

Nuclear Power Plant Safety in the Aftermath of Major Emergencies

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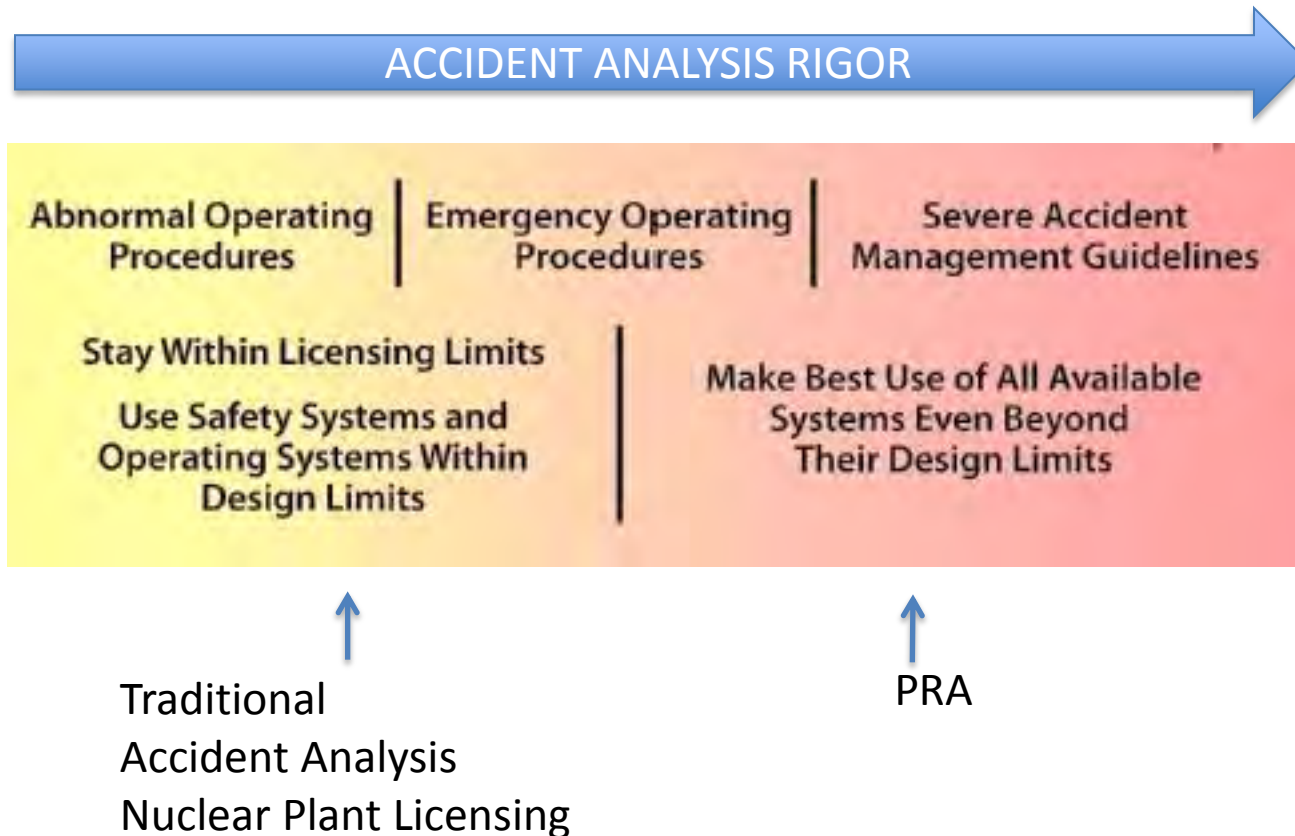
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Overview of this Talk

- 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



Nuclear Accidents: The PRA Perspective

Plant Condition:

1. Full Power
2. Low Power & Shutdown

Initiating Event:

