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PSA Technology Challenges Revealed by the Great East Japan Earthquake

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Washington, DC, USA

Presented at PSAM Topical Conference
In Light of the Fukushima Dai-ichi Accident
Tokyo, Japan
April 15-17, 2013

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Outline

- Background
- Project overview
- Results to date
- Concluding remarks

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PRA Policy Statement (1995)

"The use of PRA technology should be increased in all regulatory matters to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy…"

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L3PRA Project Objectives

- Develop a Level 3 PRA generally based on current state of practice that
  - reflects technical advances since the last NRC-sponsored Level 3 PRAs
  - addresses scope considerations not previously considered
- Extract new insights to enhance regulatory decisionmaking and to help focus limited agency resources on issues most directly related to the agency's mission
- Enhance PRA staff capability and expertise and improve documentation practices
- Demonstrate technical feasibility and evaluate the realistic cost of developing new Level 3 PRAs

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L3PRA Project Scope

- All major site radiological sources (all reactor cores, spent fuel pools, and dry storage casks).
- All internal and external hazards, and all modes of plant operation. Excludes initiating events involving malevolent acts.
- Incorporates improvements in PRA technology as well as changes in plant operational performance and safety since completion of NUREG-1150
- Excludes some aspects for which no risk model or analytical method has been established (e.g., software failure and aging)
- Single multi-unit site (not likely to provide insights applicable to all sites and all technical issues).

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Review – Great East Japan Earthquake

- Purpose
  - Identify potential lessons regarding PSA technology (methods, models, tools, data)
  - Support L3PRA project, future R&D
  - Support ongoing dialog in PSA community
- Scope
  - All affected plants
  - Limited extrapolation
- Current status
  - Events at Fukushima Dai-ichi
  - Partial coverage of literature

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Review Approach

- Literature review
- Event review
  - Timeline-based
  - PSA-topic based

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

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Example – Timeline Entries

J25 fx Remove IC from service (concerned about failing lines). Entered R/B and T/B to manually open MOV for FP lineup. Hard time finding valve, had wrong key, hard to operate hand wheel. Lor

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
13	11-Mar	15:50	1:04			1537-1550: Gradual loss of instrumentation, indications (including IC valve status, RV level), alarms, MCR main lighting	2								
14	11-Mar	16:35	1:49					*D/DFP indicator lamp indicates "halted"*	3						
15	11-Mar	16:36	1:50							Cannot determine RV level or injection status; work to restore level indication; do not put IC in service	4	Review accident management procedures, start developing procedure to open containment vent valves without power	5	Declared emergency (inability to determine level or injection)	6
16	11-Mar	16:45	1:59							Determine RV level	4			Emergency cancelled	6
17	11-Mar	16:55	2:09	*Tsunami alert*	1					*Workers on way to check D/DFP had to turn back*	4				
18	11-Mar	17:07	2:21							Lose ability to determine RV level or injection status	4			Reentered emergency plan	6
19	11-Mar	17:12	2:26									Site superintendent directs investigation of using fire protection to inject water	5		
20	11-Mar	17:19	2:33	*Tsunami alert cleared*	1										
21	11-Mar	17:30	2:44			Diesel-driven fire pump started and left to idle	2	Pressure above 100 psi	3	*Manually open valves (in dark) from fire protection system to core spray system; take turns holding D/DFP switch to keep in standby*	4				
22	11-Mar	18:00	3:14											*Govt orders seawater injection*	6
23	11-Mar	18:18	3:32			DC power partially returned	2	MO-3A and MO-2A indicate closed	3						
24		18:18	3:32			MO-3A and MO-2A opened	2			Open IC valves MO-3A and 2A. Steam from condenser observed	4				
25	11-Mar	18:25	3:39			MO-3A closed	2			*Remove IC from service (concerned about failing lines). Entered R/B and T/B to manually open MOV for FP lineup. Hard time finding valve, had wrong key, hard to operate hand wheel. Long*	4				
26	11-Mar	19:00	4:14							*Close valves for broken outdoor FP pipes. Broke lock to allow passage between Units 2 and 3.*	4	*Ask Tokyo for more fire engines*	5	*Following PM question about possible recriticality, TEPCO makes strong request to site superintendent to suspend seawater injection*	6
27	11-Mar	20:07	5:21					No pressure indication in MCR; Reactor pressure = 1000 psi (local indication)	3						
28	11-Mar	20:49	6:03			Small portable generator installed	2			MCR has temporary lighting	4				
29	11-Mar	20:50	6:04											Local authorities order evacuation within 2 km	6
30	11-Mar	21:19	6:33					Level indication restored; level = 8" above TAF	3						

1F1 processed / 1F2 processed / 1F3 processed / Sheet5

Ready

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Other Reviews (PSA Technology Implications)

