A Dynamic Coupled-Code Assessment of Mitigation Actions in an Interfacing System Loss of Coolant Accident

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Outline

• Dynamic PRA
• ADAPT Overview
• Plant & Transient
• Dynamic Modeling
• Results & Analysis
Dynamic Probabilistic Risk Assessment (PRA)

• Traditional PRA requires analysts to assume order of events
  • Does not explicitly account for timing of events
    • Will an event have different effects on incident progression based on its timing?
  • Uncertainties in event ordering increase with incident complexity and time

• Dynamic PRA is driven by time-resolving models of the relevant phenomena
  • Events occur according to physically-meaningful rules
    • E.g., hydrogen igniter success is queried only when a combustible mixture has accumulated
  • Events may re-occur as appropriate (e.g., valve failure query on cycling)
  • Dynamic event trees (DETs) are easily incorporated into a traditional PRA
ADAPT Approach

• DET driver developed for/by SNL (2006-present)
  • Tracks DET database, launches jobs, and presents results
  • Jobs may be run on local machines up to HPCs
  • Supports linking multiple simulator codes
  • Calculates figures of merit using time-dependent output data

• Simulator- and domain-agnostic
  • Simulators must meet a short list of requirements
    • Capable of restarting from saved state with new input
  • Simulator interactions performed via signal files rather than shared memory
    • Traceability
    • Portability over diverse computational hosts
## ADAPT Applications

<table>
<thead>
<tr>
<th>Years</th>
<th>System</th>
<th>Incident</th>
<th>Simulator(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006-2011</td>
<td>PWR</td>
<td>SBO</td>
<td>MELCOR</td>
</tr>
<tr>
<td>2009</td>
<td>SFR</td>
<td>Aircraft Crash</td>
<td>RELAP5</td>
</tr>
<tr>
<td>2013</td>
<td>PWR</td>
<td>SBO</td>
<td>MELCOR</td>
</tr>
<tr>
<td>2013-2014</td>
<td>PWR</td>
<td>SBO</td>
<td>MELCOR</td>
</tr>
<tr>
<td>2014</td>
<td>HTGR</td>
<td>LOFC</td>
<td>MELCOR</td>
</tr>
<tr>
<td>2015-2017</td>
<td>PWR</td>
<td>SBO</td>
<td>MAAP4</td>
</tr>
<tr>
<td>2015-2017</td>
<td>SFR</td>
<td>TOP</td>
<td>SAS4A/SASSYS-1</td>
</tr>
<tr>
<td>2015-2018</td>
<td>PWR</td>
<td>ISLOCA</td>
<td>MELCOR, RADTRAD</td>
</tr>
<tr>
<td>2015-2018</td>
<td>BWR</td>
<td>SBO</td>
<td>MELCOR</td>
</tr>
<tr>
<td>2016-2018</td>
<td>SNF Cask</td>
<td>Derailment</td>
<td>STAGE, RADTRAN</td>
</tr>
</tbody>
</table>

PWR: Pressurized Water Reactor  
SFR: Sodium-cooled Fast Reactor  
HTGR: High Temperature Gas-cooled Reactor  
BWR: Boiling Water Reactor  
SNF: Spent Nuclear Fuel  
SBO: Station Blackout  
LOFC: Loss of Forced Cooling  
TOP: Transient Overpower  
ISLOCA: Interfacing System Loss of Coolant Accident
Interfacing System Loss of Coolant Accident (ISLOCA)

- ISLOCAs have the potential for large early release due to containment bypass

- Residual heat removal (RHR) ISLOCA
  - Damage to equipment used for safe shutdown
  - Rapid depressurization
    - Difficult to analyze in traditional PRA
    - Common practice is to assume core damage if isolation is lost at power

- Dynamic coupled-code analysis
  - Consider evolution of auxiliary building conditions for operator action success
    - Room flooding, modeled in MELCOR
    - Radiation hazards, modeled in RADTRAD
  - Investigate effects of input parameters on plant state and release fractions
• RHR outside of containment
  • Components reside in lowest level of auxiliary building
  • Shares pumps with low pressure safety injection (LPSI)
  • Suction and return lines must penetrate containment
  • Suction line isolated by motor-operated valves (MOVs) in series
    • Interlocked against high reactor coolant system (RCS) pressure
      • RCS operating pressure 15.5MPa
      • RHR design pressure 2MPa
  • Interfaces with component cooling water (CCW) system

• CCW provides cooling to numerous systems
  • LPSI/RHR pumps
  • High pressure safety injection (HPSI) pumps
• Manual valves relating to RHR and CCW in equipment rooms
  • Isolation of CCW from RHR
  • Bypass of failed RHR heat exchanger (HX)
  • Isolation of RHR from RCS

• Doors and drains will influence flooding
  • Operators may be hampered by flooding or radiation
    • RCS inventory spilled into rooms
Transient (1/2)