1. Internal
2. External

$IE * HW_1 * \dots * HW_n * SW * HE * NR$

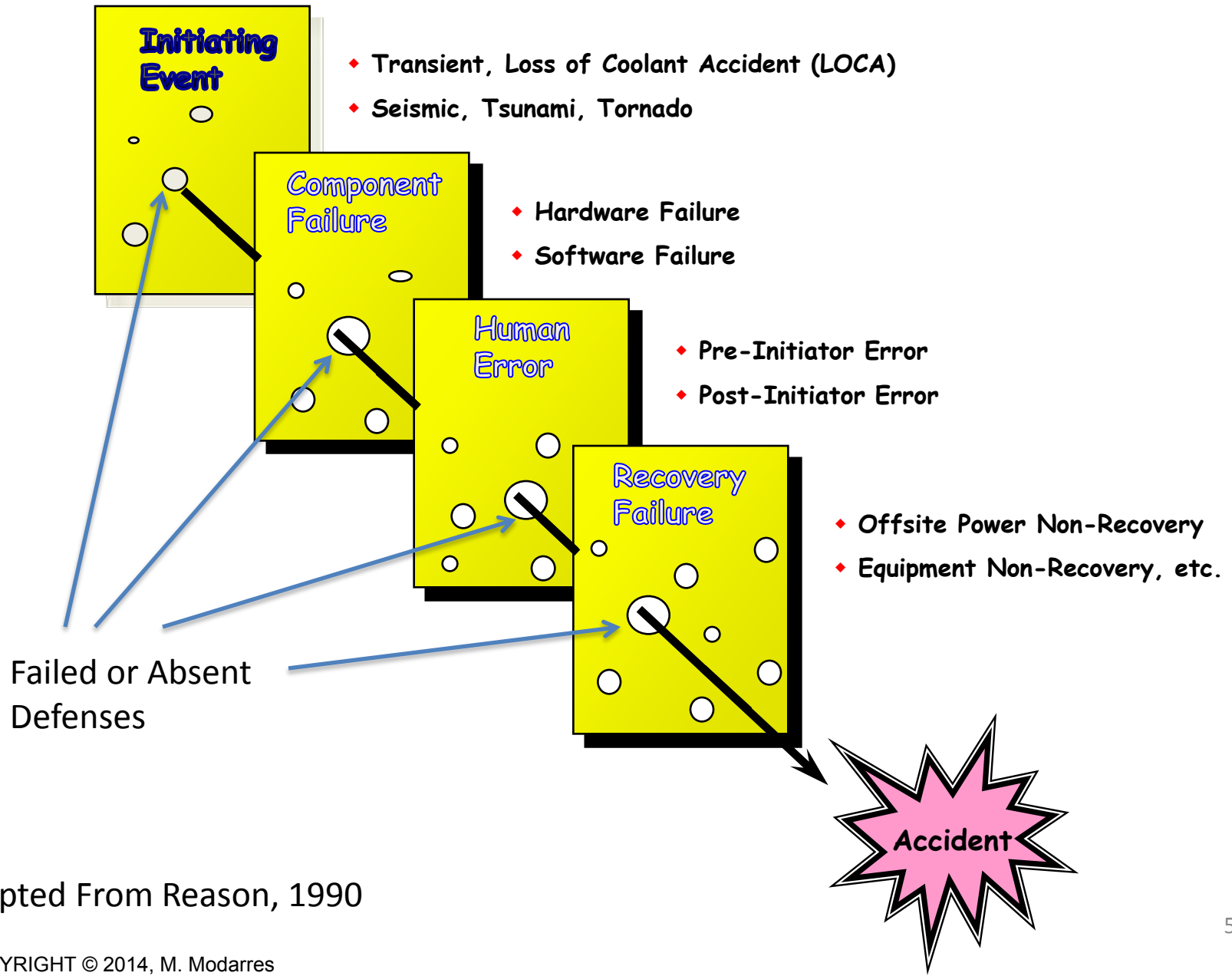
Analysis Level:

