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EXTERNAL MULTI-HAZARD PROBABILISTIC RISK ASSESSMENT METHODOLOGY AND APPLICATIONS: A REVIEW OF THE STATE-OF-THE-ART

Harleen Kaur Sandhu[1], Parth Patel[1], Abhinav Gupta[2], Yoshinori Mihara[3]

[1] Doctoral Student, Department of CCEE, North Carolina State University, USA (hksandhu@ncsu.edu)
[2] Director, Center for Nuclear Energy Facilities and Structures, North Carolina State University, USA
[3] Senior Manager, Nuclear Power Department, Kajima Corporation, JAPAN

INTRODUCTION

United States Nuclear Regulatory Commission (USNRC, 2009) defines probabilistic risk assessment (PRA) as the science used to examine the risk posed by a complex system and to identify the key problems with the most impact on safety. A PRA helps in identifying a nuclear power plant's strengths and weaknesses in managing operational and emergency conditions. A risk assessment should identify and analyze the initiating events, the safety functions and the accident sequences. A PRA is used to observe the frequency and consequences of an unsafe and unstable end-state for a nuclear power plant. Therefore, risk can be attributed to two factors: frequency of an undesired event and the subsequent consequences to safety as represented by the following Equation 1 (EPRI, 2011):

$$Risk\left[\frac{Consequence\ Magnitude}{Unit\ of\ Time}\right] = Frequency\left[\frac{No.of\ Events}{Unit\ of\ Time}\right] * Consequences\left[\frac{Consequence\ Magnitude}{No.of\ Events}\right] \quad (1)$$

In the nuclear industry, the overall risk is typically categorized in the context of risk associated with Core Damage Frequency (CDF), Large Early Release Frequency (LERF), and Radiological consequences to public. Consequently, PRA methodology is classified into three levels (EPRI, 2011) as:

- Level 1 PRA: Determines the response of the plant systems and operators to the initiating events; Outcome: Core Damage Frequency (CDF)
- Level 2 PRA: Determines the risk of nuclear power plant containment failure;
  Outcome: Large Early Release Frequency (LERF)
- Level 3 PRA: Determines the consequences to public health;
  Outcome: Estimation of radiological consequences to public, and economic losses.

Probabilistic Risk Assessment is an advantageous tool because of the rigorous and systematic analysis, integration of available information on a plant, consideration of complexity in the hazard interactions, developments of qualitative designs and quantitative decision-making measures, provision for formal sensitivity studies, and the identification of major sources of uncertainty. PRA methodology results in reduction of vulnerabilities, which successively results in the enhancement of existing nuclear plant designs. When a nuclear plant is in operation, multiple systems must be maintained, and the PRA models help facilitate risk reduction.

CONSIDERATIONS OF MULTIPLE HAZARDS IN PRA

IAEA (International Atomic Energy Agency) Studies

Following Fukushima-Daiichi Nuclear Power Plant incident in March 2011, an Action Plan for IAEA was developed in order to reinforce the existing and future global nuclear safety framework. In November 2011, IAEA responded by submitting a report titled "A Methodology to Assess the Safety Vulnerabilities of Nuclear Power Plants against Site Specific Extreme Natural Hazards" (IAEA, 2011). In the light of the Fukushima-Daiichi nuclear incident, the nuclear industry has discovered that the operator management of an accidental situation at a Nuclear Power Plant is as important as the performance of all safety significant SSCs (structures, systems, and components) in the event of an extreme natural hazard.

This study (IAEA, 2011) focuses on seismic hazards and flooding hazards, but the methodology can be formulated and extended for other IAEA characterized external hazards. Short-term assessments and detailed long-term assessments are integrated in this proposed safety assessment methodology. It is required that the assessment consider the external seismic and flooding hazards at a minimum, and include any other hazards, such as geotechnical, meteorological, human induced and volcanic, as appropriate. This proposed assessment is aimed at determining:

- if the plant is up-to-date on the potential external hazard sources, and the corresponding design basis of the plant is adequate.
- if the above-mentioned design basis of the plant is being exercised.
- the consequences of surpassing the above-mentioned design basis of the plant.
- the modifications required in the event of an external hazard at the plant site.

