Human Reliability Analysis (HRA) methodologies used in the Canadian Probabilistic Safety Assessment (PSA) for external events

Hayat Chatri[a], Smain Yalaoui[a], and Yolande Akl[a]
[a] Canadian Nuclear Safety Commission, Ottawa, Canada

Abstract: There are a wide variety of available methods to perform human reliability analysis (HRA) in support of probabilistic safety assessment (PSA). However, the existing HRA methods were developed primarily for internal events PSA. These methods often contain assumptions that may or may not be applicable to new conditions created by external hazards such as fire, flood, and seismic events. Therefore, Canadian Nuclear Safety Commission (CNSC) staff initiated a project to evaluate the strengths and limitations of external events HRA methodologies used by Canadian licensees in order to identify areas for possible improvement.

Discussions surrounding external hazards HRA have increased since the accident at Fukushima Daiichi, which have in turn prompted licensees in Canada and internationally to re-evaluate their NPP's risk profile for external events. This paper presents the status of external hazards HRA as implemented in Canadian licensees' PSAs and discusses the commonalities and differences between these methodologies.

The paper provides a description of different HRA methodologies as used for seismic PSA, fire PSA and flood PSA. Additionally, it highlights the specific challenges and limitations of these methodologies as well as the impact on the overall PSA results.

Keywords: PSA, HRA, external hazards, seismic PSA, fire PSA

1. INTRODUCTION: CNSC PSA REQUIREMENTS

The Canadian Nuclear Safety Commission issued the regulatory document REGDOC-2.4.2, "*Probabilistic Safety assessment (PSA) for Nuclear Power Plants*" [1] in April 2014 as an amendment of the previous CNSC standard S-294 [9] in response to CNSC Fukushima Task Force recommendations [8]. This standard sets high level requirements which call for the development of Level 1 and Level 2 PSA by applying a formal quality assurance process for conducting the PSA. The regulatory document REGDOC-2.4.2 also requires the licensees to seek CNSC acceptance of the methodology (including HRA method) and computer codes to be used for the PSA, which means that the methodology and the computer codes have to be formally accepted by the CNSC prior to the submission of the PSA reports. As a basis for methodology acceptance, REGDOC-2.4.2 refers to the IAEA specific safety guides SSG-3 [10] and SSG-4 [11]. International best practice and standards, such as ASME-Ra-2009 [12], are also used.

Regarding the scope of the PSA, REGDOC-2.4.2 requires consideration of internal and external hazards as well as their potential combinations. The standard allows the use of alternative analysis methods for external events; however, the screening criteria of hazards shall be acceptable to the CNSC.

2. SCOPE

This paper summarizes the current HRA methodologies, already accepted by the CNSC, as implemented in the Canadian licensees' PSAs for internal and external hazards, specifically HRA for internal fire and seismic PSA. In addition, the paper will discuss some HRA challenges and their impact on the overall PSA results.

3. BRIEF HISTORY ON HRA METHODS DEVELOPED AND USED IN CANADA

In Canada, the development of models for the quantification of operator error has evolved from very simple models used in the early probabilistic studies of CANDU designs called the safety design matrices (SDMs) to more elaborate ones developed for Ontario Hydro's risk assessments and Atomic Energy of Canada Limited (AECL) PSA studies of research reactors. The human reliability model used in the SDMs was a three-stepped time-based model in which the probability of a post-accident human error was taken to be 1 if available time was less than 15 minutes, 0.01 if between 15 and 30 minutes, and .001 if greater than 30 minutes. These early studies did not focus much on pre-accident human errors, based mainly on the expectation that they could be considered adequately included in equipment failure data.

A detailed human interaction (HI) taxonomy was developed during the conduct of the Darlington Probabilistic Safety Evaluation (DPSE) in the early 1980s to characterize the various types of human interactions [7]. Quantification models were developed to obtain preliminary, or screening, estimates of both pre- and post- initiating event human error probabilities. The pre-initiating event models took into account the location where the error was postulated to occur (e.g., whether in the main control room, or field areas), the nature of the indications available to advise the operator of the occurrence of the error, and the likelihood of error recovery by either inspection of control room panels, field walkarounds, or periodic tests. Post-initiating event models considered the available time for action, indications received, and level of familiarity with the task. Basic human error probabilities (HEPs) were derived using the Technique for Human Error Rate Prediction (THERP) methodology and data provided in the Human Reliability Handbook [4].

