PSA Technology Challenges Revealed by the Great East Japan Earthquake

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Abstract

This paper presents the current results of an ongoing, limited-scope review of the Fukushima Dai-ichi accident and related events aimed at identifying potential lessons regarding Probabilistic Safety Assessment (PSA) methods, models, tools, and data. The purpose of this review is to: a) support a variety of activities being conducted by the U.S. Nuclear Regulatory Commission's Office of Nuclear Regulatory Research, including a recently initiated Level 3 PSA project and the planning of future research and development, b) obtain a better understanding of the limitations of current PSA studies, and c) contribute to the PSA community's dialog on this subject. Several PSA challenges are identified, including challenges that involve the general conduct of current PSAs, as well as those that involve specific technical elements (e.g., human reliability analysis, external events analysis).

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Abstract: This paper presents the current results of an ongoing, limited-scope review of the Fukushima Dai-ichi accident and related events aimed at identifying potential lessons regarding Probabilistic Safety Assessment (PSA) methods, models, tools, and data. The purpose of this review is to: a) support a variety of activities being conducted by the U.S. Nuclear Regulatory Commission's Office of Nuclear Regulatory Research, including a recently initiated Level 3 PSA project and the planning of future research and development, b) obtain a better understanding of the limitations of current PSA studies, and c) contribute to the PSA community's dialog on this subject. Several PSA challenges are identified, including challenges that involve the general conduct of current PSAs, as well as those that involve specific technical elements (e.g., human reliability analysis, external events analysis).

Keywords: PSA methods, challenges, research, Fukushima

1. INTRODUCTION

Probabilistic safety assessment (PSA) for nuclear power plants (NPP), i.e., the process of identifying potential NPP accident scenarios, their consequences, and their probabilities [1], involves the modeling of rare events. With the increasing use of PSA results and insights in support of integrated, risk-informed, decision making [2,3], it is important to use information from incidents and accidents to support the identification and development of PSA improvements.

Much has been (and continues to be) written about the events preceding, during, and following the March 2011 Tōhoku earthquake and subsequent tsunamis.[1] The reports from a number of official investigations [4-10] and external reviews (e.g., [11-13]) provide a wealth of details regarding event progressions and potential causal factors. In addition, a number of papers cover aspects of interest to the PSA community. These include a conditional, PSA-oriented, analysis of the events at Fukushima Dai-ichi Units 1, 2, and 3 [14]; a Bayesian analysis of the frequency of large earthquakes and tsunamis [15]; a Markov model analysis supporting the post-accident exploration of "what-if" scenarios [16]; and a listing of a number of PSA topic areas that could be enhanced [17].

The purpose of our paper is to present the current results of an ongoing review of the Fukushima accident and related events aimed at identifying potential lessons regarding PSA technology (i.e., PSA methods, models, tools, and data). The purpose of our limited-scope review, which includes but is not limited to the most salient aspects of the event (e.g., the likelihood of large external hazards), is to support a variety of activities being conducted by the U.S. Nuclear Regulatory Commission's (NRC) Office of Nuclear Regulatory Research, including a recently initiated Level 3 PSA project [18] and the planning of future research and development, as well as contributing to the PSA community's dialog on this subject. Our review is focused on the technical attributes of PSA; we are interested in identifying where and how we might improve PSA technology and, thereby, future PSAs.

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[1] In this paper, we use the general term "event" at a variety of levels, including the global level (i.e., the earthquake and all subsequent occurrences), the site level (e.g., the accidents at Fukushima Dai-ichi), the plant level (e.g., the core melt accident at Fukushima Dai-ichi Unit 1), and below (e.g., the operators' closing Isolation Condenser motor-operated valve MO-3A).

2. SCOPE AND APPROACH

The scope of the review covers all of the Japanese NPPs affected by the earthquake and tsunamis. At present, the focus of our review has been on the events at the Fukushima Dai-ichi plant (and principally, Units 1, 2, and 3). In addition, we have also given some consideration to events at the Fukushima Dai-ni and Onagawa plants.