The safety assessment proposed in this study utilizes two types of methodologies: the deterministic Seismic Margin Assessment (SMA) and the Seismic Probabilistic Safety Assessment (S-PSA). This report (IAEA, 2011) describes the effect of time on the safety assessment. Moreover, it classifies the safety assessment into two categories:

- Short term hazard assessment: The hazards can be characterized by utilizing relevant expert judgement and conservative assumptions, such that the estimated hazards should be in accordance with the IAEA safety standards. This may result in a higher hazard level when compared to the long-term hazard assessment.
- Long term hazard assessment: The hazard parameters can be evaluated by incorporating the guidelines issued by IAEA safety standards and authenticated industry practice in a thorough analytical approach.

While this report appears to adequately address most of the elements in a nuclear plant safety analysis, IAEA submitted another report in 2017 (IAEA, 2017), in response to the additions expressed by the member states to the initial report submitted in 2011. The methodology presented in this safety report generalizes the process for a much wider range of external events such as, earthquakes, floods, explosions and hazardous releases, high winds and hurricanes, and aircraft impact. It identifies the importance of logic diagrams (success paths, event trees and fault trees) along with the flexibility to include multi-hazard scenarios. The safety report (IAEA, 2017) gives a detailed explanation on the following topics:

- Identification of relevant site-specific external hazards and their combinations. It also describes various methods to perform screening on the selected hazard scenarios;
- Identification of the SSCs to be evaluated as a part of the vulnerability assessment, and the approaches to be undertaken for the same (Success path approach or Event tree/Fault tree approach);

- Development of a general methodology for the assessment of a nuclear plant. This approach is further elaborated with respect to the five hazards as specified above;
- Description of a procedure to obtain risk estimation from the afore-mentioned capacity assessment. An understanding of the obtained results is also detailed.
- Finally, the establishment of a qualified team for the vulnerability assessment is also illustrated.

IAEA (2017) provides the basis to consider correlation between various external hazards and hence, it can be a valuable tool for future multi-hazard probabilistic risk assessments. Although this report adequately addresses most of the shortcomings of the previous vulnerability assessment report, it can be further enhanced by incorporating internal extreme hazards like pipe failure and flooding, internal fire, etc., and considering credible combinations of the external and internal induced hazards.

The importance of considering the combined effect of external hazards on single unit and multi-unit nuclear power plants as a part of the probabilistic safety assessment (PSA), as a complement to the existing IAEA Safety Standards, is explained in another safety report (IAEA, 2018). The external hazards being considered should include seismic hazards as well as flooding and heavy winds. The PSA methodology for single unit and multiple unit NPPs (Nuclear Power Plants) should incorporate an initial screening of hazards (external and induced) and their realistic combinations, as is provided in this Safety Report. The consequences of induced hazards (defined as hazards that are caused due to or soon after an initiating external hazards) are also included in this study.

USNRC (United States Nuclear Regulatory Commission) Studies

In the light of events at Fukushima-Daiichi Nuclear Power Plant, USNRC (2012) encourages the use of PRAs in the NPP design and maintenance activities. According to USNRC, the licensed NPPs should also be expected to develop, maintain and periodically update and enhance their PRAs throughout the operating life of the reactors. The PRAs are also expected to include the results for internal hazards as well as external hazards. USNRC expects NPP licensees to perform and update their seismic and flooding hazards once every 10 years.

Another USNRC study (Cooper et al., 2013) focuses on the need to develop and enhance the existing HRA (Human Reliability Analysis) techniques that are used in the probabilistic risk assessment. It illustrates the problems that will be encountered by the current HRA procedures, given the multi-hazard Level 3 PRA project by USNRC (Kuritzky et al., 2012). Previously, the HRA used to concentrate on at-power, internal initiating events, and operator actions that were taken when the emergency operating procedures were being followed. The new challenges to HRA will be faced due to the use of different procedures, a shift from the traditional decision-making responsibility by operator, multi-hazard scenarios and corresponding operator actions, effects of environmental events on control room actions, and insufficient manpower for multiple hazards.

