HOLISTIC APPROACH TO MULTI-UNIT SITE RISK ASSESSMENT: STATUS AND ISSUES

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Probabilistic safety assessments of nuclear power plants (NPPs) have primarily focused on estimating the risk associated with a single unit, with little consideration of the inter-unit dependencies or multi-unit effects due to common-cause initiating events or failures in the shared systems. In this paper we first characterize the site risk with explicit consideration of the risk associated with spent fuel pools as well as the reactor risks. The status of multi-unit risk assessment is discussed next, followed by a description of the emerging issues relevant to the multi-unit risk evaluation from a practical standpoint.

I. INTRODUCTION

Probabilistic safety assessments of nuclear power plants (NPPs) have primarily focused on estimating the risk associated with a single NPP unit (in particular, the reactor risk rather than the risk of the spent fuel pool operation) with consideration of availability of the shared system (e.g., AAC diesel generator) to the unit for which the probabilistic safety assessment (PSA) is performed. As such, little attention was paid to the possibility of concurrent accident sequences or simultaneous multi-unit accidents at a site. The Fukushima accident has highlighted among others that multi-unit accidents can occur in reality, and so, they must be considered in the risk analysis of nuclear power plants because a majority of NPPs in the world consist of multiple units at a single site. In the case of the Republic of Korea, the four nuclear plant sites are each expected to hold 6 to 10 units in the near future.

Multi-unit accident sequences can be identified by performing a multi-unit probabilistic safety assessment (MUPSA). At an international workshop on multi-unit PSAs recently held in Canada [1], it was recognized among the experts that there is a critical need for evaluating site risk in an integrated manner so that the various risk contributions from different radiological sources (e.g., reactors, spent fuel pools), hazard groups, and plant operating states can be properly captured. The insights gained from MUPSAs may be applied in the decision making process for the site safety management with due consideration of the uncertainties involved.

In this paper we first define multi-unit site risk with explicit consideration of the risk associated with spent fuel pools (SFPs). The status of the practice in conducting MUPSAs is then described, followed by a discussion on the issues associated with multi-unit risk evaluation.

II. CHARACTRISTICS OF MULTI-UNIT SITE RISK

Suppose for the sake of illustration that there is a site with three pressurized water reactor (PWR) nuclear power plant units, each unit consisting of a nuclear reactor in the Containment Building and a spent fuel pool (SFP) in the Auxiliary/Fuel Building as shown in Fig. 1. When a unit is at power operation, nuclear fuel is stored in both reactor and spent fuel pool with no water in the refueling pool, and with the fuel transfer tube and the SFP gate locked closed. During refueling, the refueling pool is filled with water, and then the fuel assemblies are transferred between the reactor pressure vessel (RPV) and the spent fuel pool through the open fuel transfer tube with the SFP gate open.

In evaluating multi-unit site risk thus far, the risk associated with the spent fuel pool operation was not specifically taken into account. However, it should be noted that a spent fuel pool contains a much larger inventory of radionuclides than the core (sometimes by a factor of 3 or more), particularly Cesium137. Furthermore, the spent fuel pool of a PWR plant has no protective containment structure to mitigate potential radionuclide releases other than the Fuel or Auxiliary Building which is

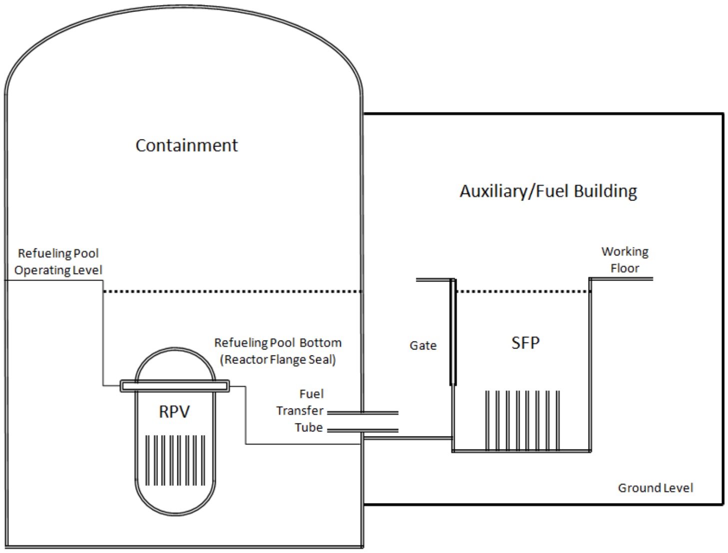

Fig. 1. A PWR nuclear power plant unit consisting of a reactor and a spent fuel pool [2].