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*

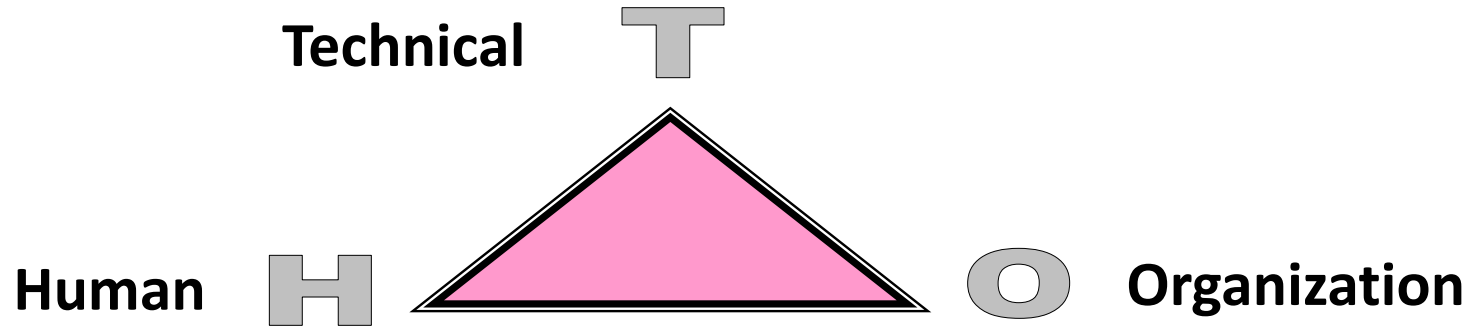
IE = Initiating Event; HW = Hardware; SW = Software; HE = Human Error; NR = Non-Recovery;

Nuclear Accidents: The PRA Perspective (Cont.)