USDOE (United States Department of Energy) Studies

A US-DOE study (Gencturk et al., 2016) illustrated the importance of a probabilistic multi-hazard assessment for the storage units of spent nuclear fuel. Currently, almost all the spent fuel is stored in temporary/short-term storage facilities such as dry cask structures and spent fuel pools. When we consider the absence of long-term storage facilities and solutions, we comprehend the significance of maintaining and strengthening the existing nuclear waste storage units such that they can withstand any current or future catastrophic consequences. Vertical reinforced concrete dry cask structure and the corresponding probabilistic multi-hazard assessment through an experimental and numerical study, is the focus of this report (Gencturk et al., 2016). As a part of the experimental study, three models of a concrete cask structure were fabricated. The combination of aging and mechanical loading was considered for the long-term performance of the structures, and the process of aging was calculated by the material level analysis of the concrete model. Thermal analysis was carried out for varying seasons and temperatures, and the degradation of the models was observed and investigated over a period of two years. As a part of the numerical study, the seismic and impact analysis of the cask structures was carried out and incorporated into the proposed methodology.

The probabilistic multi-hazard assessment framework (Zhou et al., 2013) was developed for the impact analysis and seismic analysis of the structure. Various aleatoric and epistemic uncertainties were included in the probabilistic analysis models such as: hazard parameters, ground input motions, structure material, soil and pad properties, structure-pad interface friction etc., to evaluate the conditional and the total probabilities of failure for all the hazards. Finite element models of the cask structures are utilized to study the response of the structures to seismic and impact loads. As a result, the seismic fragility curves (Limit State: Sliding and tip-over) and impact fragility curves (Limit State: tip-over) are obtained.

The technical pathway towards Risk Informed Safety Margin Characterization (RISMC) is comprised of a new set of tools and methods which are also known as the “RISMC toolkit” (Szilard et al., 2016). As the demand for a better and advanced PRA technique is on the rise, the virtual RISMC toolkit is aimed at aiding the quantification of a Nuclear Power Plant’s performance. Coleman et al., (2016) demonstrates the capabilities of some of these tools for the application of multi-hazard Risk-Informed Margin Management (RIMM).

The overall objective of the RISMC toolkit is to provide an economical aging management of the NPPs, as well as improving the safety and reliability of NPPs over long periods of operation. The advanced features of this toolkit are intended to enable probabilistic risk assessments due to primary external hazards such as earthquakes, floods, hurricanes, etc., as well as the secondary external hazards such as landslides, dam failures, induced internal flooding and fire. It is intended to help combine the state-of-the-art procedures with reliable industry experience and other data gathered over the past few decades. RISMC toolkit, a multi-hazard PRA toolkit, is still in the preliminary stages of development. A unique aspect of this study relates to the illustration of seismically induced internal flooding scenario and the corresponding risk assessment.

Other Studies

A report by the National Academy of Sciences (2014) highlights the importance to update the risk calculations in nuclear power plants every few years. Burgazzi et al. (2014) highlights the gaps in existing PRA methodologies, as realized after the Fukushima accident, such as multi-hazard risk assessments that include combinations of various external initiating events, risk assessment of nuclear plant sites with more than one reactor unit and accidents in the performance of existing safety systems. A few external event combinations are described and defined as Common Cause Initiating Events (CCIE): seismic activity and tsunami (events with the same origin), seismic induced fire (cascading events) and strong winds and heavy rains (correlation between events). Westen et al. (2011) provides a good summary of the various steps involved in this process.

Ebisawa (2015) describes an approach to evaluate core damage frequency considering correlation of failure at multiple units and sites, due to a strong seismic input ground motion. Another study by Kim et al. (2017) aims to shed light on the existing multi-unit risk assessment approaches. In addition to considering multiple reactor units, this study also highlights the necessity to consider multiple spent fuel pools in the risk analysis. A recent study focuses on the Level 2 PSA of a six-unit nuclear power plant site (Cho et al., 2018). A multi-unit Level 2 PSA methodology is proposed and applied to a full-power operating six-unit OPR1000 reactor site. For future work, this study recommends incorporating various inter-unit interactions and subsequent impacts on the total risk evaluation. It also points out that different types of reactor units and operational modes should be considered.

Another study aims at developing a risk assessment approach for an earthquake-induced landslide event at a nuclear power plant (Kwag and Hahm, 2018). The analysis results observed a significant risk to the core damage frequency due to the peripheral slope failure and subsequent run-out effects.

