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Risk perspectives and academic research on severe accidents and dynamic simulation-based risk assessment

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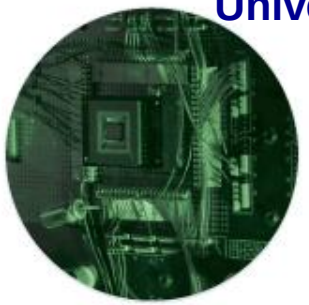

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Outline

- Purpose
- Multi-unit risk analysis methodology
- Simulation tool development

Risk Assessment Perspective on Simulation

- Technological gaps
  - Current probabilistic risk assessment (PRA) relies on an iterative process between system engineers, thermal-hydraulic specialists, and PRA practitioners to calculate risk metrics for severe accidents
  - Components of the accident sequence progression (human performance, thermal-hydraulics, core damage phenomena, hardware reliability, etc.) remain fragmented pieces of a full-scope PRA
- Needed advances post-Fukushima
  - IAEA Action Plan on Nuclear Safety recommended to “improve analytical modelling capabilities and further develop tools for assessment of multi-unit sites under the impact of correlated multiple hazards induced by complex natural event scenarios” [IAEA, 2012].
  - Recognition that the 2012 earthquake and tsunami at the Fukushima nuclear power plant in Japan is evidence that it is no longer sufficient to assess safety at multi-unit nuclear power plant sites by extrapolating the results from a single unit nuclear power plant safety assessment [IAEA, 2013].

Purpose

Today

- Multi-unit (or multi-module) site risk is not formally considered [Fleming, 2003; Fleming, 2005; Hakata, 2007]
- Risk metrics (Core Damage Frequency and Large Early Release Frequency) don't capture integrated site risk
- Nuclear reactor regulation based on single-unit safety goals [U.S. NRC, 2013, 2011; Muramatsu, 2008]

Tomorrow

Need to develop simulation technology and methods to analyze multi-unit nuclear reactor accidents factoring in human actions, system dependencies and reactive feedback.

Research Objectives

- Expand the application of dynamic PSA to multiple reactors at a site
- Enhance the currently available simulation tools in order to model multiple reactors
- Establish a practical framework for system dependency classification and *relative risk* of integrated site risk
- Apply the framework and tools to a multi-unit design

Multi-Unit Events Exist in Current Fleet

- Licensee Event Reports (LERs) from 2000 to 2011 that affected multiple units (Schroer, 2013)
- 391 LERs affected multiple units of 4207 total LERs (9% of total)
- 29 of the multi-unit LERs affected three units

Classification	Percentage of Total
Initiating Event	6.91
Definite	3.84
Conditional	3.07
Shared Connection	34.27
Single	27.62
Time Sequential	5.88
Standby	0.77
Identical Component	10.49
Proximity	4.60
Human	3.07
Pre-Event	2.81
Post-Event	0.26
Organizational	40.66

