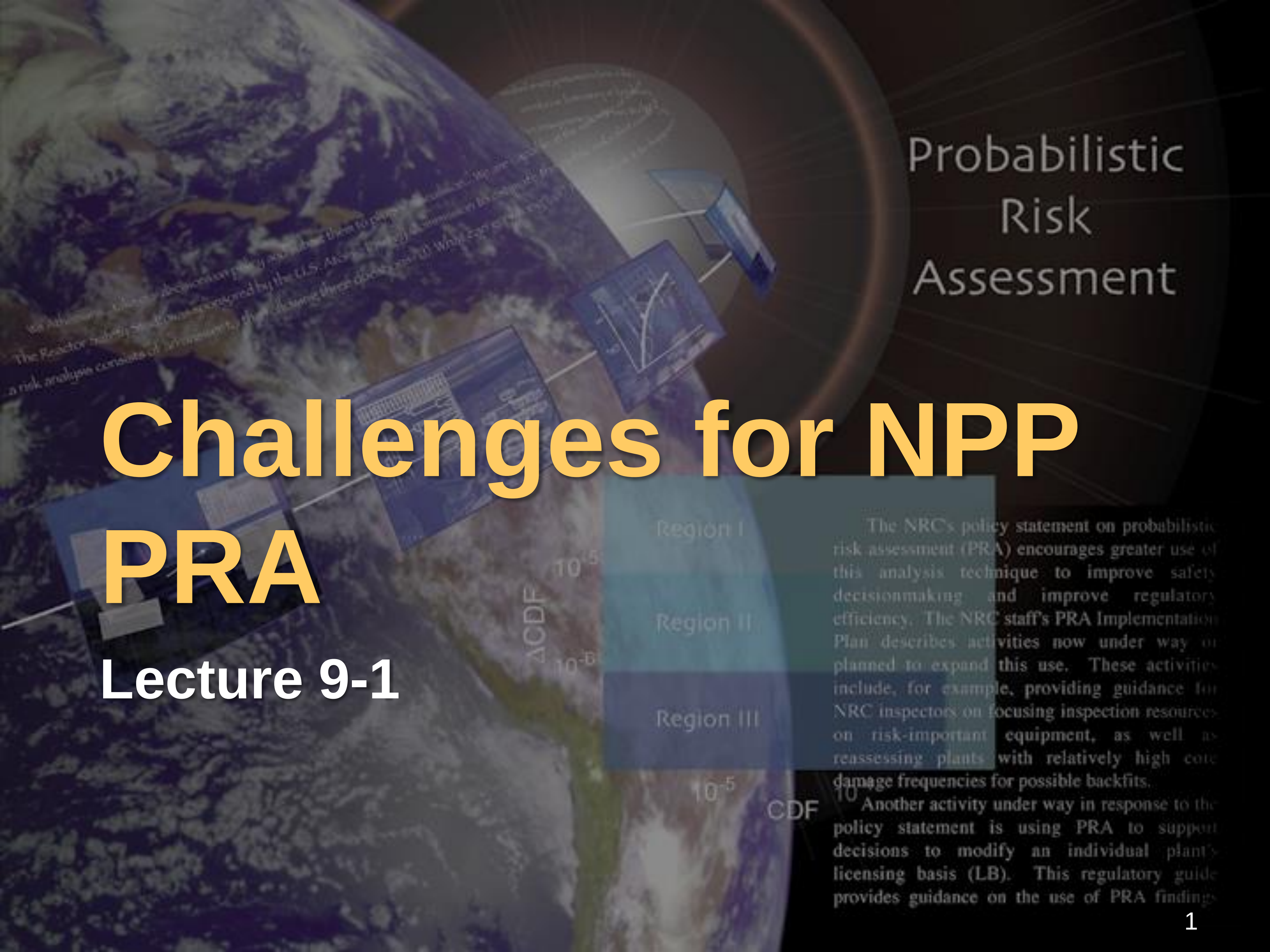
Challenges for NPP PRA

Lecture 9-1



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Schedule

	Wednesday 1/16	Thursday 1/17	Friday 1/18	Tuesday 1/22	Wednesday 1/23
Module	***1: Introduction***	***3: Characterizing Uncertainty***	***5: Basic Events***	***7: Learning from Operational Events***	***9: The PRA Frontier***
9:00-9:45	L1-1: What is RIDM?	L3-1: Probabilistic modeling for NPP PRA	L5-1: Evidence and estimation	L7-1: Retrospective PRA	L9-1: Challenges for NPP PRA
9:45-10:00	**Break**	**Break**	**Break**	**Break**	**Break**
10:00-11:00	L1-2: RIDM in the nuclear industry	L3-2: Uncertainty and uncertainties	L5-2: Human Reliability Analysis (HRA)	L7-2: Notable events and lessons for PRA	L9-2: Improved PRA using existing technology
11:00-12:00	W1: Risk-informed thinking	W2: Characterizing uncertainties	W4: Bayesian estimation	W6: Retrospective Analysis	L9-3: The frontier: grand challenges and advanced methods
12:00-1:30	**Lunch**	**Lunch**	**Lunch**	**Lunch**	**Lunch**
Module	***2: PRA Overview***	***4: Accident Sequence Modeling***	***6: Special Technical Topics***	***8: Applications and Challenges***	***10: Recap***
1:30-2:15	L2-1: NPP PRA and RIDM: early history	L4-1: Initiating events	L6-1: Dependent failures	L8-1: Risk-informed regulatory applications L8-2: PRA and RIDM infrastructure	L10-1: Summary and closing remarks
2:15-2:30	**Break**	**Break**	**Break**	**Break**	
2:30-3:30	L2-2: NPP PRA models and results	L4-2: Modeling plant and system response	L6-2: Spatial hazards and dependencies	L8-3: Risk-informed fire protection	Discussion: course feedback
