Nuclear Power Plant Safety in the Aftermath of Major Emergencies

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Overview of this Talk

• Nuclear Accidents: The Probabilistic Risk Assessment (PRA) and Management Perspective
• Nuclear Accidents: Human, Technical, Organization Perspective
• Overview of U.S. Responses to Three Major Nuclear Power Plant Accidents:
  – Three Miles Island (TMI) Accident
  – Chernobyl Accident
  – Fukushima Daiichi Accident
• Conclusions
U.S. Nuclear Safety Strategy

ACCIDENT ANALYSIS RIGOR

Abnormal Operating Procedures | Emergency Operating Procedures | Severe Accident Management Guidelines

Stay Within Licensing Limits | Make Best Use of All Available Systems Even Beyond Their Design Limits

Traditional Accident Analysis
Nuclear Plant Licensing

PRA
Nuclear Accidents: The PRA Perspective

Plant Condition:
1. Full Power
2. Low Power & Shutdown

Initiating Event:
1. Internal
2. External

IE * HW$_1$ * ... * HW$_n$ * SW * HE * NR

Analysis Level:
1. Core Damage
2. Release
3. Dose / Consequences

1. Initiating Events Analysis
2. Event Tree Analysis
3. Fault Tree Analysis
4. Basic Events Analysis
5. Common Cause Failure Analysis
6. Human Reliability Analysis
7. Risk Quantification

IE = Initiating Event; HW = Hardware; SW = Software; HE = Human Error; NR = Non-Recovery;
Nuclear Accidents: The PRA Perspective (Cont.)

- 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.

Failed or Absent Defenses

Adapted From Reason, 1990
HTO Perspective

Technical

Human

Organization

Regulation
Accident Causation from an HTO Perspective

HTO Triad

Organizational Factors

Technological/Environmental Factors

Personnel Factors

Unsafe Acts

Latent Conditions

Active Failures and/or Latent Conditions

Active Failures

Accident
Accidents Resulting from Weaknesses in the HTO Elements

<table>
<thead>
<tr>
<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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<tr>
<td>H</td>
<td>o Inappropriate definition of design basis</td>
<td>Globally was the case prior to the Fukushima accident</td>
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<td>o 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>T</td>
<td>o Lack of sufficient equipment to cope with extreme events simultaneously affecting the whole site o 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>o 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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U.S. Responses After the TMI Accident

- Upgrading and strengthening of plant design and equipment requirements: fire protection, piping systems, auxiliary feedwater systems, containment building isolation, reliability of individual components (pressure relief valves and electrical circuit breakers), and the ability of plants to shut down automatically;
- Revamping operator training and staffing requirements, followed by improved instrumentation and controls for operating the plant, and establishment of fitness-for-duty programs for plant workers to guard against alcohol or drug abuse;
- Enhancing emergency preparedness, plants to immediately notify NRC of significant events and an NRC Operations Center staffed 24 hours a day. Drills and response plans are now tested by licensees several times a year, and state and local agencies participate in drills with the Federal Emergency Management Agency and NRC;
- Integrating NRC observations about licensee performance and management effectiveness into a periodic, public report;
- Having senior NRC managers regularly analyze plant performance for those plants needing significant additional regulatory attention;
- Expanding NRC's resident inspector program – first authorized in 1977 – to have at least two inspectors live nearby and work exclusively at each plant in the U.S. to provide daily surveillance of licensee;
- Expanding performance-oriented as well as safety-oriented inspections, and the use of risk assessment to identify vulnerabilities of any plant to severe accidents;
- Strengthening and reorganizing enforcement staff in a separate office within the NRC;
- Establish the Institute of Nuclear Power Operations, the industry's own "policing" group, and formation of what is now the Nuclear Energy Institute to provide a unified industry approach to generic nuclear issues;
- Installing additional equipment by licensees to mitigate accident conditions, and monitor radiation levels;
- Enacting programs by licensees for early identification of important safety-related problems, and for collecting and assessing relevant data so operating experience can be shared and quickly acted upon; and
- Expanding NRC's international activities to share enhanced knowledge of nuclear safety with other countries in a number of important technical areas.
TMI Status

