Reconsideration of PRA Framework – Addressing Level 3 PRA Coverage and Multi-unit Issues

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Abstract: The accident at the Fukushima Daiichi Nuclear Power Station (1FNPS) stimulated the consideration of the total risk of accident among PRA analysts. Several solutions have been proposed, including the enlargement of the scope of traditional level 3 PRA framework and the consideration of multi-unit effects. This study aims to identify foreseen issues arising from these solutions, and to propose an alternative approach to evaluate the total risk of accident. Enlargement of PRA coverage can create (1) difficulty attributed to multidisciplinary approach, (2) difficulty in acquisition and management of excessive amount of data, (3) difficulty in decision-making, and (4) difficulty in communicating with stakeholders. An alternative approach is proposed to address these issues. It is better to stick with the traditional PRA scope, and cover multi-unit evaluation and consideration of various accident consequences by the qualitative or semi-quantitative assessment. All results are put on the table and go through deliberation process where all parties gather and discuss the results before making decisions. The alternative approach enables the assessment of the total risk of accident without facing all aforementioned issues.

Keywords: PRA framework, impact assessment, deliberation, level 3 PRA, multi-unit

1. INTRODUCTION

1.1. Structure of PRA

It is commonly recognized that a probabilistic risk assessment (PRA) of a nuclear power plant (NPP) is divided into three levels [1]. Figure 1 depicts the inputs and outputs of the three levels, and the main expertise needed to perform each of them. A level 1 PRA starts from the identification of initiating events, and outputs the reactor core damage accidents and their respective frequencies. Since the assessment mostly deal with the responses of fuel and coolant within the reactor cooling system in terms of temperature, pressure, flow rate, enthalpy and so on, thermal hydraulic engineers play an important role in a level 1 PRA. A level 2 PRA uses the core damage accidents delivered by level 1 PRA as its inputs, and analyzes the progression of these accidents by considering the response of the containment vessel to the accidents. Physical chemists are positioned at the core of level 2 PRA, since the assessment has to cover the understanding of the behavior of the radioactive materials in the containment vessel, and the estimation of the amount and timing of the radioactive release to the environment (a.k.a. source term). Radioactive release accidents are used as the input of a level 3 PRA which assess the consequences of these accidents in terms of radiation exposure (and consequent health effects, e.g. acute injuries or death, or long-term cancers) and land contamination. The methodology of a level 3 PRA is similar to that of the environmental impact assessment (EIA), thus it is normally performed by a team of health physicists.

Three levels of PRA have been usually performed separately. Outputs from upstream assessments are tailored to fit in with the format of downstream assessments and used as their inputs. Outputs of each level are also used for other purposes, e.g. to satisfy regulatory requirements, to justify facility modification, or to plan accident management and emergency response strategies. However, this paper focuses on PRAs performed as a series of PRAs from level 1 PRA to level 3 PRA, and deliver the

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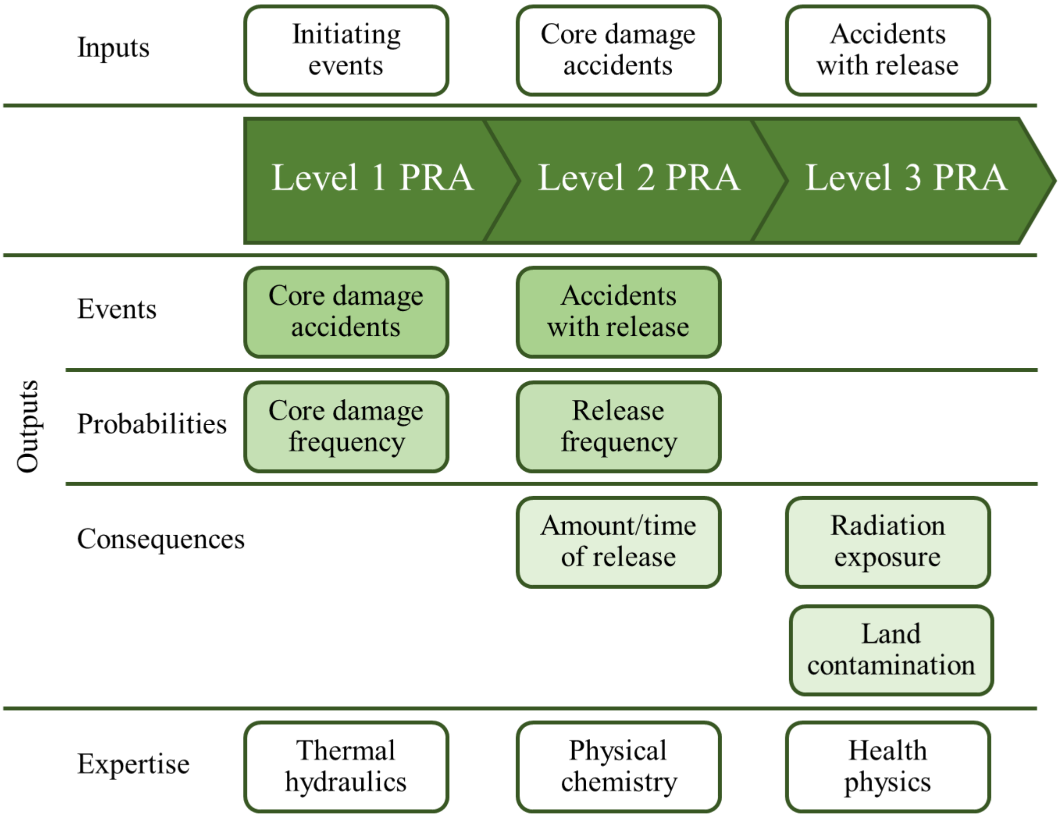

