PSA TECHNOLOGY REMINDERS AND CHALLENGES REVEALED BY THE GREAT EAST JAPAN EARTHQUAKE: 2016 UPDATE

Nathan Siu, Keith Compton, Susan Cooper, Kevin Coyne, Fernando Ferrante,
Donald Helton, Don Marksberry, and Jing Xing

U.S. Nuclear Regulatory Commission, Rockville, Maryland, USA

This paper presents the results of a review of the Fukushima Daiichi 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 and the planning of future research and development, and b) contribute to the PSA community's dialog on this subject. This paper, which uses recent information to update a project status paper presented at the PSAM Topical Meeting in Light of the Fukushima Daiichi Accident in 2013, identifies a number of reminders for the application of current PSA technology and challenges to this technology.

I. INTRODUCTION

In the five years since the Fukushima Daiichi reactor accident, much has been written and much has been done to identify and implement plant safety improvements. Looking forward, recognizing that risk-informed and performance-based approaches continue to play an important role in the U.S. Nuclear Regulatory Commission's (NRC) regulatory activities,[1,2] it is natural to ask what lessons from the accidents might be used to inform these approaches. In particular, what are the key lessons for the application of Probabilistic Safety Assessment (PSA[a]), which provides a key input to risk-informed and performance-based decision making?

This paper presents the results of a review of the Fukushima Daiichi accident and related events stemming from the Great East Japan earthquake of 2011. The review is aimed at identifying potential lessons regarding PSA methods, models, tools, and data (referred to henceforth as "PSA technology"). The purpose of this review is to: a) support a variety of activities being conducted by the NRC's Office of Nuclear Regulatory Research, including a Level 3 PSA project[3] and the planning of future research and development, and b) contribute to the PSA community's dialog on this subject.

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II. SCOPE AND APPROACH

This paper provides the results of a review whose early results were presented in a 2013 paper.[4] The review involves the collection, synthesis, and analysis of information developed by other review reports and papers (including Refs. 5-23); although we have benefited from discussions with staff from involved organizations and a site visit by one of the authors, we have not attempted to systematically develop independent data sources.

Similar to the 2013 paper, this paper provides a table of PSA reminders and challenges[b] and expanded discussions for a selected set of topics. For each topic, we provide a general description, illustrative examples from the accident, and the implications for PSA technology. For brevity, we generally do not dwell on major points raised in the 2013 paper that we believe remain valid as of this writing (see Table I).

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[a] For the purposes of this paper, the term PSA is used synonymously with the term Probabilistic Risk Assessment (PRA).

[b] "Reminders" involve phenomena or situations for which current PSA technology is probably adequate but needs to be appropriately exercised. "Challenges" involve phenomena or situations for which current PSA technology does not appear to be sufficiently developed to support routine, efficient analysis.

TABLE I. Previously Identified PSA Technology Concerns[4]

Topic	Issues
PSA scope	Multiple units/sources, systems not normally analyzed (e.g., security systems), off-site organizations, post-accident risk
Feedback loops	Feedback from Level 3 to Level 1/Level 2 (e.g., venting delays due to delayed evacuation), multi-unit/source interactions
"Game over" modeling	Intentional conservatisms skewing risk results and insights, masking important scenarios, de-valuing mitigative activities
Long duration scenarios	Offsite resources, additional warnings and shocks, toll on operators, definition of safe and stable state
External hazards analysis	Beyond design basis events, multiple correlated hazards, multiple shocks, finite duration of elevated hazard, multiple damage mechanisms
Human reliability analysis (HRA)	Errors of commission, technical support center and external decision making, ex-control room actions, new/re-defined performance influencing factors, support of creative HRA methods applications
Uncertainty in phenomenological codes	Varying views and treatments of uncertainty (e.g., sensitivity cases, ensemble modeling, probabilistic/non-probabilistic methods) across technical disciplines
Searching vs. screening	Screening of beyond design basis hazards, biases (e.g., focusing on extreme events), systematic methods to search for failures

III. PSA REMINDERS AND CHALLENGES

Table II provides an updated version of the table presented in our 2013 paper. As with the earlier version, the ordering of events in the table does not reflect any sense of priority, nor is the table expected to be definitive – different observers can develop different lists of topics with different characterizations. We view the table as an input for discussions (e.g., when discussing potential areas for PSA improvements.)

IV. SELECTED TOPICS

In this section, we provide additional discussion on four topics: external hazards, human performance and human reliability, Level 2 PSA, and Level 3 PSA.[c]

IV.A. External Hazards

The potential risk significance of external hazards has been recognized since the early days of PSA,[24] and, in fact, several notable external-hazard induced events have occurred, including the flooding events at Blayais (1999) and Madras (2004) and the Niigata-Chuetsu-Oki earthquake involving the Kashiwazaki-Kariwa plant (2007)[6]. However, despite this awareness, the PSA treatment of external hazards has not been considered essential by many in the PSA community, let alone the broader nuclear safety community. Worldwide, many analysts and organizations have focused on the results of internal events analyses. It took the events of March, 2011 to prompt the broader PSA community to take another look at current PSA standards and technology for external hazards analyses.

As of this writing, many of the PSA technology lessons regarding external hazards (e.g., see Tables I and II) are well-recognized. Nevertheless, much remains to be considered. In the following subsections, we discuss three topics of interest: the use of PSA to ensure defense-in-depth (DID), the importance of dealing with the full hazard spectrum, and the treatment of correlated hazards.