- CSNI/WGRISK
  - 2011 Annual Meeting (Mar 30-Apr 1)
  - Several potential topics based on early information
  - Event-based and PSA-based structure
- IAEA Paper and Multi-Unit Safety Workshop
  - Lyubarskiy, Kuzmina, and El-Shanawany (Sep 2011): enhancements for modeling hazard and plant response
  - Fleming (Oct 2012): treatment of multi-unit issues
- PSAM 11/ESREL 2012 (June, 2012)
  - Matsuoka: conditional analysis
  - Epstein: Bayesian assessment of earthquake and tsunami
  - Cuadra et al: Markov model for what-if analysis

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WGRISK: Potential Questions and Topics
(March 29, 2011)

- Are there previously unrecognized or underappreciated vulnerabilities?
- If so, can we analyze them using current PSA technology?
- What are the potential implications?
- What are the decision options and what should we do to support RIDM?

Event-Based Topics	PSA-Structure Based Topics
Fukushima - Design basis vs. actual - _Combined hazards effect (ground motion and tsunami)_* - _Procedural coverage_ - _Appropriateness/effectiveness of operator actions_ - H2 from partial core damage scenarios - BWR venting capabilities - Multi-unit interactions (support, failures) - SFP damage mechanisms - Challenges to long-term cooling/UHS - Effects of seawater - Limited, uncertain information - International response (organizations, government, public) - Accident management - National program decision making - Emergency communication (who, what, when) - Explanatory communication	Hazard - Source "location" and "strength" - Multiple hazards - Multiple occurrences - Attenuation - Direct challenge to SSCs - Challenge to power - Challenge to UHS - Challenge to AM efforts Fragility - Response to new loads (e.g., H2 explosion) - AM-related SSC - Success criteria (e.g., SW clogging) - Multiple loads over time - Correlation (importance or lack thereof) Plant Response - Training and procedural coverage - Impact of "home and family" concern - Multiple unit interactions - PSA masking (escalation of non-catastrophic)
Extension/Abstraction - Integrated treatment of other events with potential near- and long-term effects on UHS (volcanoes: tsunami, ash, water blockage/degradation; floods; storms) - Success criteria (apparently bounding choices may not be the most risk significant) - Analogous situations wrt H2 (small volume buildings) - Ability of downsized plant staffs to cope - PSA use in real-time AM - Realistic possibilities, better questions/alternatives/decisions - Degree of realism, ability to calibrate on the fly	Accident Management - Training - Availability/adequacy of onsite resources - Time for arrival of offsite resources, time to perform actions, and adequacy of 24 hour mission time - Performance factors (positive and negative) Emergency Response - Timing and effectiveness - Impact of offsite effects (e.g., infrastructure damage, loss of power, aftershocks) Recovery/Restoration - Residual risk of damaged site - Fuel movement/management - Implications for undamaged units

*Italics = topic a little more speculative; may resolve with more event information

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IAEA: Needed PSA enhancements*

1) External hazard screening/frequency assessment
2) Correlated hazards
3) External hazard impact assessment
4) Multi-unit sites
5) Mission time in Level-1 PSA
6) Human reliability assessment for external hazards
7) Failure possibility for qualified equipment
8) Hydrogen explosion in the case of SBO
9) Transient explosive materials in external event conditions
10) Connections between plant buildings and compartment
11) Spent fuel pool; waste treatment facilities
12) Modeling severe accident management guidelines

*Lyubarskiy A., Kuzmina I., and El-Shanawany M. Notes on potential areas for enhancement of the PSA methodology based on lessons learned from the Fukushima accident. Proceedings of the 2nd Probabilistic Safety Analysis / Human Factors Assessment Forum, Warrington, UK, September 8-9 2011.

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Potential PSA Technology Challenges (1 of 3)

1) Extending the PSA scope
   - Multiple sources
   - Additional systems
   - Additional organizations
   - Post-accident risk