• The TMI-2 reactor is permanently shut down and all its fuel had been removed.
• The reactor coolant system is fully drained and the radioactive water decontaminated and evaporated.
• The accident's radioactive waste was shipped off-site to an appropriate disposal area, and the reactor fuel and core debris was shipped to the Department of Energy's Idaho National Laboratory. In 2001
• FirstEnergy acquired TMI-2 from GPU. FirstEnergy has contracted the monitoring of TMI-2 to Exelon, the current owner and operator of TMI-1.
• The companies plan to keep the TMI-2 facility in long-term, monitored storage until the operating license for the TMI-1 plant expires, at which time both plants will be decommissioned.
Effect on Nuclear Safety in the Aftermath of the TMI Accident

• The average number of significant reactor events over the past 20 year: nearly zero.
• Very few, much less frequent and far smaller risk-significant events.
• The average number of times safety systems activated: one-tenth of what it was before TMI accident.
• Radiation exposure levels to plant workers: one-sixth of the 1985 exposure levels and well below federal limits.
• The average number of unplanned reactor shutdowns: one-tenth of what it was before the TMI accident (for example around 2 unplanned shutdowns vs. 530 shutdowns).
• Capacity factor measuring the total electricity generated as a percentage of year-round potential generation: 86.4 percent in 2012
U.S. Trend in Nuclear Safety after TMI
U.S. Actions After Chernobyl

U.S. NRC’s Chernobyl response had three phases: (1) determining the facts, (2) assessing the accident’s implications on U.S. commercial nuclear power plants, and (3) performing long-term studies.

• Designing reactor systems properly on paper and implementing them correctly during construction and maintenance;
• Maintaining proper procedures and controls for normal operations and emergencies.
• Having motivated plant management and operating staff.
• Ensuring the availability of backup safety systems.
U.S. NRC Response to Fukushima Event

• Carried out Special Inspection of All 104 U.S. Reactor Units
  – Assessed licensee’s capability to mitigate conditions that result from beyond design basis events
  – Testing of active and passive equipment specifically designated for B.5.b (i.e., post-9/11 mitigative measures) or SAMG (Severe Accident Management Guidelines) mitigation such as the portable B.5.b diesel driven pump, B.5.b auxiliary equipment such as adapters and hoses, and the site fire engine
  – Verified that procedures are in place and can be executed (e.g., walkdowns, demonstrations, tests, etc.); adequacy of training and qualifications of operators and support staff
  – Inspection reports for each unit publicly available

• Near-Term (i.e., 90-Day) and Longer-Term NRC Task Forces
  – 34 recommendations; 12 orders, 7 proposed rules, 15 NRC staff and long-term recommendations
NRC Actions After Fukushima Tier 1

- **Mitigation Strategies**: To enhance the capability to maintain plant safety during a prolonged loss of electrical power.

- **Containment Venting System**: To provide a reliable hardened containment vent system for boiling water reactors (BWRs) with Mark I or Mark II containment designs.

- **Spent Fuel Pool Instrumentation**: To provide a reliable wide-range indication of water level in spent fuel storage pools.

- **Seismic Reevaluations**: To reanalyze potential seismic effects using present-day information to determine if safety upgrades are needed.

- **Flooding Hazard Reevaluations**: To reanalyze potential flooding effects using present-day information to determine if safety upgrades are needed.

- **Seismic and Flooding Walkdowns**: To inspect existing plant protection features against seismic and flooding events, and correct any degraded conditions.

- **Emergency Preparedness – Staffing and Communications**: To assess staffing needs and communications capabilities to effectively respond to an event affecting multiple reactors.

- **Station Blackout Mitigation Strategies**: To enhance the capability to maintain plant safety during a prolonged loss of electrical power.

- **Onsite Emergency Response Capabilities**: To strengthen and integrate different types of emergency procedures and capabilities at plants.

