EFFECT OF PAR DEACTIVATION BY CARBON MONOXIDE IN THE LATE PHASE OF A SEVERE ACCIDENT

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Containment Phenomena & Processes

Multi-phenomena interactions

Complementary use of System Codes & CFD
OUTLINE

Effect of PAR Deactivation by Carbon Monoxide in the Late Phase of a Severe Accident

• Background
• Effect of carbon monoxide
  • Experimental results
  • Numerical model enhancement
  • Accident simulation: Generic Containment (COCOSYS)
• Summary & Outlook
BACKGROUND

Motivation and Objectives

Passive Autocatalytic Recombiners (PARs)

• ... are key elements of hydrogen mitigation strategy in LWRs worldwide
• ... reduce flammable gases (hydrogen and carbon monoxide)
• ... interact with the containment atmosphere

Objectives of PAR research

• Reliable simulation of PAR operation under severe accident conditions
• Contribution to PAR implementation strategy and performance assessment

Source: Siempelkamp
BACKGROUND

Model development strategy (REKO-DIREKT code)
CHALLENGES FOR PAR OPERATION*

From normal operation to accident

Normal reactor operation before \( \text{H}_2 \) release \( \rightarrow \) Accident \( \rightarrow \) after \( \text{H}_2 \) release

Permanent effects
- Containment atmosphere pollutants
- Maintenance products

PAR inspection
- Periodic tests
- Regeneration procedure

Incidents
- Fire products
- Earthquakes

Core melt products
- Water-soluble aerosols
- Water-insoluble aerosols
- Gaseous fission products
- Cladding materials and consecutive reactions

Others
- Condensate
- Fire products
- Thermal loads
- Combustion/explosion
- Radioactive irradiation
- Adverse flow conditions

Core melt products
- Water-soluble aerosols
- Water-insoluble aerosols
- Gaseous fission products
- Cladding materials and consecutive reactions
- Gaseous MCCI products

Others
- Condensate
- Fire products
- Thermal loads
- (Hydrogen) combustion/explosion
- Radioactive irradiation

Potential performance reduction
- MCCI – carbon monoxide \( \rightarrow \) catalyst poisoning
- Iodine species \( \rightarrow \) catalyst poisoning

*) Reinecke, Allelein, Bentaïb et al., “Operating behavior of passive auto-catalytic recombiners under severe accident conditions”, ISAMC, Ottawa (Ontario), Canada, October 15-18, 2018
IMPACT OF CARBON MONOXIDE

Experimental results

Experimental program reveals 3 different regimes

REKO-3 facility
IMPACT OF CARBON MONOXIDE

Experimental results

Experimental program reveals 3 different regimes

(I) Undisturbed parallel H₂ and CO reaction (oxygen-rich)*

\[
\begin{align*}
\text{H}_2 + 0.5 \text{ O}_2 & \rightarrow \text{H}_2\text{O} \\
\text{CO} + 0.5 \text{ O}_2 & \rightarrow \text{CO}_2
\end{align*}
\]

\[
\dot{r}_{CO} = \left( \frac{D_{CO}}{D_{H_2}} \right)^{2/3} \cdot \frac{y_{CO}}{y_{H_2}} \cdot \dot{r}_{H_2}
\]

IMPACT OF CARBON MONOXIDE

Experimental results

Experimental program reveals 3 different regimes

(I) Undisturbed parallel H₂ and CO reaction (oxygen-rich)

(II) Constrained parallel H₂ and CO reaction (oxygen-lean)

\[ y_{O_2,\text{crit}} = \frac{1}{2} \left[ \left( \frac{D_{H_2}}{D_{O_2}} \right)^{2/3} \cdot y_{H_2} + \left( \frac{D_{CO}}{D_{O_2}} \right)^{2/3} \cdot y_{CO} \right] \]
IMPACT OF CARBON MONOXIDE

Experimental results

Experimental program reveals 3 different regimes

(I) Undisturbed parallel $H_2$ and CO reaction (oxygen-rich)

(II) Constrained parallel $H_2$ and CO reaction (oxygen-lean)

(III) Reaction stop due to catalyst poisoning

$T_{\text{cat,crit}}$
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Experimental results
IMPACT OF CARBON MONOXIDE

Experimental results

- Hydrogen recombination
IMPACT OF CARBON MONOXIDE

Experimental results

- Hydrogen recombination
- CO injection: 3 regimes
  1. Undisturbed parallel $H_2$ and CO reaction (oxygen-rich)
IMPACT OF CARBON MONOXIDE

Experimental results

- Hydrogen recombination
- CO injection: 3 regimes
  
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IMPACT OF CARBON MONOXIDE

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- CO injection: 3 regimes
  I. Undisturbed parallel $\text{H}_2$ and CO reaction (oxygen-rich)
  II. Constrained parallel $\text{H}_2$ and CO reaction (oxygen-lean)
  III. Reaction stop (catalyst poisoning)
IMPACT OF CARBON MONOXIDE

Experimental results

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- CO injection: 3 regimes
  I. Undisturbed parallel $\text{H}_2$ and CO reaction (oxygen-rich)
  II. Constrained parallel $\text{H}_2$ and CO reaction (oxygen-lean)
  III. Reaction stop (catalyst poisoning)
- Catalyst recovery after termination of CO injection
IMPACT OF CARBON MONOXIDE

