INL/CON-17-41526
PREPRINT

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PSAM Topical Conference 2017, Human Reliability, Quantitative Human Factors and Risk Management

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March 2017

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Abstract: This paper uses the insights from the Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) methodology to help identify human actions currently modeled in the single-unit probabilistic safety assessment (PSA) that may need to be modified to account for additional challenges imposed by a multi-unit accidents. Additionally, this paper identifies possible new human actions that might be modeled to more accurately characterize multi-unit risk. In identifying these potential human action impacts, the use of the SPAR-H method is used to identify characteristics of a multi-unit accident scenario that may impact the selection of the performance shaping factors (PSFs). The lessons learned from the Fukushima Daiichi reactor accident are addressed to further help identify areas where improved modelling may be required. While these multi-unit impacts may require modifications to a Level 1 PSA model, it is expected to have much more importance for Level 2 modelling. There is little currently written specifically about multi-unit human reliability analysis (HRA) issues. A review of related published research will be presented. While this paper cannot answer all issues related to multi-unit HRA, it will hopefully serve as a starting point to generate discussion and spark additional ideas towards the proper treatment of HRA in a multi-unit PSA.

Keywords: HRA, Multi-Unit

1. INTRODUCTION

The 2011 reactor accident at the Fukushima Daiichi site has drawn significant attention to the analysis of site risk. Probabilistic safety assessments (PSAs) have traditionally focused on the risk associated with an event at a single unit. The Fukushima Daiichi event clearly demonstrated that multi-unit accidents can occur, and that existing PSA models might not adequately evaluate the total risk involved at a multi-unit site.

An international workshop on multi-unit PSAs was held in Ontario, Canada, in 2014 to bring together PSA professionals to discuss the challenges of multi-unit PSA. Participants from fourteen countries shared experiences and challenges related to implementation of multi-unit PSA at this conference. One of the significant findings of this workshop was that treatment of human actions and organizational dependencies in modelling multiple reactor accidents is one of the most important challenges in advancing multi-unit PSA [1].

Given the increasing emphasis on multi-unit risk, and the important role Human Reliability Analysis (HRA) plays in multi-unit modeling, this paper attempts to further characterize the state of practice and attempt to identify key considerations for HRA in a multi-unit PSA.

2. SUMMARY OF CURRENT TREATMENT OF HRA IN MULTI-UNIT PSA

Several countries are working to further develop techniques for addressing multi-unit risk. Some of these efforts have specifically addressed HRA, while others have acknowledged that more work is needed in this area. The following is not meant to be a complete list of multi-unit PSA efforts, but rather a sample of current efforts.

In a pilot study by the NUBIKI Nuclear Safety Research Institute to determine the feasibility of a site risk model at the four-unit Paks Nuclear Power Plant in Hungary, several HRA issues were identified. The team determined that decisions related to deployment of shared resources would need to be modeled. Additionally, this decision would likely occur after command and control had transferred to the emergency response team and would likely be guided by Severe Accident Management Guidelines (SAMGs) vs. Emergency Operating Procedures (EOPs). It was concluded that this in an important analysis area that is in need of further development [2].

The Republic of Korea is in the early stages of developing multi-unit PSA [3]. Several research studies are underway to determine appropriate methods for assessing site risk as well as establishing site based safety goals. This research is being divided between research institutes, universities, industry, and the regulatory authority. Korea has several sites with more than six units with plans to build more units so that a site will have up to nine units. In addition to having many units at a site, the population density is also relatively high near these sites. For these reasons, proper treatment of site risk is considered a priority in Korea. Current research activities are focused on quantifying site risk event frequencies, identifying dependencies between units, quantification of multi-unit risk models and establishing a roadmap for regulation of multi-unit PSA. Human error modeling is identified as one of the major issues in performing a multi-unit PSA [4].

The Canadian nuclear power fleet comprises twenty-two units. Out of these, twenty units located in Ontario are placed on three sites, Bruce Nuclear Generating Station with eight units (Bruce A and Bruce B, each with four units), Darlington Nuclear Generating Station with four units, and Pickering Nuclear Generating Station with eight units (Pickering A and Pickering B, each with four units). The remaining two units are single units, one in Quebec and one in New Brunswick. Currently, two units at Pickering A site and the single unit at Quebec are permanently defueled.

The Canadian Nuclear Safety Commission (CNSC) has indicated to the industry to provide a pilot project on whole-site PSA with the objective of characterizing the site-wide risk considering all reactor units, spent fuel bays, internal and external events and hazards for all operating modes. The industry works toward completing this pilot project by the end of 2017.

