Benefits and Lessons Learned from PRA / Operations Interface at Nuclear Power Plants

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Abstract: The Pressurized Water Reactor Owners Group (PWROG) has recently championed several efforts to increase collaboration between Probabilistic Risk Assessment (PRA) experts and nuclear power plant operators and procedure writers. The result of these efforts has been successful in promoting realism in the probabilistic representation of the role of human interface with nuclear power plants (i.e., Human Reliability Analysis (HRA)). Specifically a number of meetings and workshops have been held with PRA analysts, HRA experts and representatives from plant operations, procedure writing, and training to review current state-of-practice HRA methods and assumptions and identify areas that may be overly conservative. Guidance and recommendations have been developed and in some cases challenge state-of-practice HRA assumptions and methodologies. In these cases, specific methods or assumptions have been identified that could be revised to better reflect modern plant operational practices. Other areas of HRA have also be identified as opportunities for future research in order to ensure realistic treatment of the role of human operators on accident response. This paper intends to discuss several insights, best practices, operational improvements, and future research areas that have been recommended as a result these PWROG efforts.

1. INTRODUCTION

The PWROG began working towards increased collaboration efforts between the Risk Management Committee and the Procedures Committee within the PWROG starting in 2019 with the formation of the Risk Beneficial Procedure Changes (RBPC) Core Team. This core team currently consists of 13 PRA experts, 13 current or formerly licensed nuclear operators, and 2 experts in nuclear safety analysis. This mix of expertise has allowed for deep exploration of the role of plant operators in plant-specific PRA models in order to ensure actions are accurately reflected. In addition, simple plant procedure changes can be recommended by PRA experts that may result in substantial risk reduction or safety improvements at Nuclear Power Plants (NPPs).

In this paper we will present some of the key outcomes from the PWROG's RBPC core team, including:

- Enhancements to Generic Procedure Sets and HRA Methods
  - Opportunities for Expanding Credit for Diverse and Flexible Coping Strategies (FLEX) Equipment Beyond Extended Loss of AC Power (ELAP)
  - Considerations for Realistic HRA
- Enhancements to Plant-Specific Procedures and HRA Methods
  - Best Practices for Plant-Specific Operations / PRA Interface
  - Considerations for Adding Beyond Design Basis (BDB) Strategies to Plant Procedure Sets
  - Strategies for Improving Defense in Depth in Emergency Procedures
  - Strategies for Replacing a Function lost due to Maintenance or Surveillance
  - Considerations for Procedure Changes to Improve Time Margin in Operator Actions
  - Considerations for Plant-Specific Procedure Changes to Reduce Risk

While these insights were generated by the PWROG and were focused on Pressurized Water Reactor (PWR) PRA models and procedure sets, many of them are believed to be applicable to other power plant designs (e.g., Boiling Water Reactors (BWRs)). Further, this paper will illustrate lessons learned from increased communication between human operators and PRA modeling experts that may even be applicable to other industries that model Human Error Probabilities (HEPs) using similar techniques.

2. ENHANCEMENTS TO GENERIC PROCEDURE SETS AND HRA METHODS

This Section discusses a number of potential improvements that could be made to generic PWROG procedure and guideline sets based on the recommendations from the RBPC core team. The PWROG manages generic procedure and guideline sets from the three different PWR vendor types: Westinghouse, Combustion Engineering (CE) and Babcock & Wilcox (B&W). On a generic basis, the PWROG maintains the full set of generic Emergency Operating Procedures (EOPs) for all three vendor types, a number of generic Abnormal Operating Procedures (AOPs) and the full set of generic FLEX Support Guidelines (FSGs).

In addition, this section will present feedback on generic HRA methodologies that has been developed based on a workshop that was held in 2021 with PWROG and Electric Power Research Institute (EPRI) representatives. The intent of the workshop was to review the current state of practice in HRA methods with industry HRA experts and current and former licensed operators. This workshop allowed for a review of HRA methods with plant operators and feedback was documented regarding potential opportunities for improving realism in HRA.