IV.A.1. Using PSA to ensure DID

As discussed by the International Atomic Energy Agency (IAEA), a lack of sufficient DID for the tsunami hazard and protection against common cause failure of critical safety functions was a contributing cause to the Fukushima Daiichi accident.[6] In principle, PSA should be a natural tool to identify such weaknesses, as well as potentially effective countermeasures.[25] However, in practice, there can be difficulties in identifying these insights using PSA techniques, particularly for external hazards PSA. For example, in the external hazards area, the following reminders and challenges need to be addressed:

[c] In this paper, we use the term "Level 2 PSA" to refer to that portion of the analysis following core damage and ending with release to the environment. Similarly, we use the term "Level 3 PSA" to refer to that portion of the analysis dealing with post-release consequences.

TABLE II. 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 [C] 2) Treatment of the feedback from offsite consequences to plant decision making [C] 3) Improving realism of accident progression modeling [C] 4) Addressing long-duration scenarios, including availability of supplemental offsite resources (e.g., fuel oil, water, equipment) [C] 5) Characterizing uncertainty in phenomenological codes [C]
Low Power and Shutdown	1) Treatment of post-accident shutdown risk (maintaining long-term safe state) [C] 2) Treatment of shutdown risk associated with a pre-emptively shutdown plant [R] 3) Lack of operational experience data [C]
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] 3) Ensuring adequate reliability data for temporary mitigating equipment and systems [C] 4) Ensuring adequate reliability data for containment penetration integrity [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), including those involving intentional disabling of passive safety systems [C] 2) Treatment of operator performance when digital control or safety systems are lost [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) Treatment of groundwater contamination [C] 4) 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) Identifying appropriate endpoints for assessment [R] 2) Development of appropriate risk metrics for multi-unit/source and multi-site scenarios [C]
Risk Perception &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] 3) Framing the risks of nuclear power plant operation to allow comparison to other societal and individual risks [C]
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) [C] 2) Quantitative treatment of uncertainties in external hazard analysis [C,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] 2) Treatment of concurrent and correlated hazards (e.g., seismically induced fires) [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]

TABLE II. Potential PSA Technology Challenges and Reminders (continued)

Topic/Area	Challenges [C] and Reminders [R]
Special Topics	
Human Reliability Analysis	1) Identification and treatment of "errors of commission (EOCs)" involving intentional disabling of safety systems [C] 2) Treatment of different or multiple decision makers, including external distractions and conflicting orders [C] 3) Treatment of the psychological impact on operators, experts, and decision makers (e.g., life-threatening decisions and actions, fears of recurring events) [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] 9) Assessment of the possibility of control room or even site abandonment due to hazardous conditions [C] 10) Treatment of extremely reduced onsite staffing due to evacuation, especially for multi-unit sites [C]
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 [C]
Digital systems	1) Treatment of operator performance when digital control or safety systems are lost [C] 2) Reliability of digital systems, particularly under harsh or severe accident conditions [C]
Multiple Units and Sites	1) Treatment of multi-unit and multi-source interactions (e.g., common threats, physical interconnections, physical effects, area events, 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, damage to onsite emergency response facility) [C] 2) Treatment of the impact of containment penetration failures on control room habitability and plant access [C]
External Hazards	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 [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, onsite accessibility by staff and vehicles) [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 (e.g., improving realism of accident progression modeling) [C,R] 2) Treatment of Level 2 HRA concerns (e.g., control room abandonment) [C,R] 3) Addressing effects of external event on accident management (e.g., availability of portable equipment and offsite resources) [R] 4) Modeling of human and emergency response organization behavior in a post core damage environment [C] 5) Treatment of impacts of delayed offsite protective actions on plant actions (e.g., containment venting, liquid releases) [C] 6) Blurred responsibilities between onsite and offsite decision makers (e.g., control room, onsite emergency response facility, offsite emergency response facilities) [R]
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, evacuation, and mitigation [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, response staff traveling to the plant, and emergency response facilities [R] 5) Addressing the effects of multi-site events on offsite decision making [R] 6) Treatment of multiple offsite population moves due to expanding evacuation zones [R]

- Ensuring the PSA has sufficiently broad scope to cover all important hazards and is performed with sufficient rigor to avoid premature screening. For external hazards not already recognized as being potentially important, this can be easier said than done. The analyst may have to: a) overcome previous biases within the PSA community (e.g., external floods were generally discounted prior to Fukushima) and the urge to dismiss lessons from events involving plants of different designs and in different countries, and b) consider divergent points of view within the scientific community. Regarding the latter point, the Senior Seismic Hazard Analysis Committee's (SSHAC) philosophy of developing distributions intended to represent the state of knowledge of the informed technical community (as opposed to a "best estimate," or a distribution representing the views of a small set of experts) is helpful.[26]
- Avoiding simplistic, "game over" modeling. For example, the assumption that floods exceeding a specified height will always cause core damage can artificially increase the estimated benefit of some countermeasures (e.g., raising the height of external flood walls) in comparison with others (e.g., improving detection and warning capabilities to support pre-emptive actions, ensuring the integrity of and/or improving passive and active flooding barriers for buildings and within buildings, improving the flood resistance of important components, improving the ability to recover from flood-induced loss of key equipment and functions). Furthermore, terminating sequence development at core damage when potential releases can be readily mitigated may overestimate the potential public health impact.
- Addressing current technical challenges in external hazards analysis. In addition to those listed in Table I, these include the realistic modeling of: a) equipment and function recovery (e.g., offsite power) during and after a wide-ranging extreme event, and b) common cause failures caused by the event. Regarding the former, a realistic treatment of time delays is important. For example, although mobile power supply vehicles started arriving at the Fukushima Daiichi site late on March 11 (some six hours after the station blackout) and more arrived overnight, the first connection to one system in Unit 2 was not completed and suppling power, until the afternoon of March 12. This equipment and connections were damaged minutes later from the hydrogen explosion of Unit 1 reactor building. Regarding the latter, a key challenge is the treatment of multiple hazards (seismic and flooding in the case of Fukushima) associated with the event. This is further discussed in Section IV.A.3 below.