In the US, the most common site arrangement is two units, but there are also several three-unit sites, and a four-unit site is under construction. Multi-unit PSA is not currently required for the existing sites. The US Nuclear Regulatory Commission (NRC) is currently working on an integrated site Level 3 PSA research project [5]. This project is evaluating PSA methods to integrate risk from multiple operating units, in multiple operating states for multiple hazards with multiple end states. The results of this research will inform future decisions regarding site risk metrics.

3. MULTI-UNIT CHALLENGES TO HUMAN RELIABILITY

3.1. Human Events to Be Considered for Multi-Unit HRA

Multi-unit accidents pose additional challenges on operators that may not be currently modeled in a single unit PSA. These challenges may arise from constrained human resources, additional complexity in managing multiple scenarios from a common location, shared system prioritization, prioritizing the deployment of portable equipment, and others. Existing human events modeled in a single-unit PSA may need to be modified to account for multi-unit challenges and new human failure events may need to be added to support a multi-unit PSA. The degree of added complexity for multi-unit accidents will depend greatly upon the amount of inter-dependence between the individual units. This inter-dependence may come from the nature of the initiating event, the amount of shared systems/equipment or the amount of shared resources. There are additional challenges for HRA that arise from extreme external events that are not unique to a multi-unit analysis, but are likely to result in challenges to all units at a multi-unit site such as earthquakes, external floods, Loss of Offsite Power, etc. Current HRA methods may not treat extreme environmental challenges adequately, which will also then pose challenges for evaluating human reliability for certain multi-unit events.

Some considerations to be made in determining what new human failure events should be modeled:

- Are there additional complexities or opportunities for human errors due to a shared main control room? Conversely, are there additional opportunities for recovery afforded by other-unit operator resources in the main control room?
- Are there additional complexities or opportunities for human errors in deciding where to deploy shared systems initially or when to alternate between units, such as a shared emergency diesel generator (EDG) or makeup water systems?
- Is there an opportunity for human error for field workers performing a task on the wrong unit?
- What are the impacts on the time to deploy portable emergency mitigation equipment (EME) due to prioritization decisions and constrained resources?
- If a shared emergency response organization (ERO) is managing multiple accidents at different accident phases from the same location, are there opportunities for human error induced by staff changing focus between units?
- How will radiation/contamination from a damaged unit impact human actions at an adjacent unit in a different phase of accident progression?
- How are field workers affected by extreme environmental conditions associated with certain external events?
- How should decisions directed from SAMG guidance related to mitigation strategies be modeled? It may be necessary to model the probability of competing human decisions directed from the SAMGs rather than model a single human error probability (HEP).

This list is not intended to be all-inclusive, rather a starting point in evaluating HRA modifications that may be required when performing a multi-unit PSA.

3.2. Using SPAR-H to Evaluate Multi-Unit Human Events

The Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) [6] method was developed on behalf of the US NRC to support streamlined HRA evaluations in response to reportable events at US nuclear plants. The SPAR-H approach is focused on using eight performance shaping factors (PSFs) to account for human error precursors and quantify the associated HEP. In general, the shaping factors used in the SPAR-H method provide a structured means of evaluating HEP, supported mainly by the operational practice and programs experienced within a nuclear power plant (NPP) organization. SPAR-H was originally designed for design-basis events but has successfully been generalized to support severe accident analysis [7,8]. In the remainder of this paper, we now explore the applicability of SPAR-H to be used for HRA within multi-unit PSAs.

By continuing the employment of the same methodology to calculate the HEP of all types of PSA studies, SPAR-H facilitates selection of the multipliers and identifies the important PSFs of the specific action of a specific mitigation action. When an existing human action needs to be modified to account for multi-unit impact, identification of the PSFs with the major effect on the task compared to the single-unit event is easily identifiable and documented.

For new multi-unit human actions, using the same method as the single unit employed to quantify the HEP gives a better association to the operational practices and programs of the modeled NPP. If gaps are identified between operational practices and programs and the evaluated multi-unit shaping factors, a corrective action plan could be developed to close the gap. Following is brief discussion on how some of the SPAR-H PSFs may be impacted by the characteristics of a multi-unit event.

3.2.1 Available Time

The time available to perform mitigating actions may need to be updated to account for multi-unit dependencies. The available time is typically determined by thermal hydraulic analysis, and a deeper modelling of plant inter-dependencies may result in reduced time available for some mitigating human actions.