2.1. Opportunities for Expanding Credit for FLEX Equipment Beyond ELAP

The primary candidates for improvements to the generic PWROG procedure sets was related to expanding credit for FLEX equipment to BDB scenarios in addition to Extended Loss of AC Power ELAP. Procedures developed in response to NEI 12-06 [1], were reviewed to identify new applications for FLEX and portable equipment that would improve reliability. FSGs considered by the core team are listed below:

- FSG-1, Long Term RCS Inventory Control
- FSG-2, Alternate Auxiliary Feedwater (AFW) / Emergency Feedwater (EFW) Suction Source
- FSG-3, Alternate Low Pressure Feedwater
- FSG-4, ELAP DC Bus Load Shed/Management
- FSG-5, Initial Assessment & FLEX Equipment Staging
- FSG-6, Alternate Condensate Storage Tank (CST) Makeup
- FSG-7, Loss of Vital Instrumentation or Control Power
- FSG-8, Alternate Reactor Coolant System (RCS) Boration
- FSG-9, Low Decay Heat Temperature Control
- FSG-10, Passive RCS Injection Isolation
- FSG-11, Alternate Spent Fuel Pool (SFP) Makeup
- FSG-12, Alternate Containment Cooling
- FSG-13, Transition from FLEX Equipment
- FSG-14, Shutdown RCS Makeup

PWROG surveys related to identifying the PRA functions that may benefit the most from additional credit for FLEX equipment. The results of this survey were reviewed by the RBPC core team during a 2019 workshop and the following FLEX functions were identified as the primary candidates for inclusion in the generic EOPs on a functional basis:

- Low Pressure AFW pumps (FSG-3)
- AFW suction source (long term AFW for plants with small CST) (FSG-2, FSG-6)
- Backup Electrical Power

    - Loss of individual bus
    - Battery chargers/battery depletion time (FSG-4)
    - Loss of instrumentation (FSG-7)
    - Vital AC
    - Loss of DC
- Loss of Ultimate Heat Sink (UHS)
- Decay heat removal via Steam Generators (SGs)

In addition, the following matrix lists the primary frontline functions and potential opportunities to use FLEX or B.5.b equipment to mitigate the loss of function.

Table 1: Matrix of Potential Frontline Functions to FLEX or B.5.b Strategies

Primary Frontline Functions	FLEX / B.5.b Strategy
Short Term Reactivity Control	• FSG-1, Long Term RCS Inventory Control • FSG-8, Alternate RCS Boration
Long Term Reactivity Control	• FSG-1, Long Term RCS Inventory Control • FSG-8, Alternate RCS Boration
Short Term RCS Injection (Injection Phase)	• FSG-1, Long Term RCS Inventory Control • FSG-8, Alternate RCS Boration
Long Term RCS Injection (Recirculation or Refueling Water Storage Tank (RWST) Makeup)	• B.5.b, RWST Makeup
Hot Leg RCS Injection (Boron Precipitation for Large Break Loss of Coolant Accident (LBLOCA))	• FSG-1, Long Term RCS Inventory Control • FSG-8, Alternate RCS Boration
Short Term Decay Heat Removal (SG Cooling)	• FSG-3, Alternate Low Pressure Feedwater
Long Term Decay Heat Removal (SG Cooling - CST makeup or similar)	• FSG-3, Alternate Low Pressure Feedwater • FSG-2, Alternate AFW/EFW suction Source • FSG-6, Alternate CST Makeup
Short Term Decay Heat Removal (Once Through Cooling - Injection Phase)	• FSG-1, Long Term RCS Inventory Control • FSG-8, Alternate RCS Boration
Long Term Decay Heat Removal (Once Through Cooling - Recirculation or RWST Makeup)	• FSG-1, Long Term RCS Inventory Control • B.5.b RWST Makeup
Containment Cooling	• FSG-12, Alternate Containment Cooling
Component Cooling	• Plant-Specific strategy
RCP Seal Cooling	• FSG-1, Long Term RCS Inventory Control • FSG-8, Alternate RCS Boration
RCP Seal Injection	• FSG-1, Long Term RCS Inventory Control • FSG-8, Alternate RCS Boration
Room Cooling	• FSG-5, Initial Assessment and FLEX Equipment Staging
Vital AC Power	• FSG-4, ELAP DC Bus Load Shed/Management
Vital DC Power	• FSG-4, ELAP DC Bus Load Shed/Management