significantly less robust than containment, and so, can lose confinement when internal pressure reaches a small pressure differential with respect to the outside atmosphere due to the opening of pathways such as hatches, roll-up doors, or ventilation systems [3]. Hence, the risk associated with SFP operation must explicitly be considered in evaluating multi-unit site risk as well as single-unit risk, because of: 1) larger inventory of radionuclides in SFPs; 2) less radionuclide-confinement capability of the Fuel/Auxiliary Building than the Containment Building; and as a result, 3) lager consequences than the reactor accident.

In general, site risk may be partitioned into the following different types of risk (Fig. 2):

1) Individual Reactor Risk (e.g., 'Reactor 1 Risk' in Fig. 2): The risk associated with only a single reactor at the site without any significant impact on other radiological sources. For example, core damage occurs at Reactor 1 with no influence on SFP 1 or other reactors/SFPs at the site.

2) Individual SFP Risk (e.g., 'SFP 1 Risk' in Fig. 2): The risk associated with only a single SFP at the site without any significant impact on other radiological sources. For example, fuel damage occurs at SFP 1 with no influence on Reactor 1 or other reactors/SFPs at the site.

3) Intra-Unit Reactor-SFP Interaction Risk (e.g., 'Interaction 1 Risk' in Fig. 2): The risk due to the interaction between reactor and SFP within each unit. For example, 'Interaction 1 Risk' in Fig. 2 consists of two different parts: the risk for Reactor 1 that is induced by accident sequences initiated in SFP 1; and the risk for SFP 1 that is induced by accident sequences initiated in Reactor 1. In a recent study by EPRI for SFP risk assessment integration, the following three different types of events and interactions between the reactor and SFP accident progression and risks were considered:

    a) SFP events impacting the reactor/containment (e.g., SFP heatup and boiling degrades Auxiliary/Fuel Building environment);

    b) Reactor/containment events impacting the SFP (e.g., a severe accident energetic containment failure due to hydrogen deflagration which causes the loss of the isolation barriers such as fuel transfer tube, or the failure of SFP cooling or required support systems); and

    c) Common events impacting the reactor/containment and SFP simultaneously (e.g., loss of offsite power, electrical bus failure, seismic event, fires, internal flooding).

4) Multi-Unit Risk (e.g., ‘2 & 3 Risk’ in Fig. 2): The risk associated with multiple units regardless of the types of radiological source (i.e., reactor or spent fuel pool). For example, ‘1 & 2 Risk’ in Fig. 2 involves:

   a) Double combinations such as: Reactor 1 has core damage and SFP 2 has fuel damage; Reactor 2 has core damage and SFP 1 has fuel damage; or Reactor 1 has core damage and Reactor 2 has core damage;

   b) Triple combinations such as: Reactor 1and 2 each has core damage with SFP 1 suffering fuel damage; Reactor 1and 2 each has core damage with SFP 2 suffering fuel damage; Reactor 1 has core damage with SFP 1 and 2 each suffering fuel damage, etc.; and

   c) Quadruple combinations such that all the radiological sources in Units 1 and 2, namely, Reactor 1 and 2 along with SFP 1 and 2, suffer core/fuel damage.

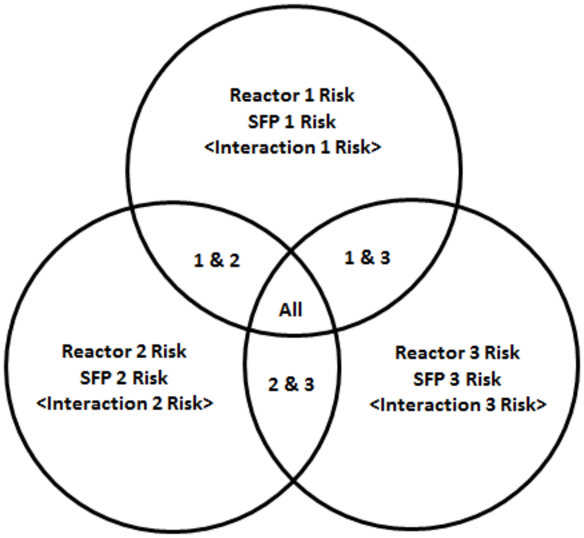

Fig. 2. Composition of the site risk at a 3-unit nuclear power station.