In keeping with the goal of identifying PSA technology lessons, we are limiting our review to aspects potentially affecting the performance of a full-scope, Level 3 PSA. Similar to the approach used in a past review of major fire events [19], our review is being performed from two perspectives. The first looks at the chronological chain of events, considering what happened and how (or even whether) this would be modeled using current PSA technology. The second goes through a generic list of PSA topic areas and asks what are the implications (if any) of the observed events. This list, a modified version of a list developed to support strategic planning of PSA research activities [20], is shown in Table 1.

We note that in both the chronological and topic-based reviews, our results are largely based on consideration of documented observations. For the purpose of this exercise, we have generally limited extrapolations to unobserved situations. (Thus, for example, we have omitted the issue regarding transient explosive materials identified in Ref. 17.)

The remainder of this paper is based largely on the Government of Japan investigative reports [4,5] the reports prepared by the Institute of Nuclear Plant Operations (INPO) [12,13], and the International Atomic Energy Agency (IAEA) expert mission report [11]. (In a few cases, we incorporate information obtained from other sources, including discussions with colleagues and public meetings.) As our work progresses, we plan to more thoroughly review other investigative reports (principally the ones identified in the list of references below). However, we expect that most of the factual information of principal interest to our review is contained in the above reports.

Table 1. PSA Topic Areas

Area	Topic	Area	Topic
Reactors	Level 1	General Systems Analysis Methods and Tools	PSA Tools
	Level 2		Uncertainty and sensitivity analysis
	Level 3		Advanced computational methods
	Low power and shutdown		Advanced modeling methods
	Operational data		Elicitation methods
	Event analysis	Special Topics	Human reliability analysis (HRA)
	New reactors		Ageing
	Research and test reactors		Success criteria
Non-Reactor Facilities and Activities	Geologic repositories		Passive components
	High-level waste (including on-site)		Passive systems
	Low-level waste/decommissioning		Digital systems
	Fuel cycle facilities		Common-cause failure
	Transportation		Design and construction
	Sources		Multiple units and sites
Implementation and Application	PSA guidance and standards		Internal hazards
	Metrics (including performance indicators)		External hazards
	Risk-informed regulation applications		Safety-security interface
	Risk perception and communication		Accident management
	PSA knowledge management		Emergency preparedness and response

3. POTENTIAL PSA TECHNOLOGY CHALLENGES

Table 2 lists the set of potential PSA technology challenges identified to date, organized by PSA topic area. These challenges involve phenomena or situations for which current PSA technology does not appear to be sufficiently developed to support routine, efficient analysis. A number of these challenges have been identified previously (notably in [17]). Table 2 also identifies a number of PSA "reminders," i.e., phenomena or situations for which current PSA technology is probably adequate but needs to be appropriately exercised.

The remainder of this section enlarges on a number of challenges and reminders (or groups of challenges/reminders) identified in Table 2. Note that the order of discussion is somewhat arbitrary and does not reflect the relative importance of the topic.

