SFP LOCA Analysis with MELCOR

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EU DuC=N

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Outline

- Introduction
  - NRG applications of MELCOR
- NUGENIA+ AIR-SFP
- Results of the Calculations
  - SFP Loss of Cooling Accident
  - SFP LOCA
- Modelling Issues
  - SFP reactor type
  - Zircaloy Oxidation
- Conclusions
Introduction

Uses of MELCOR @ NRG:

- **Post-Fukushima SFP analyses**
  - Spent Fuel Pool analyses in MELCOR (and other codes) in order to assess the coolability after a SFP LOCA scenario

- **Severe accident analysis for KERENA**
  - (Part of) PSA Level 2 analysis
  - Safety analyses for shutdown and power scenarios

- **HFR calculations for license renewal**
  - Severe accident analyses
  - PSA Level 2 analysis

- **Severe accident analyses for the KCB power plant**
  - Safety analysis calculations

- **KCB power plant desktop simulator**
  - Development of an interactive simulator of the Borssele NPP
  - Dutch regulator personnel training

- **GKN Dodewaard Power Plant**
  - PSA Level 2 analysis
  - Direct containment heating analysis (comparison of MELCOR vs CONTAIN)
Introduction

Desktop simulator

- TH codes: MELCOR, RELAP, MAAP and SPECTRA (NRG code)
- Visor: NRG visualization software compatible with the most widespread TH and SA codes
AIR-SFP: Description

- Analysis of severe accidents of SFP
- The SFP model is derived mainly from the Fukushima-Daiichi Unit 4 SFP
- Two scenarios are considered:
  - SFP Loss of Cooling Accident
  - SFP LOCA
AIR-SFP: Model

- **SFP**: 1 fuel & 1 bypass channel per ring + downcomer and pool top
- **CORE**: 3 rings × 13 axial levels (8 for active fuel)
- One radioisotope inventory representative of the hottest FAs
Sequence of events of the Scenario 1

Rack base plate failure occurs in all three radial rings

- The fuel in the ring 3 does not produce power (fresh fuel)
- Power is radiated from neighbor ring 2

<table>
<thead>
<tr>
<th>Event</th>
<th>Time [s]</th>
<th>Time [days]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap release in rod group 1</td>
<td>1,275,350</td>
<td>14.8</td>
<td></td>
</tr>
<tr>
<td>Gap release in rod group 2</td>
<td>1,378,310</td>
<td>16.0</td>
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<tr>
<td>Gap release in rod group 3</td>
<td>1,396,770</td>
<td>16.2</td>
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</tr>
<tr>
<td>Core support structure has failed in cell ia= 2 ir= 1</td>
<td>1,443,720</td>
<td>16.7</td>
<td>Failure was by yielding at axial level 2 and radial ring 1</td>
</tr>
<tr>
<td>The lower head in segment 1 of ring 1 has failed from creep rupture</td>
<td>1,455,220</td>
<td>16.8</td>
<td></td>
</tr>
<tr>
<td>Core support structure has failed in cell ia= 2 ir= 2</td>
<td>1,458,230</td>
<td>16.9</td>
<td>Failure was by yielding at axial level 2 and radial ring 2</td>
</tr>
<tr>
<td>The lower head in segment 2 of ring 2 has failed from thru-wall yielding</td>
<td>1,458,230</td>
<td>16.9</td>
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</tr>
<tr>
<td>Core support structure has failed in cell ia= 2 ir= 3</td>
<td>1,472,450</td>
<td>17.0</td>
<td>Failure was by yielding at axial level 2 and radial ring 3</td>
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<tr>
<td>The lower head in segment 3 of ring 3 has failed from thru-wall yielding</td>
<td>1,472,450</td>
<td>17.0</td>
<td></td>
</tr>
<tr>
<td>End of calculation</td>
<td>2,592,000</td>
<td>30.0</td>
<td>Normal termination by end time reached.</td>
</tr>
</tbody>
</table>
SFP Loss of Cooling