With such a PSA, it may be possible to systematically estimate the value of different DID layers/barriers (perhaps considering the multiple risk measures discussed later in Section IV.D of this paper) and support the identification of a reasonable balance between these different layers/barriers.

IV.A.2. Dealing with the full hazard spectrum

The term "cliff-edge failure," commonly used when discussing extreme flooding hazards but applied to other external hazards as well, is appealing with its vivid imagery. However, a too-literal use of the term can cause problems when performing external hazard PSAs intended to support risk-informed decisions.

First, the term tends to focus attention (and therefore analysis resources) on extreme events that exceed some physical threshold (e.g., flooding events whose maximum levels exceed those of the design basis flood). Because design basis events are unlikely by design, the analysis needs to deal with very unlikely events which are typically well beyond historical experience and for which, therefore, quantitative estimates of likelihood and severity are highly uncertain and potentially controversial. (Indeed, some technical communities may even reject the concept of estimating the likelihood of such rare events.) The focus on extreme events tends to ignore the risk contribution from scenarios involving lower severity hazards acting in concert with other, possibly dependent failures, i.e., an "uncommon combination of non-uncommon events."[27] Not only does underestimate risk, it devalues potentially effective countermeasures (e.g., ensuring penetration seal integrity).

The concern with less extreme events is illustrated by the March 2011 events at the Onagawa plant where the tsunami did not exceed the site elevation but nevertheless surged past a barrier and caused significant flooding and, in concert with the earthquake-induced loss of multiple offsite power lines, complicated shutdown efforts.[14,28] The NRC's post-Fukushima flooding walkdowns[29] identified a number of similar issues involving flood barriers and procedures and showed that significant risk could be accrued at much lower flooding elevations (i.e., well below design basis level) in combination with the failure of seal penetrations and/or unanalyzed flow paths.[30]

A second problem with the "cliff-edge" term is that it tends to provide a simplistic view of damage mechanisms. For example, in the case of external flooding, overtopping is only one of a number of means by which a flood can fail a protective dyke. (Other mechanisms include flood-induced instabilities, seepage/piping, and erosion.) As another example, water inundation is only one possible mechanism for damaging equipment and failing essential functions. At Fukushima Daiichi, tsunami-carried debris damaged seawater pumps providing plant ultimate heat sink. At the Cruas 4 plant in 2009, flood-borne vegetation led to a loss of plant service water.[31] As with the case of extreme events, a focus on one damage mechanism can lead to underestimates of risk and a failure to identify and evaluate potentially effective countermeasures.

From a PSA technology standpoint, adopting a more nuanced, non-binary view of external hazards means that hazard curves are needed for the full spectrum (or at least a much broader spectrum) of possible events. The availability of such curves varies with the hazard and associated technical discipline. In the case of seismic events, detailed information is available for all U.S. plants. In the case of external flooding, initiatives are underway at NRC and elsewhere.[32,33] For "new" hazards not yet addressed in any PSAs (e.g., Coronal Mass Ejection), further work is needed.[34]

IV.A.3. Characterization and Treatment of Correlated Hazards in PSA

As indicated in Table I, it is important to recognize that external hazard events can involve multiple external hazards. The Great East Japan Earthquake led to seismic and tsunami hazards at Fukushima Daiichi and other Japanese plants. (Furthermore, the earthquake led to ground subsidence as well as shaking; the tsunamis caused drawdown and dynamic loads from water and debris, as well as inundation.) The 1999 Blayais event, in which storm-induced high winds caused a loss of offsite power before storm-driven waves (on top of a high estuary tide) led to plant flooding, provides another example.

Further, it is also important to recognize that, as illustrated by both the Fukushima and Blayais events, the multiple external hazards need not strike the plant at the same time (where "same" is measured relative to the characteristic time scale of activities to achieve safe shutdown).

Finally, especially for mechanistic analyses that use phenomenological models to predict hazard levels (e.g., flood heights), it should be noted that multiple external events may contribute to the ultimate hazard faced by the plant. The well-publicized 2011 flooding of the Fort Calhoun site provides a good example.[36] In the months leading up to the flood, a mixture of above normal snowpack conditions, lower than expected temperatures, and record precipitation across various parts of the Missouri River basin produced severe flooding conditions. In two weeks, certain areas received a total rainfall comparable to the expected total precipitation in one year.[35] Due to the danger associated with these conditions, the operators for multiple dams were authorized to make record releases. At the Fort Calhoun site, the resulting flood waters eventually surrounded the switchyard, the dry-cask storage area, the power block (i.e., containment, turbine and auxiliary buildings), and support buildings (e.g., administrative building, training center, security building). Elevated flood levels remained for several months.