Table 2. Potential PSA Technology Challenges and Reminders

Topic/Area	**Challenges [C] and Reminders [R]**
Reactors	
Level 1/2/3 PRA	1) Extending the PSA scope to address: a) multiple units and sites, b) post-accident shutdown risk, and c) on- and off-site emergency response organizations (see Section 3.1) [C] 2) Treatment of the feedback from offsite consequences to plant decision making (see Section 3.2) [C] 3) Improving realism of accident progression modeling (see Section 3.3) [C] 4) Addressing long-duration scenarios (see Section 3.4) [C] 5) Characterizing uncertainty in phenomenological codes (see Section 3.7) [C]
Low Power and Shutdown	1) Treatment of post-accident shutdown risk (see Level 1/2/3 1b above) [R] 2) Treatment of shutdown risk associated with a pre-emptively shutdown plant [R]
Operational Data	1) Ensuring appropriate use of the Fukushima data (and worldwide events) in high-level estimates of CDF [R]. 2) Ensuring adequate basis for excluding operational data, especially for rare or infrequent occurrences [R]
Event Analysis	1) Performing real-time "on-the-fly" event risk analysis for incident response and early investigations [C]
New Reactors	1) Identification and treatment of "errors of commission (EOCs)" involving intentional disabling of passive safety systems (see HRA, below and Section 3.6) [C] 2) Treatment of operator performance when digital systems are lost (see HRA, below and Section 3.6) [C] 3) Addressing staffing requirements (possibly including offsite personnel) when responding to accidents [R] 4) Addressing reliability of passive components (e.g., rupture disks) [R]
Non-Reactor Facilities and Activities	
High Level Waste	1) Treatment of competing resource demands associated with multi-source (e.g., reactor and spent fuel pool – SFP) scenarios [C] 2) Treatment of external hazards effects on stored spent fuel [R].
Low Level Waste	1) Treatment of wastewater concerns (e.g., storage, leakage, area accessibility) on operator actions [C] 2) Treatment of aqueous transport of wastewater and consequences (public safety, environmental, and economic) [C] 3) Addressing pre-accident wastewater storage capacity [R]
Implementation and Application	
PSA Standards and Guidance	1) Ensuring appropriate treatment of issues identified in this table, especially with respect to external event screening [R]
Metrics	1) Development of appropriate risk metrics for multi-unit/source and multi-site scenarios [C]
Risk Perception and Communication	1) Treatment of the psychological impact on operators, experts, and decision makers [C] 2) Treatment of anticipated non-radiation related fatalities and health effects in evacuation decision making [C]

Table 2. Potential PSA Technology Challenges and Reminders (continued)

Topic/Area	**Challenges [C] and Reminders [R]**
General Systems Analysis Methods and Tools	
PSA Tools	1) Ability of PSA codes to solve detailed, multi-source models in reasonable timeframes [C]
Uncertainty and Sensitivity Analysis	1) Consistent characterization of model uncertainties associated with phenomenological code predictions (e.g., severe accident progression, earthquake/tsunami prediction, atmospheric transport) (see Section 3.7) [C] 2) Quantitative treatment of uncertainties in external hazard analysis [R] 3) Assessment of the effects of model uncertainty on overall results (e.g., combinations of key modeling uncertainties) [R]
Advanced Modeling Methods	1) Probabilistic treatment of factors affecting observed accident evolution (e.g., multiple shocks over time; partial successes, failures, and recoveries; uncertain information; conscious allocation of recovery resources; feedback loops) [C]
Elicitation Methods	1) Eliciting (and using) the technical community's state of knowledge regarding the frequency and magnitude of key (rare) external hazards [R]
Special Topics	
Human Reliability Analysis	(See Section 3.6 for discussion) 1) Identification and treatment of "errors of commission (EOCs)" involving intentional disabling of safety systems [R] 2) Treatment of different or multiple decision makers , including external distractions [C] 3) Treatment of the psychological impact on operators, experts, and decision makers [C] 4) Treatment of the feedback from offsite consequences to plant decision making [C] 5) Assessment of the feasibility of recovery actions and delays in performing these actions [R] 6) Assessment of the effects of uncertainty (including uncertainties due to loss of instrumentation and control) on operator actions and decision making [R] 7) Assessment of cumulative effects (e.g., fatigue, radiation exposure) on operators [C] 8) Assessment of the variability in plant crew performance [R]
Passive Components	1) Treatment of failure location(s) and mode(s) for primary system (e.g., suppression pool welds, primary containment penetrations) during severe accident analysis. [C] 2) Addressing reliability of passive components (e.g., rupture disks, drywell penetration and head seal) [R].
Passive Systems	1) Identification and treatment of EOCs involving intentional disabling of passive safety systems (see HRA) [C]
Digital systems	1) Treatment of operator performance when digital systems (e.g., SPDS) are lost [C]
Multiple Units and Sites	1) Treatment of multi-unit and multi-source interactions (e.g., common threats, physical interconnections, physical effects, resource/staffing allocations) [C] 2) Treatment of multi-site interactions (e.g., common threats, resource/staffing allocations) [C] 3) Development of appropriate risk metrics for multi-unit/source and multi-site scenarios [C]
Internal Hazards	1) Treatment of the multiple effects of internal explosions on operations (e.g., scattered radioactive debris limiting area access, damaged barriers, evacuation on non-essential staff) [C]
External Hazards	(See Section 3.5 for additional discussion) 1) Characterization and treatment of full spectrum of hazards [C] 2) Treatment of correlated hazards (e.g., earthquake-induced tsunamis and fires) [C] 3) Treatment of multiple shocks (and associated component fragilities) and periods of elevated hazard (e.g., tsunami warnings), including direct and psychological effects on staff [C] 4) Avoiding premature screening (see Section 3.8) [R] 5) Addressing all damage mechanisms for hazards and associated fragilities (e.g., dynamic loadings, water drawdown, debris loading/blocking) [R] 6) Addressing effects of on- and offsite damage caused by external hazard (e.g., anticipated damage to underground piping, availability/installation of portable equipment, effect on offsite resource availability and timing)[R]
Safety-Security Interface	1) Addressing event effects on access systems (e.g., gates, doors) [R]
Accident Management	1) Treatment of general Level 2 concerns (see Level 1/2/3 PSA #1-#6) [C,R] 2) Treatment of Level 2 HRA concerns (see HRA #2-#8) [C,R] 3) Addressing effects of external event on accident management (see External Events #4-#5) [R]