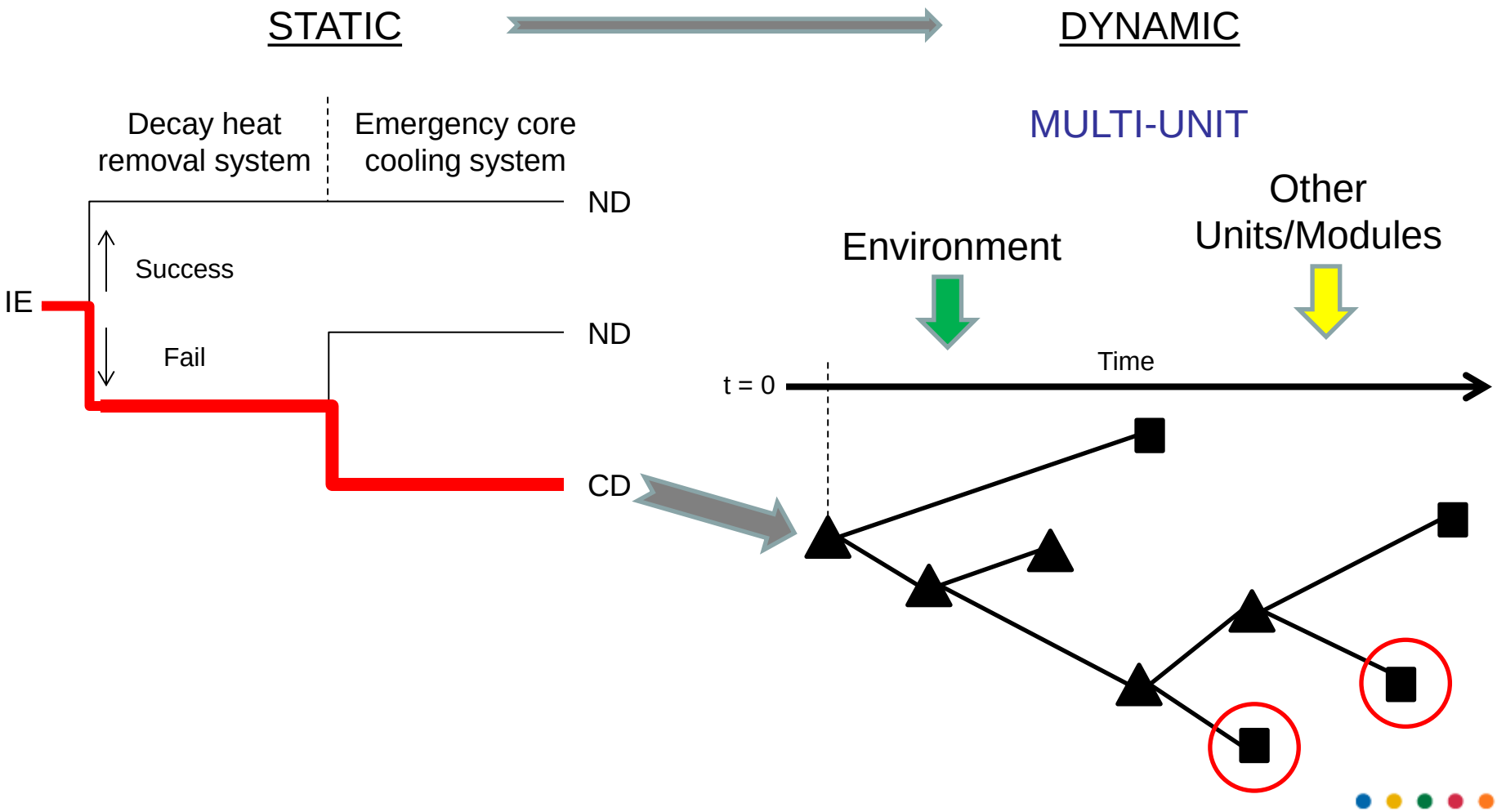
Multi-Unit Analysis Methodology

1. Classify commonalities
   - initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies [Schroer and Modarres, 2013]
2. Develop dependency matrix for use in classification
3. Rank base PRA accident sequences
4. Matrix multi-unit dependencies with risk significant systems
5. Develop T-H model of reactor system
6. Expand fault trees to capture cross-unit dependencies
7. Develop ADS-IDAC multi-unit model
8. Prune accident sequences via probability truncation, event time, or end state condition
9. Assess relative risk of dynamic PRA accident sequences

Classification Matrix Example

Accident Sequence Classifications	Definition	Potential Systems Belonging to Classification
Initiating Events	Single events that have the capacity to affect multiple units	Loss of Offsite Power, Loss of Ultimate Heat Sink, seismic event (including seismically-induced tsunami), external fire, external flood, hurricane, high wind, extreme temperature
Shared Connections	Links that physically connect SSCs of multiple units	Reactor pool, chilled water system, BOP water system, spent fuel pool cooling system, circulating water system, reactor component cooling water system, high, medium and low voltage AC distribution systems
Identical Components	Components with same design, operations or operating environment	Safety DC electrical and essential AC distribution system, reactor vault/bay, containment, decay heat removal system, emergency core cooling system, non-safety instrumentation and control, chemical volume and control system, power conversion system
Proximity Dependencies	A single environment has the potential to affect multiple units	Reactors, ultimate heat sink, containment, non-safety DC electrical and essential AC distribution system, control room HVAC
Human Dependencies	A person's interaction with a machine affects multiple units	Shared control room, operator staffing more than one reactor
Organizational Dependencies	Connection through multiple units typically by a logic error that permeates the organization	Same vendor for safety and non-safety system valves, consolidated utility ownership of multiple nuclear power plant sites, decision-maker overseeing more than one reactor or more than one operator