The ‘All Risks’ in Fig. 2 can be interpreted in a similar manner as for ‘1 & 2 Risk’. Namely, it involves either core damage or fuel damage in each unit at the minimum, and core damage and fuel damage in each radiological source of the site at the maximum. These multi-unit risks may be induced by various reasons. For instance, the ‘1 & 2 Risk’ involving core damage in Reactor 1 and fuel damage in SFP 2 may be caused by an initiating event due to failure of a shared system between Unit 1 and Unit 2 resulting in no damage to Reactor 2 and SFP 1, but damage to Reactor 1 and SFP 2.

III. STATUS OF MULTI-UNIT RISK ASSESSMENT

III.A. Regulatory Considerations of Multi-Unit Risk

The possibility of simultaneous core damage events on the same site has been considered particularly in connection with systems design and siting criteria via General Design Criterion (GDC) 5 [4] and the Reactor Site Criteria [5], respectively. GDC 5 limits the sharing of systems, structures and components (SSCs) important to safety among nuclear power units unless it can be shown that such sharing will not significantly impact their ability to perform their safety functions, including, in the event of an accident in one unit, an orderly shutdown and cooldown of the remaining units. The justification for sharing SSCs among several units on a site presumably used to be made without due consideration of adverse environmental conditions as caused by extreme natural hazards (thereby limiting accessibility to locations where mitigation measures can be taken, hindering the communication among plant staff due to lack of electrical power, etc.). The Reactor Site Criteria included as Subpart A to 10 CFR Part 100 provide requirements for determining the exclusion area, the low population zone, and the population center distance for multi-unit sites. An overly conservative assumption was made such that: if the reactors are interconnected to the extent that an accident in one reactor could affect the safety of operation of any other, the size of the exclusion area, low population zone and population center distance shall be based upon the assumption that all interconnected reactors emit their postulated fission product releases simultaneously.

In addition, the NRC considered the need to establish additional regulations to reduce the likelihood and consequences of multi-unit accidents following the accident at Three Mile Island in 1979 [6]. The subject of multi-unit risk was also considered during development of the Commission's Safety Goal Policy Statement [5], which was issued in 1986.

Furthermore, during the State-of-the-Art Reactor Consequence Analysis (SOARCA) project [6], completed in 2012, the project staff identified "Multi-Unit Core Damage Events" as a proposed Generic Issue (GI). Such events can potentially occur as a result of random or common cause failures of onsite emergency diesel generators following a loss of offsite power, or due to failures of structure, systems, and components (SSCs) resulting from common cause initiators such as internal flooding or seismic events. Multi-unit events impact not only the potential source terms, but also the implementation effectiveness of mitigation measures since the plant staff must now deal simultaneously with accidents in more than one unit.

As pointed out by M. A. Stutzke of the U.S. NRC [7]: "The 2011 accident at Fukushima Daiichi in Japan has reemphasized the fact that multi-unit accidents can happen, and that it is important to understand their risks." As small modular reactors (SMRs) like NuScale are designed so that as many as 12 modular reactors will form an integral set, the NRC's Office of New Reactors established a Working Group in 2012 to consider how to address the risk of accidents that affect small modular reactors in the design certification and combined operating licensing processes. A draft criterion to evaluate multi-module risk was proposed by the NRC staff without establishing any quantitative risk criteria in such a way that multi-module risk (core damage, large release) should be systematically addressed [8].

It is also notable that in developing the Technology Neutral Framework (TNF) as a generic licensing structure encompassing both water-cooled and non-water-cooled advanced reactors, the NRC reconfirmed that the integral risk from multiple units should satisfy the safety goals [9]. For instance, the regulatory requirements set forth in the frequency-consequence (FC) curve is supposed to be satisfied for accident sequences for the new reactors at a site. Although the integral risk of multiple units was required to be applied to the FC curve, the TNF study did not actually show how the integral risk could be evaluated.