Table 2. Potential PSA Technology Challenges and Reminders (continued)

Topic/Area	Challenges [C] and Reminders [R]
Special Topics (continued)	
Emergency Preparedness and Response	1) Treatment of non-radiation related fatalities and health effects, and impact of anticipated effects in evacuation decision making [C] 2) Probabilistic treatment of failures in on-site/offsite emergency response [C] 3) Addressing delays in evacuation due to poor communication, lack of information, or unavailability of offsite emergency facilities [R] 4) Addressing effects of external event (including but not limited to damage) on evacuation [R] 5) Treatment of multiple offsite population moves due to expanding evacuation zones [R]

3.1. Extending the PSA Scope

As widely recognized by many others, the events at Fukushima clearly demonstrate the potential risk significance of accidents involving release of radionuclides from multiple sources. The concurrent events at other Japanese plants further indicate the potential risk significance of accidents triggered by regional events that involve multiple sites. Multi-source dependencies that need to be considered in a more broadly scoped PSA arise from exposure to a common hazard, physical connections (e.g., unit cross-ties), the physical impacts of consequential events (e.g., explosions, radioactive material release), and accident response resource limitations. Most of these dependency mechanisms could also apply to multi-site scenarios.

Other potential PSA scope extensions suggested by Fukushima include the treatment of: systems not normally analyzed (e.g., security systems affecting site or local access); offsite organizations (directly affecting operations through suggestions such as delaying saltwater injection, or indirectly through requests for information); and post-accident risk associated with a stabilized but severely damaged site. Regarding the last item, although the decay power level for a stabilized site will be relatively low and the associated time available for reaction and recovery will be relatively long, the risk may still be significant, considering the degraded state of the reactor coolant system boundary and safety systems (if any remain available), use of temporary or ad-hoc means to provide essential safety functions, and the possibility of a subsequent external event or system failure.

3.2. Treating Feedback Loops

NPP PSAs are often discussed as “once-through” processes, progressing from a core damage (Level 1) analysis to an accident progression and source term analysis (Level 2) and then to an offsite consequences analysis (Level 3). In practice, the demands of a Level 2 analysis may lead to refinements of the Level 1 analysis (e.g., to provide more precise treatment of scenarios important to particular plant damage states and release categories). However, feedback from the Level 3 analysis to the Level 2 or Level 1 analysis is not treated. The delay in containment venting for Fukushima Dai-ichi Unit 1 caused by incomplete evacuation provides one indication that this “once-through” approach may need to be revisited. Furthermore, as indicated in Section 3.1, when multi-unit impacts are considered, the analyses performed for one unit may need to feed back to the PSA analyses for the other units.

