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Advances in multi-unit nuclear power plant probabilistic risk assessment

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ABSTRACT

The Fukushima Dai-ichi accident highlighted the importance of risks from multiple nuclear reactor unit accidents at a site. As a result, there has been considerable interest in Multi-Unit Probabilistic Risk Assessment (MUPRA) in the past few years. For considerations in nuclear safety, the MUPRA estimates measures of risk and identifies contributors to risk representing the entire site rather than the individual units in the site. In doing so, possible unit-to-unit interactions and dependencies should be modeled and accounted for in the MUPRA. In order to effectively account for these risks, six main commonality classifications—initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies—may be used. This paper examines advances in MUPRA, offers formal definitions of multi-unit site risk measures and proposes quantitative approaches and data to account for unit-to-unit dependencies. Finally, a parametric approach for the multi-unit dependencies has been discussed and a simple example illustrates application of the proposed methodology.

1. Introduction

Nuclear power plants consisting of more than one unit and other radioactive inventories are not formally evaluated in an integrated manner in the traditional Probabilistic Risk Assessment (PRA). Most PRAs are based on single-unit PRA evaluations that don't provide a complete picture of all possible accident sequences and radioactive sources to assess the radiological risk arising from severe events on the site. Models for accident sequences involving concurrent releases from multiple radiological sources on the site are still in their infancy. Although the risk triplet [1] defined from a general perspective also applies to the multi-unit risk concerns and sporadic ad hoc approaches exist which have considered seismically induced multi-unit accidents involving loss of coolant accidents, station blackout, and multi-unit common cause failures, there is still a need for an integrated approach to Multi-Unit PRA (MUPRA). A formal approach to MUPRA would not only improve our understanding of the complete risk profile, but the results would also improve regulatory decision-making and accident management.

The accident in March 2011 involving the six-reactor Fukushima Dai-ichi nuclear power plant site clearly underlined that scenarios involving nearly concurrent release of multiple sources of radioactivity on a site and multiple core damage events should be carefully evaluated. While the accident started from a seismic external event, it led to a devastating tsunami that, coupled with inadequate emergency response to adequately cope with the complex intertwined severe accident challenges to all six reactor units and their spent fuel storage facilities, despite some initially successful measures that delayed the radioactive releases that permitted public evacuations, resulted in serious radiological releases. The end result was severe core damage of three operating reactor units along with containment breach of one of the reactors and releases of radioactive material exceeded only during the Chernobyl accident. Major weaknesses in emergency response and incompetence in accident management in handling multi-unit accidents with extended station blackout conditions were clearly alarming. The two units that were down for maintenance and refueling plus operation of a single emergency diesel generator circumvented core damage in all six units.

Multi-unit sites, although physically independent to a large extent, have many direct and indirect inter-connections that make them practically dependent. Examples of these dependencies include certain initiating events simultaneously occurring in multiple units, a transient in one unit affecting some or all of the other units, proximity of the units to each other, shared structures or components (e.g., shared batteries and diesel generators), common operation practices and human actions, and substantial procedural and other organizational similarities. Besides considering all sources of radioactivity and dependencies among the facilities

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on a site, to gain an accurate view of a site's risk profile, a measure of Core Damage Frequency (CDF) and radiation release metrics such as the Large Early Release Frequency (LERF) representing the site rather than the unit should be considered and estimated in a fully integrated MUPRA. MUPRA refers broadly to an extension of the traditional PRA techniques to assess the risks of multi-unit sites. This includes single-unit PRAs that consider the accident sequences that may propagate from one unit to another, fully integrated PRA models that address accident sequences that may involve any combination of reactor units and radiological sources, and hybrids of these models. This paper will discuss the technical aspects of an integrated MUPRA, including consideration of dependencies and assessment of the multi-unit dependency data and models for quantifying such dependencies. The paper also provides discussions on formal definitions and metrics for multi-unit site risks. Finally, parametric methods are used to address multi-unit dependency situations. A conceptual two-unit logic example is used to demonstrate the application of proposed methodology.

2. Background

In a MUPRA it is necessary to account for possible interactions between the units collocated at a site when a single reactor accident may propagate to affect other units (causal interaction), or when a common cause event impacts multiple units and radiological sources concurrently. Consideration of these interactions in MUPRA leads to some technical issues and challenges that this paper attempts to characterize and offer possible solutions for. It is clear that MUPRA requires development and modeling of initiating events, accident sequences, end states and risk metrics that are relevant to multi-unit sites.