- Saturation conditions are reached after about 1 day
- Fuel elements uncovery starts after about 10 days
SFP Loss of Cooling

- Failure of the rack base plate occurs in all three radial rings
- The event is highly dependent on the rack temperature

![Average stress magnitude in the rack base plate](chart)

![Maximum rack base plate temperature](chart)
SFP Loss of Cooling

- Peak fuel temperature are reached as a consequence of oxidation breakaway
- The rate of hydrogen production increases in correspondence of cladding temperature increase
Sequence of events of the Scenario 2
- Rack base plate failure occurs in radial rings 1 and 2 (corresponding to the powered FAs)
- During the LOCA the FAs are almost immediately exposed to air, while in the Scenario 1 they are exposed mainly to steam

<table>
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<th>Event</th>
<th>Time [s]</th>
<th>Time [days]</th>
<th>Remarks</th>
</tr>
</thead>
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<td>Gap release in rod group 1</td>
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<td>The lower head in segment 1 of ring 1 has failed from thru-wall yielding</td>
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<td>Gap release in rod group 2</td>
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<td>End of calculation</td>
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<td>5.00</td>
<td>Normal termination by end time reached.</td>
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</tbody>
</table>
SFP LOCA

- Saturation conditions are reached during the blowdown phase
- Fuel elements uncovery starts after about 2.5 days
SFP LOCA

- Failure of the rack base plate occurs in radial rings 1 and 2 (only powered FAs)
- The event is highly dependent on the rack temperature
SFP LOCA

- Peak fuel temperature are reached as a consequence of oxidation breakaway
- The rate of hydrogen production increases in correspondence of cladding temperature increase
Modelling Issues
SFP Reactor Type

- Rack component model:
  - SFP-BWR: new component type ‘rack’ (mass in COR_KRK, surface in COR_RSA cards)
  - BWR: generic NS SUPPORT component

- Different treatment of the loads on the structures (other differences?)

<table>
<thead>
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<th>SFP-BWR</th>
<th>BWR</th>
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<tr>
<td>(etc.)</td>
<td>(etc.)</td>
</tr>
</tbody>
</table>

EDIT OF CORE COMPONENT MASSES (KG)

(...)

*** LOAD (kg) CARRIED BY SUP-STR = 1.5696E+05
*** STRESS IN SUP-STR = 1.2647E+07

(...)

*** LOAD (kg) CARRIED BY SUP-STR = 1.8738E+05
*** STRESS IN SUP-STR = 1.5098E+07
Modelling Issues
Zircaloy Oxidation

- **MELCOR lifetime of Zircaloy:**
  \[
  \log_{10} \tau = 42.038 - 12.528 \cdot \log_{10} T
  \]

- **Life function for breakaway:**
  \[
  LF = \int_{0}^{t} \frac{t'}{\tau(T)} dt' = 1
  \]
  \[
  t = \sqrt{2\tau}, \quad T = \text{const}
  \]
  - LF is dimensional [s] (?)
  - A test calculation \((T = 963 \text{ K})\) results in \(t \approx 40,000 \text{ s}\) (in agreement with the Figure), while from the formula results \(t \approx 283 \text{ s}\)

- **Suggested modification of User’s Guide (COR_OXB):**
  \[
  LF = \int_{0}^{t} \frac{\text{d}t'}{\tau(T)} = 1
  \]
  \[
  t = \tau, \quad T = \text{const}
  \]
Modelling Issues

Zircaloy Oxidation

- The zircaloy oxidation section (2.5.1) of the COR package reference manual has not been modified since version 1.8.6 (September 2005)

Solid-state diffusion of oxygen through an oxide layer to unoxidized metal is represented by the parabolic rate equation

$$\frac{d(W^2)}{dt} = K(T)$$

(2-162)

For the Zircaloy-O$_2$ reaction, the rate constant is evaluated using constants from Reference [22], which are also implemented in sensitivity coefficient array C1001:

$$K(T) = 50.4 \exp\left(\frac{-14630.0}{T}\right)$$

(2.143)

$$K(T) = C1001(1,/) \exp(-C1001(2,/) / T), T \leq C1001(5,/)$$

$$K(T) = C1001(3,/) \exp(-C1001(4,/) / T), T \geq C1001(6,/)$$

where $l = 1$ for oxidation by H$_2$O and $l = 2$ for oxidation by O$_2$. An interpolated value is used in the temperature range of $C1001(5,/) < T < C1001(6,/)$.  

