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

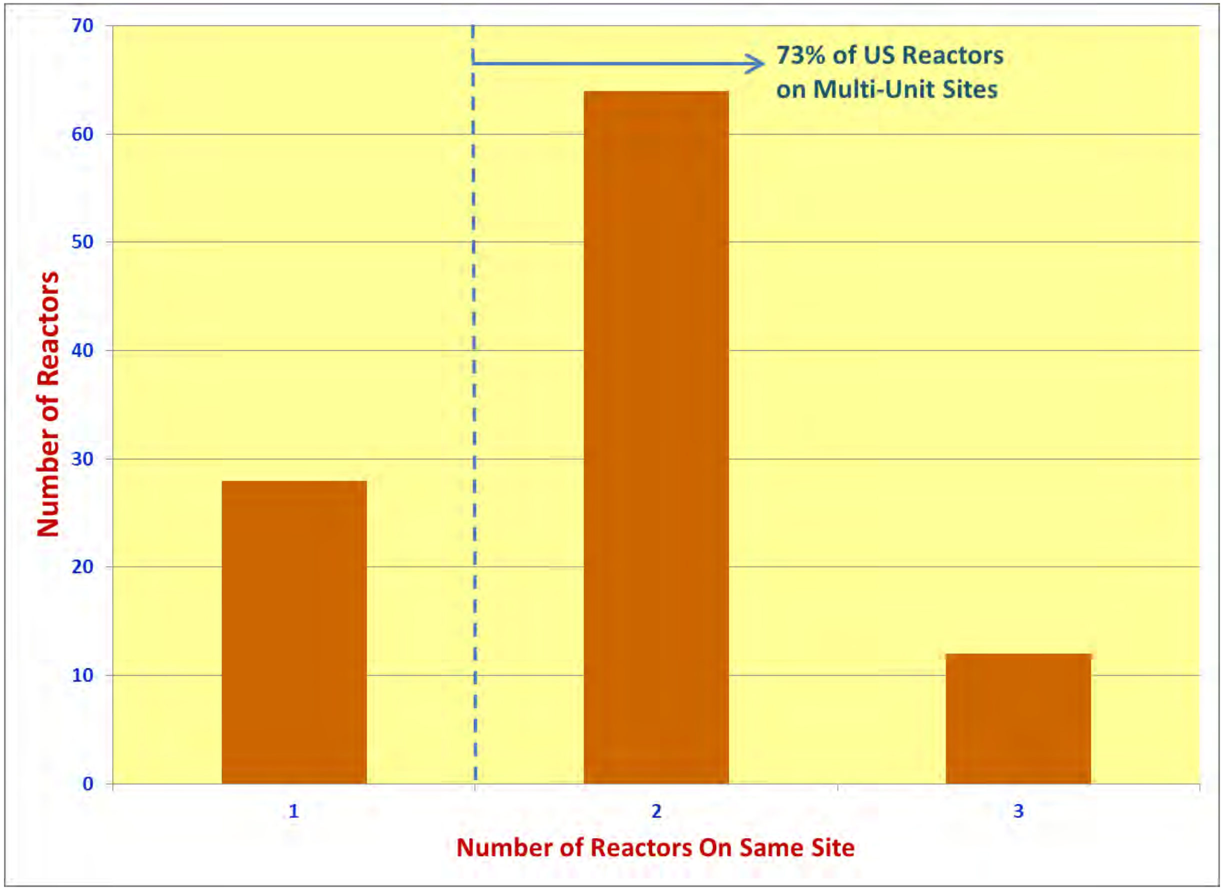
Critical Safety Implications of Fukushima Events