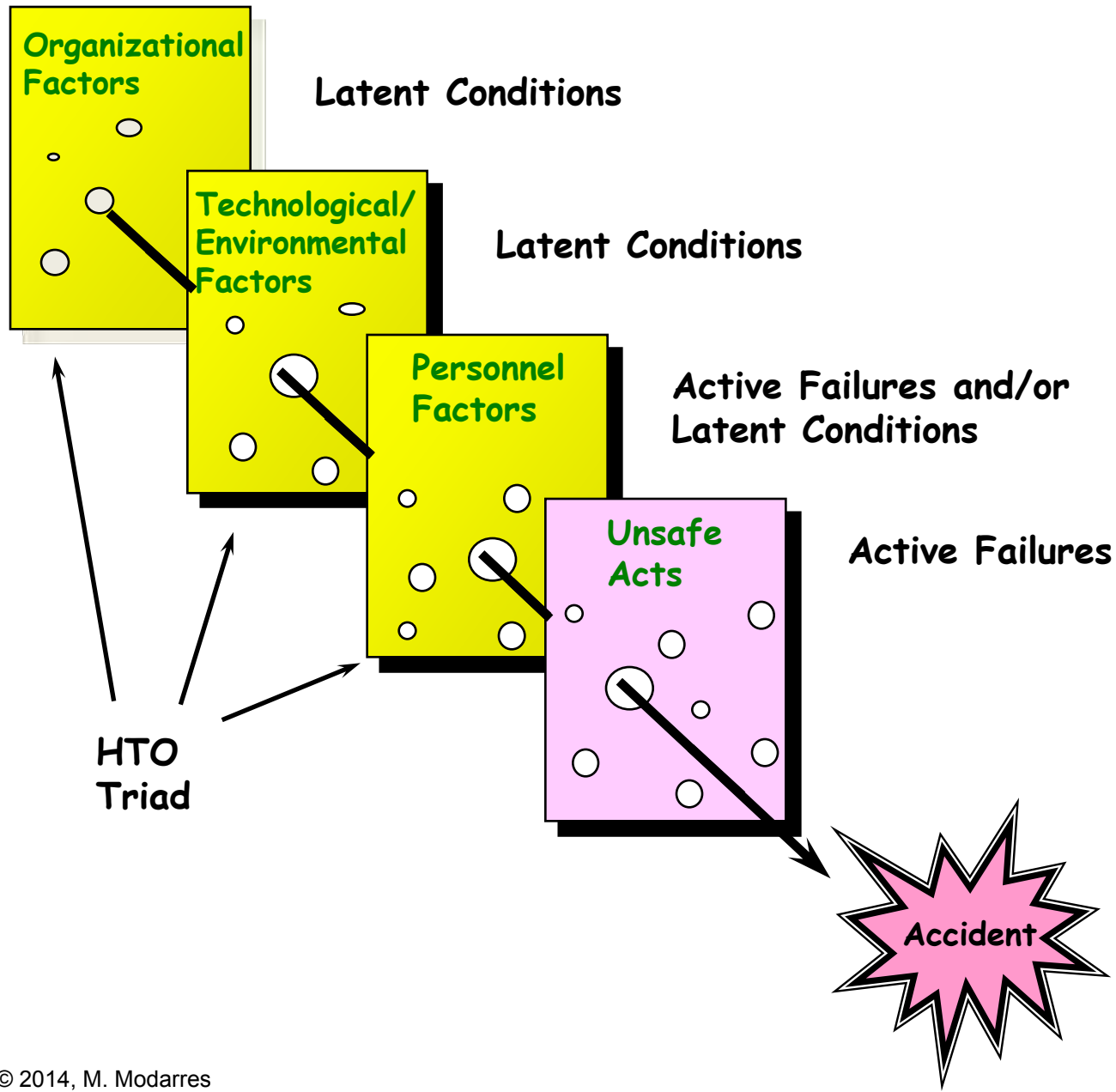
Adapted From Reason, 1990

HTO Perspective



Regulation

Accident Causation from an HTO Perspective



Accidents Resulting from Weaknesses in the HTO Elements

Element of HTO	Weakness in HTO Elements as Revealed by the Fukushima Accident	Remarks on Global Status
H	<ul style="list-style-type: none"> o Inappropriate definition of design basis o Improper analysis of plant risk (e.g., underestimation of external events risk, less emphasis on concurrent events and site risk) [2] 	Globally was the case prior to the Fukushima accident
T	<ul style="list-style-type: none"> 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) 	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)
O	<ul style="list-style-type: none"> o Lack of emergency management capability for multiunit events 	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

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.