MULTI-HAZARD RISK ASSESSMENT FRAMEWORKS

Multi-hazard scenarios have not been considered in traditional PRA studies because the possibility of simultaneous occurrence of two different extreme events such as earthquake and hurricane or earthquake and flood is extremely rare and almost impossible. However, there have been several instances of closely-related multiple hazards that have resulted in significant damage or a major disaster. One may argue that such a multi hazard scenario is quite rare and limited to very specific regions in the world. On the other hand, there are many instances of significant damage or a major disaster due to seismically induced internal flooding such as those due to failure of fire piping or tanks in a hospital or other industrial facilities. Only a limited number of studies have been conducted to consider multi-hazard scenario in the design or risk-assessment, such as: Ellingwood (2001), Ayyub et al. (2007), Li and Ellingwood (2009), Beavers et al. (2009), and Kameshwar and Padgett (2014). The common theme in all these studies is that the risk is calculated for each individual hazard using the traditional approach wherein the hazard curve is convoluted with the fragility data. The effect of multiple hazards on the overall risk is computed by using the total probability theorem.

The fundamental assumption in using the total probability theorem is that individual hazards are statistically independent, mutually exclusive, and collectively exhaustive. Therefore, it cannot be used for assessment of risks associated with multi-hazard scenarios such as seismically induced internal flooding or flooding induced fires in which the undesirable response of the plant to one hazard acts as the initiator of another hazard making them correlated events. Traditional PRAs do not exhibit such correlated events because failures of these nature are not encountered in a plant that is well designed to withstand the design basis events. On the contrary, identifying and suppressing such events are the primary reason for the strong emphasis on evaluating vulnerability beyond design basis. The response of a plant’s structures, systems, and components to beyond design basis events is quite different from that to the events at or below the design basis levels. Consequently, there is need for developing multi-hazard risk assessment methodologies to account such correlated events beyond the design basis levels and to determine a plant’s vulnerability. As additional studies are conducted, and new data becomes available, such methodologies should allow easy and continued updating of plant risk.

Design and retrofit approaches for multi-hazard scenarios have received considerable attention in recent years. However, the concept of multi-hazard analysis is quite broad and the nature of existing studies varies across a wide spectrum of problems (Kappes et al., 2012; Barbato et al., 2017). In some cases, the focus is on hazards that either occur simultaneously or are closely correlated with one another (Rathje and Saygili, 2009; Asprone et al., 2010; Wang et al., 2013; Kwag, 2016; Kwag and Gupta, 2016; Kwag and Gupta, 2017), such as flooding and fires that are induced by the same seismic event. In other cases, multi-hazard studies relate to hazards that are not dependent or correlated but have a strong likelihood of occurrence at different points in the lifetime of a structure (Ellingwood, 2001; Li and Ellingwood, 2009; Potra and Simiu, 2010; Beavers et al., 2009; Kameshwar and Padgett, 2014). Design and retrofit assessments for earthquake and extreme wind hazards fall within the latter category.

The concept of Bayesian networks for multi-hazard risk assessments has been investigated by a few researchers and it has provided promising results in this field. Wang et al. (2013) provided a methodology to develop powerful earthquake disaster chains by using Bayesian networks. This study summarized 23 earthquake disaster chains including the serial, parallel and the serial-parallel chain types. A Bayesian network model for a disaster chain, as earthquakes, landslides, barrier lakes and floods, is constructed and the most critical links are identified using probabilistic inference. This paper also describes the Bayesian network concepts in detail and how to apply to the disaster chain concepts.

A study by Kwag and Gupta (2017) introduces a Bayesian framework for PRA of structural systems under multiple hazards. This framework allows for consideration of correlations and dependencies between various initiating events and for updating the framework to incorporate newly collected data at any level. The study focuses on the use of Bayesian statistics for the probabilistic risk assessment of structures under multiple hazards. A systems analysis for a traditional PRA usually consists of fault tree analysis and event tree analysis. Instead, a Bayesian network with Bayesian inference is used to conduct a multi-hazard risk assessment in this paper by mapping the conventionally used fault tree approach into the Bayesian network

The mapping typically involves two steps, graphical representation and numerical computation. First, all events in a fault tree - the basic, intermediate, and top events - are converted into the nodes of BN. The basic events map into the root nodes of a BN and the intermediate events map to child nodes of the root nodes. The top event of a fault tree maps into a child node of basic and intermediate events. For numerical computation, the probabilities of the basic events in a fault tree are assigned to the marginal probabilities of the root nodes of BN. For the intermediate and top events of fault tree defined by gates, the conditional probability tables (CPTs) are established at corresponding child nodes of BN. An example of a simple fault tree and corresponding mapped Bayesian network is illustrated in Figure 1 (Kwag and Gupta, 2017).