- For $l = 1$, low temperature range constant coefficient
  - default = 29.6 for $l = 1$, 50.4 for $l = 2$; units = kg$^2$(Zr)/m$^4$–s, equiv = none

- For $l = 2$, low temperature range exponential constant
  - default = 16820.0 for $l = 1$, 14630.0 for $l = 2$; units = K, equiv = none
Modelling Issues
Zircaloy Oxidation

- From MELCOR version 2.1 (build 3166) the default values of the sensitivity coefficients for zircaloy-air oxidation have been changed
- No information is given in the Reference Manual regarding the new correlation!

For the Zircaloy-O₂ reaction, the rate constant is evaluated using constants from Reference [28], which are also implemented in sensitivity coefficient array C1001:

\[
K(T) = 50.4 \exp \left( \frac{14630.0}{T} \right) \quad (2-166)
\]

These coefficients are used to calculate the rate constant for oxidation of Zircaloy by parabolic kinetics. The rate constant \( K(\text{kg}^2/\text{m}^4\text{s}) \) as a function of temperature \( T(\text{K}) \) is calculated by:

\[
K(T) = C1001(1,I)\exp(-C1001(2,I)/T), T \leq C1001(5,I)
\]

\[
K(T) = C1001(3,I)\exp(-C1001(4,I)/T), T \geq C1001(6,I)
\]

where \( I=1 \) for oxidation by H₂O and \( I=2 \) for oxidation by O₂. An interpolated value is used in the temperature range \( C1001(5,I) < T < C1001(6,I) \).

- Low temperature range constant coefficient.
  (default = 29.6 for \( I=1 \); 26.7 for \( I=2 \); units = \( \text{kg}^2(\text{Zr})/\text{m}^4\text{s} \), equiv = none)

- Low temperature range exponential constant.
  (default = 16820.0 for \( I=1 \); 17490.0 for \( I=2 \); units = K, equiv = none)
Modelling Issues
Zircaloy Oxidation

- From MELCOR version 2.1 (build 6840) a new model option for zircaloy oxidation is available (COR_OX)
- No description is given in the Reference Manual regarding the new correlations!

```
PSI Oxidation breakaway model
active H2O Air O2 breakaway
1 0 0 0 0
```

(1) STEAM
Steam oxidation model
  0 - Catchart-Pawel/Urbanic-Heidrick;

(2) AIR
Air Oxidation Model
  0 - Hofmann-Birchley;
OXYGEN
Oxygen oxidation model
  0 - Uetsuka-Hofman;
NOBRK
Breakaway Switch
  0 - enable in steam and air (recommended);

![Graph showing temperature over time for different scenarios](image-url)
Conclusions

- MELCOR has been used to simulate severe accidents evolution of a generic SFP within the framework of the NUGENIA+ project
- SFP applications of MELCOR lack of full validation (SNL analysis on Fukushima SFP4 only covers the boil-off phase)
- The MELCOR 2.1 reactor types SFP-BWR and SFP-PWR includes a few enhancements towards SFP modelling application:
  - The new rack component is not considered in the load calculation of the support plate, which is consistent for SFP applications
  - There are not evidences that the rack component and the standard NS structures are treated differently in the COR package
- Some deficiencies/inconsistencies in the MELCOR 2.1 Reference and User’s Guide manuals have been found in regards of the zircaloy oxidation model
  - In MELCOR version from (at least) 2.1.3166 the coefficients of the oxidized metal rate correlation are different between the Reference Manual and User’s Guide
  - In MELCOR version 2.1.6843 the PSI oxidation model has been introduced but no information is given about the correlations adopted by the code
Thank you for your attention! Questions?