1. RHR Isolation Valves Open at Power
   - No: ISLOCA, Begin Recovery
   - Yes: RHR HX Tube Break

2. RHR HX Tube Break
   - No: ISLOCA, Begin Recovery
   - Yes: RHR HX Shell Break

3. RHR HX Shell Break
   - No: CCW Disabled, Begin Recovery
   - Yes: RHR Intake Pipe Break

4. RHR Intake Pipe Break
   - No: Aux. Building Flood
   - Yes: LPSI Disabled, Begin Recovery
Transient (2/2)

• Procedures emphasize depressurization after ISLOCA diagnosed
  • Direct inventory into containment through pilot-operated relief valve (PORV)
  • Preferable to releasing inventory to auxiliary building
  • Water may collect in sump for later use in mitigating accident

• RHR ruptures must be isolated from rooms in the auxiliary building
  • Uncertain success and timing
  • May be defeated by high water level or high radiation
    • Uncertain operator dose tolerance
• General accident progression evolves in MELCOR under ADAPT
  • MELCOR is a severe accident analysis code developed for the United States Nuclear Regulatory Commission (USNRC)

• RADTRAD is run under ADAPT when operator doses must be calculated
  • RADTRAD is a radionuclide transport, removal, and dose calculation code developed for the USNRC

**Diagram:**

**MELCOR branch x**
- Reached operator action finish time $t_{\text{end}}$

**RADTRAD branch x+1**
- Calculated doses from $t_0$ to $t_{\text{end}}$
  - Operator action elapsed time $t_{\text{action}}$
  - Operator action location in aux. building
  - Source term to aux. building from $t_0$ to $t_{\text{end}}$

**MELCOR branch x+2**
- Determines whether operator action succeeds
  - Accumulated dose from $(t_{\text{end}} - t_{\text{action}})$ to $t_{\text{end}}$
Dynamic Modeling (2/5)

- Auxiliary building doors may have failed seals or be left open
  - Initial Door Status
    - RHR Pump Room Door Status
      - Closed: 0.97
      - Open: 0.03
    - RHR HX Room Door Status
      - Closed: 0.97
      - Open: 0.03
- Operator dose tolerance
  - Crew will have limited information regarding the physical state of the plant
  - Dose Tolerance
    - Operator Dose Tolerance
      - 5 rem: 1/3
      - 25 rem: 1/3
      - No limit: 1/3
- Ending conditions
  - 24 hours simulation time
  - 90% of fuel intact
Dynamic Modeling (3/5)

- Uncertain pressure capacity of RHR components

\[
\begin{align*}
\text{Break Location} & \quad \text{RHR Suction Pipe Capacity} \\
& \begin{cases}
4.2 \text{ MPa} & 0.1 \\
8.9 \text{ MPa} & 0.8 \\
16 \text{ MPa} & 0.1 \\
7.8 \text{ MPa} & 0.1 
\end{cases} \\
& \begin{cases}
11 \text{ MPa} & 0.8 \\
16 \text{ MPa} & 0.1 \\
6.1 \text{ MPa} & 0.1 
\end{cases} \\
& \begin{cases}
9.4 \text{ MPa} & 0.8 \\
15 \text{ MPa} & 0.1 
\end{cases}
\]
• Uncertain success of mitigation actions

- PORV Blowdown
- RHR Pump Suction Isolation
- RWST Isolation from RHR
- RHR HX Tube Isolation
- RHR HX Shell Isolation

\[
\begin{align*}
\text{Success} & : 0.97 \\
\text{Failure} & : 0.03 \\
\end{align*}
\]
Uncertain timing of mitigation actions given success
- Only actions taken outside the control room
- Actions taken from control room timed using SOARCA ISLOCA simulation results
- HPSI/LPSI not available until any RHR HX ruptures isolated from CCW

Mitigation Action Timing

- RHR Pump Suction Isolation Timing
  - 393 s, 0.1
  - 608 s, 0.8
  - 1050 s, 0.1

- RHR HX Tube Isolation Timing
  - 393 s, 0.1
  - 608 s, 0.8
  - 1050 s, 0.1

- RHR HX Shell Isolation Timing
  - 393 s, 0.1
  - 608 s, 0.8
  - 1050 s, 0.1
Results (1/7)

• Not all sequences ran to completion
  • 1,448,618 branches identified
    • 697,663 completed
    • 46.7TB of data

• Scoping is important
  • Originally run with internal failure events as well
Results (2/7)

• This ISLOCA can outpace assumed PORV depressurization timing
  • 6 minutes after initiation
• Injection capability may be recovered through isolation of ruptures
  • Sump suction availability is not branched directly
    • Net positive suction head
    • Successful alignment of valves in RHR pump room

Results (3/7)
Results (4/7)

- Used dynamic importance measures (DYIs) to evaluate the impact of input parameters on output measures

<table>
<thead>
<tr>
<th>Importance Measure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$DY11 = \frac{R(x=1)}{R(x=0)}$</td>
<td>Consequence ratio of occurrence to non-occurrence</td>
</tr>
<tr>
<td>$DY12(i) = \frac{R(x=1_i)}{R(x=0)}$</td>
<td>Consequence ratio of occurrence value $x = 1_i$ to non-occurrence</td>
</tr>
<tr>
<td>$DY13(i) = \frac{R(x=1_i)}{\bar{R}(x=1)}$</td>
<td>Consequence ratio of occurrence value $x = 1_i$ to average of occurrence $x = 1$</td>
</tr>
</tbody>
</table>
• Core damage is insensitive to these parameters

• Isolation activities have positive impact on some output measures
  • E.g., “When RHR HX shell isolation is successful, the expected value of the Cs environmental release fraction is 0.56 times its expected value when isolation fails.”