- 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

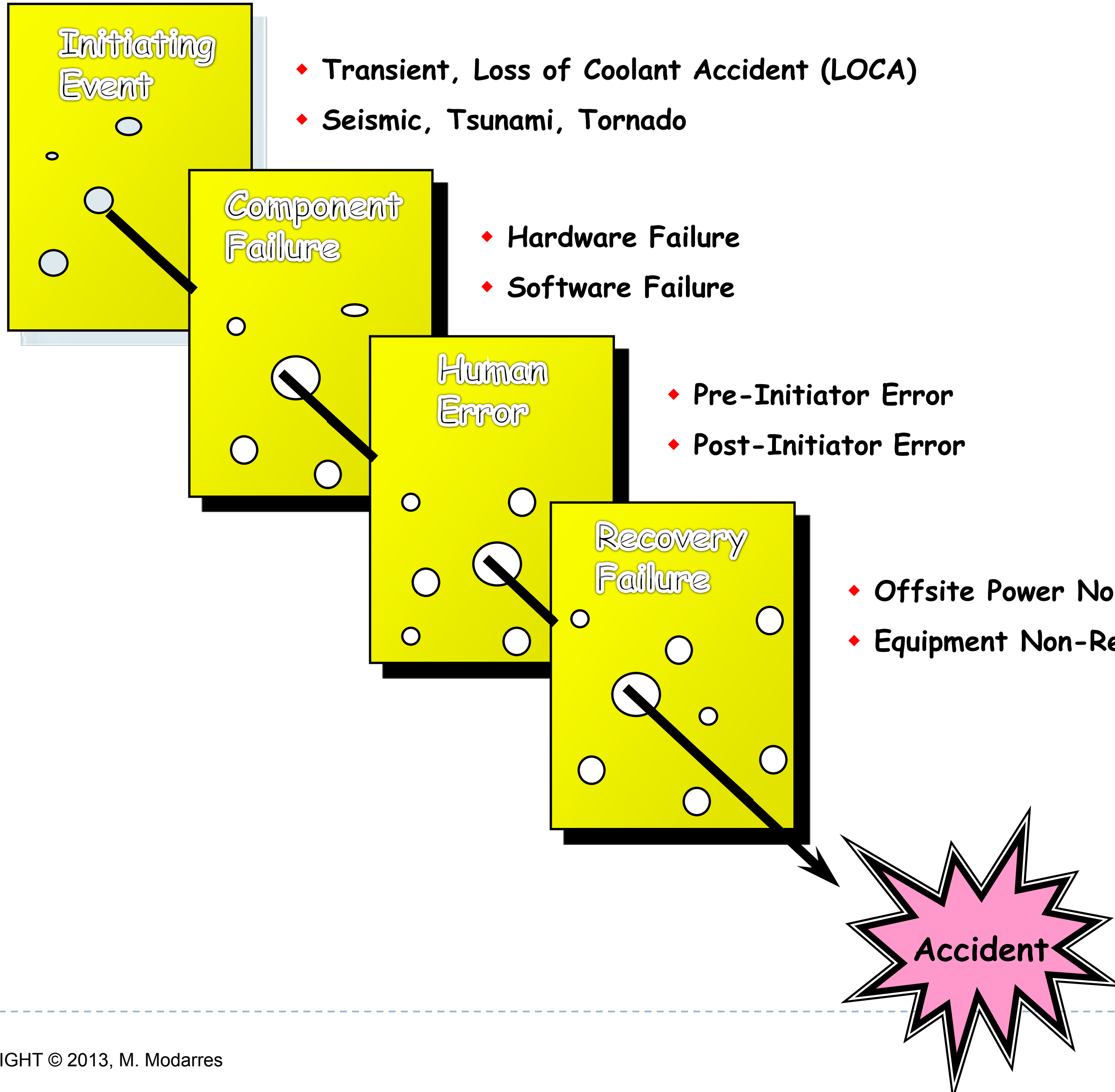
- Units 1, 2, 3 experienced core damage and large releases of radioactive material from containment
- No core damage at Unit 4 largely due to shutdown/defueled state
- Units 5 and 6 averted core damage due to one EDG being protected from flooding and heroic operator actions
- Key cause of accident was 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



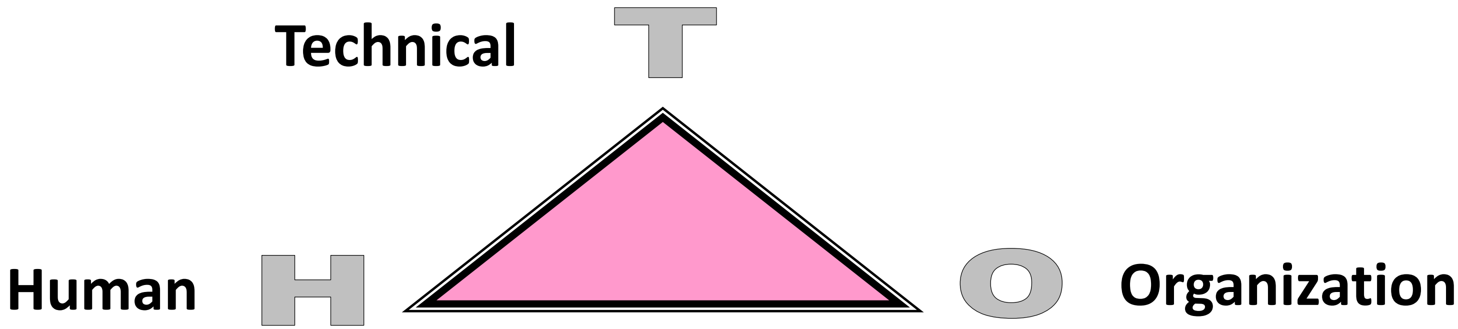
- Transient, Loss of Coolant Accident (LOCA)
- Seismic, Tsunami, Tornado