3.3. Reconsidering “Game Over” Modeling and Intentional Conservatism

PSA models, as with any models of complex systems, employ many approximations. Some of these approximations, e.g., the neglect of partial successes leading to cooling water injection that delays (but does not prevent) core melt, are useful for many risk-informed decisions but not for others. “Game Over” modeling relies on conservative simplifying assumptions to terminate PSA accident scenarios early. For example, typical PSA treatments of scenarios involving complete loss of power lead to predictions of core melt much quicker than the times reported for Fukushima Dai-ichi Units 2 and 3. Such treatments not only miss the opportunity to identify and assess potentially effective accident management improvements, they also provide skewed input to the Level 3 analysis. More generally, well-intentioned conservatism in different PSA technical elements can sufficiently skew the analysis results that truly risk-significant scenarios may be masked. Furthermore, such conservative modeling may result in operations staff and emergency responders being unaware of mitigative activities that could reduce offsite impacts.

3.4. Treating Long Duration Scenarios

The multi-day or even multi-week scenarios that may result from more realistic treatments of possible accident progressions present a number of PSA challenges. These include the explicit treatment of: offsite emergency resources (these are implicitly credited in current PSAs via standard mission time assumptions); subsequent external events (at Fukushima Dai-ichi, earthquake aftershocks and tsunami warnings disrupted site operations as operators had to take shelter and then assemble for accountability); and the toll on operators (discussed in the section on Human Reliability Analysis – HRA – below). A particular challenge involves the determination of when an accident scenario results in a stable and sustainable plant condition, particularly when essential safety functions may be provided by temporary systems or unconventional means (as discussed in Section 3.1 above).

3.5. Improving and Expanding External Hazards Analysis

Table 2 lists a number of challenges and reminders for external hazards analysis, including the treatment of: beyond design basis events (considering both extreme hazards and concurrent failures); multiple correlated hazards (earthquake and tsunami in the case of Fukushima); multiple shocks (and warnings) and, more generally finite durations for periods of elevated hazards (i.e., the hazard is not a point event in time); and multiple damage mechanisms (e.g., a tsunami analysis should, in addition to inundation, consider such things as dynamic loads from water and debris, clogging from debris, water level drawdown effects, and soil erosion). A number of these issues (e.g., the treatment of multiple shocks and persisting hazards) may present new demands on the relevant scientific and engineering communities.

3.6. Improving HRA

Table 2 also lists a number of HRA challenges and reminders. These include the treatment of: errors of commission (e.g., the intentional isolation of the Isolation Condenser system at Fukushima Dai-ichi Unit 1); different decision makers (i.e., not the typical control room crew) who made potential errors in the prioritization of work (possibly due to incorrect information regarding system and plant status or input from external organizations); and potential psychological impacts on operators, advisers, and decision makers (including loss of confidence or even despair); recovery action feasibility and time delays (some actions took several hours to complete); uncertainty ("fog of war") effects; the effects of long scenario duration (including fatigue, stress, and cumulative dose); and crew-to-crew variability.

Errors of commission continue to be implicated in severe NPP accidents (e.g., TMI 2, Chernobyl, and now Fukushima). However, with a few exceptions, post-initiator EOCs are not included in PRA models[2] along with the associated contexts that would make such errors likely. However, PSAs that address post-core damage events may be forced to recognize the need for such Human Failure Events (HFEs). There are HRA methods capable of treating some aspects of EOCs (e.g., [21, 22]), and such methods (or at least their key underlying concepts) should be useful when searching for cognitively challenging HFEs the Level 2 analysis.

Traditionally, HRAs address decision making by the control room crew only.[3] Discussion of how to model the Technical Support Center began in the 1990s [23], but has not been addressed formally in HRA development efforts. The Fukushima event illustrates that: 1) decision makers might include government officials, 2) as postulated in by Dougherty [23], decision makers outside the control room can make mistakes (due to, for example, lack of understanding of the event-specific plant conditions, as well as NPP operations, generally), and 3) organizational responsibilities may not be clear. Post-core damage events are further complicated by missing information (e.g., accurate containment pressure indications) and other instrument failures that are not expected or trained on. Modeling such decision makers in HRA will be especially challenging since, unlike the many control room simulator exercises that are performed, the