Figure 1. Common structure of PRA

accident consequences represented by radiation exposure and land contamination as their outputs. A good example of this kind of PRAs is the State-of-the-Art Reactor Consequence Analyses (SOARCA) performed by USNRC [2]. This paper will revisit the framework of this kind of PRAs, address important foreseen issues during the assessment, and try to propose some solutions to them.

1.2. Enlargement of PRA Coverage for Evaluation of Total Risk of Accident

The accident at the Fukushima Daiichi Nuclear Power Station (1FNPS) revealed a number of issues of PRA. This paper pays particular attention to the effort in PRA to quantify the total risk of accident. The 1FNPS accident brought about various consequences other than radiation exposure and land contamination which are not covered in the traditional level 3 PRA, e.g. psychological burden, disruption of communities, societal/political impacts on business continuity of other nuclear power plants, economic impacts from evacuation and relocation of people, or harmful rumors regarding Fukushima people and products. It could also be observed that an accident in one unit may induce simultaneous accidents in adjacent units, which can potentially lead to more consequences and more complication in accident management. Many researchers and practitioners have tried to solve these issues by enlarging the coverage of the traditional PRA framework. There are a great deal of level 3 PRA studies on estimation of the economic impacts of accidents (i.e. accident cost) [3], or conversion of various accident consequences into monetary values [4], all of which aim to cover broader spectrum of accident consequences.

There are also other studies on multi-unit PRA at all PRA levels [5-7] that intend to quantify effects of events or accidents in one unit to the adjacent units especially after external events, e.g. earthquake, tsunami, flood, in order to complement to the traditional single-unit PRA. Not only do risk scholars seek for exploring this new frontier, but also nuclear industry and regulators in some countries have begun to work on this issue. For example, CANDU Owners Group published a report on preliminary study for developing a whole-site PRA methodology [8]. Reflecting recent international trends, IAEA also officially launched relevant projects including technical consideration and pilot studies for practical application of multi-unit PRA [9].

The ambition to quantify the 'total' risk of accident in a nuclear facility, that may seem to make risk-related decisions easier and more justifiable, would be attractive to both risk assessors and risk managers. In general, such effort on illustrating and understanding the total risk of a nuclear power plant accident is considered favorable from the aspect of continuous improvement of risk assessment and management. On the other hand, this effort which somehow became the mainstream in the PRA community can lead to some new issues. The objective of this study is to identify foreseen issues arising from the enlargement of PRA coverage, and to propose an alternative approach to tackle the issue on quantification of the total risk of accident.