3:30-4:30	L2-3: PRA and RIDM: point-counterpoint	W3: Plant systems modeling	L6-3: Other operational modes L6-4: Level 2/3 PRA: beyond core damage	L8-4: Risk communication	Open Discussion
4:30-4:45	**Break**	**Break**	**Break**	**Break**	
4:45-5:30	Open Discussion	W3: Plant systems modeling (cont.)	W5: External Hazards modeling	Open Discussion	
5:30-6:00		Open Discussion	Open Discussion		

Key Topics

- Stakeholder perspectives
- Sample viewpoints
  - Fleming (2003)
  - Mosleh (2012)
  - Siu et al., (2013, 2016)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Resources

- K.N. Fleming, "Issues and Recommendations for Advancement of PRA Technology in Risk-Informed Decision Making," NUREG/CR-6813, April 2003.
- A. Mosleh, "Delivering on the Promise: PRA, Real Decisions, and Real Events," Closing Plenary Talk, International Conference on Probabilistic Safety Assessment and Management (PSAM 11/ESREL 2012), Helsinki, Finland, June 25-29, 2012. (Available from: http://www.iapsam.org/www.psam11.org/www/fi/program/PSAM11-ESREL_2012_CL-Fr4_Ali_Mosleh.pdf)
- Siu, N., et al., "PSA technology challenges revealed by the Great East Japan Earthquake*," Proceedings of PSAM Topical Conference in Light of the Fukushima Dai-Ichi Accident*, Tokyo, Japan, April 15-17, 2013. (ADAMS ML13038A203)
- N. Siu, et al., "PSA technology reminders and challenges revealed by the Great East Japan Earthquake: 2016 update," *Proceedings of 13th International Conference on Probabilistic Safety Assessment and Management (PSAM 13)*, Seoul, Korea, October 2-7, 2016.