Expansion of static PRA accident sequences



Dynamic vs. Static PRA

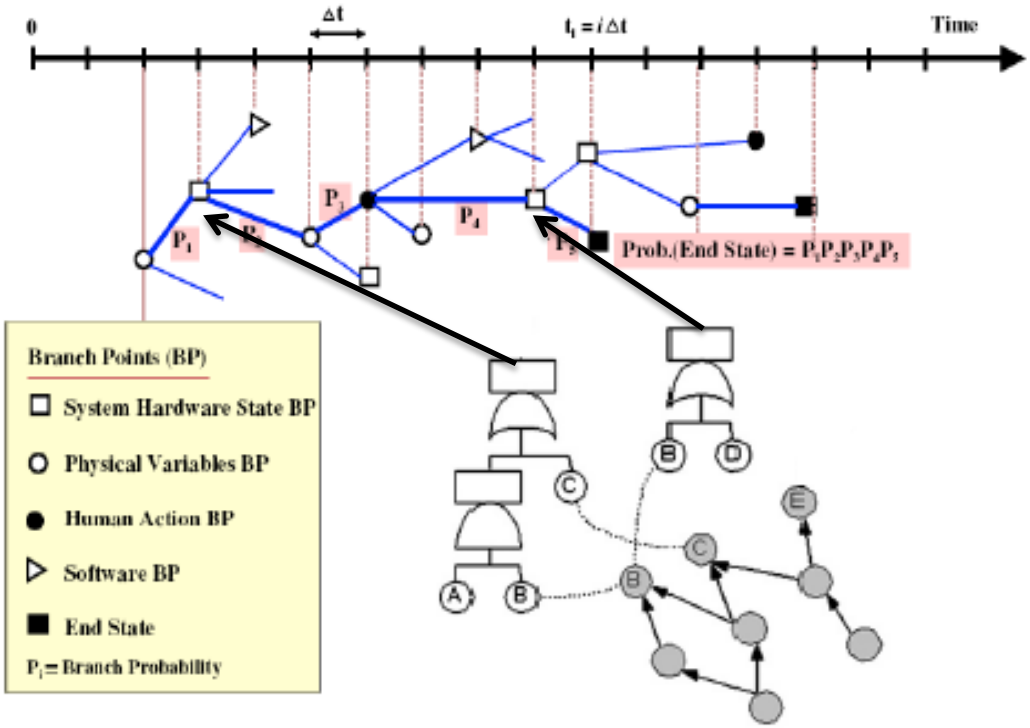
- Dynamic includes explicit modeling of deterministic dynamic processes that take place during plant system evolution along with stochastic modeling [Hakobyan, 2008]
  - Parameters are represented as time-dependent variables in event tree construction with branching times determined from the systems analysis code (MELCOR, RELAP, MAAP, etc.)
  - The discrete dynamic event tree (DDET) starts with an initiating event and branches occur at user specified times or when an action is required by the system or operator, thus creating a sequence of events based on the time of their occurrence
  - Information passed from the system T-H model will inform how the dynamic system variables will evolve in time for each branch
  - The main advantage of DDET methodology over the conventional event tree method is that it simulates probabilistic system evolution in a manner consistent with the deterministic model

Coupling Simulator Technology with ADS-IDAC

- Accident Dynamic Simulator – Information, Decision, and Action in a Crew context cognitive model (ADS-IDAC) [Coyne, 2009; Zhu, 2008; Hsueh, 1996]
  - Thermal-hydraulic (T-H) model (RELAP5) coupled with operations crew cognitive model
  - Generates DDET using simplified branching rules to model variations in crew responses
- Explicitly represent timing and sequencing of events
- Calculates impact of variations of hardware and operator performance on the plant model
- Captures complex interdependencies