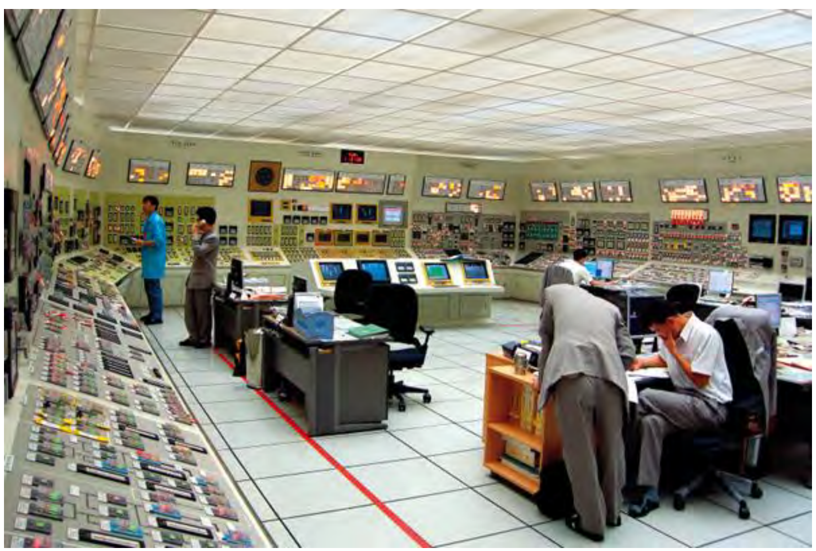
- Hardware Failure
- Software Failure

- Pre-Initiator Error
- Post-Initiator Error

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

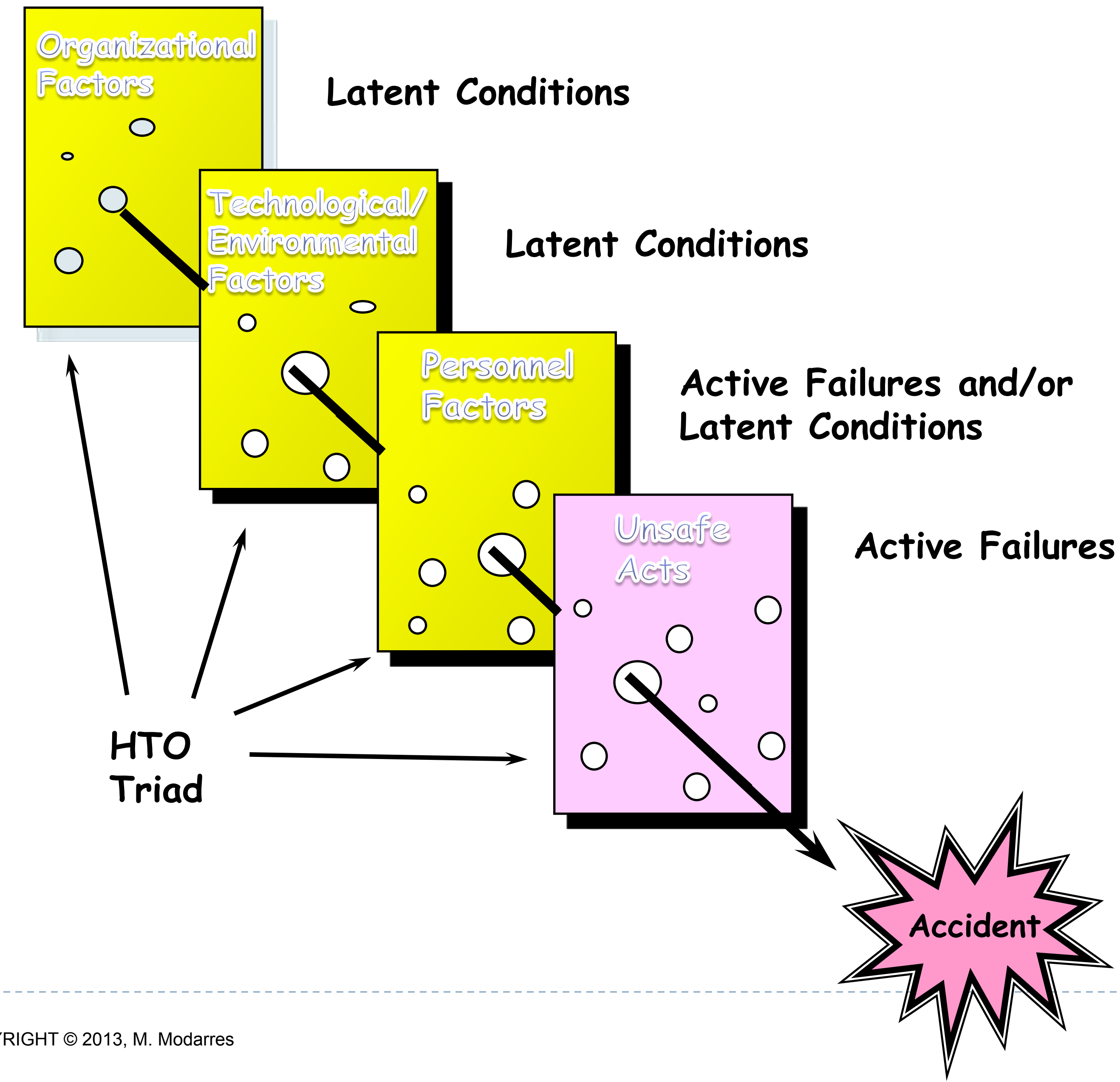
HTO Perspective





Regulation

Accident Causation from an HTO Perspective



Weaknesses in HTO Elements

Element of HTO	Weakness in HTO Elements as Revealed by the Fukushima Accident	Remarks on Global Status
H	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)	Globally was the case prior to the Fukushima accident