Ontario Hydro's subsequent PSAs, such as the Pickering A risk assessment, the Bruce B risk assessment, and the Bruce A risk assessment have generally followed the DPSE methodology. However, improvements have been made in the application of the preliminary models by simplifying the models and making them plant-specific.

In 1995, AECL's Chalk River Laboratories developed a human error probability quantification method for use in PSA studies of the National Research Universal (NRU) reactor upgrades. Among its attributes were explicit considerations of performance shaping factors such as task unfamiliarity, design mismatch leading to misleading or ambiguous representation on control panels of plant conditions, lack of job aids such as schematics and checklists, poor feedback from actions, poor procedures, lack of checking, and information overload. It also incorporated a procedure for accounting for dependencies between human error events. The values of basic HEPs were determined based on a review of the various models described in the literature such as: the Systematic Human Action Reliability Procedure (SHARP) [17], the Human Error Assessment and Reduction Technique (HEART) [18] and THERP [4].

In 2001, AECL developed the HRA methodology for the Level 1 PSA of Point-Lepreau Generating Station in the province of New Brunswick. This methodology used the Accident Sequence Evaluation Program (ASEP) [2] for preliminary HEP quantification; and THERP methodology [4] for the final quantifications, for those human error actions that are dominant risk contributors.

4. OVERVIEW OF HRA IN EXTERNAL EVENTS PSA

Canadian Licensees, as part of their compliance with REGDOC 2.4.2, have completed the PSAs for the seismic, internal fires, internal floods, and high wind hazard groups. The PSA for the seismic events were completed either through a PSA-Based Seismic Margin Assessment (SMA), or a Seismic PSA (SPSA).
The CNSC regulatory document REGDOC-2.4.2 requires the licensees to seek CNSC acceptance of the methodology, including the HRA methodology, prior to the conduct of the PSA. While there is no

regulatory guidance related specifically to the HRA, there is a recently published Canadian Standards Association (CSA) Group standard, CSA N290.17, on *"Probabilistic Safety Assessment for Nuclear Power Plants"* [14] which includes high-level expectations related to HRA.

HRA methodologies, submitted by licensees as part of internal and external hazards PSAs are mainly based on existing HRA methods developed primarily for level 1 internal event PSA. The general approach consists of the following steps:

- Identification and definition: Within the PSA, operator actions typically come from one of two sources: 1) Human failure events (HFEs) already existing in the internal events PSA; or 2) new HFEs related to the modelled external event (such as seismic, fire or flood event).
- Qualitative analysis
- Quantification (preliminary and detailed)
- Model integration

The scope of the HRA for internal and external hazards is focused on the post-initiator operator actions. Pre-initiator operator actions are excluded from consideration since they are performed prior to an external event and are consequently not affected by this event. Therefore, their assessment remains the same as in the internal events PSA HRA.

Two different HRA approaches are generally used by Canadian licensees for seismic and internal fire PSAs and are discussed in the following subsections.

For HRA used in flood PSA, licensees use an HRA method similar to that which is used in the internal event PSA. However, the HEPs in flood model PSA are adjusted to account for the effects of flood including, equipment access restrictions, risk of electrocution, additional workload, stress and uncertainty in event progression.

5. HRA IN LEVEL 1 SEISMIC EVENT PSA

Canadian licensees have completed the PSA analyses of the seismic events either through a PSA-based seismic margin assessment (SMA), or a seismic PSA.

For the seismic HRA, it is reasonable to assume that the impact on human actions will vary with the strength of the seismic event. Thus, it is assumed that operators will be unable to perform required actions at seismic levels high enough to fail the building structure because they may be physically blocked by fallen debris. If some part of the building collapses, then the operators will be unable to perform actions, at least in that area. On the other hand, for very mild "g" earthquake levels, it is expected that there will be no degradation of the human action error probability if compared with the internal events PSA case. Regardless of the earthquake g level, most of the operators have not experienced a seismic event, and this can adversely affect their performance.

HRA used in seismic PSA is mainly based on existing HRA methods developed primarily for level 1 internal event PSA. HRA process for human error probability (HEP) in the seismic model includes the four following steps:

1. Identification of HFEs including:
    a. HFEs already modelled in the internal events model
    b. New HFEs related to the seismic events with the specification of the location of the action (in the control room, or in the field)
2. Characterization of the time available to perform each identified post-initiator action
3. Quantification of the post-initiator HEPs:

a. For existing HFEs, the seismic HEPs are obtained by multiplying the HEPs calculated as for internal events PSA with the performance shaping factors (multipliers).
b. For seismic specific HFEs, develop the HEPs consistent with the internal events methods and factor in the applicable performance shaping factors.