Following an in-depth review of the Fukushima accident, the NRC's Near-Term Task Force (NTTF) made the following recommendations [10]:

- 4.2 Prolonged Loss of AC Power: Order licensees to provide reasonable protection for equipment currently provided pursuant to 10 CFR 50.54(hh)(2) from the effects of design-basis external events and to add equipment as needed to address multi-unit events while other requirements are being revised and implemented.

- 9.1~9.4 & 10.1~10.3 Emergency Preparedness Considerations for Multi-Unit Events and Prolonged Station Blackout: Rulemaking and contingency measures are needed for emergency preparedness (EP) enhancements for multi-unit events in personnel and staffing; dose assessment capability; training and exercises; equipment and facilities; emergency response data system (ERDS); command and control, etc.

'The equipment provided pursuant to 10 CFR 50.54(hh)(2)' in the NTTF Recommendation 4.2 above imply the so-called B.5.b portable equipment that were added to nuclear power plants of the United States following the September 11, 2001, terrorist attacks; along this line, Extensive Damage Mitigation Guidelines (EDMG) [11] were also developed and implemented in all the plants. In the NTTF Recommendation 4.2, the equipment further added to address multi-unit events means the FLEX equipment that have been newly augmented in all the U.S. nuclear power plants following the Fukushima accident in accordance with the NRC-endorsed NEI document [12]. One can also note that although site risk is accounted for in developing EP program under overly conservative assumptions, the NTTF Recommendations 9.1~9.4 and 10.1~10.3 require further enhancements in diverse areas of relevance (e.g., staffing, training, data, command structure) reflecting lessons from the Fukushima accident.

Recently, the NRC stated that the issue of multi-unit risk would be addressed as part of the full-scope site Level 3 PRA project (SECY-12-0105 and associated Staff Requirements Memorandum). Although a double-unit site of Southern Nuclear Operating Company (i.e., Vogtle Units 1 and 2) was selected as a sample site, the result of this project is expected to provide considerable insights into simultaneous multi-unit accidents and their associated risk. The Level 3 PRA project [13,14] will build on the state-of-the-art reactor consequence analysis (SOARCA) work to gain a better understanding of potential radiological effects of postulated accident sequences, particularly in the analysis of accidents at multiple units on a site and from the additional source terms contributed by spent fuel pools and dry casks.

III.B. Status of Multi-Unit PSA Related Activities

In the aftermath of the Fukushima accident, several studies were performed to evaluate multi-unit risk. However, the two-unit Level 3 PSA performed on the Seabrook nuclear power station in early 1980's is still one of the most notable studies in this regard [15]. Table I describes in a self-explanatory manner the salient aspects of various studies intended to address multi-unit risk, including the Seabrook study. It is notable that K. Fleming has emphasized that safety goal QHOs (quantitative health objectives) should be applied to the site as a whole [16]. The recent study on multi-module PRA framework [17] is rather unique because dynamic PRA methodology is used along with thermal hydraulic (T-H) simulation by RELAP5 code. The T-H model for each module is coupled together to support the ADS-IDAC computer code.

Another notable work is the investigation of multi-unit events that have occurred in operating nuclear power plants of the USA [18]. All LERs submitted to the NRC from 2000 through 2011 were evaluated to identify multi-unit LERs. This study showed that 391 of 4207 total LERs reported to the NRC affected multiple units on a site, which amounts to 9% of all the LERs. The most common link between multiple units was organizational dependencies. These included everything from symmetrical procedures and technical specifications across units to vendor and departmental logic errors. This accounted for 41% of the 391 multi-unit LERs. Single shared SSCs were the next most common link and accounted for 28% of the multi-unit LERs.

The examples of organizational dependencies found from the LER analysis include:

- Incorrect procedure that has been mirrored for multiple units
- Design issue that affects multiple units
- Incorrect calculation that is used on multiple units
- Incorrect technical specifications that have been mirrored for multiple units
- Incorrect vendor guidance that has been applied to multiple units
- Incorrect engineering judgment that has been applied to multiple units
- A misinterpretation of guidance or requirements that affects multiple units
- A misunderstanding of system configuration or function that affects multiple units
- Poor safety culture, which leads to errors of judgment and execution across the organization
- Lack of adequate training and skills for events that affect multiple units

The multi-unit LERs associated with organizational dependencies represent degradation in SSC performance capability, accident mitigation capability of the plant response staff, effectiveness of operating procedure or guidance, and the like. Hence, those units involved were in a situation more vulnerable to multi-unit accidents than otherwise possible.