T	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	o Lack of emergency management capability for multiunit events	Globally was the case prior to the Fukushima accident except the US wherethe emergency management capability has been considerably enhanced since the 9/11 terrorist attack

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

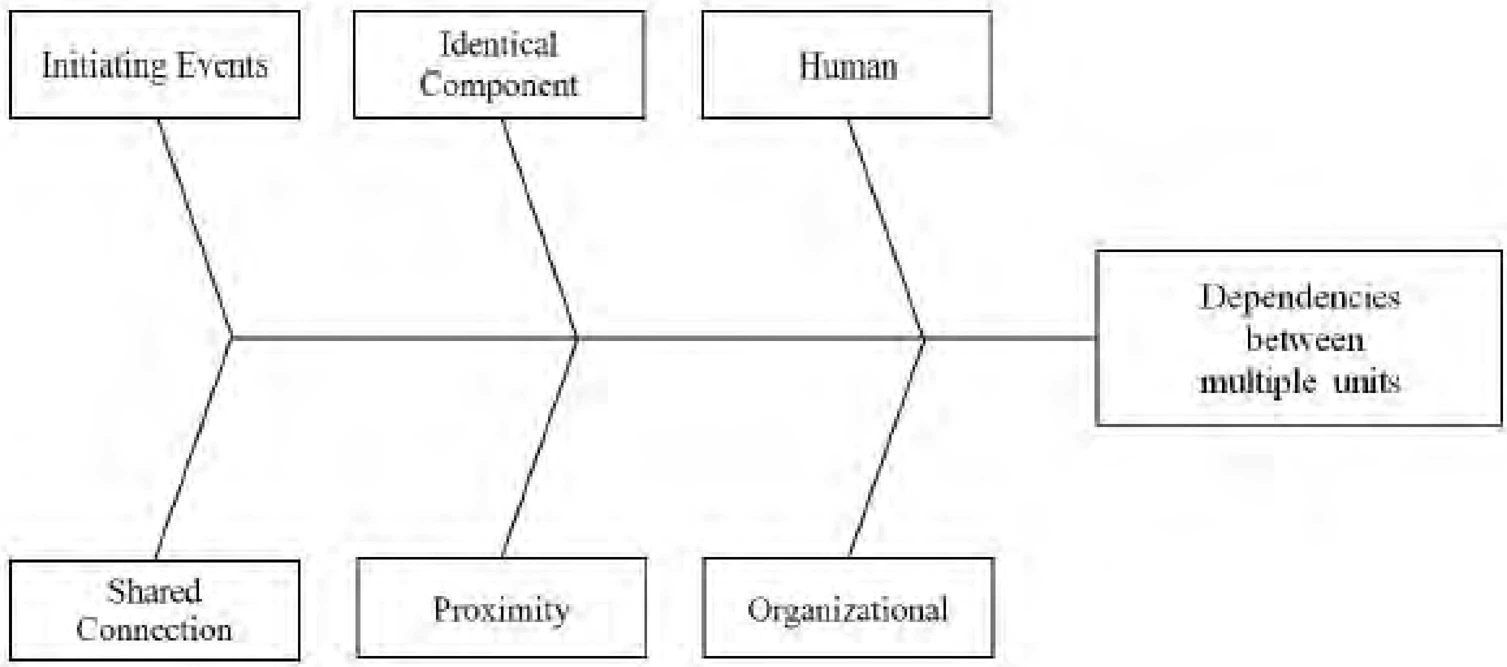
Issues with PRA Applications to Multi-Units