Other References

- N. Siu, “PRA R&D – Changing the Way We Do Business?” Invited Plenary Lecture, *ANS International Topical Meeting on Probabilistic Safety Assessment (PSA 2017)*, Pittsburgh, PA, September 24-28, 2017. (ADAMS ML17263B165)

Many Identified Technical Challenges

- PRA is a critically-oriented enterprise
- Recognized good practice (and required by PRA standards): identify/discuss key sources of uncertainty

=> Many views and lists of areas for improvement

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

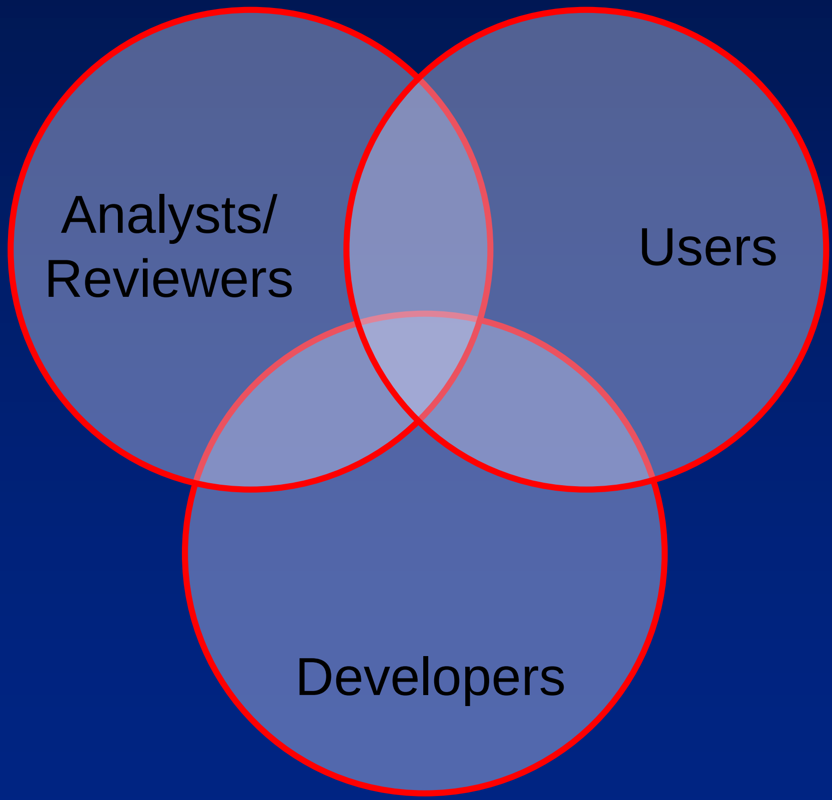
Risk Assessment Review Group ("Lewis Committee") – 1978

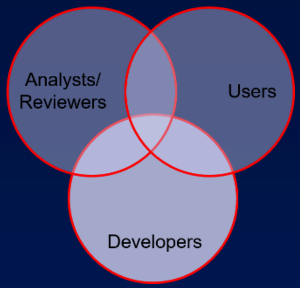
- Inadequate data base, "wrong statistical methods"
- Common cause failure analysis
- Human reliability analysis (particularly operator adaptability)
- Unconvincing screening of some initiators (fires, earthquakes, human-initiated events)
- Site-specific atmospheric dispersion modeling
- Biological effects modeling
- Understated error bounds

What to “Fix”? Domain Perspectives

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

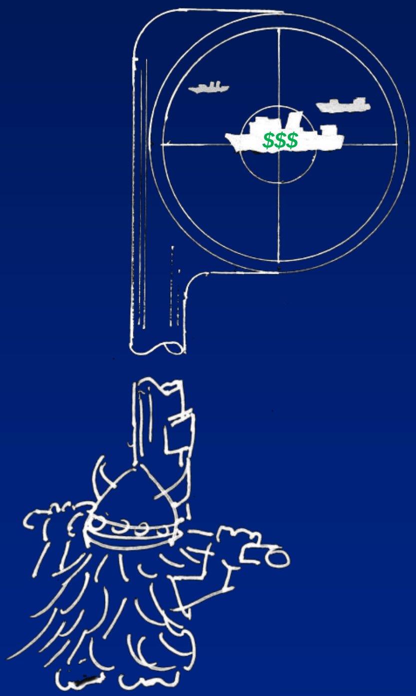
What to "Fix"? Functional Perspectives



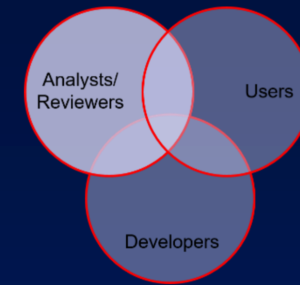


Developers

- Challenges include
  - Academic contribution
  - Nexus between personal/professional and external interests
  - Support (especially with declining budgets!)
- Solutions include
  - Frameworks, methodologies, conceptual demonstrations
  - N+1 projects (New Analysis Technology + Interesting Problem)