Accident simulation (COCOSYS with enhanced REKO-DIREKT model)

- Calculation based on SARNET-2 Generic Containment Benchmark
  - LP code-to-code comparisons with systematically increasing complexity
  - Plant based on German 1300 MW_el PWR (Konvoi-like 4-loop plant with vertical U-tube SGs)
  - SB-LOCA with loss of secondary heat sink and breakdown of all active safety supply systems
  - Simplified 17-zone nodalization
  - Implementation of 57 Areva-type PARs

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 h</td>
<td>Break and blow-down</td>
<td></td>
</tr>
<tr>
<td>0.5 h</td>
<td>Begin of core heat-up and degradation</td>
<td></td>
</tr>
<tr>
<td>0.8 h</td>
<td>Injection of hot leg accumulators</td>
<td>In-Vessel</td>
</tr>
<tr>
<td>3.1 h</td>
<td>Lower plenum core melt relocation</td>
<td></td>
</tr>
<tr>
<td>3.4 h</td>
<td>RPV failure and melt relocation to the cavity</td>
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<tr>
<td>&gt;3.4 h</td>
<td>Molten Corium Concrete Interaction (MCCI)</td>
<td>Ex-Vessel</td>
</tr>
<tr>
<td>13.0 h</td>
<td>End of simulated transient</td>
<td></td>
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</table>
IMPACT OF CARBON MONOXIDE

Accident simulation (COCOSYS with enhanced REKO-DIREKT model)

Zone R-DOME: 43,000 m³ free volume
IMPACT OF CARBON MONOXIDE

Accident simulation (COCOSYS with enhanced REKO-DIREKT model)

- Enhanced PAR model
- PAR poisoning @ 6.8 h
IMPACT OF CARBON MONOXIDE

Accident simulation (COCOSYS with enhanced REKO-DIREKT model)

- Enhanced PAR model
- PAR poisoning @ 6.8 h

<table>
<thead>
<tr>
<th>Location</th>
<th>t_pois</th>
<th>H₂</th>
<th>CO</th>
<th>O₂</th>
<th>Steam</th>
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<tbody>
<tr>
<td></td>
<td>h</td>
<td>vol.%</td>
<td>vol.%</td>
<td>vol.%</td>
<td>vol.%</td>
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<tr>
<td>R-SUMP</td>
<td>7,0</td>
<td>2,56</td>
<td>0,47</td>
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<tr>
<td>R-SG12</td>
<td>6,8</td>
<td>2,63</td>
<td>0,46</td>
<td>2,69</td>
<td>73</td>
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<tr>
<td>R-SG34</td>
<td>8,0</td>
<td>3,69</td>
<td>0,69</td>
<td>2,77</td>
<td>71</td>
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<tr>
<td>R-DOME</td>
<td>7,0</td>
<td>2,63</td>
<td>0,47</td>
<td>2,67</td>
<td>73</td>
</tr>
<tr>
<td>R-ANN12</td>
<td></td>
<td></td>
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<td></td>
<td>no poisoning</td>
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<tr>
<td>R-ANN34</td>
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<td>no poisoning</td>
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<tr>
<td>R-DUCT</td>
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<td></td>
<td></td>
<td></td>
<td>no poisoning</td>
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</tbody>
</table>
IMPACT OF CARBON MONOXIDE

Accident simulation (COCOSYS with enhanced REKO-DIREKT model)

- Enhanced PAR model
  - PAR poisoning @ 6.8 h
  - H$_2$ concentration: 8.5 (4.5) vol.%
IMPACT OF CARBON MONOXIDE

Accident simulation (COCOSYS with enhanced REKO-DIREKT model)

- Enhanced PAR model
  - PAR poisoning @ 6.8 h
  - H$_2$ concentration: 8.5 (4.5) vol.%
  - CO concentration: 1.6 (1.0) vol.%
IMPACT OF CARBON MONOXIDE

Accident simulation (COCOSYS with enhanced REKO-DIREKT model)

- Enhanced PAR model
  - PAR poisoning @ 6.8 h
  - $H_2$ concentration: 8.5 (4.5) vol.%
  - CO concentration: 1.6 (1.0) vol.%
  - $O_2$ concentration: 3.0 (0.5) vol.%
SUMMARY

Effect of PAR Deactivation by Carbon Monoxide in the Late Phase of a Severe Accident

• Objective: Realistic simulation of PAR operation under severe accident conditions
• Carbon monoxide interacts with PAR in three regimes
  (I) Undisturbed parallel H₂ and CO reaction (oxygen-rich)
  (II) Constrained parallel H₂ and CO reaction (oxygen-lean)
  (III) Reaction stop due to catalyst poisoning
• Generic Containment simulation: PAR poisoning after 6.8 h
  ➔ Unmitigated hydrogen and carbon monoxide releases
  ➔ After steam condensation (e.g. FCVS), possibility of flammable mixtures

➔ Implemented PAR models cannot predict PAR poisoning!
OUTLOOK
Towards the improvement of hydrogen and carbon monoxide explosion risk assessment models and safety management procedures

~ 25 partners from Europe, Canada, Japan, Korea, China
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THANK YOU FOR YOUR KIND ATTENTION!