4. Model integration

As a first step, a review of human interactions (HIs) from the internal events PSA is performed to identify the post-initiator operator actions modelled as human failure events along with their associated human error probability (HEP). The operator actions that are identified to be part of the internal event PSA and that have been retained in the seismic fault tree logic are examined to determine the effect of seismic events on their quantification. As mentioned before, pre-initiator operator actions were excluded from consideration since they are performed prior to a seismic event and are therefore not affected by this event.

During a seismic event, the operator faces a complex situation due to the supplementary stress caused by the earthquake itself, random damage of systems and components, possible blockage of the seismic route, possible induced fires and floods, aftershocks, and likely impaired communications and control room indications. The time available for diagnosis and for execution is also likely to be lower than for internal events.

In accordance with international practice, Canadian licensees have used seismic HRA methodologies based on HEP multiplier approach to account for seismic HRA performance shaping factors (PSFs). The HEP multiplier is based on the time available, the location of operator action and seismic intensity.

Two different approaches have been used for the identification of HEP multipliers. In the first approach, no credit is given to the operator action in the field if the peak ground acceleration is higher than the design basis earthquake (DBE). In the second approach, used by some licensees, operator actions following seismic events higher than the DBE are credited with a high multiplier (up to a factor of 1000).

<u>In the first approach</u>, the seismic HRA methodology takes into account the influences of the intensity of the earthquake and of the elapsed time from the earthquake, separately for operator actions in the control room and for the actions on the field as follows:

- <u>Time from the earthquake:</u> Three intervals are considered: 15 to 30 minutes, 30 to 60 minutes, and more than 60 minutes.
- <u>If the action is located in the main control room (MCR) or secondary control area (SCA)</u>: the seismic hazard intensity is divided into four levels:
    - 0 to MCR design earthquake (MCRDE): for which MCR structure and functionality are maintained.
    - MCRDE to DBE: where the plant operation is performed from SCA which is designed for DBE.
    - DBE to margins in DBE (XDBE): A margin X provided by fragility analysis is considered for crediting operator actions in SCA.
    - > XDBE: The operator actions in SCA are not credited for earthquakes more intense than XDBE, when the access to SCA for the MCR operators and/or structural integrity of SCA is not demonstrated.
- <u>If the action is located in the field:</u> The credit for operator actions in the field are taken only when fragility analysis and/or the findings of the walkdown have indicated that there are sufficient margins for the unqualified structures that may be required for operator access or action. Credit for field actions will also depend on the timing of the required actions. The seismic hazard intensity is divided into three Levels:

    - 0–MCRDE
    - MCRDE–DBE
    - > DBE

Based on the combination of these factors, a HEP multiplier is developed. The multiplier varies from 1 to 10 depending on the severity of the earthquake, time available and the location of the action. The multiplier is a direct multiplier on the internal events HEP. This is used in the seismic PSA for each applicable seismic intensity bin.

In the second approach, the Seismic PSA uses the HRA analysis from the internal events PSA as the starting point for the seismic HRA input. The HRA for level 1 internal event PSA was performed based on reference [7]. As per this HRA method, operator actions are divided into three categories:

- Category 1 contains the simple pre-initiating event actions;
- Category 2 and 3 contain the complex interactions (which may be either pre- or post-initiating event).

The framework for the preliminary quantification of error probability of the post-initiator operator actions considers the following three important determinants, namely:

- Task type: Three types of tasks are considered – straightforward and/or familiar, average complexity and familiarity, very complex or unfamiliar.
- The quality of indication: This may be either unambiguous indication, requires interpretation, unclear, or non-existent (four possibilities).
- Time available for diagnosis and execution. This may be either unrestricted, greater than required, about equal to required, or less than required (also four possibilities).

The quantification process consists of determining the nature of a task based on each of the three characteristics, and assigning the error probability from the appropriate cell of a table with 48 cells, that has been developed to permit the selection of HEPs once the task attributes are established. The rationale and basis for quantification of complex human interactions is provided in [7].

The final quantifications are generally conducted using the THERP method [4].