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

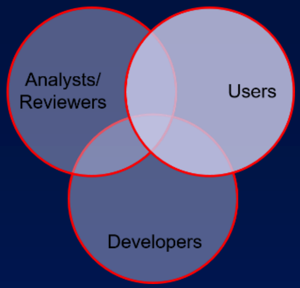


Analysts/Reviewers

- Challenges include:
  - Near-term solutions: heavy time/budget pressure
  - Huge problem size and complexity
  - Multiple technical communities/cultures
  - State of technology: Too much/little diversity, “Holes”
- Solutions include:
  - Approved approaches (“Tried and true”)
  - Engineering judgment
  - Acknowledgment of completeness uncertainty

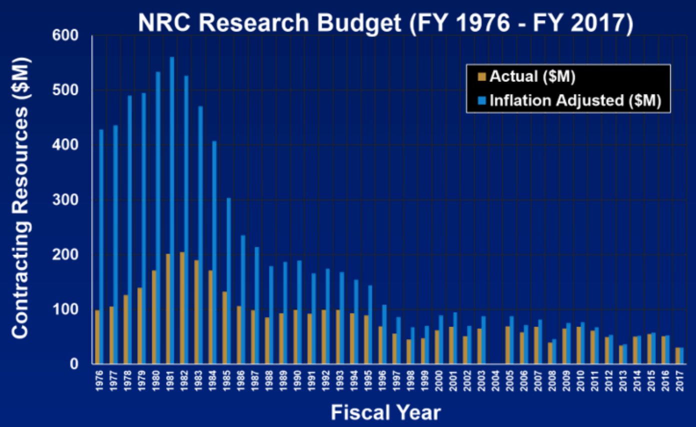
United States Nuclear Regulatory Commission
Protecting People and the Environment

Perspectives



Users

- Challenges include:
  - Fundamental nature of risk problem (complexity, uncertainty, multiple consequence types and potentially large magnitude, multiple stakeholders, …)
  - Competing problems with attentional and resource demands
  - Declining budgets
  - Predicting the future (value added, additional benefits)
- Solutions include:
  - Near-term focus (“today problems”)
  - Leveraging opportunities (interesting to others?)



Data from NUREG-1350 (NRC Information Digest)

Three Example Perspectives

- Fleming (2003) – what are the technical issues in advancing RIDM, and how might they be addressed?
- Mosleh (2011) – what needs to be done to deliver on the promise of PRA?
- Siu et al. (2013, 2016) – what technical lessons can be developed from the Fukushima Dai-ichi reactor accidents?

Fleming (2003)

- Performed to support ACRS
- Sources
  - Interviews
  - Case studies in risk-informed regulation (including Davis-Besse head corrosion)
  - Experience in performing/reviewing PRAs

Risk-Informed Regulation Success Stories

- Regulatory Guide 1.174 (licensing basis changes)
- Reactor Oversight Process
- Maintenance Rule (10 CFR 50.65)
- Consensus on need to [formally] ensure technical adequacy
- Consensus on improvement of industry PRAs

Risk-Informed Regulation Difficulties

- Scope, level of detail, and technical adequacy of existing PRAs
- Treatment of uncertainties in submittals and reviews
  - Unverified modeling assumptions (shared with deterministic analyses)
- Minimum capabilities needed to support RIDM
- Consistency in submittals and reviews
- Potential for risk insights for applications meeting deterministic requirements*