Finally, one can note that considerable progress has been recently made by the study of the CANDU Owners Group (COG) and the international workshop sponsored by the CNSC in formulating the conceptual basis for multi-unit risk assessment. As indicated in Table I, the COG's approach is to establish site goals with the associated parameters, and then, aggregate all site core damage frequency (SCDF) and large release frequency (LRF) risk contributions for comparison against site safety goals and interpretation of results and their significance. In order to accomplish this objective, a road map was established, and the main issues identified include residual risks that cannot be easily quantified, domino effects of fission product release or radiation shine to other facilities of the site, and compounding factors in accident modeling such as design deficiencies due to failure to recognize system interactions, procedural non-compliance, or institutional failures. The important findings from the CNSC international workshop on multi-unit PSA, delineated in Table I, are also noteworthy.

IV. ISSUES OF MULTI-UNIT RISK EVALUATION FROM A PRACTICAL STANDPOINT

Continuing the example of the 3-unit site, Fig. 3 shows the operational condition of each radiological source on the site when a seismic event occurred: Units 1 and 3 were at full power, and Unit 2 in shutdown condition. It also indicates that the priority of shared systems, such as AAC diesel generator or other portable equipment available at the site, should be determined during the accident management stage of the site so that they can be allocated to the radiological sources which need the limited shared systems the most.

For a reasonable estimation of the multi-unit risk from a practical standpoint, the following issues may need to be addressed, among others:

1) <u>Explicit Consideration of the SFPs and the Operational Conditions of Each Radiological Source</u>: In the reactor PRA, the operational conditions of the reactor are defined in terms of plant operating conditions (POSs), usually 12 to 15

TABLE I. Status of multi-unit risk assessments.

Item	Salient Aspects
Seabrook Level 3 Multi-Unit PSA, 1983 [15]	● A pioneering multi-unit Level 3 PRA performed to address emergency planning issues on the two-unit Seabrook nuclear power station with explicit consideration of multi-unit initiating events (e.g., LOOP, truck crash into transmission lines, earthquakes, external flooding of service water pumps) and associated event sequences along with interunit CCF potential (e.g., failures of multiple diesel generators in both units, and motor-operated valve failures in the service water system) ● This two-unit Level 3 PSA on the Seabrook Station attributed more than 14% of the single-unit CDF to multi-unit accidents, although the degree of independence between the reactor units designed for Seabrook was very high ● The consequences of a dual unit reactor accident can be much greater than the linear combination of single reactor consequences ● The frequency of multiple concurrent reactor accidents on the same site is significant and needs to be taken into account when addressing the integrated risk issue
Perspective on Integrated Risk by K. Fleming, 2005 [16]	● If an accident were to occur on one of the sited reactors initially, there would be at a minimum control room habitability issues to contend with on the other reactors ● Safety goal QHOs should be applied to the site as a whole, because there may be event sequences that could impact a combination of reactors on the site
Seismic Level 1 Multi-Unit PSA, 2007 [17]	● Seismic Level-1 PSA models for analyzing simultaneous failure probability of multiple nuclear power plants in a site at earthquakes have been developed by using Fault-Tree Linked Monte Carlo approach ● Mathematic models to compute multivariate multi-unit correlation models, from partial and complete, inside and across units are developed ● The whole models for maximum nine plants in maximum three groups have been programmed on personal computers as CORAL reef
Multi-Unit PSA Methodology by EDF, 2012 [20]	● Methodological approach to convert a Level 1 unit PSA model to a model for the site suggested by taking into account the multi-unit dependencies including inter-unit common-cause failures, human factor, and organizational factor ● A couple of single-unit PSA models upgraded to a site PSA model in Riskspectrum by differentiating initiating events in terms of type I (affecting only a single unit at a time) and type II (affecting one or both units at the same time)
Multi-Unit LER Events Analysis, 2013 [18]	● In order to effectively account for risks in a multi-unit PRA, six main dependence classifications can be defined: initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies ● Evaluation of the U.S. operating experience data over an eleven-year period shows that almost 10% of events that occur at nuclear power plant sites affect multiple units
Concept-Level Whole-site PSA Methodology Study by CANDU Owners Group, 2014 [21]	● A preliminary whole-site PSA methodology (addressing risk aggregation) applicable to CANDU NPPs defined on a concept-level basis ● An integrated strategy for further methodology development, i.e., a "road map", devised to further develop the whole-site PSA methodology in more detail ● Proposed an approach for site-wide characterization and assessment of NPP risk, within a hierarchal safety goals framework that is founded on defense-in-depth principles ● Site safety goals established to protect the life and health of the public in terms of a hierarchy of safety goals and their supporting elements, namely; QHOs, Practical Elimination of Extensive Societal Disruption, Large Off-Site Release Safety Goal (LORSG) and site-based Severe Core Damage Frequency (SCDF) ● The needs to augment PSA with complementary approaches recognized in order to address the "residual risks" that are not quantifiable, e.g., the use of SAMG and the deployment of portable emergency mitigating equipment as well as the threat-risk assessment ● Consideration of impacts of multiple external events occurring sequentially such as consequential flooding, and “domino” effects from one reactor or station to another due, for example, to plant habitability issues arising from fission product release or radiation shine ● Compounding factors in accident modeling recognized, including design deficiencies (e.g., failure to recognize system interactions), procedural non-compliance, inadequate training, inadequate emergency preparedness, institutional failures (e.g., poor safety culture, focus on economic factor or