The time required for certain human actions may also need to be adjusted. Detailed task analysis is used to determine how much time will be required for modelled human actions. When command and control is shifted to the emergency response organization (ERO), additional delays in communication and decision making may be expected for multi-unit events. The time required for actions that occur outside the plant may be significantly impacted by external events. Since the exact nature of the impacts will be hard to estimate, a conservative estimate is recommended.

3.2.2 Stress/Stressors

Any event significant enough to induce multiple events at a multi-unit site can be assumed to place additional stress on operating crew. Multi-unit initiating events such as seismic, flooding, or high winds are likely to create additional physical hazards the will create stress for both decision makers and field workers attempting to perform recovery actions.

3.2.3 Complexity

Multi-unit accidents are likely to increase the complexity of certain decisions and actions. Increased complexity may be more pronounced in the early stages of an event for plants with shared main control rooms or plants with a high level of shared systems. In later stages of an accident, when command and control shift to the ERO, additional complexity will be encountered as communications need to be carefully parsed to the appropriate unit, and decision makers need to keep the status of multiple accident states clearly maintained. Operating experience has shown that there may be degraded plant instrumentation that needs to be compensated for. Accident conditions may drive certain plant instrumentation outside of its calibration conditions or instrumentation may fail due loss of support systems. Decision makers will be constantly challenged to verify all incoming plant parameters to determine their validity which will significantly increase the complexity of managing multiple accidents.

3.2.4 Experience/Training

Fortunately, no site has a high level of experience for managing multi-unit accidents. Some sites are now increasing the scope of ERO drills to include multi-unit scenarios, but given the widely variable nature of possible multi-unit scenarios it is not possible to train all crews on all possible scenarios. Adding the multiple combinations that would result from postulating accidents at various stages of and how that would impact adjacent units only compounds the challenge of training plant staff.

Credit for deployment of emergency mitigating equipment (EME) may require additional consideration. Training and practice on EME involves moving, installing and operating portable equipment. Even for stations with N+1 equipment availability, there may be limited human resources available to simultaneously deploy all the equipment. The decision makers should train to prepare for making complex prioritization decisions for multi-unit scenarios.

3.2.5 Procedures

For many actions that may be modeled in a Level 2 multi-unit PSA, the expected guidance may be coming from SAMGs vs. EOPs. Since the decisions that are likely to be made while operating from SAMGs are less prescriptive than for EOPs, the HEP will likely be higher. This is not necessarily different than the shift that occurs at a single-unit plant. However, the challenge of using the procedures may be compounded, because the state of an adjoining unit may compound the complexity of the situation, potentially exceeding the reasonable scope of the procedures. It is not possible for the SAMG to anticipate every circumstance of the single-unit event, and the multi-unit event introduces additional unknowns and a broader spectrum of faults that may not be expected to be covered by the procedure.

3.2.6 Ergonomics/HMI

There may be many unforeseen physical challenges that may result from many of the likely external events that may lead to a multi-unit accident. In addition to the environmental hazards for actions taken outside of the plant, there will be likely reductions in instrumentation and lighting that may not be explicitly modeled in the PSA. Human-machine interface (HMI) issues may lead to the possibility of an operator taking an action on the wrong unit in a multi-unit accident. An evaluation of plant labelling and processes should be evaluated in determining the possibility of taking actions on the wrong unit. Many of the challenges to human actions related to ergonomics or HMI arise from any severe accident and are not unique to multi-unit accidents however.

3.2.7 Fitness for Duty

It may be anticipated that multi-unit accidents will take longer to resolve than a single-unit accident. For long lasting events, crew fatigue may become a factor in performance. Actions that are likely to take place later in a scenario will more likely be impacted by crew fatigue than those that occur prior to core damage. Minimum crew staffing levels and the availability of relief workers will impact the level of fitness of workers for long duration scenarios.

3.2.8 Work Processes

Several work processes and organizational characteristic should be evaluated for multi-unit impacts. A few of the most relevant to multi-unit analysis include the readiness of the ERO to handle multiple accidents simultaneously and the plant staffing levels. ERO readiness for a multi-unit accident involves procedures that provide guidance for dealing with a multi-unit accident, staffing plans that account for expected resource requirements during a multi-unit accident, and ERO drills that test multi-unit accident readiness.