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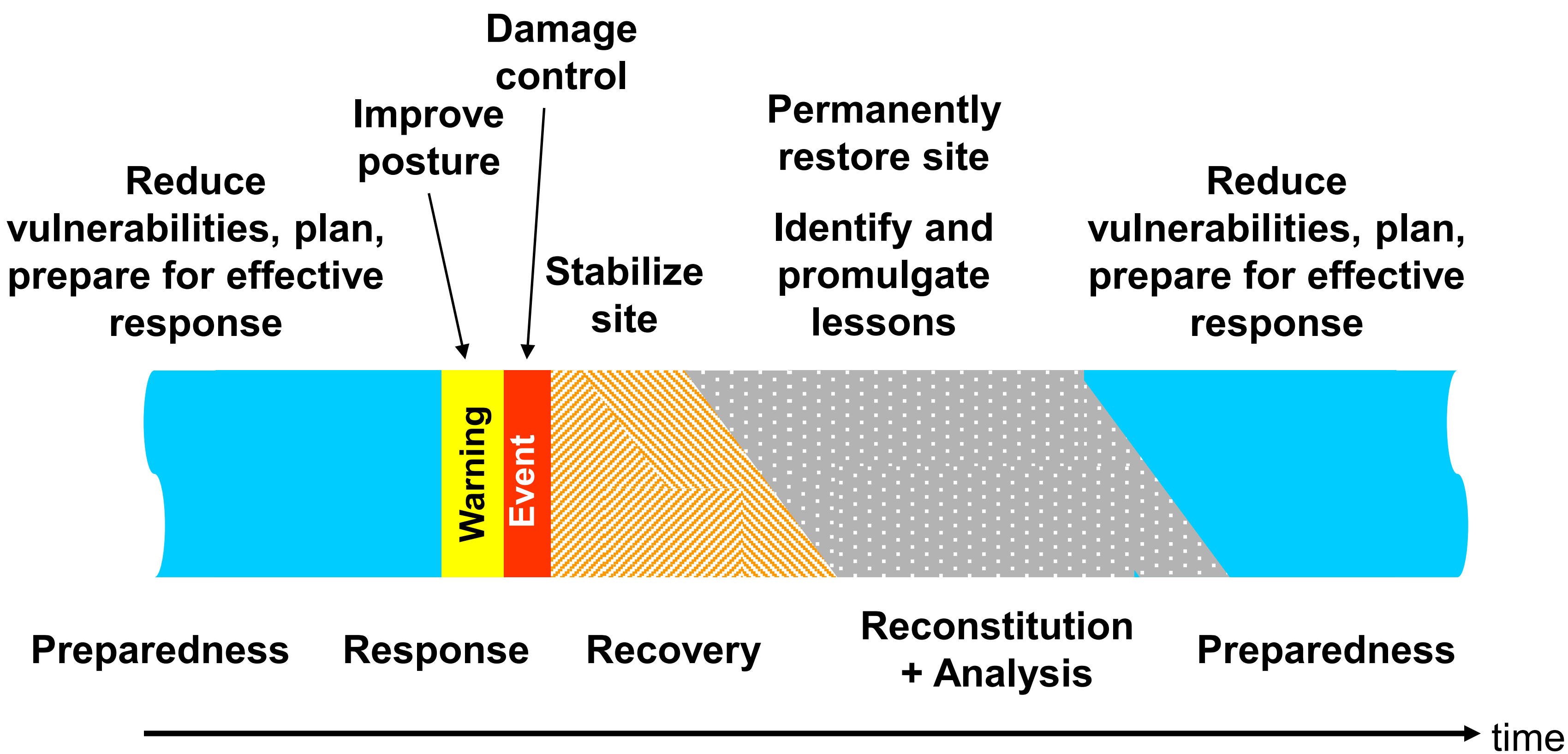
Potential Expanded Range of PSA



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Potential PSA Technology Challenges (2 of 3)

2) Treating feedback loops (e.g., offsite to onsite)
3) Reconsidering intentional conservatism ("game over" modeling)
4) Treating long-duration scenarios
    a) Severe accident management
    b) Offsite resources
    c) Aftershocks
    d) Success criteria (analysis termination)

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Potential PSA Technology Challenges (3 of 3)

5) Improving HRA
   a) Errors of commission
   b) Severe accident management
   c) Psychological effects
   d) Recovery feasibility and time delays
   e) Uncertainty in actual status
   f) Cumulative effects over long-duration scenarios
   g) Crew-to-crew variability
6) Uncertainty in phenomenological codes
7) Increasing emphasis on “searching”

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Repeat lessons?

- Extending PSA scope
  - Multi-unit events (Blayais 1999; Narora 1993; Armenia 1982; Beloyarsk 1978; Browns Ferry 1975)
  - Multiple organizations (Beloyarsk)
  - Very long-term (Chernobyl 1991)
- Feedback loops
  - TMI 1979 – Hydrogen bubble
- Conservative modeling
  - Non-proceduralized actions (Browns Ferry; Armenia)
  - Actions in extremely challenging environments (Beloyarsk; Armenia; Vandellos 1989; Narora)
- Multiple hazards
  - Blayais: wind and flooding (surge and waves)
  - Vandellos: fire + flooding + fire transport by flooding
  - Armenia: secondary hydrogen explosions and oil fire
- HRA
  - TMI – error of commission
  - Beloyarsk – Busy telephone system delayed communications with OFD
- Screening
  - Blayais: beyond design basis flood
  - Armenia: multiple fires

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Concluding Remarks

- Review has provided additional, useful insights regarding current PSA technology (methods, models, tools, and data) and guidance
- Benefits to date
  - Support L3PRA technical planning
  - Support discussions with other NRC activities (e.g., IDHEAS HRA method development)
  - Support discussions with other organizations (e.g., WGRISK, IAEA, ASME)
  - Support development of new PSA standard for non-light water reactors

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Concluding Remarks (cont.)