2.2. Considerations for Realistic Human Reliability Analysis (HRA)

A PWROG workshop was held in June 2021 to assess the degree of realism that exists in standard HRA assumptions and investigate alternative assumptions that could reduce conservatism in HRA calculations. The workshop included PRA analysts, HRA experts and representation from plant operations, procedure writing, and training. Representatives from EPRI also participated. Deliberations were guided by referring to the structure of the EPRI HRA Calculator [2,3]. However, comments and suggestions were not limited to details included in the calculator. This section documents the outcome of the HRA workshop and communicates the general areas that can be investigated on a plant-specific basis in order to reduce the amount of conservatism in typical plant-specific HRA.

With respect to typical HRA assumptions applied in the selection of various branches of the Cognitive Unrecovered event trees as they apply to the Cause Based Decision Tree Method (CBDTM) HRA methodology, this section offers practical guidance and examples of when it is appropriate to select the various branches of these trees.

- Indication Available in Control Room
    - This branch is mostly concerned with if the operators have the information they need to take an action, not if the indication is physically located in the control room. Therefore, "Yes" should be selected as long as the control room can get the information needed to take the action in question.
- Control Room Indication Accurate
    - In general, it can be assumed that the indications in the control room are accurate; however, there are exceptions to this treatment. The origin of this question is rooted in outdated examples of control rooms where there were known malfunctioning lights / indicators; this is not common in control rooms anymore. However, in hazard PRA models, such as internal fire, seismic or flooding, it is possible that electrical failures could result in control room indications not being accurate; this should be considered on a plant-specific basis for each hazard HRA being developed. Note that plants may have proceduralized guidance to confirm indications using a separate device or panel; this can be credited in the HRA.
- Check vs. Monitor
    - While this branch may be somewhat straight forward to determine for a given Human Failure Event (HFE), there was some general feedback related to the resulting failure rates associated with this branch. It was noted that operators have a good idea of key parameter trends that they are monitoring. Based on these trends, operators typically will change the frequency at which they monitor these plant parameters as key limits are approached. The feedback from plant operators here is that parameters that are monitored (as opposed to parameters that are checked only once) may have a higher reliability as operators will have the opportunity to correctly read the indication multiple times and they will likely be watching as key thresholds / limits are reached. This is especially true when it involves monitoring a critical parameter.
- Front vs. Back Panel
    - Similar to check vs. monitor, this branch is somewhat obvious how to apply for an HFE; however, this again was an area where operators present at the workshop wanted to clarify that applying a different failure probability to actions that take place on the front vs. back panel may not be accurate. In general, reactor operators instructed to take an action or read a parameter on a back panel are equally likely to be successful. While it is possible that this could have somewhat of an impact on parameters that are being monitored on a back panel, generally, operators do not see a significant difference with respect to the front vs. the back panel and do not believe this has an impact on operator performance.
- Indication Easy to Locate, Good/Bad Indicator
    - For the most part, this branch should be determined through operator interviews that are specific to the action being modeled in the PRA. It was noted in the workshop that operators frequently identify opportunities to correct some of these issues and make recommendations to ensure that indications are easy to locate and read. It was also noted that alarm functions may provide some compensation and should be credited when evaluating this branch.
    - This branch could have some impact for plants that move to digital indications on computer screens if the on-screen indications are not located in a prominent location. If this is important in HRA, it could be flagged in a condition report or similar if there is an opportunity for safety enhancement.

- Formal Communication
    - The origin of this branch is from a time in nuclear operations where communication was not always conducted in a formal manner. In the last few decades, plants have drastically improved communication practices. For plants with highly formal control room communications practices it should generally be acceptable to select "Yes" for this branch.
- Graphically Distinct
    - Given that current procedures, especially EOPs, are generally considered state of the art, the vast majority of steps should be considered distinct. Specifically, it was discussed that if a step has a number or letter designator dedicated to a specific action or has an individual place-keeper sign-off, it should be considered graphically distinct.
- Placekeeping Aids
    - Placekeeping aids are commonly used throughout the industry and can be credited on a per step basis as well as on a per page basis; either method should be considered acceptable for this branch.
- Standard or Ambiguous Wording
    - As discussed above, current PWROG member procedures, especially EOPs, are generally considered state of the art and most plants rely on generically developed procedure writers' guides. Therefore, the majority of steps credited in HRA should be considered to have standard wording as most ambiguous step wording has been scrubbed from EOP procedure sets. It was noted during the workshop however, that plants with new procedures that have not had many opportunities to be exercised in the field may encounter ambiguous wording. If ambiguous wording is assumed in plant-specific HRA, feedback should be given to the site procedure writers that there is an opportunity for improvement to plant risk and nuclear safety to ensure procedure step wording is clear.