3.2.9 Suitability of SPAR-H for Multi-Unit Events

Overall, SPAR-H would be a suitable method for most multi-unit human actions that required quantification. SPAR-H was derived from THERP,[9] but whereas THERP provided fairly specific scenario look-up tables, SPAR-H mapped these to more generalizable PSFs. These PSFs are not limited to single-unit, design-basis events. The broad coverage of the PSFs makes it a method well suited for quantifying human errors for multi-unit and severe accident scenarios. For extreme environmental events, some additional method may be required simply because the PSFs have not been validated to such events, but by using each of the PSFs to evaluate an action, reasonable results may be obtained.

As an example, for a particularly challenging postulated human action during a multi-unit event, the PSFs may be evaluated as High Stress, Highly Complex, Low Experience/Training and Poor Ergonomics/HMI. This would lead to a HEP of 0.3, and given the uncertainty in conditions for these type of scenarios, it is probably a reasonable value.

While SPAR-H was not developed for the extreme events that may be encountered in a multi-unit scenario, it may be a viable option. Given the highly uncertain nature of these events, it is doubtful any HRA method could be proven to be more accurate than another. The highly likely answer is that expert judgement will be required to assign HEPs to certain events, and values between 0.1 and 1.0 might be expected. Using SPAR-H, at least in evaluating each of the PSFs to determine a HEP, some insights into the human action may be documented rather than using pure expert judgement in assigning an HEP. Additionally, using the same HRA method when performing Level 1, Level 2 and a multi-unit analysis may result in more consistent results and better identify organizational weaknesses that could be improved.

One risk in using SPAR-H or any other PSF-based HRA method is that the PSFs are not entirely independent. As such, there is the possibility of double-counting effects. This holds equally true for single- and multi-unit analysis. The high complexity of the multi-unit event clearly causes additional stress in the operators, and the inapplicability of some procedures may confront the inexperience of operators in dealing with some events. In both cases, the PSFs are essentially capturing the same underlying phenomenon, and it may not manifest as degraded conditions for both PSFs. Reasonable care must be exercised not to double-count PSF effects and ensure that multi-unit events do not result in inflated HEPs as a result.

3.3. Lessons Learned from Multi-Unit Operating Experience

There are several examples of multi-unit events that provide insight into potential human events that could be modeled in a multi-unit PSA such as the 2011 Fukushima Daiichi accident, the 2009 French loss of heat sink event, and the 2003 North American Blackout.

The recent push for improved modelling of multi-unit accidents was initially driven by the Fukushima Daiichi accident. Insights derived by analysis of this event are driving several improvements in the nuclear industry, including improvements in emergency response preparedness, installation of EME, and improved risk analysis. Several aspects of the response to the Fukushima Daiichi accident relate to HRA for a multi-unit PSA. The Fukushima accident can be classified as an external flooding event leading to station blackout at four units. Extensive site damage from the tsunami created additional challenges for operator recovery actions. There were significant challenges to the decision making of the ERO including confusion caused by managing multiple reactor accidents, lack of information reported to the technical support center (TSC), and difficulty in deploying EME. Extreme stress was placed on operators due to both the reactor accident event as well as concern for family members affected by the tsunami. The difficult conditions at the site from the tsunami damage added additional time to the normally required time to take actions. There was a high level of complexity as decision makers attempted to prioritize the deployment of pumper trucks between units in varying accident stages. It was certainly recognized that the experience and training level of the ERO was not adequate to handle multiple reactor accidents simultaneously. Operators attempting to perform recovery tasks were hampered by poor lighting and lack of instrumentation. Operator fitness for duty was challenged as the duration of the reactor accident far exceeded normal work periods and operators stayed on site for several days.

The French nuclear industry has placed a focus on potential loss of heat sink as a likely multi-unit initiating event. In 2009, a large ingress of vegetable matter caused a loss of the heat sink at the Cruas NPP [10]. This event followed several previous events where the heat sink had also been threatened by external hazards. In the 2009 event, there was blockage of the entrance to the pumping station to units 3 and 4, resulting in a total loss of heat sink at unit 4 and a partial loss at units 2 and 3. The national crisis organization was activated during this event. The duration of the loss of heat sink was approximately 10 hours. Lessons learned from this event have prompted several improvements for French plants, including improvements to accident procedures to deal with multi-unit loss of heat sink and loss of external power supply. Additionally, improvements in on-site emergency planning for multi-unit accidents were made.