- **Filtration and Confinement Strategies**: To evaluate potential strategies that may further confine or filter radioactive material if core damage occurs.
NRC Actions After Fukushima: Tier 2

• **Spent Fuel Pool Makeup Capability:** To provide a reliable means of adding extra water to spent fuel pools

• **Emergency Preparedness:** To address three aspects of Emergency Preparedness for multi-reactor and loss of power events:
  – Training and exercises (drills)
  – Equipment, facilities, and related resources
  – Multi-unit dose assessment capability

• **External Hazard Reevaluations:** To reanalyze the potential effects of external hazards other than seismic and flooding events (which were addressed under Tier 1).
NRC Actions After Fukushima: Tier 3

• **Periodic Confirmation of External Hazards:** To ensure external hazards, such as seismic and flooding effects, are periodically reanalyzed during the lifetime of a plant.

• **Seismically-Induced Fires and Floods:** To evaluate potential enhancements to the capability to prevent or mitigate seismically-induced fires and floods.

• **Venting Systems for Other Containment Designs:** To evaluate the need for enhancements to venting systems in containment designs other than Mark I and II (which are addressed under Tier 1).

• **Hydrogen Control:** To evaluate the need for enhancements to hydrogen control and mitigation measures inside containment or other plant buildings.

• **Emergency Preparedness:** To evaluate additional enhancements to Emergency Preparedness (EP) programs that go beyond the Tier 1 and Tier 2 EP-related activities.

• **Emergency Response Data System (ERDS) Capability:** To enhance the capabilities of the Emergency Response Data System (ERDS)

• **Decision-making, Radiation Monitoring, and Public Education:** To evaluate the need for enhancements to Emergency Preparedness programs involving decision-making, radiation monitoring, and education.

• **Reactor Oversight Process (ROP) Updates:** To improve the Reactor Oversight

• **Training on Severe Accidents:** To enhance training of NRC staff on severe

• **Emergency Planning Zone:** To evaluate the basis for the size of the emergency planning zone needs to be modified.

• **Potassium Iodide (KI):** To evaluate the need to modify program for administering potassium iodide.

• **Expeditied Transfer of Spent Fuel to Dry Cask Storage:** To evaluate expediting the transfer of spent nuclear fuel from storage pools to dry cask storage.

• **Reactor and Containment Instrumentation:** To evaluate potential enhancements for instrumentation in the reactor and containment to withstand severe accident conditions.
Post Fukushima PRA Implication: Modeling Issues

- Multi-Unit Risk
  - Hard dependencies
    - Common initiating events / shared SSCs
    - Shared instrumentation, control, other cables, electric divisions
    - Shared systems (e.g., FPS)
    - Capacity of shared equipment (e.g., batteries)
Post Fukushima PRA Implication: Modeling Issues (Cont.)

- Multi-Unit Risk (Cont.)

➤ Soft 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 to 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)
Post Fukushima PRA Implication: Modeling Issues (Cont.)

– Severe accident phenomena
  ➢ Relevance of severe accident phenomena
    ✷ H generation / explosions
    ✷ Containment failure modes
    ✷ Integrity of instrumentations

– Long-term cooling
  ➢ Capacity of heat sinks (24 hr, 72 hr, or longer accidents)
  ➢ Conditions necessary to maintain long-term cooling
Post Fukushima PRA Implication: Modeling Issues (Cont.)

– HRA
  ➢ Multi-Unit control room crew dynamics
  ➢ Errors of commission
  ➢ Recovery actions / accessibility

– External events
  ➢ Consideration of seismic hazard
  ➢ Fragilities of integrated structures
  ➢ Combined external initiators

– Spent fuel pool considerations
  ➢ Interplay with the operating Units
Concluding Remarks

• Lessons Learned from Accidents have Improved U.S. Nuclear Plant Safety
• Safety Performance Data Prove this Claim
• Traditional PRA methods should be improved
• More research needed
• New standards, regulatory guidance needed