Enhancing Hardware Reliability Analysis

- Hybrid Causal Logic Dynamic PRA
- Mimic traditional fault tree analysis
- Integrates fault tree and Bayesian belief network from Integrated Risk Information System (IRIS) into ADS-IDAC discrete dynamic event tree



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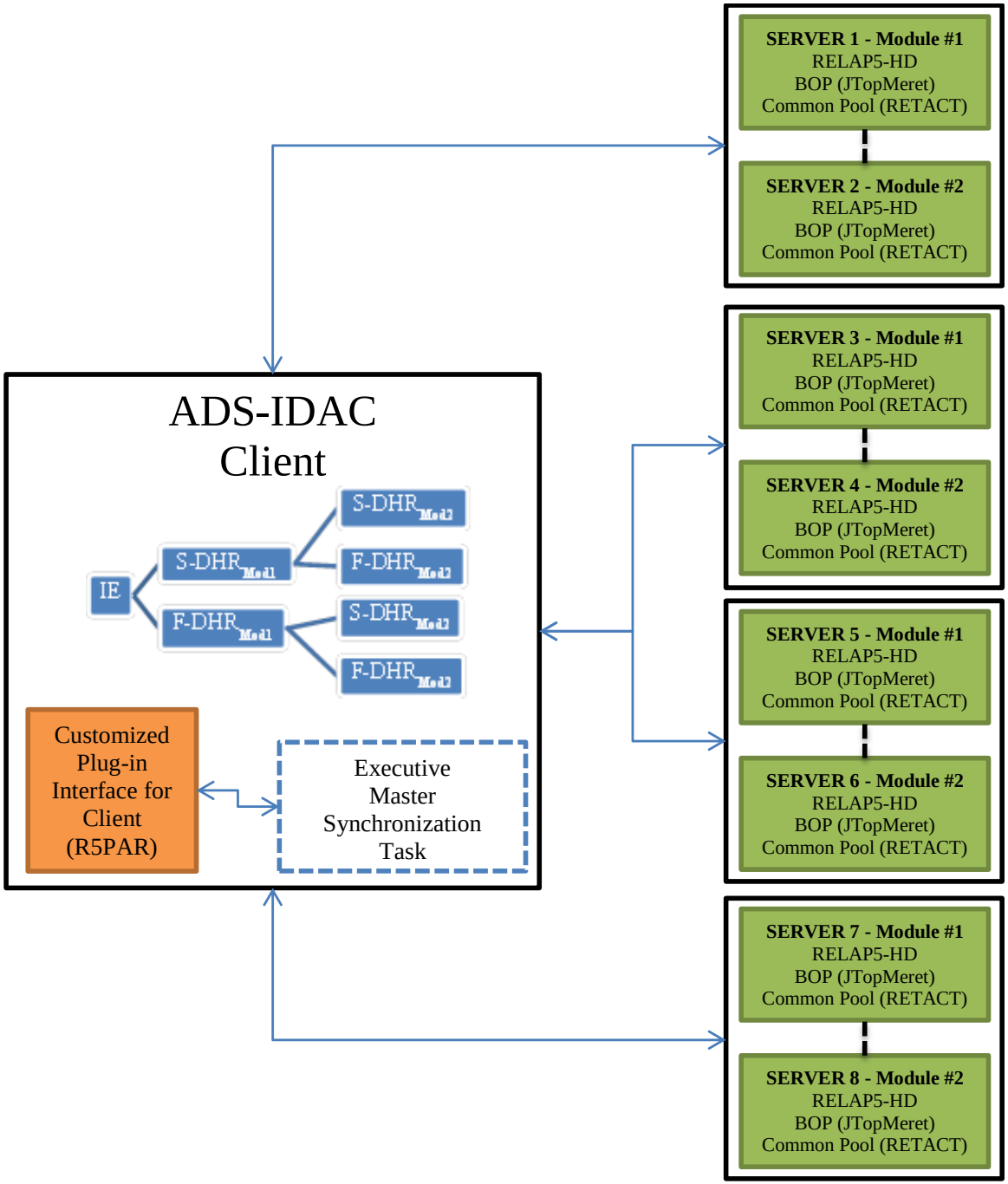
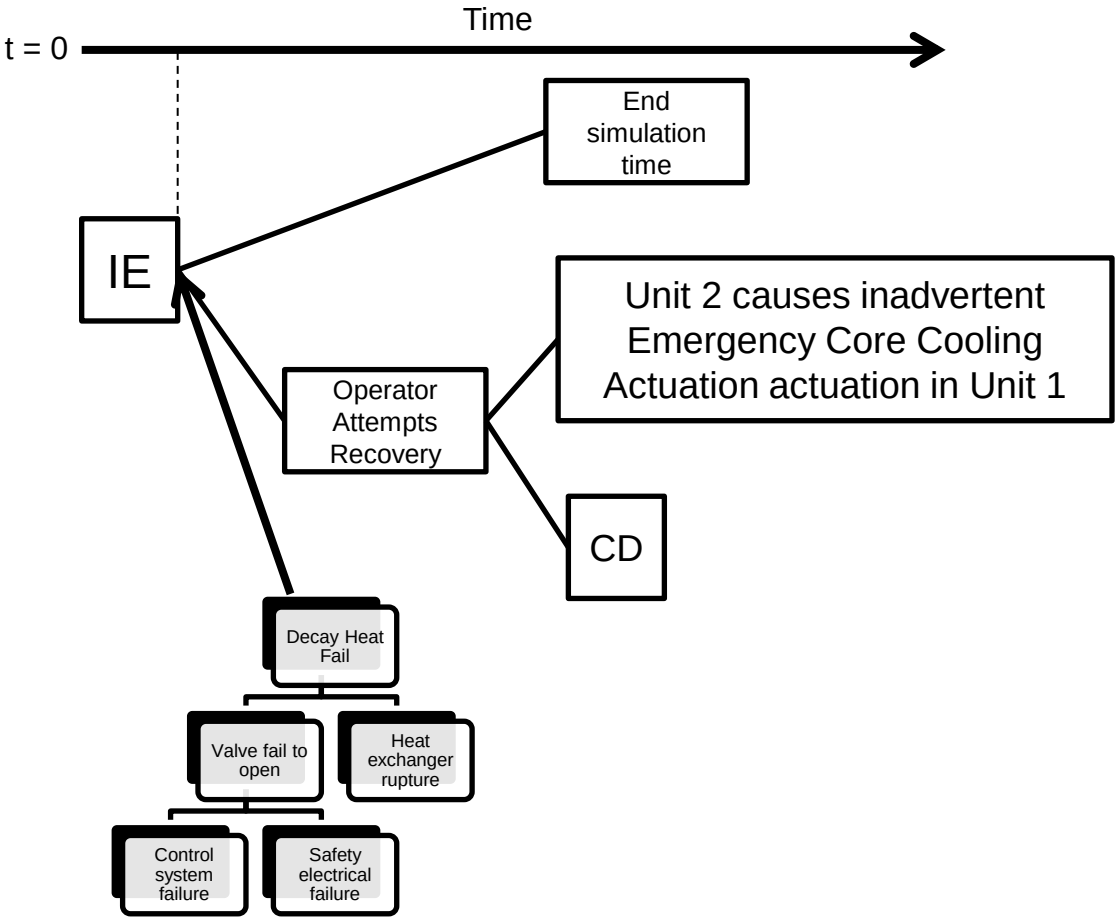
Coupled ADS-IDAC Simulator Framework



Simulation Example



Conclusion

- Simulation-based technique is needed to manage the proliferation of system information and feedback of multi-unit sites.
- A new module allows the ADS-IDAC operator control panel to interface with simulator-derived information from either RELAP-HD or other balance-of-plant simulation modules.
- This research is expected to develop and demonstrate a novel methodology that provides a framework for more realistic PRA analyses and assessment of the relative contribution of important core damage end states.

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