	public relations at the expense of safety focus in decision making, poor communication between various groups within an organization or with external stakeholder, incorrect procedures, inadequate regulation)
CNSC Multi-Unit PSA Workshop, 2014 [1]	● The state-of-the-practice in assessing the risks from multi-unit stations was discussed including: methodological challenges in performing MUPSAs, site-based risk metrics, challenges in establishing safety goals for whole sites, and risk aggregation across all units and all hazards ● Important findings include: 1) treatment of human actions and organizational dependencies in modelling multiple reactor accidents stands out as arguably the most important challenge in advancing MUPSA; 2) the importance of utilizing operational experience for multi-unit risk insights; 3) need to delineate single and multi-unit accident sequences; 4) need to account for multi-unit common cause and causal dependencies, including functional, human and spatial dependencies; need to consider adverse impacts of single reactor/facility accident on other units, thus creating multi-unit accident scenario; 5) need to consider how radiological contamination of the site may inhibit operator actions and accident management measures; 6) need for dynamic PSA approaches; 7) need to improve human reliability models and analyses to address performance-shaping factors unique to multi-unit accidents and human actions during implementation of SAMG and prioritization of emergency response measures; 8) need to define new release categories that adequately describe the releases from multi-unit accidents, including release magnitudes, energies, and timing from reactor units and spent fuel storage; and 9) need for a holistic approach that is simple enough to be traceable and applicable.
Multi-Module PSA Framework, 2015 [17]	● Multi-module probabilistic risk analysis (MMPRA) methodology developed using dynamic probabilistic risk assessment (DPRA) simulation tool ● Base PRA accident sequences are ranked in order to develop a focused MMPRA ● Traditional importance measures used to determine the components and systems which may be risk significant and compare to a list of multi-module dependencies ● Fault trees to include common cause failures and system dependencies across adjacent units or modules ● ADS-IDAC simulator model constructed including input files for crew, hardware reliability, indicators, scheduler, and system module ● Accident sequences are pruned based on probability truncation, event time or end state conditions

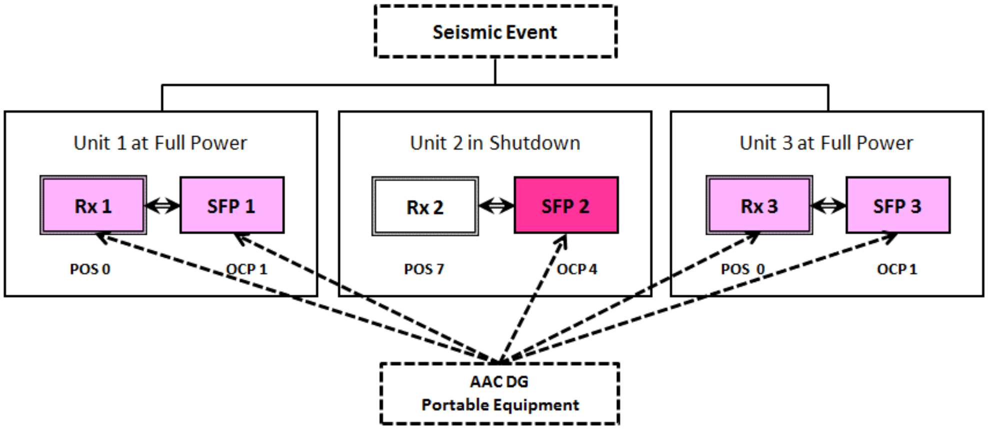

Fig. 3. Issues of multi-unit risk evaluation.