Another area that was reviewed was with respect to typical HRA assumptions related to the application of execution stress within the existing HRA methods. Similar to the guidance provided for the cognitive unrecovered trees above, this section offers practical guidance and examples related to execution stress.

- Plant Response as Expected
    - For the majority of human actions credited in a PRA model, it can generally be assumed that the plant will be responding consistent with operator expectations. This means that this question can be interpreted as the plant responding as expected to the failures that preceded the action being credited. This is also a topic that should be covered during operator interviews as it may be difficult for a PRA analyst to determine when the plant response may not be consistent with operator expectations.
- Workload
    - Workload considerations are subjective and represents an example of an area where the industry could develop guidance for how to answer these types of questions specifically considering the opinions of plant operators.
- Performance Shaping Factors
    - In order to properly account for performance shaping factors, this item should be covered during operator interviews; the specific action and the accident scenarios that it may be applied to, should be discussed with operations to ensure the full context is understood. It was noted during the workshop that it may be appropriate to apply a negative PSF if the scenario is considered stressful (e.g., starting feed and bleed, or certain actions credited in external hazard models).
    - One specific area that was discussed with related to Fire HRA. Performance shaping factors for Fire HRA should be assessed similar to internal events; it may not be necessary to assign negative Performance Shaping Factors (PSFs) across the board in this case.

One of the key areas that was discussed during the workshop was HRA dependency analysis. At a high level, the general feedback from the operators who participated in the workshop was that dependent HEPs generated using Technique for Human Error-Rate Prediction (THERP) [4] are likely conservative and may not reflect modern control room operator performance. It was recommended that dependency analysis methods should be modernized to consider more recent operating experience from nuclear power operations. In the nearer term, however, the group was able to identify revised dependency analysis treatment / assumptions that could be applied to current HRA methods. In general, it is critical that important HEP combinations be reviewed manually by HRA analysts and plant operations to determine if the inputs to the dependency analysis are realistic. The overall conclusion was that dependency analysis may represent the best opportunity for reduction of HRA conservatism.

One of the areas that was identified as having the potential to introduce more realism in current dependency analysis methods was credit for intervening successes. When discussing this area, the feedback from HRA experts indicated that credit for intervening successes is typically limited to successful actions that are analyzed in the HRA, or actions than can be proven to be successful to get from one failed action to another (e.g., failure to switch to recirculation for feed and bleed proves successful implementation of feed and bleed during the injection phase). This treatment may not be taking enough credit for successful actions that operators will likely be taking between failed HFEs. Operators have many opportunities to recover if they started down the wrong path to the point where they are failing many operator actions in a single sequence. There may be many successful actions in between multiple HFEs in a given cutset, although these actions will not always be modeled in the plant HRA. It was identified that it may be possible to credit changing to a different procedure as an intervening success. It was also noted that EOPs (and other plant procedures / guidelines) are typically written such that operators can always "reset" and reanalyze symptoms to get to the correct procedure or action.

3. ENHANCEMENTS TO PLANT-SPECIFIC PROCEDURES AND HRA METHODS

In addition to the generic recommendations, a number of plant-specific considerations for procedures and HRA have also been identified by the RPBC core team. These recommendations were collected through a number of different means. The first is through a number of PWROG member surveys that were intended to collect operational experience, lessons learned and best practices for plant-specific HRA and risk beneficial procedure changes. There were also a number of workshops where plant-specific examples were shared and subsequentially collected by the RBPC. In addition, monthly RBPC core team meetings have been occurring since January 2021 and actively solicit new operational experience, lessons learned and best practices.

This section documents many of the key recommendations, considerations and potential enhancements that can be applied to plant-specific procedure sets or HRA studies.