To our understanding, the explicit and comprehensive treatment of all potentially correlated hazards is beyond the current PSA state of practice. However, pragmatic simplified approaches (e.g., bounding analyses) are naturally available, and various rigorous approaches (e.g., the statistical development of multi-dimensional hazard curves, the use of phenomenologically-based stochastic simulations) appear to be feasible, at least for limited-scale analyses.

IV.B. Human Performance and Human Reliability

Although it is clear that the tsunami, with its widespread damage to critical plant structures, systems, and components (SSCs) was a central and unique feature of the Fukushima Daiichi accident, it is also clear that the response of plant decision makers and staff, as affected by harsh accident conditions and external decision making influences, played a major role in how the accident evolved. Immediately following the earthquake, Fukushima Daiichi operations followed a relatively calm, procedure-driven response to the seismically-induced reactor trips. However, after the tsunami, operations became more stressful during attempts to cool the reactor cores as conditions deteriorated, needed information was unavailable or unreliable, and existing accident management guidelines proved inadequate for the situation. Of particular note was that accident management procedures presumed, among other things, that the accident would be confined to a single unit, that AC power was either available or would be rapidly recovered, that DC power was available, and that communications were available. From an HRA technology perspective, these later activities and conditions are especially of interest, as they bear directly on the performance of HRA for Level 2 and Level 3 PSA, a relatively unexplored territory with special needs.[37]

The following sections briefly discuss three topics of special interest to Level 2/3 HRA: 1) decision-making under severe accident conditions, 2) ex-control room actions, and 3) teamwork.

IV.B.1. Decision-Making Under Severe Accident Conditions

For pre-core damage decision making, input parameters may be well known and a solution can be achieved by following familiar and well-trained paths.[d] On the other hand, post-core damage decision making includes unconstrained variables (e.g., variations in plant conditions, available of staff and equipment), unknown input parameters (e.g., reactor vessel level, containment pressure), and no good solution (i.e., no outcomes can be truly considered "success" as they are different levels of core and plant damage). In this situation, there are operational decision making needs at all levels: strategic (e.g., which

[d] Note that there can be a wide variety of approaches when following emergency operating procedures.[38]

unit to prioritize), operational (e.g., which cooling strategy to implement), and tactical (e.g., how to implement a chosen cooling strategy).

Some challenges for onsite decision making during the Fukushima Daiichi accident were:

- extremely stressful onsite conditions, both physical and psychological (e.g., inadequate food, rest, and hygiene; fear of mortal harm from radiation exposure and contamination);
- the need to develop innovative solutions (e.g., for injecting water using fire engines);
- unexpected behaviors which diverted response resources (e.g., the Unit 4 reactor building explosion, unexpected visit by the Prime Minister – PM);
- long time delays (e.g., to get information from the field, to see whether chosen strategies were successful);
- omitted or delayed information (e.g., failure to notify the onsite Emergency Response Center – ERC – of closure of the Unit 1 isolation condenser condensate return valve, delayed notification of the site superintendent regarding the failure of attempts to implement alternate water injection for Unit 3);
- the need to balance onsite and offsite concerns (e.g., when deciding when to vent containment);
- confusion between the site superintendent and Tokyo Electric Power Company's (TEPCO) headquarters (HQ) over the basis of a regulation to provide iodine pills to only staff under the age of 40 years and reluctance of HQ to act against regulation without a reply from the regulator; and
- offsite demands for actions or non-actions based on misinformation (e.g., regarding the use of seawater).

Some challenges for offsite decision making were:

- the loss of systems needed to project offsite doses;
- the loss of telecommunications circuits between the plant and offsite and inadequate information exchanges (leading to increased involvement by the central government, including direct inquiries via mobile phone); and
- problems with the offsite center (OFC) intended to coordinate evacuations and other protective actions (emergency diesel generator – EDG – failure, seismic damage to original building, was never fully staffed because of transportation system damage, and was later relocated due to increases in radiation).

It is also instructive to recognize that the accident involved a number of factors that supported decision making, including extensive pre-event preparation for major seismic events (e.g., the provision of a seismically-isolated onsite ERC). (Note that the plant operators were relatively confident in their response prior to the arrival of the tsunami.)

IV.B.2. Ex-Control Room Actions

Over the past few decades, HRA technology development activities have focused on addressing decisions and actions within the control room. The Fukushima Daiichi accident provides numerous reminders of challenges arising in the detailed planning and field execution of post-initiator actions (both pre- and post-core damage). In addition to local environment challenges (some of which, e.g., flooding, low lighting at night, are associated with the initiating event, and others induced by the accident – see Section IV.C.3 below) and psychological stress (mentioned above), these could include:

- inadequacy of existing procedures and guidelines and the consequent need to develop detailed procedures (e.g., for executing necessary valve lineups) "on the fly;"
- restricted or blocked access to locations where actions are to be performed (e.g., due to debris, dose levels, structural damage, failure of access systems);
- delays in obtaining information (e.g., regarding location accessibility and habitability) needed to develop detailed procedures;
- time pressure preventing a thorough vetting of the detailed procedures (e.g., to ensure a valve lineup does not involve unintended flow backflows or bypasses);
- uncoordinated evacuation of "non-essential" staff/contractors with important knowledge (e.g., the location of needed equipment);
- lack of sufficient administrative/logistical support leading to delays in obtaining requested resources; and
- changing conditions during the accident leading to delays or complete changes in plans (e.g., earthquake aftershocks and tsunami warnings prompting temporary evacuations; hydrogen explosions which stopped power recovery efforts, scattered radioactive debris, and injured five workers).