POSs. The operational conditions of the SFP may be defined in terms of operating cycle phases (OCPs), say a total of 6 OCPs [2]. Note that the operational conditions of the reactor and the SFP within a given unit are interrelated. For instance, since the reactor is at full power (i.e., POS 0) in Unit 1, the SFP of this unit is in OCP 1 that corresponds to POS 0. In the case of Unit 2, the reactor is in POS 7 (i.e., defueled state), while the SFP of this unit is in the corresponding state, i.e., OCP 4. Unit 2 stays in these states for a couple of weeks. Since the full core has been off-loaded into the SFP and the SFP is exposed to the highest decay heat, an accident in the spent fuel pool at this time will result in enormous consequences due to large inventories of fission products and lack of robust containment structure in the Fuel or Auxiliary Building. Therefore, the operational conditions of the SFPs should be explicitly considered in evaluating the site risk along with the operational conditions of the reactors, because the accident propagation and the resulting consequences depend on the states of each radiological source at the site.

2) Evaluation of Extreme External Events and Their Impacts on the Site: Extreme external events, especially severe natural hazards, are one of the largest contributors to the site risk among initiating events. Since these events seldom occur, their frequencies of occurrence are subject to large uncertainties due to lack of data. They are expected to cause devastating consequences on the site infrastructures and environment, but it is hard to predict what consequences they will bring about as time goes along. The impact of the extreme external events on the site should be evaluated in connection with the operational conditions of each radiological source, and also many other factors that potentially influence the site risk. Examples include: (a) failure of individual SSCs and intra-unit common cause failures; (b) inter-unit common cause failures (including seismic fragility correlation and relay chattering) and other inter-unit dependencies (e.g., impact of radiological release from SFP 1 to the external injection for SFP 2); (c) availability of common SSCs and their prioritized allocation to the site radiological sources; (d) increased potential of human failures and organizational failures; (e) accessibility and control-room/remote-shutdown-panel habitability issues; (f) staffing (e.g., additional emergency response staff) and organizational issues (e.g., decision making of the prioritized use of portable equipment and of the prioritized allocation of shared maintenance personnel); and (g) latent failures present in the site SSCs (e.g., design issues or incorrect engineering analysis applied to multiple units, maintenance errors repeated on several units).

3) Development of Site Accident Sequences: A key task in site risk assessment is to identify site accident sequences. Take an earthquake as an example. In principle, the possibility that concomitant events may occur following an earthquake, e.g., seismic-induced tsunami, fire or landslide, need to be considered. The impact of the initiating event(s) on SSCs or other aspects (e.g., refueling operation in the spent fuel pool of Unit 2) of the site is taken into account. Concurrent accidents on several units are to be considered (e.g., accident sequences at Reactor 1 and SFP 2, separately), with prioritized use of common resources (e.g., AAC diesel generator or other portable equipment) as needed. If core damage or fuel damage occurs in any facility of the site, it will have significant negative impact on subsequent accident sequences of the site. As the estimation of human error probabilities (HEPs) and non-recovery probabilities (e.g., failure to recover offsite power or diesel generator) is a critical element in PRA especially in LOOP or SBO scenarios, the variation in human error and recovery potentials as a function of the site situation needs to be identified along with evaluation of dependencies between multiple human failure events (HFEs) or non-recovery events in a given sequence. Thermal hydraulic analyses (e.g., using MAAP, MELCOR, RELAP) may be performed to evaluate the timing or nature of the accident sequences for a reactor or a spent fuel pool, or preferably for a combination of both.