*Could be viewed as a success

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Technical Issues

- Use of limited scope PRAs in RG 1.174 applications
- Lack of completeness within specified scope
- Model fidelity
- Lack of uncertainty treatment
- Multi-unit site issues
- Lack of capability to treat ageing issues
- Risk metric issues
- Lack of coherence between probabilistic and deterministic safety approaches

Recommendations

- Update PRA Procedures Guide (NUREG/CR-2300)
- Guidance for treatment of uncertainties
  - Analysis
  - Use in decision making
- Guidance for deterministic safety evaluations
- Generic estimates for risk contributors from missing PRA scope
- PRA validation program
- Consistent definition of risk

Mosleh (2012)

- Closing plenary speech at PSAM 2011/ESREL 2012 conference
- Key questions
  - Has PRA delivered on its promise?
  - How do we gauge PRA performance?
  - Are there disparities between what we get and what we think we are getting from PRA and its various derivatives?
  - What should be our expectation, and how do we address potential gaps?

PRA Successes

- “PRAs have successfully identified many vulnerabilities that were unknown, not adequately safeguarded against in the original designs, or simply viewed to be unimportant.”
- “Through ranking of risk contributors by probability and consequence, PRAs have provided a consistent basis for prioritization and implementation of many safety improvements and design decisions”

Main Sources of Uncertainty

- Scenario identification (completeness)
- Level of resolution ("binning")
  - Level of causality
  - Fidelity of definition of basic events
  - Probability estimation

Level of Causality Example: H.B. Robinson Fire (March 28, 2010)

- Complicated event
  - Non-vital cable failure => arc flash + breaker failure => reactor trip
  - Subsequent equipment malfunctions + operator situation assessment and action failures => complicated shutdown, could have led to reactor coolant pump (RCP) seal LOCA
- Important HRA factors
  - Simulator training didn’t match actual plant response
  - Deficient operating procedure
  - Poor command and control
- PRA concerns
  - Events would have been screened based on probability
  - Important features not easily captured by current methods

Mosleh

General Concerns and Suggestions

- Concerns
  - Potential for screening to miss important scenarios
  - How to “see” vulnerabilities “irrespective of the numbers”
  - Major accidents go beyond initial physical and organizational boundaries: closed systems become open systems
- Suggestions
  - Improve causal models for some applications (e.g., SDP)
  - Feed accident insights back into PRA methodology
  - Make better use of computer power
    - Qualitative information from risk models
    - Simulation for complex interactions
  - Remember “risk-informed” also means “consequence-informed”

Siu, et al. (2013, 2016)

- Performed to support R&D planning
- Limited to lessons directly linked to accidents
- Detailed review of multiple sources for accident progression and conditions
  - Official reports
    - Government of Japan, National Diet of Japan, TEPCO
    - U.S. organizations (National Research Council, INPO, EPRI, ANS)
    - International organizations (e.g., IAEA, WHO, UNSCEAR)
  - Other papers
  - Briefings
- Highlighted key topics and issues + detailed table of “challenges” and “reminders”

Highlighted Topics (2013)

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

Highlighted Topics (2016)

Topic	*Issues*
External Hazards	Using PSA to ensure defense-in-depth (DID), dealing with full hazard spectrum, treating correlated hazards
Human Performance and Human Reliability	Decision making under severe accident conditions, ex-control room actions, teamwork
Level 2 PRA	Long-duration scenarios, equipment survivability and I&C system-related impacts, environmental conditions and habitability
Level 3 PRA	Effect of offsite hazard on response, intentional venting, onsite contractors, aqueous pathway, training and resources, assessment endpoints

R&D Implications – HRA example

Topic

- Decision making under severe accident conditions
- Ex-control room actions
- Teamwork

Advanced Methods Needed?

- Mechanistic treatment of many challenges, e.g.,
  - ✓ Choices among options
  - ✓ Communications
- Approximations?
  - ✓ Robotic follower
  - ✓ Individual cognition with communications
  - ✓ Social organization
- Approximate > None?

Siu, et al.

