Recent Developments in Risk Assessment: Future Perspectives

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Topics

- PRA in Light of the Fukushima Daiichi Accident
- PRA Challenges
  - Modeling
  - Data
- Quick Overview of PRA Advances
- Opportunities for future developments
- Conclusions
Industries with Continued Applications of PRA

- Transportation
  - CNG and H Fueled Vehicles
  - Oil and Gas Pipeline
  - Aerospace

- Food Safety
  - Food production
  - Risks of Epidemics

- Nuclear
  - Post Fukushima
  - Small Modular Reactors
  - Dynamic Characteristics of Multi-Module / Multi-Unit Scenarios
  - Risk Management for Reactor Protection and Accident Mitigation
Critical Safety Implications of Fukushima Events

- Concurrent Events and Common Cause Failures
  - Great East Japan Earthquake followed by tsunami (50 minutes later)
    - Earthquake 9.0 vs. design 8.2
    - Tsunami wave 14 m vs. design 5.7 m
      - Maximum tsunami height 38.9 m in Aneyoshi, Miyako stone marker!
  - Lost offsite power for Units 1-6 due to earthquake
    - Units 1-3 in power operation; Units 4-6 in shutdown
  - All 12 diesel generators in service for Units 1-6 (1 DG for Unit 6 in maintenance) lost due to tsunami

- Simultaneous Damages to the Multiunit Site
  - Hydrogen explosions at Units 1, 3 and 4
  - Melting of multiple reactor cores (i.e., Units 1, 2 and 3) and spent fuels (i.e., Unit 4)
Fukushima Daiichi / Multi-Unit Issues

- Units 1, 2, 3 experienced core damage and large releases of radioactive material from containment
- No core damage at Unit 4 largely due to shutdown/defueled state
- Units 5 and 6 averted core damage due to one EDG being protected from flooding and heroic operator actions
- Key cause of accident was flood damage to emergency switchgear and EDGs located in basement of turbine buildings and resulting station blackout to Units 1-4
- An internal flooding PRA was never done but would have likely identified flood vulnerability and improved flood protection
U.S. Nuclear Plants

Source: K. Fleming
Accident Causation from a PRA Perspective

- Transient, Loss of Coolant Accident (LOCA)
- Seismic, Tsunami, Tornado

- Hardware Failure
- Software Failure

- Pre-Initiator Error
- Post-Initiator Error

- Offsite Power Non-Recovery
- Equipment Non-Recovery, etc.
HTO Perspective

Technical

Human

Organization

Regression
Accident Causation from an HTO Perspective

HTO Triad

Organizational Factors

Latent Conditions

Technological/Environmental Factors

Latent Conditions

Personnel Factors

Active Failures and/or Latent Conditions

Unsafe Acts

Active Failures

Accident
## Weaknesses in HTO Elements

<table>
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<th>Element of HTO</th>
<th>Weakness in HTO Elements as Revealed by the Fukushima Accident</th>
<th>Remarks on Global Status</th>
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<td>- Inappropriate definition of design basis</td>
<td>Globally was the case prior to the Fukushima accident</td>
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<td>- Improper analysis of plant risk (e.g., underestimation of external events risk, less emphasis on concurrent events and site risk)</td>
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<td>- Lack of sufficient equipment to cope with extreme events simultaneously affecting the whole site</td>
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<td>- Lack of plant emergency guidelines for extreme site events (e.g., as caused by natural disasters)</td>
<td>Globally was the case except the US where post 9/11 mitigative measures are already in place (e.g., Extensive Damage Mitigation Guidelines, portable pumps)</td>
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<td>O</td>
<td>- Lack of emergency management capability for multiunit events</td>
<td>Globally was the case prior to the Fukushima accident except the US where the emergency management capability has been considerably enhanced since the 9/11 terrorist attack</td>
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Issues with the Traditional PRAs

- PRAs performed one reactor at-a-time
- Increased likelihood of a single reactor accident due to interactions with other units ignored
- Impact of a severe accident from one unit on the other units ignored
- Risk metrics CDF and LERF don’t capture integrated site risk
- NRC Safety Goals for multi unit / multi-module plants unclear
  - Single reactor PRAs used to justify safety goals conformance
- Essentially all risk-informed regulation applications are based on single unit metrics
  - Risk impacts of multi-unit accidents ignored
Issues with PRA Applications to Multi-Units