The accident, as well as actions at other plants, also provides numerous examples of successful field actions under extraordinarily difficult conditions. These include:

- laying of power cables;
- installing car batteries to power key instrumentation in the control room;
- installation of temporary submersible pumps for residual heat removal at Units 5 and 6; and

- eventual establishment of paths for fresh water and seawater injection and for containment venting;

IV.B.3. Teamwork

During the Fukushima accident, the formulation and implementation of responses required coordination, communication, and cooperation among multiple entities, including: control room operators, field shift teams, the onsite ERC (including multiple unit-specific teams), the OFC, the offsite TEPCO ERC, and central and local government authorities. Teamwork challenges included:

- onsite and offsite communications systems failures;
- a lack of clarity on roles and responsibilities within the onsite emergency response organization (e.g., regarding support of activities not explicitly called out by existing accident management guidelines);
- failures to share important information within the onsite ERC (e.g., regarding the Unit 3 team's plans to implement alternate water injection); and
- the central government's lack of trust concerning the timeliness and accuracy of plant information (resulting in interference leading to unintended consequences, such as delays in issuing modifications to protective action orders, distraction of resources needed for the PM's site visit, delay in establishing water injection from offsite fire trucks due to security reasons related to the PM's visit, and an order from the PM to the site superintendent not to evaluate the site).

Examples of successful teamwork include:

- the delay of containment venting until local evacuation had been verified;
- the staff-identification and development of strategies to establish alternate water injection; and
- the strong role taken by the Unit 5/6 shift supervisor (enabling the site superintendent and onsite ERC to focus on Units 1-4).

IV.B.4. Implications for HRA Technology

Arguably, modern HRA approaches, both current and on-the-horizon, provide frameworks that can, in the hands of expert users, support at least high level treatments of the above observations. For example, the Integrated Human Event Analysis System (IDHEAS) being jointly developed by the NRC and the Electric Power Research Institutes, models four macrocognitive functions underlying operator crew decision and actions: detecting information, understanding the situation, making decisions and planning the response, and executing actions.[39] For each macrocognitive function, IDHEAS models failure mechanisms, the corresponding failure modes, and the performance influencing factors (PIFs). Thus, for example, the influence of environmental factors on decision making can, in principle, be treated using appropriate PIFs, and the need to develop innovative solutions can be treated.

However, guidance for such treatments, and the technical basis for such guidance, is lacking. Furthermore, it should be recognized that an explicit, reproducible treatment of some of the issues may require a more detailed analysis (e.g., one that provides an explicit, site-specific treatment of interactions between teams and with the plant, such as provided by dynamic PSA approaches[40,41]).

IV.C. Level 2 PSA

The three Level 2 PSA topics discussed below (i.e., long duration scenarios, equipment survivability, and habitability) are both important and in apparent need for more attention. A fourth topic, phenomenological uncertainty in severe accident modeling (e.g., hydrogen leakage, transport and ignition; turbine-driven component modeling; relief valve failures) is also important but is garnering appropriate attention in other forums.[8,42]

IV.C.1. Long-Duration Scenarios

The treatment of long-duration scenarios is potentially one of the most important decisions made in framing the accident analysis. In addition to increasing mission times (thereby increasing both the toll on operators and the likelihood of mitigating equipment failure), long durations provide increased opportunities for repair and for effective use of emergency plan resources. From a Level 2 PSA modeling perspective, scenario duration directly impacts a number of modeling decisions, such as whether to treat offsite personnel and equipment for accident management, and whether to consider long-term containment over-pressurization and basemat melt-through. Traditionally Level 2 PSAs have dealt with the phase of the accident extending through either the initial radiological release or initial plant stabilization. Thus, the analyses generally have not addressed the full timeframe considered in severe accident management guidelines. Over time, improved understanding of severe accident phenomena has led to generally longer predictions of the time to containment failure and/or large radiological releases and analyses have steadily been increasing their simulation end-time (typically to 48-72 hours after the initiating event). Nevertheless, the Fukushima Daiichi accident provides a reminder of the difference between time truncation assumptions typically used in PSAs and the actual timing of real-world accidents. Specific examples include:

- core damage at Unit 2 ensued greater than 72 hours after the earthquake;
- radiological releases were still clearly occurring more than 96 hours after the earthquake, as evidenced by the dose rate changes observed on March 20th; and
- offsite ac power was restored greater than 9 days after the earthquake.

The extended length of accident scenarios provides increased opportunities for complex actions (e.g., attempting unfamiliar valve lineups, jury-rigging car batteries to provide dc power). As discussed earlier, modeling these actions is a challenge for the HRA.