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[2] The exception is a set of HFEs that result from responding to spurious indications caused by fire-induced cable damage in fire PRAs,

[3] Some HRA applications might use the Technical Support Center (TSC), an onsite emergency response facility which provides plant management and technical support to plant operations personnel during emergency conditions, as a recovery for control room errors.

strategies and associated decision-making needed in post-core damage events is seldom exercised. We note that the guidance used in such scenarios (e.g., Severe Accident Management Guidelines – SAMGs) can call for a knowledge-based decision among a set of difficult choices, and do not provide the same degree of direction as the Emergency Operating Procedures addressed in HRA for Level 1 PSA. We further note that even the SAMGs may not cover situations faced by the operators. Such a situation appears to have arisen in the Fukushima accident.

The remaining challenges or reminders involve the consideration of a multitude of factors that are unique to PSAs beyond Level 1 internal events. For example, operator actions performed outside the control room must be assessed for feasibility (see fire HRA guidelines [24]), including adequate time, accessibility of the action location (including consideration of how debris from site damage and security measures may be a hindrance), availability of appropriate staff (in the Fukushima event, some actions were significantly delayed because only contractors or other offsite personnel knew how to perform certain actions), and environmental hazards (e.g., aftershocks, radiation). If the actions are deemed feasible, then these same factors must be considered in developing human error probabilities (HEPs). The longer duration of post-core damage events (see Section 3.4) also invokes new questions with respect to the timing of operator actions. For example, in the Fukushima event, the opening of containment vent valves was unexpectedly delayed by several hours by: 1) waiting for a nearby town to be evacuated, 2) hardware failures, and 3) hazardous conditions (that developed during the wait time). We further note that the arrival of additional resources (e.g., from offsite) does not ensure rapid situation control – the analysis needs to realistically account for potential time delays. Also, "new" (or re-defined for the context) performance influencing factors are relevant in longer events, such as fatigue (e.g., operators in the Fukushima event had long shifts with minimal food and rest), and "stress" in a very real sense (e.g., Fukushima operators were clearly worried about their personal safety).

In principle, it appears that many of the HFEs, contexts, and factors mentioned above can be addressed with creative application of current HRA methods. However, the challenge for the HRA community will be establishing a relevant knowledge-base to support such analyses with any even smaller experience base than for the Level 1 internal events context. In addition, treatment of multi-source scenarios (per Section 3.1), will add additional complexities.

3.7. Consistently Characterizing the Uncertainty in Phenomenological Codes

As discussed at the November, 2012 American Nuclear Society (ANS) International Meeting on Severe Accident Assessment and Management, data from Fukushima are being used in benchmarking activities involving codes predicting severe accident progression codes, earthquake/tsunami hazards, and atmospheric transport. Mosleh et al. [25] provide an early discussion of the issue of model uncertainty in a PSA context (noting that there are even different definitions of the term "model uncertainty"), and NUREG-1855 [26] provides a high-level description of a number of approaches, but there is, as yet, no one agreed-upon approach. Moreover, different technical communities often use different frameworks for dealing with model uncertainty. These frameworks can be implicit (e.g., involving the use of selected sensitivity cases) or explicit (including ensemble modeling, probabilistic, and non-probabilistic approaches). The PSA community needs to engage with the ongoing benchmarking activities to ensure that the products are compatible with use in PSAs.

3.8. Increasing the Emphasis on Searching (vs. Screening)

The current version ("Addendum A") of the ASME/American Nuclear Society (ANS) PSA standard [27] and past external events guidance [28] allow the screening of non-seismic external events that meet the likelihood-informed, deterministic criteria of the NRC's 1975 Standard Review Plan. It has been recognized that such an approach would likely lead to the screening of beyond design basis scenarios analogous to Fukushima, and an updated criterion is expected in the latest update ("Addendum B") of the ASME/ANS standard. Specific screening criteria aside, the possibility that a PSA could screen an important scenario (or class of scenarios) may not be limited to external events analysis and raises a question as to what we might do to avoid this situation.