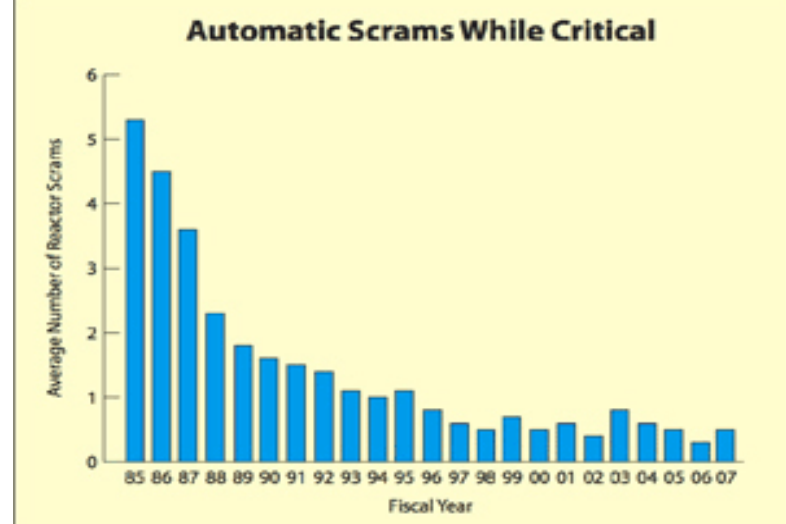
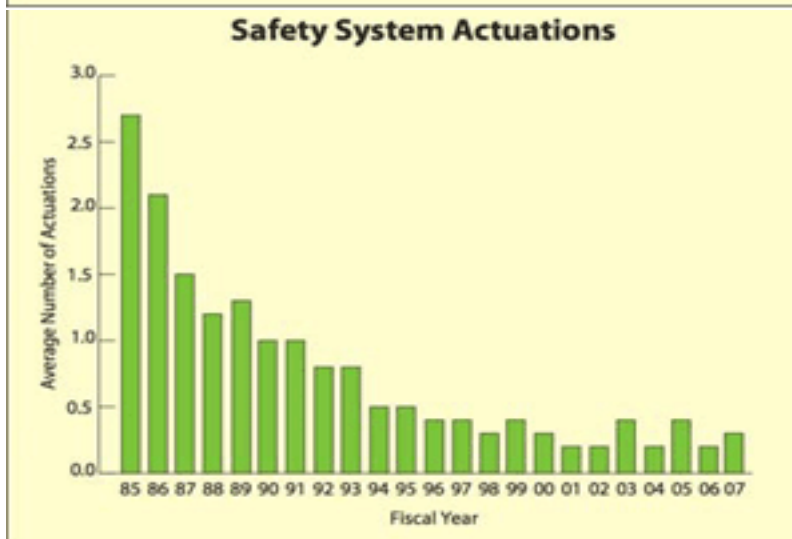
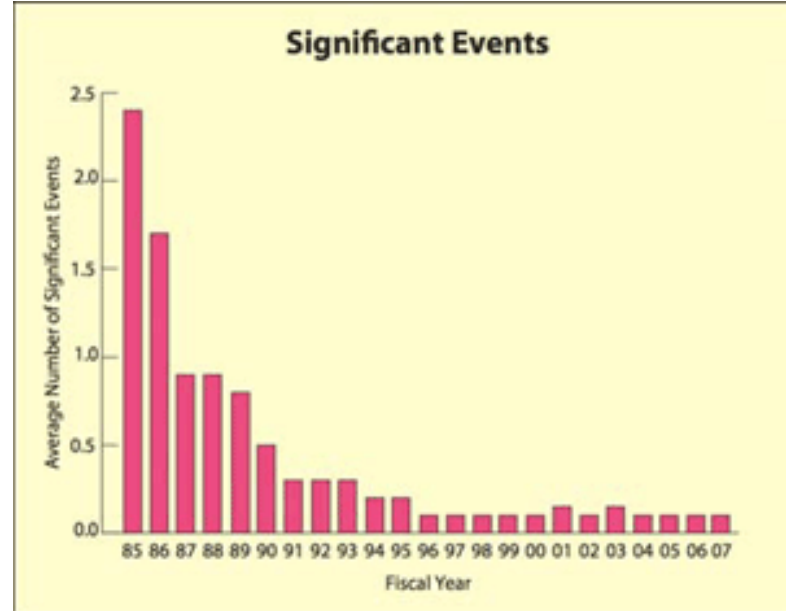
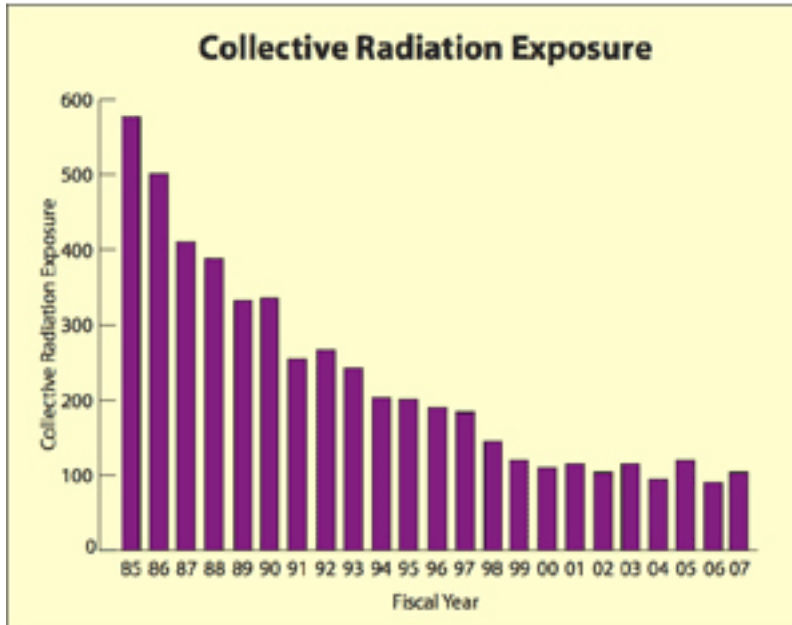
TMI Status

- 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.
- **Expedited 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