2. FORESEEN ISSUES FROM THE ENLARGEMENT OF PRA COVERAGE

2.1. Difficulty Attributed to Multidisciplinary Approach

2.1.1. Level 3 PRA

A preceding study divided consequences of a nuclear power plant accident into four categories, namely health effects, economic impacts, societal impacts and environmental impacts [4]. Evaluations of health effects due to radiation exposure, which are included in the traditional level 3 PRA framework, can be done by health physicists. A medical doctor may need to be included into the team to be able to correctly determine the psychological effects from the accident. The team will also need a social scientist to help capture the impacts of the accident to society and communities and identify whether or not they are attributed to the accident. It is definitely necessary to have an economist to quantify the economic impacts of the accident, or to turn different consequences into monetary values. An ecologist may also be added to the team if environmental impact to the biota is of interest. Consequently, a team to perform level 3 PRA will have to be considerably large to be able to cover all consequences and come up with reasonable results. In reality, a traditional level 3 PRA is normally performed by a team of health physicists [10], and 'new' level 3 PRAs have been performed by economists [3], and nuclear engineers [4], separately. As a result, we obtained a level 3 PRA that incompletely cover all (or more) categories of accident consequences, instead of a level 3 PRA that accurately cover the radiation-induced health effects.

2.1.2. Multi-unit PRA

In level 1 and 2 single-unit PRAs, the analysts only needed to have an expertise in thermal hydraulics and physical chemistry, respectively. If a multi-unit PRA is going to be performed to justify facility modification or to plan the accident management strategy, the analysts may only need additional skills in statistics and data analysis. But if the results are to be reflected to the level 3 PRA to help capture the total risk of accident, thorough understanding of the downstream assessments are needed in order to precisely determine the multi-unit aspects to be taken into account. In other words, a multi-unit PRA may not be useful for the quantification of the total risk of accident, if it is not performed by a team of analysts that have adequate knowledge of level 3 PRA.

2.2. Acquisition and Management of Excessive Amount of Data

2.2.1. Level 3 PRA

Quantification of accident consequences is not an easy task. And what is worse, Estimation of the total risk of accident requires quantification of a number of different consequences. Various types of data covering several thousands of square kilometers are needed, including meteorological data, population data, land use data, economic data, and so on. The acquisition and the processing of this amount of data would be time-consuming. Furthermore, management of different types of data within the same framework is also not a simple task. Monetization is a common method for this purpose, but it is often confused with the estimation of economic impacts of an accident. A normalized or virtual unit can be used as well, but it may not be easily comprehensible to other researchers, practitioners or public. Conversion of all data to a common unit will again require tremendous effort.

2.2.2. Multi-unit PRA

It is widely known that a great deal of data is needed even for each level of a single-unit PRA. If multi-unit characteristics of the PRA are to be evaluated through the consideration of common cause failures for all possible combinations among reactor units in the power station, or even just for two adjacent units, the analyst will need to deal with several-fold of data, or in some cases a few orders of magnitude greater amount of data. If we want to utilize the results from upstream assessments in downstream assessments, grouping of the upstream results in order to match with the sequences to be assessed in downstream assessments is needed, and this kind of treatments of large amount of data would require tremendous time and resources. In reality, many multi-unit PRAs [5-7] focus on specific parts of the nuclear power plant or some specific accident sequences. They are not connected to downstream assessments as well, and thus cannot contribute to the estimation of total risk of accident.

2.3. Difficulty in Decision-Making

As mentioned above, the venture for quantifying total risk of nuclear installations in a thorough manner inevitably requires much wider expertise and broader perspective than conventional PRA practices, which accordingly means the quality and amount of information to be taken into account by risk managers increase dramatically. Even traditional PRAs, with limited scope of level 1 and single unit, have been sometimes alienated by decision makers such as corporate managers or regulators who are required to make binary administrative decisions due to the difficulty of dealing with error bars and uncertainties associated with PRA results [11]. Enlargement of PRA coverage to level 3 and multi-unit may have the potential of worsening this gap between risk assessors and risk managers.

Besides, one of the challenges of PRA consists in how to convey presumptions and uncertainties inherently accompanied by risk assessment to decision makers in a comprehensible fashion. Indeed, PRA could notify risk managers of some kinds of uncertainties by utilizing probability distributions which represents the risk assessors' degree of confidence. Still, it remains difficult to let decision makers know directly a series of assumptions and uncertainties accompanied by risk calculations, including collecting data and establishing data set, modeling event sequences, defining minimal cut-sets, deciding success criteria, and allocating concrete probabilistic numbers to logic trees. Communicating such assumptions and uncertainties has been a major challenge in risk-informed decisions. The more uncertain and complex results the expanded PRAs produce, the more difficult it must be to ensure communication between risk assessor and managers.