On August 14, 2003, a large power outage occurred in Northeastern United States and parts of Canada, causing a loss of offsite power (LOOP) for many plants, seven US sites with nine NPPs (Fermi2, Fitzpatrick, Ginna, Indian Point 2 and 3, Nine Mile 1 and 2, Perry, Oyster Creek) and three Canadian sites from Ontario Province (Bruce, Darlington, Pickering) with twenty NPPs affected [11]. There are two other NPPs in Eastern Canada, one single unit in New Brunswick—Point Lepreau—which responded with power de-rating and recovered within 30 minutes, and the second single unit is Hydro Quebec, which continued to operate normally as the grid was not affected by the disturbance. A summary of the Canadian plant response is found in Table 1.

Table 1. Summary of Plant response for Canadian NPP

NPP	Unit	Operating Status	Turbine Trip	Reactor Trip	Stepback to 60%FP
Pickering A	1	Not operating			
	2	Not operating			
	3	Not operating			
	4	Start Up		SDS1	
Pickering B	5	Full Power	TT	SDS1	
	6	Full Power	TT	SDS1	
	7	Start Up		SDS1	
	8	Full Power	Manual TT	SDS1	
Darlington	1	Full Power	TT	SDS1	
	2	Full Power	TT	SDS1	
	3	Full Power	TT		Supplied the grid
	4	Full Power	TT	SDS1	
Bruce A	1	Not operating			
	2	Not operating			
	3	Not operating			
	4	Not operating			
Bruce B	5	Full Power	TT		Supplied the grid
	6	Full Power	TT	SDS1	
	7	Full Power	TT		Supplied the grid
	8	Full Power	TT		Supplied the grid
Point Lepreau	1	Full Power			De-rated to 460MW [from 680MW] for 25minutes

Following the review of the data provided by the Canadian nuclear power plants, the Task Force concluded that:

- None of the reactor operators had any advanced warning of impending collapse of the grid.
- Canadian nuclear power plants did not trigger the power system outage or contribute to its spread.
- There were no risks to the health and safety of workers or the public as a result of the concurrent shutdown of several reactors.
- Automatic safety systems for the turbine generators and reactors worked as designed.

As a result of further information about the event progression and mitigation, CNSC staff conducted follow up investigations. The corrective actions and lesson learned applied to the operational performance. Some HRA related improvements are:

- **Procedure Improvements** of Symptom based procedure (i.e., Critical Safety Parameter Monitoring), where monitoring of Reactor Outlet Header (ROH, similar to hot leg concept) temperature has been added to existing Reactor Inlet Header (RIH, similar to cold leg concept) temperature monitoring. The temperature difference is an indication on core cooling effectiveness.
- **Training -** Develop a tabletop simulation of the event for future training
- **Command and control** was challenging due to:
    - roles and responsibilities were unclear
    - loss of power in Site Management Center (SMC) and technical support
    - sporadic communication equipment and information technology were available

- Less than adequate communication protocol and interface with Independent Market operator IMO and Hydro One

Overall, the 2003 North American Blackout event showed that while all the stations were able to cope with the event, there were some multi-unit issues identified and improvements made to better deal with this type of event.

4. CONCLUSION

Site level risk analysis is becoming increasingly important. Several initial studies into performing a site level PSA have identified HRA as a challenge for improving the state of the art. In attempting to determine what human actions should be modeled in a multi-unit PSA, there have been several industry events that may be studied. Some human actions that will be modeled in a multi-unit PSA will arise due to the modeling of inter-unit dependencies between units while others will arise from the additional challenges multi-unit accidents will impose on operators. Once the required human actions are identified, they will need to be quantified. Existing HRA methods may be adequate to quantify multi-unit human actions if the characteristics are properly accounted for. In this review, the SPAR-H shaping factors could be mapped to the expected characteristics of multi-unit scenario that would affect human reliability. Other HRA methods would likely also support the quantification of multi-unit human actions as long as the additional challenges are accounted for. There may be certain human actions that current methods were not designed to quantify, especially those that occur in extreme conditions that may result from external environmental events such as seismic, flooding, or high winds. Analysts may either decide to substitute expert judgement or modify an existing HRA method to address any shortcomings.

Acknowledgements and Disclaimer

This work has been supported by the Canadian Nuclear Safety Commission. The opinions expressed in this publication do not necessarily reflect those of the Canadian Nuclear Safety Commission. This paper is prepared under an international cooperative agreement for the purpose of exchanging technical information. This study is intended for research purposes only, may be preliminary, and certain procedures described may be untested. The research paper is purely for information purposes. The paper also includes analysis and views expressed by the research team. The recipients of this material should take their own professional advice before acting on this information.

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