FRAMEWORK FOR ASSESSING INTEGRATED SITE RISK OF SMALL MODULAR REACTORS USING DYNAMIC PROBABILISTIC RISK ASSESSMENT SIMULATION

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Outline

• Motivation and objective
• Dynamic multi-unit PRA (MUPRA) methodology
• Hardware reliability analysis
• Simulation tool development
Motivations

- **Technological gaps**
  - Current PRAs rely on iterative processes between system engineers, thermal-hydraulic specialists, and PRA practitioners.
  - Accident sequence progression modeling (human performance, thermal-hydraulics, core damage phenomena, hardware reliability, etc.) remain fragmented in PRAs.

- **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. . . ” [IAEA, 2012].
  - The 2012 earthquake and tsunami at Fukushima underlined multi-unit nuclear power plant risk and the need for extrapolating the results from a single unit nuclear power plant safety assessment [IAEA, 2013].
Purpose

Today

- Multi-unit (or multi-module) PRA not formally considered [Fleming, 2003; Fleming, 2005; Hakata, 2007]
- Risk metrics (CDF and LERF) don’t fully capture site risks
- 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 feedback
Objective

• Develop dynamic MUPRA (D-MUPRA) framework
• Enhance the current simulation tools for D-MUPRA
• Establish a framework for system dependency classification and assessment of *relative site risk*
• Apply the D-MUPRA framework and tools to a multi-module concept
Probabilistic Estimation of Dependencies

• Assume events $CD_1, \ldots, CD_n$ represent random variables describing the “events of a core damage” in units 1 to n.

• Site CDF as summation of individual unit $CD_i$’s: $Expressed\ as\ either:\$
  - marginal CDF for all conditions in the other unit(s)
  - conditional CDF of a unit, given a condition in other unit(s)
Multi-Unit Analysis Methodology

1. Classify dependencies
   • initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies [Schroer and Modarres, 2013]
2. Develop dependency matrix
3. Rank base static PRA accident sequences
4. Identify dependencies associated with risk significant systems
5. Develop T-H model of reactor system
6. Expand fault trees to include dependencies
7. Develop ADS-IDAC that includes multi-unit model
8. Develop algorithms to avoid computational explosion by pruning dynamic scenarios via probability truncation, event time, or end state condition
9. Assess relative risk of D-MUPRA accident sequences
Expansion of static PRA accident sequences

STATIC

Decay heat removal system
Emergency core cooling system

SUCCESS

FAIL

IE
ND
ND
CD

DYNAMIC

MULTI-UNIT

Environmental conditions
Other Units/Modules

Time

Other Units/Modules

Environment

t = 0
## Base PRA Usage – System Identification

### Dedicated and Shared Systems

<table>
<thead>
<tr>
<th>Dedicated Single-Unit Structure, Systems and Components</th>
<th>Shared Multi-Unit Structures, Systems and Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety DC Electrical and Essential AC Distribution System</td>
<td>Cooling towers, pond or other ultimate heat sink</td>
</tr>
<tr>
<td>Reactor Building or Bay</td>
<td>Turbine-Generator Building</td>
</tr>
<tr>
<td>Pressure/Containment Vessel</td>
<td>Reactor Building</td>
</tr>
<tr>
<td>Decay Heat Removal System</td>
<td>Control Room</td>
</tr>
<tr>
<td>Emergency Core Cooling System</td>
<td>Spent Fuel Pool</td>
</tr>
<tr>
<td>Non-safety Control and Instrumentation System</td>
<td>Site Cooling Water System</td>
</tr>
<tr>
<td>Chemical Volume and Control System</td>
<td></td>
</tr>
</tbody>
</table>
## Dependency Classification Matrix

<table>
<thead>
<tr>
<th>Accident Sequence Classifications</th>
<th>Definition</th>
<th>Potential Systems Belonging to Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiating Events</td>
<td>Single events that have the capacity to affect multiple units</td>
<td>Loss of Offsite Power, Loss of Ultimate Heat Sink, seismic event (including seismically-induced tsunami), external fire, external flood, hurricane, high wind, extreme temperature</td>
</tr>
<tr>
<td>Shared Connections</td>
<td>Links that physically connect SSCs of multiple units</td>
<td>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</td>
</tr>
<tr>
<td>Identical Components</td>
<td>Components with same design, operations or operating environment</td>
<td>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</td>
</tr>
<tr>
<td>Proximity Dependencies</td>
<td>A single environment has the potential to affect multiple units</td>
<td>Reactors, ultimate heat sink, containment, non-safety DC electrical and essential AC distribution system, control room HVAC</td>
</tr>
<tr>
<td>Human Dependencies</td>
<td>A person’s interaction with a machine affects multiple units</td>
<td>Shared control room, operator staffing more than one reactor</td>
</tr>
<tr>
<td>Organizational Dependencies</td>
<td>Connection through multiple units typically by a logic error that permeates the organization</td>
<td>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</td>
</tr>
</tbody>
</table>
D-MUPRA Analyses