We first note that even without the additional complexities introduced by the issues discussed earlier in this paper, NPP PSA models need to address an enormous number of possibilities, and screening is essential to enable efficient analysis. However, the ultimate success of screening depends on the pre-screening identification of all potentially important scenarios. Care is needed to ensure that this identification process is not unduly biased by prior expectations regarding what's likely to be important. For example, an external flooding scenario identification process that assumes that the flooding risk is dominated by physical damage directly cause by the flood could focus on very large magnitude floods, and could miss risk contributions coming from scenarios involving lesser, more likely floods in combination with other failures (e.g., operator errors, independent hardware failures). A number of approaches (e.g., Master Logic Diagrams, Failure Modes and Effects Analysis, Hazards and Operability Studies) are available to support the systematic identification of potentially important initiating events [27, 29]. It remains to be demonstrated if these tools are sufficiently flexible and powerful to support the guiding PSA principle of searching for failures. This issue is further exacerbated with newer designs with lower core damage risk, where traditional frequency based approaches may miss major contributors to core damage frequency.

4. DISCUSSION AND NEXT STEPS

At a quick glance, the PSA technology lessons from Fukushima might appear to be obvious. The high level event narrative is simple. A beyond design basis earthquake and subsequent tsunamis overwhelmed plant defenses and caused core damage and release from multiple reactors. Such a narrative suggests that we should focus our PSA technology improvement efforts on the assessment of the likelihood of severe natural hazards. Clearly such efforts are important. However, limiting our efforts to this topic will miss other useful lessons that could lead to improvements in how we assess the risk of future accidents, which, should they occur, may or may not look like the events following the Tōhoku earthquake.

Table 2 identifies several PSA technology issues. Some of these represent challenges to the current state-of-the-art, while others represent reminders to PSA analysts. We note that:

- Although the boundary between "challenges" and "reminders" is fuzzy and certainly subject to discussion, we believe the issues, each of which is supported by specific observations from the accident and its aftermath, are clear.
- Some of the issues are associated with specific technical elements of a PSA (e.g., HRA, external events analysis). Others are associated with the general conduct and underlying assumptions of typical PSA studies. Some of these assumptions derive from current risk-informed applications (which, at least in the U.S., generally emphasize accident prevention); others reflect historical limitations in our ability to address key phenomena in a PSA context.
- The list of issues is probably not complete. We expect that the list will grow as we continue our review.

Our identification of PSA issues does not refute the value of PSAs past, present, or future. For example, since the earliest studies, PSAs have identified previously unexpected scenarios (including scenarios triggered by external events); provided a mechanism for assessing the significance of these scenarios; and suggested potentially effective measures to manage the risk from these scenarios. Rather, this exercise represents an application of an essential PSA concept – the importance of searching for potential failures of the entire, integrated system – to the process of performing a PSA. It is critical that our searches, which need to challenge common assumptions, not themselves become slaves to routine, that the valuable experience from decades of analyses and applications not blind us to the lessons from real events and associated potential improvements.

As mentioned earlier in this paper, the NRC has recently initiated a Level 3 PSA project. This project is intended to address all relevant site radiological sources (including the spent fuel pool), internal and external initiating event hazards, and modes of operation for a 2-unit, Westinghouse four-loop pressurized water reactor station with a large, dry containment [18]. As of the writing of this paper, the project team is finalizing the project technical plan. We are feeding the early insights from our review into project planning and expect to continue to use review insights as both our review and the project proceed. Furthermore, recognizing that the Level 3 project is limited to current PSA state of practices, our review work is also providing input to ongoing development projects (e.g., a project aimed at developing a common HRA method for NRC use [30]) and strategic planning discussions regarding PSA research and development.

5. CONCLUSION

Our limited-scope review of events at Japanese NPPs following the March 2011 Tōhoku earthquake has identified a number of potential PSA technology issues. These issues involve typical assumptions (e.g., regarding scope, important interactions) affecting the overall conduct of the PSA, as well as particular PSA technical elements. We expect that some of these issues will be addressed by the NRC's recently initiated Level 3 PSA project. Others likely will require research and development.

Our review is not yet complete. We will continue to review the tremendous amount of information available (and still being generated), and expect to report our final results at a future conference.

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