3.1. Best Practices for Plant-Specific Operations / PRA Interface

An item that is frequently discussed by the RBPC core team are best practices for utilities to consider in order to establish a healthy relationship between plant PRA departments and plant operators and/or procedure writers. In order to ensure realism is established in plant-specific HFEs, it is key to perform operator interviews (which is also required by the American Society of Mechanical Engineers (ASME) / American Nuclear Society (ANS) PRA Standard [5]). However, there are a number of additional opportunities for PRA / operations interface that can result in more realistic HEPs, improved plant procedures, and can generally result in lower risk estimates and improved plant safety. This section documents some of the key best-practices or recommendations for plant-specific PRA / operations interface.

- Minimum criteria that should trigger procedure writer / PRA meetings
    - Changes to EOPs (or procedures referenced in HRA Notebook)
    - New or upgraded PRA Hazard models
    - Change in highest contributors to risk (accident sequences / operator actions / hazard models)
- Regular meetings between plant operations staff and operations training leads are seen as beneficial. Educating plant operators about the PRA model, the HRA and specific assumptions or methodologies that are used to quantify human performance in the PRA offers additional insights from a different perspective. In addition, ensuring all the latest operator performance timings and insights from the operations training group will help ensure that the PRA model represents the current as-built, as-operated plant.
- The PRA group should review all non-editorial changes to operations procedures listed in the HRA Notebook or new operations procedures prior to finalization. The review should ensure the change does not adversely affect any PRA-modeled operator actions or accident progression (timing, critical steps, cues, etc.). They would also determine if the change should be factored into any of their other analysis (i.e., success criteria, event trees, accident progression, etc.).
- Ensure the PRA group is tied-in closely when changes are being considered that could impact time-critical or time-sensitive operator actions. Review the actions to ensure scenario and timing estimates are consistent with operations. A Steering Committee can also review all official simulator timing sheets as they are completed; this ensures PRA is aware of any changes to timing of actions that may have been used in the PRA. Violations for significant timing changes that impact a configuration specific risk profile can be avoided by monitoring the simulator timing validations. This also gives PRA an opportunity to discuss operator timing of Time Sensitive Actions (TSAs) or Time Critical Actions (TCAs).
- Ensure that realistic assumptions are being applied with respect to PSFs or cognition or execution recovery opportunities (see previous Section).
- Risk-significant operator actions should be reviewed with operations to determine if procedure changes could lower risk-significant HEPs.

3.2. Considerations for Adding BDB Strategies to Plant Procedure Sets

The following considerations can be used when determining the best way to implement a BDB strategy into plant-specific guidelines or procedures:

- When crediting a BDB strategy steps should be included on how to restore the credited strategy if it becomes available again.
- Fire Procedure actions for recovery of a function after a fire:
    - FLEX can be credited and to restore the function.
    - Operations and PRA interface required to discuss specific actions that could be taken to realign or restore certain functions. Plant specific investigations are required.
- Design / Licensing basis type analysis is not needed to credit actions/strategies in PRA. Best-estimate Thermal / Hydraulic (T/H) analysis can be used to support PRA related procedure changes.
- If used to replace design basis equipment or strategies, commercially obtained equipment may open other questions related to mission time etc.
- Equipment may need to be pre-staged to ensure the FLEX action is going to be viable when needed.
- When PRA models are developed, simultaneous loss of equipment is assumed even though it is more likely components supporting a function will be lost one-by-one. For instance, loss of all AFW Pumps at the same time is very unlikely, therefore, when one pump has been lost, compensatory action such as prestaging a backup source of feed water may be beneficial if resources are available.

3.3. Strategies for Improving Defense in Depth in Emergency Procedures

This section documents several strategies that have been identified by the RBPC in order to improve defense-in-depth in EOPs.