The standard HRA method used in the internal events PSA was revised to address the effects of seismic motions on operator performance. The seismic motions range from minor ground motion to more extreme ground motion. The approach used for seismic HRA is to develop an integrated performance shaping factor (IPSF) representative of the seismic accident sequence and apply the appropriate factor to the individual internal events PSA HEPs.

The HEP integrated performance shaping factor (IPSF) approach used for the seismic PSA considered three primary issues as described in the following:

- Location of action: The first consideration is physical accessibility and takes account of the location where the action has to take place, the path taken to get there, and the characteristics of the pathway and the size of the earthquake. If a specific location dependent fragility is identified to cause access issues, then the operator action is not credited. The location of action is divided into three categories:
    - In the MCR or common SCA
    - Outside the MCR in seismically-designed buildings
    - Outside the MCR and outside a seismically-designed building
- Time available: Time available is divided into three time frames:
    - Less than 30 min.
    - 30 to 60 min.
    - >60 min.

- Ground motion magnitude: The third issue is the magnitude of the seismic event as it affects accessibility and personnel availability. The seismic hazard intensity is divided into three levels:
    - Low (<0.3g): in general for low intensity, HEPs from internal events are used
    - Moderate (0.3 to 0.7g)
    - High (>0.7g)

Subsequently, based on the combination of these factors, a HEP multiplier (IPSF) is developed. The multiplier varies from 1 to 1000 depending on the severity of the earthquake, time available and the location of the action. The multiplier is a direct multiplier on the internal Events HEP. This is used in the seismic PSA for each applicable seismic intensity bin.

6. INTERNAL FIRE PSA

The purpose of fire HRA is to identify, characterize, and quantify events representing human failures used in the development and quantification of a fire PSA model. Fire HRA includes modifications to existing HFEs from the internal events (non-fire) PSA to incorporate fire impacts and scenarios as well as the analysis of new fire HFEs to be included in the fire PSA model. The scope of the fire HRA focuses on post-initiating event human failure events. These are grouped into the following categories:

- Internal events HFEs: events accounting for actions from, or associated with, the internal events PSA, typically using the normal (non-fire) set of emergency operating procedures.
- Fire response HFEs: events reflecting failures of actions added to the fire PSA, typically from fire procedures, fire response plans or pre-plans. These actions include those associated with MCR abandonment.
- HFEs corresponding to undesired response to spurious actuation or spurious instrumentation.

In general, the fire PSA uses the HRA from the internal events PSA as the starting point for the fire HRA input. The HRA process for HEPs in the fire model is the same for all plants. It includes the four following steps:

1. Identification of HFEs from the following:
    a. HFEs from internal events model:
    b. Add new HFEs related to the fire events (Location: in-control room ex-control room)
2. Characterization of the time available to perform each identified post-initiator action
3. Quantification of the post-initiator HEPs:
    c. For existing HEPS, the fire HEPs is obtained by multiplying the HEPs calculated as for internal events PSA with the performance shaping factors (multipliers).
    d. For fire specific HEPs, develop the HEPs consistent with the internal events methods and factor in the applicable performance shaping factors.
4. Model integration

However, two different approaches for the HEPs quantification are used in Canada, depends on the site-specific PSA models.

In the first approach, the HRA in fire PSA consists of the development of an integrated performance shaping factor (IPSF) representative of the fire accident sequence and application of the appropriate factor to the individual internal events PSA HEPs. This approach is consistent with HRA modelling in the IPEEE for Zion and for Byron plants, references [5] and [6], which are plants constructed in the same period as the site using this method.

During fire events, operating’s staff access to certain locations for mitigating actions may be impaired. If the location in the field is not accessible, then that operator action is not credited. If the operator needs more time to access the location (for example, via alternate routes), then this supplementary time needs to be considered in establishing the time available for the action. Post-accident operator actions have been quantified according to the methodology established in the HRA for internal events PSA [2]. In particular, an additional factor (HEP multiplier) was applied to the HEP due to the increased stress experienced during actions required in areas affected by heat or smoke. The multiplier varies from 1 to 5 depending on the location of the action.

In the second approach as a first step, a review of HIs from the internal events PSA is performed to identify the post-initiator operator actions modelled as human failure events along with their HEPs.