- 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

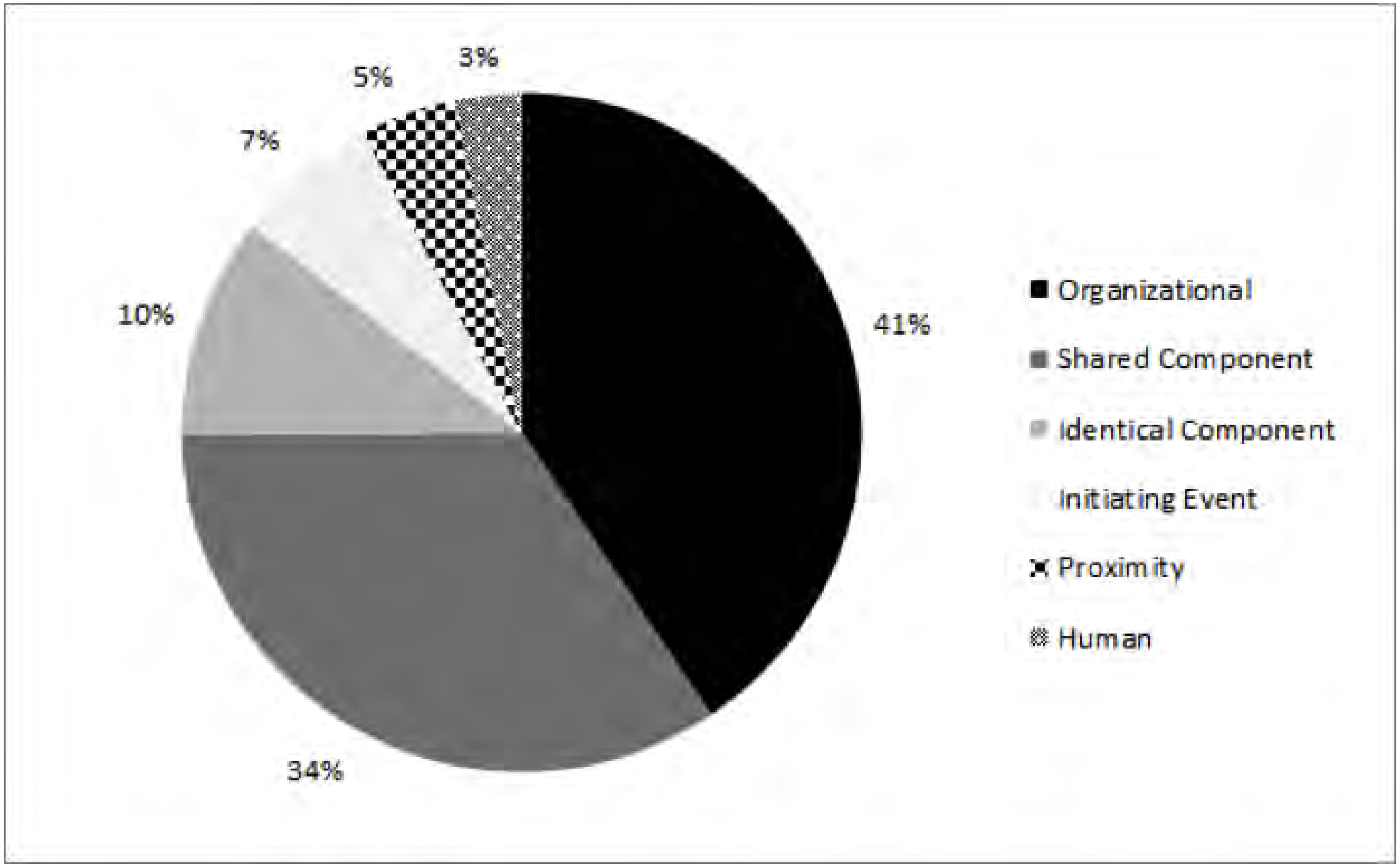
- Rudimentary multi-unit Seabrook PRA (mid 1980s) and Byron/Braidwood PRA (late 1990’s) has been done
- Modular HTGR PRAs (mid 1990’s)
- Multi-Module PRA of SMRs (Ongoing)