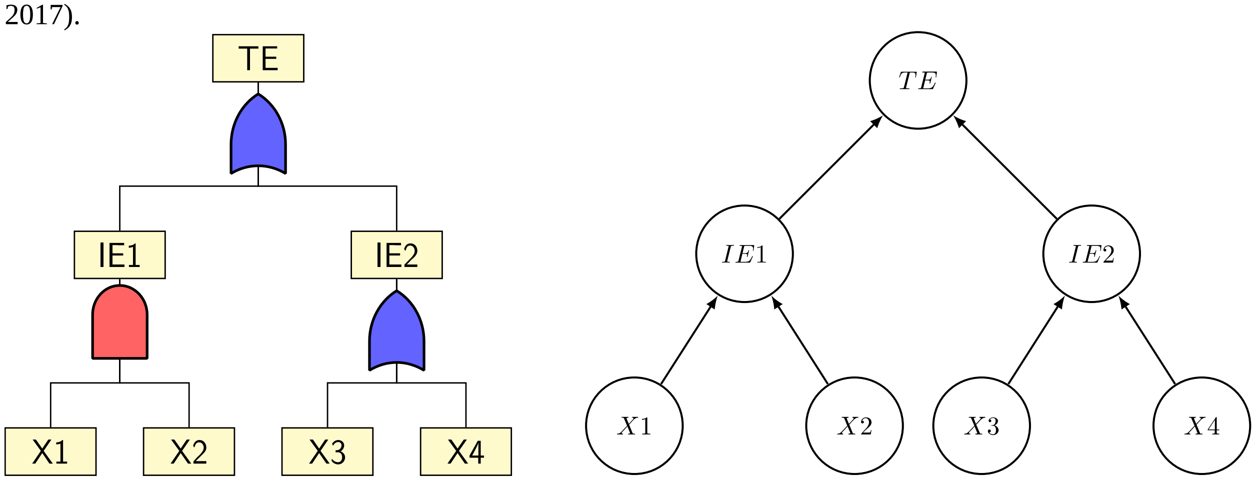

Figure 1. Example of Simple Fault Tree (left) and Corresponding mapped BN (right)
(by Kwag and Gupta, 2017)

It is noteworthy that the mapped BN from the fault tree have the specific conditional probabilities consisting of binary values 0 and 1, which is a special case of BN. Unlike the fault tree, the BN can be extended to more general problem by using non-binary values in the CPT within the same BN structure or creating arcs among the nodes for representing the correlation of events. Incorporating Bayesian inference provides a new way to explore system-level vulnerability. It is likely that the system level vulnerability may produce different results than the original one due to consideration of correlation and dependency between the initiating events. This method can also give better results for scenario with a single hazard since it will allow for consideration of the correlation between multiple failure modes of various SSCs of an NPP. This paper further illustrates the approach by employing it for a single hazard PRA and a multi-hazard PRA (earthquake, high winds and flooding). A correlated seismically induced internal flooding hazard scenario is also highlighted as a part of this study.

EARTHQUAKE INDUCED EXTERNAL FLOODING HAZARDS

Jang and Yamaguchi (2018) proposed a dynamic PRA approach for considering earthquakes and internal flooding events. The Kewanee nuclear power plant in the United States was selected for the case study. It is assumed that an earthquake induces a tube rupture in the power plant and a numerical simulation is carried out for incorporating internal flood propagation. The continuous Markov model and Monte Carlo methods are utilized in the proposed approach in order to generate the accident scenario quantification.

Another study was recently conducted to include the accident-sequence analysis methodology considering seismic-tsunami events (Muta et al., 2018). The paper proposes a PRA approach for seismic-tsunami events by characterizing the dependencies and correlations between various nuclear power plant SSCs; creating logic trees for failure of SSCs leading to nuclear core damage; and modeling of an intermediate state (degraded state) between the normal and failure state of the core-damage logic tree. The proposed model is applied to the reliability analysis of parallel and series systems. The paper indicates future research to be carried out by applying this technique to a realistic nuclear power plant model and to incorporate actual external hazard data in the process.