There have been limited experiences in performing MUPRAs in the past in the U.S., Canada, and other countries; however, such efforts are neither formally nor adequately considered. This includes operating plant sites in either the regulatory or the commercial nuclear environments [2–4]. Fleming et al. have recommended methods to deal with facets of a MUPRA analysis [5–8], yet no well-established integrated approach and understanding of the implications of MUPRA exists. In the early 1980's the PRAs for the Indian Point Station [9], addressed the dual-unit releases as a result of seismic and high wind. The other example of a MUPRA was the Level 3 PRA for the Seabrook Station in New Hampshire, U.S., performed in the mid-1980's [10]. More recently, MUPRAs have been performed for some CANDU plants in Canada [11]. There have also been some Level 1 PRAs of multi-unit sites that provide very limited considerations of the concurrent states of the other units. Unfortunately, much of what is known today about the risks of multi-unit sites is based on what has been learned through operating experiences [2] and the multi-unit accident at the Fukushima Dai-ichi plant.

The U.S. Nuclear Regulatory Commission (NRC) has dealt with multi-unit risk in a limited manner. For example, after the Chernobyl accident the NRC issued recommendations involving limiting noble gases and airborne volatiles being transported to the other units during the accident through a shared ventilation system.[1] This included addressing issues such as control room habitability, contamination outside of the control room, smoke control, and shared shutdown systems [12]. Also, the Criterion 5 of the General Design Criteria (GDC) [13] in the U.S. for nuclear power plants recommends no sharing of structures, systems and components (SSC) among units at a nuclear plant site, “unless it can be shown that such sharing will not significantly impair their ability to perform their safety functions”. More recently, the U.S. NRC has been conducting an effort to create an integrated Level-3 PRA that includes the effects of multiple units, as well as the risk from all radiation sources onsite, such as the spent fuel pool [14]. The U.S. nuclear industry's integrated site risk solutions generally focus on only one facet of the MUPRA at a time without considering other concurrent events. For example, the station blackout event has been investigated because of its site impact and the interdependencies in its shared electrical systems. Similarly, the seismic-induced dependencies between units and component fragilities across a site have been of major interest. But although specific aspects of MUPRA have been looked at in an ad hoc fashion with greater detail in the U.S., no integrated approach exists.

In the international arena, the International Atomic Energy Agency (IAEA) has been working on this area, and its International Seismic Safety Centre has been working on developing a series of Safety Reports for MUPRA [15–17]. Also, the IAEA General Safety Requirements Part 4 in its requirement 4.31 for evaluation of external events states:

> “… *Where there is more than one facility or activity at the same location, account has to be taken in the safety assessment of the effect of a single external event, such as an earthquake or a flood, on all of the facilities and activities, and of the potential hazards presented by each facility or activity to the others.*"

In 2012, the IAEA sponsored a workshop that discussed the issue of multi-unit PRA, but did not offer any methodological solutions to perform practical PRA analysis, including: (1) the possible combinations of hazards induced by external events, (2) the ways they may affect multi-unit site, (3) how to address the dependencies under the impact of external events among multiple units [18]. NEA/CNSC organized a workshop on this subject that took place in Ottawa, Canada, in November 2014 [19]. Finally, the ASME/ANS Joint Committee on Nuclear Risk Management (JCNRM) is discussing the development of a standard for PRA applications to SMRs, but this effort is still in its infancy with no standards available.

In moving forward, the NEA/CNSC Workshop in Ottawa listed many recommendations, including the following critical needs for further advances in the future:

1. Designation of additional risk metrics beyond Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) to better capture risk profile of multi-unit sites.
2. Delineation of single and multi-unit accident sequences including effects of single reactor/facility events on other units in form of additional initiating events and accident scenarios.
3. Accounting for multi-unit common cause and causal dependencies involving functional, human, and spatial dependencies and development of supporting data to address inter-unit and intra-unit common cause failures.
4. Evaluation of interactions between operator actions that would adversely affect multiple-units.
5. Proper accounting of the timing and amount of source-term releases from different units.
6. Consideration of site condition in restricting operator access, recovery actions and implementation of planned accident management measures.
7. Definition of site-level plant damage end states including the effects of cumulative radiological releases and other correlated hazards, as well as release categories reflecting multi-unit

[1] A similar transport mechanism also occurred during the Fukushima Dai-ichi event, during which the fire/explosion at Unit 4 was caused by leakage of hydrogen released from Unit 3 through shared ductwork with Unit 4.