2.4. Difficulty in Communicating with Stakeholders

Recently-proposed risk management frameworks almost exclusively require ensuring communication with external and internal stakeholders [12, 13]. Above all, in the post-Fukushima era, we definitely need sharing risk information including likelihood of severe accident and possible radiological consequences with various stakeholders, such as local communities, for improving nuclear emergency preparedness and deepening policy dialogue around nuclear energy use. Despite not a few democratic countries who utilize nuclear power have tackled with communicating nuclear risks with local stakeholders and the public, these efforts have often faced with several challenges, in particular, how to communicate calculated risks with great uncertainties. Some studies suggest one of the possible reasons why Japan had been reluctant to implement risk assessment before the Fukushima accident as a fear that disclosing PRA outcomes with uncertainty could lead to excessively negative and/or sensitive societal reactions, considering the previous official explanation and public mind on the safety of nuclear utilization that presuppose deterministic concept of safety [14]. Such difficulty in communication may justify the reluctance on PRA practices and result in hindering expeditious and proactive risk management. Increasing uncertainties connoted by the enlarged PRAs implies that communicating risk information with stakeholders might be much more difficult.

Risk communication studies and practices have shown that communicators should avoid expert jargons and adopt plain terms as far as possible when talking with lay people [15]. On the other hand, over-simplified argument on complex and intricate PRA could fail to recognize the essence of risk insights which are supposed to be gained by risk assessment activities. For example, explaining to the public a partial multi-unit PRA as an overall risk of the power plants not only has problems from both technical and ethical viewpoints but also may cloud practitioners' judgment on risk issues.

3. PROPOSAL OF AN ALTERNATIVE FRAMEWORK

3.1. Following Traditional PRA Scope

In order to fully utilize the expertise of all PRA analysts, the authors propose to stick with the traditional PRA scope and have the specialists improve the elements within their territory. All levels of PRA will be performed for a single unit. Level 1 PRA will be performed by thermal hydraulic engineers, and level 2 PRA will be performed by physical chemists. Level 3 PRA will cover only atmospheric dispersion, radioactive material deposition and radiation dose assessment. It can thus still be performed by a group of health physicists, without including more members with different expertise or training the health physicists to have knowledge in psychology, social science, economics or ecology. The analysts will only need to obtain and manage the meteorological data which they are accustomed to. Amount of data to be acquired and managed will also be limited since all PRAs are for a single unit. By following the traditional PRA scope, teams for respective PRA levels will effectively use their expertise for the assessment, and will be able to acquire and manage the data needed for the assessment. Yet the issues on the limited coverage of level 3 PRA and on not being able to account for the multi-unit characteristics of the accident remain. These will be addressed by the introduction of qualitative or semi-quantitative impact assessment.

3.2. Qualitative or Semi-quantitative Impact Assessment

Evaluation of accident consequences other than radiation-induced health effects and multi-unit consideration can be covered by qualitative or semi-quantitative impact assessment. The main difference between the introduction of the impact assessment and the scope enlargement of level 3 PRA is that all consequences are not necessarily quantified in the former case. Some consequences, e.g. psychological burden, social disruption, or impact or energy policy, cannot be easily quantified especially when monetary unit is used for the quantification, but it can be properly captured by qualitative assessment (e.g. participatory analysis [16], questionnaire survey [16], Delphi method [17], qualitative impact assessment protocol [18]) or semi-quantitative impact assessment (e.g. Likert scale [19], overall percentage score [19, 20]). Instead of increasing the items to be quantified within the quantitative framework of PRA, the authors view as more appropriate to select proper methods for respective consequences, put all results in the same showcase, and go through deliberation process which will be discussed further in the following section.

For all accident consequences that are not included in the traditional PRA framework, quantifiable consequences can be estimated using the most suitable unit. Semi-quantitative methods can be used for consequences of which the extent can be easily converted to score. All other consequences are evaluated qualitatively. Then all results are put on the table for deliberation. It would also be good to show the trade-offs among different consequences, for example, relocation can reduce public radiation exposure, though it will increase loss of income and decrease in value of properties. As for the multi-unit consideration, the major contribution to the total risk of accident would be the multi-unit influence on the source term characteristics which may be worth being quantified. For other contributions, if any, quantifiable ones can be quantified, while others can be qualitatively or semi-quantitatively discussed, considering the effects of multi-unit consideration on all aforementioned accident consequences.