HRA concerns aside, addressing long-duration scenarios in PSAs may require consideration of multiple simulation end-times, and assessment of the impact on important figures-of-merit. For instance, in a recent NRC analysis[43] iodine and cesium releases from bypass accidents were not sensitive to the simulation end-time, but releases from non-bypass accidents were. (On the other hand, molybdenum releases were sensitive for both accident types.) Furthermore, and as one might expect, the large early release frequency (LERF) was not particularly sensitive to the simulation end-time, but the conditional containment failure probability (CCFP) was. As a caution, the analyst should consider the increasingly uncertain nature of model predictions as the accident duration is extended. Per the US Level 2 PRA Standard, the documented analysis should identify the limitations associated with what hasn't been considered and the pedigree of what has been considered.[44]

IV.C.2. Equipment Survivability and I&C System-Related Impacts

It is well-recognized that hydrogen explosions at Fukushima Daiichi damaged equipment (e.g., cables, hoses, and fire engines) being used in recovery efforts, and thereby had a "game changing" effect on accident progression.[8] However, there were other failures of equipment due to accident-generated conditions that also played an important role. For example, after some instrumentation power had been restored in all three units, "several ex-containment pressure and radiation monitoring instruments failed or their performance degraded (showing large errors), even though many of these sensors were located in areas where environmental conditions were within the environmental qualification envelope for design basis accidents in BWR/3 and 4 plants."[7] These failures contributed to the uncertainty as to whether core melt had begun in the various units, whether the melted fuel was in-vessel or ex-vessel, whether containments were intact, and whether fuel in the spent fuel pools was in jeopardy of becoming exposed.

Other possible examples of equipment survivability problems include:

- reference leg boil-off leading to false Unit 1 reactor pressure vessel water level indication;[7]
- a ruptured vacuum breaker valve on Unit 2;[45]
- the drop in Unit 2 suppression chamber pressure on March 15th, apparently due to a sensor failure (but at the time, correlated to suppression chamber failure based on misleading coincidental timing with the Unit 4 explosion);[8]
- an unexpected enabling signal for automatic depressurization on high suppression chamber pressure in Unit 3;[46] and
- erratic behavior of certain reactor pressure vessel temperature thermocouple circuits.[7]

The need to treat the possibility of phenomenologically-triggered degradations and failures (with appropriate fragilities) increases the complexity of the thermal-hydraulic analysis and of the coupled HRA.

Given the enormous number of components involved (many of which are not explicitly modeled in conventional PSAs), the potential need to model degradation as well as failure of these components, and the wide range of conditions that they may see depending on the accident sequence, it's not apparent that this issue can be practically addressed using current PSA technology. Reviews of past operational experience (e.g., Ref. 7) and sensitivity analyses can help ensure that the base analysis isn't overly optimistic and identify where attention might be focused. If the scope of the analysis is narrow enough (e.g., a limited set of sequences are of interest), simulation-based methodologies ("dynamic PSA") might be viable in exploring scenarios that have complex interplays between the accident progression, component response, and operator action. We caution that it is important to understand the resolution of the models (conventional as well as dynamic), and to place caution on results for complex interplays for which the models are not designed to capture.

IV.C.3. Environmental Conditions and Habitability

The accident induced environmental conditions at Fukushima Daiichi (e.g., heat, loss of lighting, radiation) affected local conditions for field work (e.g., inspection, monitoring, equipment manipulations), access to work locations, the psychological state of the plant staff (both operators and decision makers), and even the size and makeup of the staff. (A temporary evacuation following the Unit 1 hydrogen explosion left only three senior level staff in the Unit 1/2 and 3/4 control rooms.) Recognizing that the HRA does not require precise predictions of conditions, some of these conditions (e.g., local heat, lighting levels, and radiation) can be adequately addressed using current practices. Other conditions, e.g., far-field radiation from fixed sources, radiation due to backflow when operating the Standby Gas Treatment System,[45] radiation from explosion-generated debris, represent modeling challenges. Indeed, the latter two would likely have been difficult to anticipate prior to the accident.

From a modeling perspective, some of the specific challenges involve the treatment of airborne contamination, water management, and explosions. Regarding airborne contamination, atmospheric transport and dispersion models routinely used for offsite calculations are not sufficiently detailed to address dispersion near buildings, and are not scoped to address dispersion within buildings. Note that the anticipated as well as actual timing of contamination is important, as this can affect the prioritization of operator actions. (For example, at Unit 2, operators took early actions to manually align condensate system valves, recognizing that exposure concerns would prevent such actions later.)

Regarding water management, as at Three Mile Island 2 (TMI-2), the Fukushima Daiichi accident generated large quantities of liquid radioactive effluents. For the Level 2 analysis, there are challenges in addressing potential contamination buildups over time, release pathways, pooling locations, and operator influences (including work demands as well as direct hazards).

Regarding hydrogen explosions, the Fukushima Daiichi accident demonstrated a need for the analysis to address a range of phenomena (e.g., blast overpressures and missiles, induced fires, debris blockage of access routes, building venting) which can affect operator actions. The latter include temporary staff evacuations and distractions to decision makers (e.g., the Unit 4 explosion led to considerable attention on that unit's spent fuel pool water inventory), as well as delays to or even avoidance of actions due to life safety concerns. Hydrogen explosions also present a potential long-term concern – as late as April 7 (nearly a month after the earthquake and tsunami), actions were being taken to preclude possible hydrogen explosions at Unit 1.[6] Tools and techniques exist to handle many of these phenomena at a crude level, but the state-of-practice is such that potentially important interplays may be missed, leading to incorrect risk insights for a given application.