- RG 1.160 [6] allows for crediting FLEX and other portable equipment in the EOPs without the burden of including this equipment in the scope of the Maintenance Rule as long as the FLEX strategy is utilized after the credited strategy is lost.
- When implementing a BDB procedure change Licensing should be represented on the multi-discipline team. Involve Regulatory Affairs and others reviewing the 10 CFR 50.59 evaluation and ensure that they are all in agreement with the change
- Ensure, through validation, that the change is successful and the credited strategy is not interrupted
    - Need to show that ALL credited functions have failed, and ensure the credited strategy is not interrupted.
    - If you are on a FLEX strategy and the credited strategy becomes available, you need to have transition back to credited strategy
- Provide classroom training, prior to procedure issue, for operators to show that this is a BDB strategy that does NOT interrupt the credited strategy
- Reference generic guidance to demonstrate why the procedure change is acceptable
- Brief your resident before you implement the procedure

3.4. Strategies for Replacing a Function lost due to Maintenance or Surveillance

Something that comes up frequently during regular RBPC core team meetings are strategies related to replacing a function that was lost due to maintenance or surveillance. This section documents some of the key insights that the RBPC has documented over the years related to this concept.

- Procedure changes related to components removed from service due to test or maintenance:
    - Adding procedure steps may allow for recovery from Test & Maintenance (T&M) events in a short period of time that may be able to be credited in PRA.
    - Guidance to direct recovery of equipment out-of-service can be placed in the Operations expectations or Operations standard at the site.
    - Inform plant staff regarding how to log the availability / unavailability depending on the time the activity is expected to take.
    - May need to split up PRA modeling for short term (failed) vs. long term (restored) failure states in order to maximize credit for restoration or repair.
    - Use of a dedicated operator (stationed at the Structure System or Component (SSC)) or a designated operator (located near the SSC) may improve the basis for crediting restoration.
    - Consider staging a piece of FLEX equipment for use if the redundant train fails unexpectedly. This will ensure the FLEX equipment will be useful within the time window necessary for the PRA to credit its availability.
- FLEX equipment Preventive Maintenance Schedules (PMSs) are based on intended function and anticipated storage. Using or storing the equipment other than originally intended may have an impact on the PMS.

3.5. Considerations for Procedure Changes to Improve Time Margin in Operator Actions

This section documents several considerations that have been shared with the RBPC core team related to some plant-specific procedure changes that have been made for at least one utility that have been judged to be potentially applicable to other plants.

- Investigate if there are procedure changes that could make important time critical operator actions more reliable or occur earlier in the event. Example: Tripping Reactor Coolant Pumps (RCPs) on loss of seal cooling
    - Consider laminating a portion of a procedure and having it available in the control room (i.e., developing a "hard card") for a combination of alarms (e.g., for total loss of seal cooling a hard card to trip the RCPs can be used)
        - Hard cards can be faster than going through a procedure
        - Verbal communication can take time
        - Provides more consistent margin on the time response
    - Consider having an immediate operator action (for example, for loss of seal cooling to trip the pumps)
- Consider taking recoverable actions at the first alarm, taking them out of the critical timeline.

3.6. Considerations for Plant-Specific Procedure Changes to Reduce Risk

Other miscellaneous plant-specific strategies that were implemented at an individual plant but may be applicable to other utilities are documented in this section.

- Add steps to locally start equipment to address equipment that failed to start from failure of the auto-start
    - This may be easier to credit for Turbine-Driven AFW (TDAFW) pump where it is common to trip on overspeed and it is easy to restart (note that other considerations would need to be modeled in order to credit recovery from this type of failure; for example a basic event and appropriate data would need to be develop for the specific failure mode that offers the opportunity for recovery)
    - Trained operator response for certain events – although not typically credited, these are trained on regularly
- Verify documented operations expectations and training reinforcement that control room actions are to dispatch an operator for conditions such as unexpected pump trip or similar situations and allow PRA to credit these actions for risk benefit. If PRA credit can be taken for the actions based on operations expectations and training reinforcement, the explicit direction to "dispatch an operator" can be removed from the procedures, which eliminates the superfluous information.

3. CONCLUSION

The PWROG has been focusing on generically improving the relationship between utility PRA group leads and utility procedure writers. This has primarily been accomplished by forming the RBPC core team, which consists of approximately half PRA experts and half current or former licensed plant operators. Since 2019 this team has been collecting insights related to how to improve plant procedures to lower plant risk and improve plant safety while also sharing operational experience, best practices and lessons learned on how to improve realism in plant-specific HRA models and methods. This paper documents a number of the insights that have been collected by this team and outlines strategies for plants to conduct similar information sharing on a plant-specific basis going forward.

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