- Lack of experience and methods with multi-reactor PRAs
- Dynamic nature of multi-unit interactions
- Single reactor risk metrics such as CDF and LERF are inadequate to capture integrated risks of multi-unit sites
- PRA treatment of accident management is limited to prevention of severe accidents-- not protection and mitigation
- Impact of site contamination on operator actions not considered in PRAs
- Initiating events and accident progression in each reactor don’t consider causal accidents of other units
- Treatment of common cause failures involving components on multi-units not addressed
- Seismic correlation issue already addressed in single reactor PRAs needs to be addressed in multi-unit context
- Operator actions in multi-unit settings are dynamic and different
Past Experiences with Multi-Unit PRAs

- Rudimentary multi-unit Seabrook PRA (mid 1980s) and Byron/Braidwood PRA (late 1990’s) has been done
- Modular HTGR PRAs (mid 1990’s)
- Multi-Module PRA of SMRs (Ongoing)
Causes of Unit-to-Unit Dependencies

Source: S. Schroer
Observed LERs Involving Multi-Units

Source: S. Schroer
Future Directions and Opportunities: SIM-PRA

Source: A. Mosleh
Elements of DPRA

- Modeling system dynamics
- Modeling human interaction and digital control systems
- Capturing uncertainty quantification and sensitivity analysis in the simulation
- Immediate and much needed applications to address multi-unit / multi-module SMR PRA
SMR PRA Modeling Considerations/Complexities

- Integrated Design
  - Integrated Steam Generator / Health Management
  - Integrated Control Rod Drive Mechanism
  - Integrated RCP
  - New Containment-RCS Interactions
  - Integrated Pressurizer

- Passive systems
  - Operability / conditions of operation
  - Failure modes
  - Thermal/mechanical failure mechanisms (e.g., PTS)
  - Long-term component/structure degradation
Multi-Module Risk

- Direct Dependencies
  - Common initiating events / shared SSCs
  - Shared instrumentation, control, fiber optics, other cables, electric divisions
  - Shared systems (e.g., FPS)
  - Capacity of shared equipment (e.g., batteries)
SMR PRA Modeling Considerations/Complexities (Cont.)

- Indirect Dependencies
  - Human/organizational Pre-imitating event dependencies
  - Post accident human actions (operators, fire brigade, etc.)
  - Common environments (caused by)
    - Natural events
    - Internal events (e.g., SBO)
    - Internal events external of the system (e.g., Fire)
    - Accident-induced dependencies (for example hydrogen explosion at Unit 3 of Fukushima disabled fire pumps used for seawater injection at Unit 2. Also, fire/explosion at Unit 4 was caused by leakage of hydrogen released from Unit 3 through shared duct-work with Unit 4)
Other SMR PRA Modeling Considerations/Complexities

- Severe accident phenomena
  - Relevance of severe accident phenomena
    - H generation / explosions
    - Containment failure modes
    - Melt-through phenomena
    - Integrity of integrated structures such as steam generators
    - Integrity of instrumentations

- Long-term cooling
  - Capacity of heat sinks (24 hr, 72 hr, or longer accidents)
  - Conditions necessary to maintain long-term cooling
Other SMR PRA Modeling Considerations/Complexities (Cont.)

- **HRA**
  - Control room crew dynamics
  - Errors of commission
  - Recovery actions / accessibility

- **External events**
  - Seismic hazard
  - Fragilities of integrated structures
  - Combined external initiators

- **Spent fuel pool considerations**
  - Interplay with the operating modules

- **Low Power & Shutdown Events**
What is needed?

- Spatial connections within and between units that affect SSCs
  - Shared heat sink structure
  - Seismic loads for multiple reactor modules
  - Critical initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies

- Thermal-hydraulic and severe accident simulation models of the reactor system including support systems
  - Development of discrete dynamic event tree methodology

- Development of examples (e.g., initiating events that affect multiple reactors, such as loss of offsite power, internal flooding, and seismic events)

- Development of a methodology of quantifying the site CDF using a simulation-based dynamically generated scenarios
Conclusions

• Multi-Unit SMR PRAs are very different from conventional plant PRAs
• Traditional PRA methods and data are inadequate
• Significant opportunities exist to combine simulation models with PRA principles to perform multi-unit PRAs and establish basis for multi-unit accident management
• New standards, regulatory guidance, early interactions with the NRC
• Techniques and tools will have major impact in nuclear and possibly other industries as well