPRI's SHARP and SHARP1 [5] HRA framework. After the qualitative analysis has been performed, a detailed quantification is performed using methods recommended by EPRI within the HRA approach. Specifically one or more of the following methods:

- Cognitive Methods. The Human Cognitive Reliability/Operator Reliability Experiment (HCR/ORE) and/or Cause-Based Decision Tree Method (CBDTM) [6,7] for cognition.
- Execution. Technique for Human Error Rate Prediction (THERP) [8] for execution.

One advantage of using existing methods for external events HRA is that, at a minimum, the same fundamental aspects and factors affecting human performance apply to Level 1 internal events PRA as well as external events PRA —therefore, applying these methods to external events scenarios should yield a good first-order approximation of operator failure and would further be consistent with the modeling for non-external events scenarios at many nuclear power plants. Although the methods used for external events HRA modeling are the same as those used for Level 1 internal initiating events, EPRI 1025294 provides guidance on how to make the relevant selections within the EPRI HRA Methodology to appropriately account for the impacts of the external events defined in the qualitative analysis.

## 7. FLOOR HEP FOR HIGH DAMAGE STATES

For extremely high damage states, the uncertainties dominate, so EPRI report 1025294 [1] recommends that a floor HEP to reflect the uncertainty associated with the plant damage. The floor HEP is treated as a lower bound. If the external events HRA calculates HEPs below the lower bound then they will not be used and the floor HEP will be used instead. Based on accounts of historical events, operational experience data has shown that it is possible for operators to become confused or distracted by multiple, conflicting indications such as spurious instruments or alarms or many failures caused by a highly damaging event. In theory, operators should be focused only on the safe shutdown paths, associated equipment, and instruments and alarms as directed by the applicable procedures. However, in a complicated scenario such as following a spatial event like a seismic event, maintaining this focus might be difficult. In addition, good reasons might exist for the operators to have a wider scope of attention (e.g., secondary-side systems or equipment that is commonly important during normal operations and systems or equipment of recent concern as a result of current plant configurations and preexisting conditions).

Sensitivity studies could be conducted to identify whether the applied lower bound limit has little (or no) effect, a significant effect, or perhaps a moderate effect. Effects might be represented and evaluated simply as different values of HEPs to represent the HEPs associated with different conditions for the same HFE.

## 8. MODEL INTEGRATION

Once the HEPs have been quantified at the appropriate level, the operator actions and associated HEPs must be appropriately integrated into the PRA model. Model integration consists of various tasks, depending on the PRA model, including: cut set review, HEP reasonableness check, recovery, dependency and uncertainty. EPRI 1025294 [1] provides guidance on these elements of model integration in the context of external events.

## 9. INSIGHTS AND CONCLUSIONS

EPRI report 1025294 [1] provides methods and guidance for the human reliability analysis of external events PRAs. EPRI report 1025294 was developed using insights from recent HRA advances from Fire HRA [2], as well as considering the state-of-the-art in seismic and external events PRA models and issues [3, 4]. EPRI report 1025294 provides a framework for external events HRA, a general screening approach, and a detailed quantification approach which can be applied consistently across a variety of external events were developed. The report was written to provide methods and guidance for all external events, but included specific guidance for HRA in a seismic PRA. The detailed quantification approach provided in EPRI report 1025294 is an adaptation of the “EPRI HRA Methodology”, also known as the “EPRI HRA Approach” for internal events [5, 6, 7, and 8].

In 2013, initial testing was conducted on the proposed guidance in EPRI report 1025294. The testing was limited to pilot plants that were in the process of developing seismic PRA and also to testing the concepts on plants that were conducting seismic PRA peer review. The objective of the testing was to obtain insights that would be used to refine the external events HRA methods and guidance. As part of the testing, a gap analysis was conducted on the ability of current human reliability analysis (HRA) methods to support current requirements of external flooding risk assessments [11]. The gap analysis started with a review of the requirements from the ASME/ANS PRA Standard [12] and the requirements of the Interim Staff Guidance (ISG) for the Flooding Integrated Assessment [13].

The insights from the gap analysis between the current external flood risk assessment requirements and the current state-of-practice, and the insights from the current testing, are summarized below.

- The external events HRA process (including external flood and seismic) is identical to the Fire HRA process, which includes a screening step that the internal events PRA (IEPRA) does not typically require for the IEPRA post-initiator HRA.

- External flooding requires a new category of HRA events for external flooding – those operator actions taken as preventive measures. This category includes preparatory measures such as building isolation. This new category of actions should have the same engineering treatment and modelling considerations as post-initiating event actions.

- Feasibility of operator actions applies to all types of operator actions in all hazard groups, including external flooding. A strong qualitative analysis represents the best means for supporting a detailed HRA evaluation in order to demonstrate compliance with PRA Capability Category II [3], specifically supporting requirement HR-G3 for the incorporation of plant-specific and scenario-specific factors.

- Quantitative methods for external flooding actions will likely have difficulty demonstrating compliance with PRA Capability Category II due to limitations in existing methods such that it can be difficult to tell if the resultant human error probability is conservative (Capability Category I) or best-estimate (Capability Category II) for supporting requirement HR-G1.

- Quantification of human error probabilities has the following issues related to each category of operator action: 1) Preventive actions – in general, qualitative analysis and quantitative methods need to be developed and refined, 2) Post-initiating event actions – in general, qualitative and quantitative methods essentially follow the guidance of NUREG-1921 (Chapter 4), which is being updated in the preliminary EPRI External Events HRA Guidance document [2].

- Uncertainty and dependency considerations are the same, although new sources of uncertainty are introduced.

A pilot of the EPRI 1025294 approach is underway as part of a seismic PRA development. At the same time that this preliminary guidance is being tested and the pilot being conducted, EPRI is updating its methodology for seismic PRA. This seismic HRA method will be updated and finalized based on the lessons learned from this pilot and based on changes in the general seismic PRA guidance. The general objectives of the pilot study are listed below.

1. better understand the seismic HRA issues and how they interact with the SPRA
2. test the screening method guidance for usability and reasonableness
3. test the detailed method guidance for usability and reasonableness
4. identify any gaps in the method

EPRI 1025294 [1] is considered to be a preliminary draft as it is expected that this guidance will be updated in the future. The update is expected to include a review of operational experience and additional guidance specific to other external events (e.g., External Flooding and High Winds).

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