4) Assessment of the Multi-Unit Site Risk: The multi-unit site risk can be assessed by integrating the information from all the above evaluations. The annual frequencies for single-unit initiating events (for reactor and SFP separately) and multi-unit initiating events are estimated. For the single-unit initiators (SUIs), the so-called cascading sequences, propagating sequences, and restricted sequences are identified [7]. For the common-cause initiators (CCIs) simultaneously challenging multiple units, the impact of the CCIs on each radiological source affected is identified in consideration of human, technological and organizational factors as well as the environment or any potential correlated hazards (e.g., seismic-induced fires). The frequencies of all the site accident sequences (e.g., single reactor sequences, single SFP sequences, concurrent Reactor 1 and SFP 2 multi-unit sequences) are summed up to yield the site fuel damage frequency (including site core damage frequency) and the site large release frequency per site year. The magnitude of source terms and consequences are factored into the risk curves.

The issues that need to be addressed in conducting the multi-unit PSA are also identified in Table II in terms of the basic elements of a PRA, namely: (1) initiating event; (2) hardware failure; (3) human error; and (4) recovery failure. One can note from this table, among others, that dynamic modeling is needed for a multi-unit PSA because:

- The impact of initiating events for reactor and SFP in a single unit, or multiple units depends on the status of radiological sources

- The prioritized use of shared AAC diesel generator or limited portable equipment depends on the site status

TABLE II. Major Issues in performing multi-unit PSA.

PSA Element	Major Issues
Initiating Event	● Common-cause initiating events, especially extreme natural hazards, affect all radiological sources in the site with negative impact on hardware and human performance. Large uncertainties in natural hazards evaluation (e.g., seismic hazard curves) ● Need to consider combined and correlated hazards (e.g., seismic-induced fires, seismic-induced tsunamis, external flooding due to seismic-induced dam failure, landslide due to heavy rain or typhoon) ● Shared system (e.g., common support system like component cooling water system or service water system) initiating events affect the risk impact of multiple radiological sources ● Dynamic modeling needed because the impact of initiating events for reactor and SFP in a single unit, or multiple units depends on the status of radiological sources
Hardware Failure	● Shared components (e.g., AAC diesel generator, ultimate heat sink, HVAC system, condensate storage tank, air sources, duct-work, portable equipment) potentially affecting the risk impact of multiple radiological sources need to be explicitly modeled for multi-unit PSA ● Some piping through which accident condition may propagate needs to be considered (e.g., propagation of hydrogen across units through duct-work) ● Inter-unit common cause failures (e.g., seismic fragility correlation for similar components in the reactor and SFP sides of a single unit or in the different units, relay chattering in different units due to earthquake) and causal dependencies need to be modeled ● Dynamic modeling needed especially in connection with the prioritized use of shared AAC diesel generator or limited portable equipment, because it depends on the site status
Human Error	● Dynamic modeling needed because human reliability in the multi-unit accident context depends on the site status (e.g., accessibility, communication availability, teamwork potential, work environments), especially generation of environments which are hazardous (e.g., radiological contaminations, hydrogen explosion) or negatively impact human performance (e.g., darkness, hot steam) ● Prioritization of emergency measures also depend on the site status, and ad hoc mitigation measures in emergency situation involving fuel damage need to be considered ● Need to consider organization factor (e.g., staffing) and instrumentation failure as a result of severe accidents
Recovery Failure	● Dynamic modeling needed because non-recovery probabilities (e.g., offsite power recovery, repair of failed equipment) depend on the site status (e.g., the extent of recovery needs, accessibility to the failed components), prioritization of the recovery needs, and availability of the maintenance personnel and tools at the site

- Prioritization of emergency measures also depend on the site status, and ad hoc mitigation measures in emergency situation involving fuel damage need to be considered

- Non-recovery probabilities (e.g., offsite power recovery, repair of failed equipment) depend on the site status (e.g., the extent of recovery needs, accessibility to the failed components), prioritization of the recovery needs, and availability of the maintenance personnel and tools at the site.

V. CONCLUSION

A lot of activities are being performed worldwide in order to address the important issue of multi-unit accidents. There is a consensus among domain experts that the multi-unit site risk assessment should be carried out in an integrated manner, i.e., taking into account human, organization, and technological factors associated with multi-unit accident scenarios. In addition, the following issues also need to be resolved for a realistic estimate of the site risk: a) residual risks that cannot be easily quantified; b) domino effects of fission product release or radiation shine to other facilities of the site; and c) compounding factors in accident modeling such as design deficiencies due to failure to recognize system interactions, procedural non-compliance, or institutional failures. It is envisaged that the insights gained from realistic performance of multi-unit PSAs could be applied in improving the site safety level, and thereby, enhancing the public safety.

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