• RHR pump room door being closed leads to higher fuel oxidation and Cs release
  • Retains flood water and delays mitigating actions that restore safety injection

• PORV depressurization appears to have an undesired impact on fuel oxidation and Cs release

<table>
<thead>
<tr>
<th>Branching Parameter</th>
<th>Core Intact Fraction</th>
<th>Hydrogen Generation</th>
<th>Peak Containment Pressure</th>
<th>Environmental Cs Release Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHR HX Room Door Closed</td>
<td>1.0</td>
<td>0.99</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>RHR Pump Room Door Closed</td>
<td>1.0</td>
<td>3.2</td>
<td>1.0</td>
<td>0.32</td>
</tr>
<tr>
<td>RHR HX Tube Isolation</td>
<td>1.0</td>
<td>0.98</td>
<td>1.0</td>
<td>0.56</td>
</tr>
<tr>
<td>RHR HX Shell Isolation</td>
<td>1.0</td>
<td>0.69</td>
<td>1.0</td>
<td>0.074</td>
</tr>
<tr>
<td>RWST Isolation</td>
<td>1.0</td>
<td>0.097</td>
<td>1.0</td>
<td>3.7</td>
</tr>
<tr>
<td>PORV Blowdown</td>
<td>1.0</td>
<td>3.2</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>
• Closer look at PORV depressurization

<table>
<thead>
<tr>
<th>Consequence Measure</th>
<th>DYI Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV Cs Release Fraction</td>
<td>4.0</td>
</tr>
<tr>
<td>Containment Building Cs Release Fraction</td>
<td>3.1</td>
</tr>
<tr>
<td>Auxiliary Building Cs Release Fraction</td>
<td>3.0</td>
</tr>
<tr>
<td>Peak Auxiliary Building Pressure</td>
<td>1.1</td>
</tr>
<tr>
<td>Final RCS Pressure</td>
<td>0.62</td>
</tr>
</tbody>
</table>

• Depressurization occurs too late to be helpful
  • Allows RCS to stay depressurized with low RPV level
    • Contributes to fuel oxidation and failure

• PORV depressurization mitigation action as implemented may not be appropriate for a large ISLOCA
  • Requires diagnosis of the size of the ISLOCA
• Mitigating action timing

<table>
<thead>
<tr>
<th>Branching Condition</th>
<th>Value</th>
<th>Hydrogen Generation</th>
<th>Environmental Cs Release Fraction</th>
<th>Peak Containment Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>393.0 s</td>
<td>$1.0 \times 10^{-4}$</td>
<td>$1.9 \times 10^{-4}$</td>
<td>$2.1 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>608.0 s</td>
<td>$1.3 \times 10^{-2}$</td>
<td>$4.9 \times 10^{-2}$</td>
<td>$6.4 \times 10^{4}$</td>
</tr>
<tr>
<td>RHR HX Tube Isolation Timing</td>
<td>1050.0 s</td>
<td>0.16</td>
<td>$8.4 \times 10^{-2}$</td>
<td>$3.0 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>10$^{20}$ s</td>
<td>$4.6 \times 10^{9}$</td>
<td>$1.4 \times 10^{10}$</td>
<td>$2.6 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>393.0 s</td>
<td>$5.6 \times 10^{-4}$</td>
<td>$2.3 \times 10^{-19}$</td>
<td>$2.2 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>608.0 s</td>
<td>$6.4 \times 10^{-2}$</td>
<td>$2.9 \times 10^{-3}$</td>
<td>$2.3 \times 10^{-2}$</td>
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<td>RHR HX Shell Isolation Timing</td>
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<td>$3.2 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>10$^{20}$ s</td>
<td>$1.2 \times 10^{10}$</td>
<td>$4.4 \times 10^{10}$</td>
<td>$2.4 \times 10^{10}$</td>
</tr>
</tbody>
</table>

• $10^{20}$s represents failure

• Greater sensitivity for lowest-middle time transition than for middle-high transition
  • If action cannot be completed in short time, may be advantageous to focus on other actions
Summary

• Recent modifications to ADAPT allow for quantitative comparison of input parameters for impact on output measures from multiple codes
  • Which physical parameters are most impactful?
  • How does human interaction timing affect the outcome?

• PWR RHR ISLOCA insights
  • Fast diagnosis and decision on operator actions may significantly alter outcome
    • Minutes, not hours
    • PORV depressurization may not be appropriate
  • Plant maintenance may significantly affect outcomes
    • Doors and drains in auxiliary building are important to flood water drainage