An alternate approach based on NUREG/CR-6850 [3] was developed for the treatment of fire operator actions. Per this alternative approach, for each fire-related basic event that represents a post-initiator operator action modelled as human failure, HEP multipliers were developed for fire PSA adjustments. The method to apply the HEP adjustment considered the following factors:

- Location (either inside the MCR actions or outside the MCR actions);
- Time available (based on the site documentation): Three intervals are considered: less than 60 minutes, 60 to 120 minutes, and more than 120 minutes.
- Complexity of the action
- Cue availability (availability of instrumentation and path to equipment for field actions)

The treatment is expected to involve two iterations. The first involves the assignment of an appropriate multiplier value for the human error probability (HEP). And, based on the factors above, the HEP from the internal PSA may be retained, the HEP value may be multiplied by a factor varying from 2 to 30, or no credit for the operator action may be taken (failure of operator action assigned a probability of 1).
Following initial quantification, those operator actions determined to be dominant risk contributors are analyzed using more formal and structured HRA techniques.

7. HRA for emergency mitigation equipment (EME) deployment

After the Fukushima accident and the installation of EME, some licensees, mainly Ontario Power Generation (OPG) and Bruce Power (BP) developed a separate methodology for crediting EME in PSA "*Simplified Human Reliability Analysis Process for Emergency Mitigation Equipment (EME) Deployment"* [15]. The purpose of this methodology was to estimate the component of the human error probability (HEP) associated with the deployment of portable equipment or EME.

The EME deployment consists of the retrieval, transportation and installation of the EME, which is considered to include tasks such as making temporary piping and power connections or loading a portable generator. The actions to initiate operation of the EME equipment, once deployed, are performed entirely within the control room or using field actions required to initiate EME (e.g., opening manual valves), and these can be addressed by using existing HRA methods from internal events PSA.

This approach is intended for application to a variety of hazard risk assessments, specifically internal events, internal flooding, high winds, internal fires, external flooding, and seismic events.
This methodology is a simplified process that applies adjustment factors to represent the impact of performance shaping factors (PSFs) on a hazard-specific basis on a base human error probability (HEP). A failure probability of 1.0E-01 is assigned for this base HEP, which is consistent with a screening HEP from NUREG-1792 [16]. The impacts of each PSF are tracked in an HRA decision tree and the combined impact of all decision branches, which characterize the implementation conditions for the site being evaluated, determine the scenario-specific HEP.

8. HRA CHALLENGES

As described above, licensees have used the HRA from the internal events PSA as the starting point for external hazards. HEP multipliers approach has been used to account for external hazards HRA performance shaping factors (PSFs). This approach uses subjective multiplying factors which can have an impact on the overall PSA results, including the importance analysis and the identification of dominant human actions.

Assigning more representative HEPs for the human actions following the internal and external hazards would prove to be tedious as this should take into consideration many parameters that may not be easily quantifiable. These would include the consideration of the different stress levels, habitability issues, the degree of operator training and operator readiness to react in a proper manner.

In addition, recent research studies such as [13] list the set of potential PRA technology challenges identified posed by the events at Fukushima. Response events at Fukushima provide further evidence of the need for explicit treatment of errors of commission (e.g., the intentional isolation of the isolation condenser system at Fukushima Daiichi Unit 1), different decision makers (i.e., not the typical control room crew) who made potential errors in the prioritization of work, and potential psychological impacts on operators, advisers, and decision makers, recovery action feasibility and time delays, and the effects of long scenario duration (including fatigue, stress, and cumulative dose). New performance influencing factors may need to be included in HRAs to account for interruptions in response efforts due to external factors (at Fukushima Dai-ichi, earthquake aftershocks and tsunami warnings disrupted site operations as operators had to take shelter and then assemble for accountability), and the toll on operators.

4. CONCLUSION

The Canadian approaches regarding the human reliability analysis for internal and external hazards PSA are consistent with international practices and new developed guidance. These approaches mainly consist of multiplying the HEPs calculated for internal events PSA with multipliers to account for internal and external hazards performance shaping factors (PSFs). However, the use of the multipliers is somewhat subjective and not consistent across all the licensees. This can have an impact on the overall PSA results, including the importance analysis and the identification of dominant human actions.

Some challenges and special considerations are identified for the future HRA development for internal and external hazards and application. These challenges include the consideration of many parameters that may not be easily quantifiable, such as the different stress levels, habitability issues, the degree of operator training and operator readiness to react in a proper manner. This also includes the need for an explicit treatment of errors of commission as evidenced by the Fukushima accident.

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