3.3. Establishing a Deliberation Phase

While it is desired that risk scholars and practitioners make efforts for grasping total risk quantitatively, there is a sense of techno-centrism of nuclear experts hidden in the background of such quantification. Due to several difficulties mentioned above, the authors cannot agree completely with such endeavors for quantifying overall risks and utilizing its results as a tool for public understanding and societal justification on nuclear energy use.

Instead, the authors suggest a necessity for paradigm shift from an ambition to aggregate and consolidate all the impacts, elements and features of nuclear risks into one quantified risk assessment to a framework where risk assessment aims for grasping various aspects of risks as broad as possible, through different assessment processes run in parallel in order to provide heterogeneous insights to decision makers. This alternative framework requires displaying diverse assessment results from different approaches including deterministic analysis, conventional PRAs, economic impact assessment by economists, psychological assessment by medical experts and psychologists, qualitative assessment of societal impact by sociologists, and so on, and comparing those insights with each other for more sophisticated risk decisions. We call this process a “deliberation phase”.

Deliberation phase constitutes an essential part of risk decisions. Recently-proposed frameworks on risk-informed decision-making highlight the importance of incorporating assorted elements including deterministic, probabilistic and other considerations before decision-making [21, 22]. These frameworks are underlaid by the concept that PRA should not lead to one specific decision automatically but provide insights in conjunction with other assessment results. In a deliberation phase, risk assessors who have different backgrounds gather to consider and clarify similarities and differences among their assessment results and establish risk advice for decision makers. In particular, one of the practical advices beneficial for risk managers could be trade-offs among different assessment results, for instance, a risk management option which is cost-justified may cause friction with societal concerns. Through such deliberation, risk assessment can sublimate from a method for providing calculated numbers into a prudent process of incorporating diverse perspectives and establishing strategic advice for risk management. That could be a key for addressing the gap between the expanded risk assessment and the risk management.

In this deliberation process, conventional PRA practitioners are required to depart from a sense of superiority that quantified assessment always surpasses qualified one, and to discuss among quantified, semi-quantified and qualified results in a respectful manner. This is not to underestimate the efforts on quantification, but rather to point out that efforts on systematic assessment of quantifiable and commensurable impacts may highlight non-quantifiable and non-commensurable impacts at the same time. It is the sophisticated quantitative analyses that lead to clarification of the significance of qualitative analysis.

4. CONCLUSION

Foreseen issues, arising from the enlargement of PRA coverage in order to quantify the total risk of accident, were identified. Extension of the scope of level 3 PRA to cover various accident consequences and introduction of multi-unit PRA at all PRA levels led to a number of issues:

- Difficulty in gathering the team members to cover all consequences and to propagate upstream results to downstream assessments;
- Difficulty in acquisition and management of data of which the amount will significantly increase when the scope of level 3 PRA is enlarged or when multi-unit characteristics are taken to account;
- Difficulty in decision-making as the quality and amount of information to be taken into account by risk managers increases dramatically;

- Difficulty in communicating risks with stakeholders as increasing uncertainties connoted by enlarged PRAs implies that communicating risk information with stakeholders might be more difficult.

An alternative approach was proposed to tackle aforementioned issues. In order to avoid enlarging the team or increasing the data amount, it is better to stick with the traditional PRA scope. Multi-unit evaluation and consideration of various accident consequences can be covered by the qualitative or semi-quantitative assessment. Such impact assessment will be taken into account in conjunction with quantifiable elements obtained from PRA during the deliberation process. All parties shall gather and discuss the assumptions made in the assessments, the meaning of all results, and the handling of associated uncertainties, before making decisions, in order to avoid irrational or illogical decisions. The alternative approach enables the assessment of the total risk of accident and addresses all aforementioned issues, while making sure that the expertise of the analysts is fully utilized and the results of both qualitative and quantitative assessments are precisely informed to the decision makers.

Generally, the essence of map consists in abstraction and highlighting desiderata. The same is true for risk assessment. While overlooking necessary risk insights is never allowed, ambition to reproduce all the physical phenomena will not serve its original purpose. PRA may lead to prudent decisions when allocating limited resources to high priority issues. We can add to risk assessment itself a new perspective of deploying assessment resources effectively placing priority on strategic analysis activities.

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