PRA Topics – One View

Technical	Topic
Reactors	Level 1 internal events at power
	Level 2
	Level 3
	Low power and shutdown (LPSD)
	Operational data
	Event analysis
	Generic safety issues (GSI)
	Performance indicators and thresholds
	New reactors (evolutionary)
	Advanced reactors
	Research and test reactors
Non-Reactor Facilities and Activities	Geologic repositories
	High-level waste (HLW)
	Low-level waste/decommissioning
	Fuel cycle facilities
	Transportation
	Sources

Technical	Topic
Special Topics	Human reliability analysis
	Ageing
	Passive components
	Passive systems
	Digital systems
	Common Cause Failure
	Integrated site risk (including multi-unit events, SFP)
	Design and construction
	Internal hazards (e.g., fire, flood, heavy load drop)
	External hazards (e.g., seismic, flood, wind)
	Security-related events, safety-security interface
	Emergency preparedness and response
General Systems Analysis Methods and Tools	PRA tools
	Uncertainty and sensitivity analysis methods and tools
	Advanced computational methods
	Advanced modeling methods (e.g., simulation)
	Elicitation methods
Implementation and Application	PRA quality (e.g., guidance, standards)
	Risk-informed regulation infrastructure
	Risk-informed regulation applications
	Risk perception and communication

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Comment

- General agreement on broad topic areas, e.g.,
  - Human and organizational factors
  - External hazards
  - Common cause failures
- No consensus sought (yet) or achieved on prioritization of specific items (e.g., errors of commission)
  - Varying technical and organizational perspectives on need, value, achievability, cost
  - An additional consideration: enterprise risk
    - Potential consequences if work is not done (or even attempted)
    - Requirements in some countries to use “state-of-the-art”

U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

Additional Slides

External Hazards

Topic

- Using PSA to ensure defense-in-depth
- Dealing with full hazard spectrum
- Treating correlated hazards

Advanced Methods Needed?

- Conceptually straightforward
- Data (e.g., penetration seal failures for flooding)?
- Need to treat dynamics?

Level 2 PSA

Topic

- Long-duration scenarios
- Equipment survivability and I&C system-related impacts
- Environmental conditions and habitability

Advanced Methods Needed?

- Current technology
  - ✓ Temperature
  - ✓ Lighting
- Radiation?
  - ✓ Source number, strengths, and locations
  - ✓ Transport
  - ✓ Crew information, effect on planning
- Simplifications?

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Level 3 PSA

Topic

- Effect of offsite hazard on response
- Intentional venting
- Onsite contractors
- Aqueous pathway
- Training and resources
- Assessment endpoints

Advanced Methods Needed?

- Improved transport and dispersion?
  - ✓ Higher resolution
  - ✓ Broader coverage
- Human behavior (affecting costs)?
  - ✓ Psychological impacts
  - ✓ Social response

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Fukushima Lessons – A More Detailed Look (1 of 5)

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 [R] 2) Treatment of shutdown risk associated with a pre-emptively shutdown plant [R]
Operational Data	1) Ensuring appropriate use of 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 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]

Fukushima Lessons – A More Detailed Look (2 of 5)

Topic/Area	Challenges [C] and Reminders [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) 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] 3) Framing the risks of NPP operation to allow comparison to other societal and individual risks [C]

Fukushima Lessons – A More Detailed Look (3 of 5)

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] 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]

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Fukushima Lessons – A More Detailed Look (4 of 5)

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] 9) Assessment of the possibility of control room or even site abandonment due to hazardous conditions [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]

U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

Fukushima Lessons – A More Detailed Look (5 of 5)

Topic/Area	Challenges [C] and Reminders [R]
Special Topics (Cont.)	
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]
Safety-Security Interface	1) Addressing event effects on access systems (e.g., gates, doors) [R]
Accident Management	1) Treatment of general Level 2 concerns [C,R] 2) Treatment of Level 2 HRA concerns [C,R] 3) Addressing effects of external event on accident management [R] 4) Modeling of human and organizational behavior in a post core damage environment [C]
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 [R] 5) Treatment of multiple offsite population moves due to expanding evacuation zones [R]