IV.D. Level 3 PSA

As indicated in Table II, the Fukushima Daiichi accident revealed several lessons regarding Level 3 PSA technology. Some of these, e.g., the potential for long duration accidents, the potential effects of an external hazard initiator on offsite response, are widely recognized. Less-well discussed lessons include the possibility of: major releases due to intentional actions (e.g., containment venting), large numbers of contractors working on units in outage, large releases of highly contaminated water to the environment (the "aqueous pathway"), limited pre-accident emergency training due to views concerning the likelihood of severe accidents, lack of adequate resources needed for post-accident response and recovery (e.g., staff to perform offsite radiation surveys, protective clothing, staff to manage materials from external organizations and storage space for these materials), delays in food restrictions, and unrealistic planning assumptions regarding radiation levels and resettlement.

An important aspect of risk analysis is the selection of assessment endpoints for the analysis. The selection of assessment endpoints is typically based on the intended purpose of the analysis. PSAs may be used for purposes as varied as safety assessment, cost-benefit analysis, and assessment of environmental impacts. Past Level 3 PSAs have used many different figures of merit to quantify offsite consequences of severe accidents. Although almost all analyses have focused on human radiological health impacts (both deterministic and stochastic), some have also provided information on other types of consequences such as estimated property damages or measures of the extent of contaminated land. It is instructive to compare these analysis endpoints with the types of offsite impacts (observed or potential) that were discussed after the Fukushima Daiichi accident. This is of interest from a benchmarking perspective (i.e., to determine whether the results and insights generated by Level 3 PSAs are consistent with observed outcomes) as well as from a consequence analysis design perspective (i.e., whether the Level 3 PSAs are generating information needed to inform decision making by different stakeholders). Based upon our review of a number of consensus reports,[5,6,8-10,16,17] we make the following observations. It should be noted that these observations are focused on potential lessons for PSA technology generally. They may or may not be relevant for any particular PSA, depending upon the purpose and scope of the analysis.

As can be expected, post-accident discussions of health impacts place major emphasis on human radiological health impacts, both deterministic and stochastic. Consistent with the results of many Level 3 PSAs, no cases of early health effects (e.g., acute fatalities) are expected to be observable in the offsite public due to the relatively low offsite doses. With respect to stochastic effects such as cancer, these low offsite doses also suggest that no discernible increases in cancer risk (fatal or nonfatal) are expected.[e] Noting that thyroid cancer among children is the stochastic health effect with the greatest potential to be manifested,[6] the reports discuss cancer risk on an age-, gender, and cancer site-specific basis rather than as an average over age, gender, and cancer site. Although many Level 3 PSAs focus on age- and gender-averaged fatal cancer risk as a quantitative endpoint, tools and data are either available or can be adapted to estimate specific risks to discrete subpopulations (i.e., risks of childhood thyroid cancer).

In addition to radiological health impacts, the reviewed reports also discuss impacts on mental health, non-human biota, and economic costs.

Mental health impacts are identified in multiple reports as a significant health consequence of severe accidents. Discrete subpopulations at risk for such impacts include long-term evacuees, mothers and pregnant women, and cleanup workers. There have been surveys of specific subpopulations, but these studies appear to largely focus on determining if there was a detectable effect, and the details of the specific causes of the distress that could be tied to the characteristics of an accident, or approaches to mitigating psychological impacts, are not discussed at length. Current Level 3 PSAs may be able provide information relevant to the assessment of potential mental health effects (e.g., the number of people subject to long-term displacement or the number of required cleanup workers for different accident scenarios). However, the quantitative treatment of such effects remains an open issue. Questions of scope aside (psychological impacts are not caused by the direct action of radiation on the cells of the human body, and may be outside the charter of the organization performing the PSA), it is not clear how potential psychological impacts would be related to the characteristics of the accident for quantitative evaluation in a Level 3 PSA. The magnitude and effects of such factors as the various sources of distress (e.g., concerns about potential or actual exposure and its effects, effects of long-term displacement, general uncertainty regarding the near- and long-term post-accident future and trust in institutions) and changes in these sources over time (likely a complicated and perhaps even chaotic phenomenon) may differ with the accident and protective action(s). Clearly, an explicit analysis, if feasible given the current state of knowledge, could be extremely complex.

Impacts on non-human biota can be quantitatively assessed using recognized methodologies (e.g., see Ref. 47). The consensus view emerging from the reviews of the Fukushima event appears to be that while individual organism effects cannot be excluded, population-level ecosystem effects are not expected. There is a range of opinions within the radioecological community of practice (e.g., regarding the treatment of uncertainties in dose estimation and in handling confounding effects), suggesting that the uncertainties could be large in such an assessment. Nevertheless, the existence of broadly accepted tools and data for assessing doses and impacts to non-human biota suggests that such impacts could be considered within a PSA framework with appropriate adaptation.

The economic impacts of severe accidents (for example, costs associated with population displacement, cleanup, and other activities) play a role in PSA applications such as cost-benefit assessments. Information pertaining to economic impacts from the Fukushima event are discussed in several reports. There is considerable quantitative information on types and costs of remediation efforts, and issues associated with waste management, which can be a significant contributor to remediation costs, are also discussed in some detail. However, there are some challenges in incorporating this information within a PSA framework. Ref. 8 indicates that NRC's guidance for assessing costs leads to estimates significantly lower than the costs associated with the Fukushima Daiichi accident. However, comparison of cost estimates requires a consideration of a number of factors, such as the decision framework used to develop the recovery strategy and any resource constraints. For example, recovery efforts may be constrained by infrastructure and resources available for remediation, the timing of re-occupancy decisions may depend upon local and regional decision making processes, and compensation frameworks may be quite different between different political jurisdictions. The technology for assessing costs for cost-benefit purposes is well-established; the challenge is to ensure that all costs relevant to a decision are identified and addressed, and that cost categories excluded from the analysis are explicitly identified.