Causes of Unit-to-Unit Dependencies



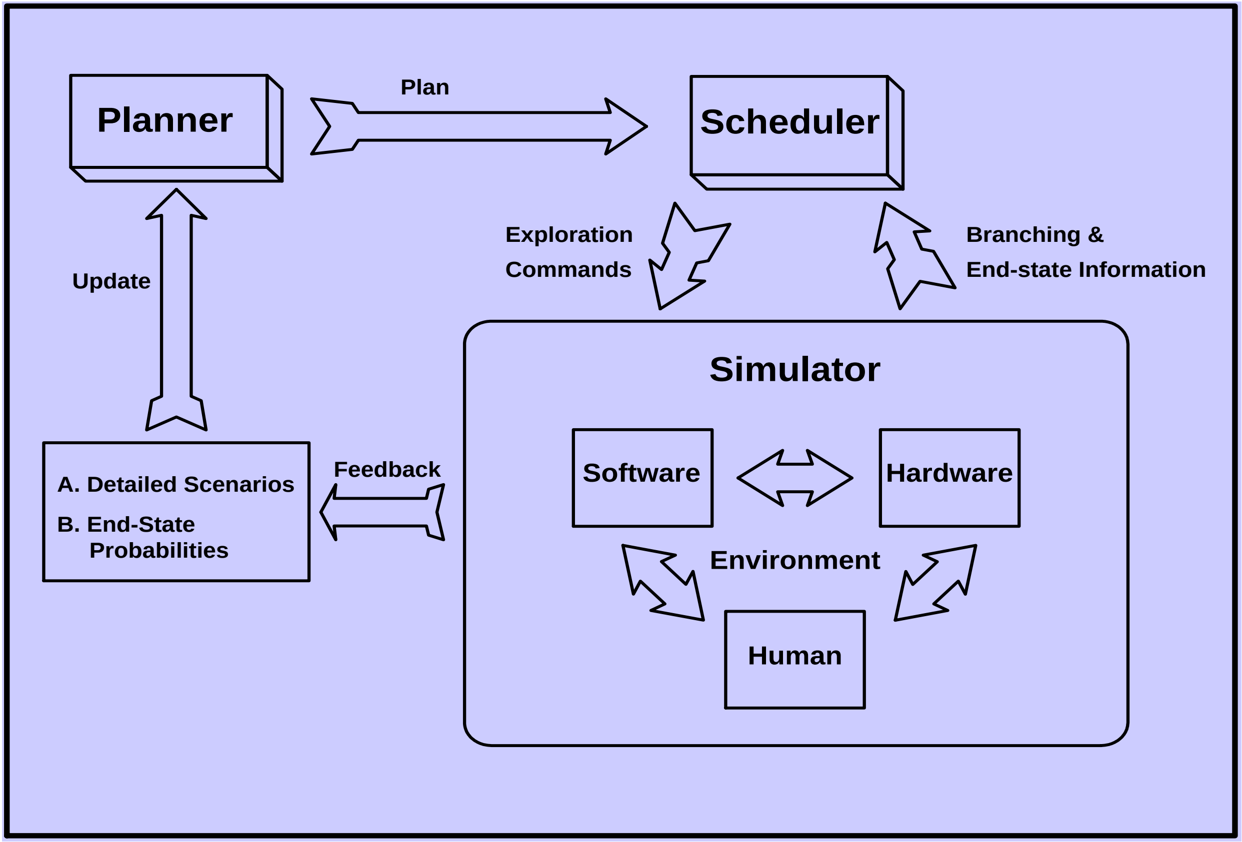
Source: S. Schroer

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

SMR PRA Modeling Considerations/Complexities (Cont.)

- 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