- **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) branches occur at user specified times or when an action is required by the system or operator
  - T-H model will inform how the dynamic system variables evolve in time for each branch
  - Advantage of DDET vs. conventional event tree is simulation of probabilistic system evolution 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]
  - T-H model (RELAP5) coupled with 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 events and operator performance
- Captures complex unit-to-unit interdependencies
Initialize RELAP Model and Read ADS-IDAC Input Data

Initialize ADS-IDAC for Initial Accident Sequence

Set $t_{counter} = 0$

Run one RELAP time step ($\Delta t_{RELAP}$)

$t_{counter} = t_{counter} + \Delta t_{RELAP}$

$t_{counter} > \Delta t_{ADS-IDAC}$?

Check and Actuate Initiating Events

Update Control Panel

Check and Actuate Component Failures

Execute Control Panel Actions

Process Information (Decision Maker)

Decision-Making (Decision Maker)

New Branches Generated?

Yes

Queue New Sequences for Later Simulation

No

Current Sequence Complete?

Yes

All Sequences Run?

Simulation Done

No

Decision-Making (Action Taker)

Process Information (Action Taker)

Decision-Making (Action Taker)

Process Information (Action Taker)

Coyne, 2008

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Current Hardware Reliability Model

- **Time dependent failures** occur at a prescribed time during the simulation evolution--used to reflect hardware failures (e.g., pump or valve failure at time $t$) or an accident initiating event.

- **Conditional failures** occur when a component changes operating state to a pre-selected target value, thereby initiating the conditional failure of another system or component.

- Recovery an option

- Probability of hardware failure and recovery modeled through beta distributions
Enhancing Hardware Reliability Analysis

- Hybrid Causal Logic Dynamic PRA
- Mimic traditional fault tree analysis
- Integrates fault tree and Bayesian belief network from into the discrete dynamic event tree
Thermal-Hydraulic Model Improvement

Simulator Host Executive System (ADS-IDAC)

- HD Client Executive #1
- HD Client Executive #2

Exec Master Sync Task

HD Server #1 RELAP5-HD*

- HD Server #2 RELAP5-HD
- HD Server #1x Other Software
- HD Server #2y Other Software

*(GSE, 2013)
ADS-IDAC Multi-Unit Data Flow

ADS-IDAC executable

Model execution thread
Loops over model advancements
- HD-Client
- Data collection and intervention logic

Client – Server Executive (SimExec)
- HD-Server
- HD-Client
- Additional Models

Server executive (for each reactor module)
- HD-Server (1...n+1)
  - RELAP-HD initialization
  - RELAP-HD advancement (Tran1)
  - [BOP models]
Event Tree Analysis

- Fault tree linking
- Marginal event tree for one unit
- Conditional event tree for more than one unit
Exploratory, stylized accident sequences

<table>
<thead>
<tr>
<th>Initiating Event</th>
<th>Top Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismically-induced loss of offsite power with degraded ultimate heat sink</td>
<td>Safety DC Electrical, Reactor Protection System, Chemical Volume and Control System, Decay Heat Removal System, Emergency Core Cooling System</td>
</tr>
<tr>
<td>External flood with loss of offsite power</td>
<td>Safety DC Electrical, Reactor Protection System, Chemical Volume and Control System, Decay Heat Removal System, Emergency Core Cooling System</td>
</tr>
</tbody>
</table>
Simulation
- Dynamic PRA code enhancement
- RELAP5 update
- T-H plant model development

System Connections
- Initiating events
- Shared connections
- Identical components
- Proximity dependencies
- Human dependencies
- Organizational dependencies

Methodology Development
- Integrated site risk
- Dependency matrix
- Hardware reliability

Application
- Multi-unit example
- Reliability data
- Branch point criteria

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Conclusions

• 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.