V. DISCUSSION

The events of March 2011 were extremely complex and there is an ever-growing mountain of relevant information, some of which is still evolving. Each report reviewed for this paper represents the results of a significant undertaking performed under real-world time pressures.

- Not surprisingly, different reports can bring differing perspectives on the key lessons to be learned, and there can be inconsistencies between reports and even within reports. For the purposes of our review, this variability

[e] Note that the reviewed reports characterize cancer risk by measures more related to risk to individuals rather than total cases of health effects integrated over large populations. Several reports cautioned against the computation of total numbers of health effect cases from aggregation of low individual doses, and discussed cancer risks in relation to whether any such risks would be statistically detectable, rather than in absolute terms.

is actually a benefit rather than a concern because our aim is to support the improved practice of PSA (through the identification of plausible possibilities[f]), not to provide an exact reconstruction of a historical event.

- Regarding the reconstruction of events, as discussed by Ref. 6, care must be taken regarding the introduction of biases due to hindsight (knowledge of the outcome can affect the manner of analysis as well as results), oversimplification (e.g., due to the imposition of linear narrative structures) and distancing through differencing ("it can't happen here"). Again, given the aim of our paper, we believe that our results are somewhat more resistant to these biases than those from analyses aimed at definitively identifying actual causes and effects. Of course our analysis is affected by the approaches taken by our source documents (e.g., in focusing on the events at Units 1-3, and not providing as much detail on events at Units 5 and 6, which also provide useful lessons for PSA).
- An enormous effort is required to read and assimilate even a subset of the literature on Fukushima. In addition to the previously mentioned volume and dynamic nature of the literature, discussions of topics relevant to our interests (e.g., external hazards, HRA, Level 2 PSA and Level 3 PSA) often appear in multiple sections of the documents. Broadening the concept of "PSA Technology" to include tools (e.g., using content analytics) to find, extract, and use information, it appears worthwhile to develop such tools to support PSA analysts. Use of these tools can help ensure awareness of precursor events (e.g., Blayais and Madras in the case of Fukushima) and reduce the likelihood of community blind spots (e.g., regarding the potential risk importance of external flooding).[48]

The focus of this paper is on PSA technology, but there are also a number of lessons for the PSA community.

- Although the direct use of the Fukushima accident in a statistical analysis of CDF is a debatable enterprise,[2] the events of March 11, consistent with the results of PSAs (when cumulated over reactors and operating years), provide a reminder that severe accidents should be treated as credible possibilities, not as purely hypothetical events.
- The PSA community should ensure that it pays adequate attention to accident precursors as indicators of challenging scenarios. Ref. 8 states that "The events at [Fukushima Daiichi Units 5 & 6] would likely have been a major story in the annals of nuclear safety had they not occurred in the shadow of the accidents at Units 1-4." Given the PSA community's lack of reaction to the Blayais event, it is unclear what effect the Unit 5 and 6 events, had they occurred in isolation, would have had.
- In principle, PSA provides an appropriate framework for addressing the oft-repeated concern that Fukushima was due to "a lack of imagination." Of course, the framework needs to be appropriately implemented (as a structured, systematic means for searching for what can go wrong, as opposed to a mechanical checklist), and the framework will not solve fundamental weaknesses in scientific and engineering understanding.

VI. CONCLUDING REMARKS

Based upon our review of numerous reports and papers concerning the events in Japan triggered by the Great East Japan earthquake of 2011, we have identified a number of PSA technology reminders and challenges. Although our review was structured and systematic, clearly we have employed a certain degree of personal judgment and experience. Others may read the same documents and come to different conclusions. Nevertheless, we believe that our results are useful for informing the NRC's planning of future PSA-related research and development.

It should be emphasized that although the multiplicity of PSA technology reminders and challengers identified in this paper could be interpreted by some to imply that PSA is a hopeless enterprise, such is not our intent or view. The general course of events observed at Fukushima Daiichi and other Japanese plants following the Great East Japan earthquake and subsequent tsunamis are consistent with PSA understanding. Indeed, Level 2 PSAs and severe accident analyses performed prior to 2011 reasonably mimicked the basic scenarios at Fukushima.[42,49] PSA is a decision support tool. As with any practical tool, it is imperfect, yet is useful when properly employed. By acknowledging and tackling some of the reminders and challenges discussed, the robustness and usefulness of PSA as a decision support tool can be further enhanced in order to appropriately disposition the lessons learned from the events of 2011.

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[f] Note that with seemingly small variations, the accident could have been worse. (For example, Units 4-6 could have been operating at full power, a higher tsunami could have flooded the Unit 6 EDG, the event could have occurred when plant staffing levels were lower and weather conditions favored onsite dispersion, and offsite power could have been lost at Fukushima Daini.) It also could have been better. (For example, offsite power could have survived at Fukushima Daiichi.)

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