- Next steps
  - Continue review
  - Feed results of the review (notably “reminders”) into L3PRA
  - Use results of review (notably “challenges”) in discussing future PSA research and development activities

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Acknowledgements

The authors would like to express their appreciation to the Government of Japan and the Tokyo Electric Power Company for their efforts in translating their investigation and lessons-learned reports and making these available to the public.

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BACKUP SLIDES

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Potential PSA Technology Challenges and Reminders (1/6)

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 [C] 5) Characterizing uncertainty in phenomenological codes [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) [C] 2) Treatment of operator performance when digital systems are lost (see HRA) [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]

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Potential PSA Technology Challenges and Reminders (2/6)

Topic/Area	Challenges [C] and Reminders [R]
Non-Reactor Facilities and Activities	
Spent Fuel and 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]

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Potential PSA Technology Challenges and Reminders (3/6)

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) [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]

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Potential PSA Technology Challenges and Reminders (4/6)

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 [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]

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Potential PSA Technology Challenges and Reminders (5/6)

Topic/Area	Challenges [C] and Reminders [R]
Special Topics	
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	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) [R]

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Potential PSA Technology Challenges and Reminders (6/6)

Topic/Area	Challenges [C] and Reminders [R]
Special Topics	
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]
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]

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Potential Issues – Other Authors

Area	Topic	Lyubarskiy and Kuzmina [1]	Fleming [2]
Reactors	Level 1		Re-characterize concepts: initiating events, dependencies and interactions, CCFs, accident management, emergency planning
	Level 2		Accident management analysis needs to go beyond prevention, new sequences with multiple releases
	Level 3		Multi-unit effect on prompt and latent fatalities, timing effects
	Low power and shutdown		
	Operational data		
	Event analysis		
	New reactors		
	Research and test reactors		
Non-Reactor Facilities and Activities	Geologic repositories		
	High-level waste (including on-site)	Treatment of SFPs	Release from non-core sources
	Low-level waste/decommissioning		
	Fuel cycle facilities		
	Transportation		
	Sources		
Implementation and Application	PSA guidance and standards		Standards cover accomplishments of stress tests
	Metrics (including performance indicators)		Need site-level metrics (CDF and LERF are inadequate
	Risk-informed regulation applications		
	Risk perception and communication		
	PSA knowledge management		Lack of experience with multi-unit PRAs
General Systems Analysis Methods and Tools	PSA Tools		
	Uncertainty and sensitivity analysis		
	Advanced computational methods		
	Advanced modeling methods	Systematic development of mission times (using Markov or semi-Markov models)	
	Elicitation methods		

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Potential Issues – Other Authors

Area	Topic	Lyubarskiy and Kuzmina [1]	Fleming [2]
Special Topics	Human reliability analysis (HRA)	Effect of multi-unit accidents; more comprehensive and less optimistic analysis; external hazards effects on infrastructure, communications, equipment, stress, personnel safety	Accident management analysis needs to go beyond prevention; effect of site contamination on operator actions
	Ageing		
	Success criteria	Systematic development of mission times (using Markov or semi-Markov models), reliability of components in near-EQ conditions	Deterministic bases needed for multi-unit accidents
	Passive components		
	Passive systems		
	Digital systems		
	Common-cause failure		Inter-unit CCFs
	Design and construction		
	Multiple units and sites	Connections between units, accident effects on other units (including mitigation), effects on source term, effects on HRA.	Need deterministic bases, experience/know-how, site-level metrics, improved treatment of accident management, effects of site contamination on operator actions, initiating events include other-unit accidents, CCFs across units, seismic correlation across units
	Internal hazards	Hydrogen explosions, transient explosives, propagation paths (connections between buildings)	Importance of internal flooding analysis to identify vulnerabilities; large TB flood and SBO frequency ~1E-3 to 1E-2/rx-yr
	External hazards	Screening criteria based on past occurrences, notes need to address all events, correlated hazards, load combinations, cumulative damage effects, propagation paths (connections between buildings)	Large tsunami frequency ~1E-3 to 1E-2/site-yr, seismic correlation across units
	Safety-security interface		
	Accident management	Hydrogen explosions; external hazards effects on infrastructure, communications, equipment, stress, personnel safety	Use of PRA to inform drills
	Emergency preparedness and response		Non-linear scaling of effects; effects of timing