FUTURE WORK RECOMMENDATIONS

As can be inferred from the discussion above, the field of multi-hazard PRA is still developing and much of the research is still in its infancy. There is significant work needed before a consensus approach can be agreed upon. Based on the review of literature as outlined in detail above, a few aspects stand out that need further investigations are listed below. It should be noted that the following items are not in any order of importance.

1. **Cascading Events**: A key observation relates to primary shortcoming of treating different hazards independently. Events in individual hazard PRA can be correlated and eventually change the critical path. Subsequently, one can exhibit cascading events which otherwise get ignored. Such scenarios are critical to identify. More work is needed to develop appropriate methodologies to address this issue. Bayesian network based methodology is a good candidate to address this issue but additional research is needed to fully develop its capability as well as identify key limitations. The negative impacts on the system can also be analyzed with a consequence/impact analysis and the cascading events can be visualized using fault trees and event trees. The applicability of importance measures in the fault tree analysis should be investigated, in order to draw attention to the initiating event with highest cascading impact.

2. **Uncertainty Quantification**: A key aspect of multi-hazard PRA relates to appropriate modeling and quantification of uncertainties. If conservative assumptions are made to address uncertainties then the whole outcome of a multi-hazard PRA changes and its benefits are lost. Therefore, it quite important to identify critical interdependent events and the uncertainties in the characterization of failure/performance for these events. It is important to address epistemic uncertainties at parameter level as well as epistemic uncertainties at science/mechanistic level by improving the mechanistic models.

3. **Multi-Limit States**: As the approaches for correlated events develop further, it might be necessary to identify correlations between multiple different limit states of an SSC.

4. **Role of Multi-hazard PRA in Decision Making under Accident and Emergency Conditions (Level 2 PRA)**: This is one area where a multi-hazard PRA can make greatest impact. As evident from many events in both nuclear and non-nuclear applications, the operators or other decision makers are often left clueless under a multi-hazard scenario. All training procedures relate to single hazard. It is very

essential for the decision makers to understand what SSCs in plant are related to cascading failures under a multi-hazard accident scenario. It is also important to relate the real time plant data under such extreme conditions to the potential strategies of mitigation and rank different options based on the prior knowledge, plant data, and simulation data. However, doing so in real time is almost impossible given the response of time of any search algorithm under such a vast set of possible scenarios. It is possible to address this concern through the use of Bayesian networks and a network of networks approaches wherein each hazard PRA is one network and a multi-hazard PRA represents network of networks. Instead of using Boolean conditions of survival and failure, it would be important to characterize appropriate fragilities for initiation of various internal events such as LOCA as well as the degree of performance (minor, moderate, or severe). A consideration of such fragilities has the potential to change the strategies of severe accident management – especially in the context of Level 2 PRA.

5. **Role of Dynamic Bayesian Network in PRA:** In conventional PRA methodologies, Event trees and Fault trees are widely used to analyze accident scenarios. Dynamic event trees are employed to capture the transient behavior of the events. However, these trees have limitations in certain applications such as: (1) statistical correlations between basic events, (2) nonbinary or distributional relationship between intermediate and basic events, (3) more than one initiating event (multi-hazard), (4) little or no experimental data available for some events, (5) treatment of uncertainty quantification, (6) incorporation of additional data, and (7) time dependencies between variables. Dynamic Bayesian networks (BN) have been successful in addressing these issues through a unified single formulation. Mapping algorithms are required to transform the conventional fault trees and event trees into a BN, and dynamic event trees into a dynamic BN.

6. **Role of FLEX Equipment in PRA:** FLEX equipment is a portable power-generating equipment that is stored at a pre-selected geographical location, as is identified with almost zero probability of occurrence of natural disasters. FLEX equipment provides an effective alternative cooling method in case of a severe accident due to natural hazards. It can alter the risk profiles and can significantly decrease the core damage frequency (CDF). However, the effectiveness of FLEX depends on the accident scenario and the time available to setup the equipment at plant.

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