Sensitivity studies of main uncertain core degradation parameters on severe accident consequences

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Contents

- Study approach - Uncertain parameters
- Impacts on hydrogen production
- Impacts on the Fission Product release
- Impacts on the corium composition
- Conclusions
Study approach

Initial and boundary conditions results of CATHARE code

8 uncertain core degradation parameters

Calculations with ICARE2 code

FP release variability

H2 production variability

Parameters leading mini and maxi consequences

Calculations with ASTEC V1 code

FP release/transport variability

Corium composition variability
Study approach - Uncertain parameters

Choice of 8 parameters distributed in terms of the limits of their range of uncertainties

Analysis of test results
Analysis of accidental transient results
Expert advices

1. Residual power during the transient
2. Oxidation kinetics of Zircaloy cladding
3. Protective effect of the zirconia layer
4. Dissolution limit of the fuel and oxidized cladding by liquid Zircaloy
5. Oxidation of U-O-Zr mixture
6. Criteria concerning the loss of oxidized cladding integrity
7. Fuel velocity of materials during relocation
8. Fuel and cladding relocation (function: solidus and liquidus temperatures)
<table>
<thead>
<tr>
<th>Possible options</th>
<th>1- Standard case</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual power</td>
<td>of values versus time given by a specific table</td>
<td>Computed by code ((f=) FP release)</td>
<td></td>
</tr>
<tr>
<td>Oxidation kinetics</td>
<td>Urbanick-Heidrick correlation with zirconia layer growth</td>
<td>Prater-Courthright correlation</td>
<td>Previous correlation with O2 mass gain</td>
</tr>
<tr>
<td>Zirconia layer protection effect</td>
<td>NO</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>Solubility limit of uranium in U-Zr-O</td>
<td>Liquidus (T^\circ)</td>
<td>Solidus (T^\circ)</td>
<td></td>
</tr>
<tr>
<td>Oxidation mixture</td>
<td>NO</td>
<td>YES</td>
<td></td>
</tr>
<tr>
<td>Cladding oxide shell criteria</td>
<td>(T &gt; 2260 \text{ K} \text{ and } e_{\text{ZrO}<em>2} &lt; 160 \mu\text{m}) or (T &gt; 2280 \text{ K} \text{ and } e</em>{\text{ZrO}<em>2} &lt; 200 \mu\text{m}) or (T &gt; 2340 \text{ K} \text{ and } e</em>{\text{ZrO}<em>2} &lt; 220 \mu\text{m}) or (T &gt; 2380 \text{ K} \text{ and } e</em>{\text{ZrO}<em>2} &lt; 240 \mu\text{m}) or (T &gt; 2450 \text{ K} \text{ and } e</em>{\text{ZrO}_2} &lt; 300 \mu\text{m})</td>
<td>(T_{\text{clad}} &gt; 2600 \text{ K} \text{ if } e_{\text{ZrO}<em>2} &lt; 250 \mu\text{m} \text{ or } T</em>{\text{clad}} &gt; 2700 \text{ K})</td>
<td></td>
</tr>
<tr>
<td>Candling velocity</td>
<td>1 cm/s</td>
<td>60 cm/s</td>
<td></td>
</tr>
<tr>
<td>UO2, ZrO2 relocation (T^\circ)</td>
<td>(T_{\text{solidus}} = 2550 \text{ K}) (T_{\text{liquidus}} = 2650 \text{ K})</td>
<td>(T_{\text{solidus}} = 2800 \text{ K}) (T_{\text{liquidus}} = 2850 \text{ K})</td>
<td></td>
</tr>
</tbody>
</table>
Study approach - Uncertain parameters

Variability of oxidation kinetics correlation

Solubility limit of uranium in the (U,Zr,O) mixture for the UO2/liquid zircaloy interaction

Parabolic models for Zr Oxidation

U/(U+Zr) wt% ratio

Solidus

Liquidus

U/(U+Zr) DISSOLUTION LIMIT IN PRECIPITATION PERIOD
Initially oxygen-free Zircaloy-4

ICARE2
V3-M00.4
Study approach - Transient description

Chronology of events (approximative times):

- \( t=0 \): loss of all SG feed-water systems
- \( t\approx30 \text{ s} \): scram reached as SG level \(<-0.7 \text{m} \)
- \( t\approx2500 \text{ s} \): fully opening of all PORVs
- \( t\approx3800 \text{ s} \): beginning of cladding oxidation, first core uncovery
- 200s later: start of accumulators discharge
- \( t\approx7900 \text{ s} \): accumulators isolation
- \( t\approx8500 \text{ s} \): final core uncovery, core heating and second phase of cladding oxidation

**REP 900 Calculation**

Primary circuit pressure evolution and core water level
Impacts on hydrogen production

- Two oxidation phases

- First phase: impact of dissolution limit on H₂ production; factor 2 (total mass equivalent)

- Minimum H₂ = 320 kg: U-O-Zr mixture relocation velocity = 60 cm/s

- Maximum H₂ = 580 kg: mixture oxidation and oxidation kinetics limited by the gain in O₂ mass

- Impact also on H₂ production kinetics: 0.1 to 0.4 kg/s
Impacts on hydrogen production

- ASTEC and ICARE2 calculations with very similar modelling option conduct to different kinetics and ≈ equivalent total mass

- Start of cladding oxidation ≈ same time

- When accumulators begging to discharge, water level of ICARE2 is ≈30 cm upper

- During accumulators discharge water level remains constant with ICARE2 and continuous to decrease with ASTEC V1

ATtec calculates cladding oxidation of upper part of the core during accumulators discharge

ASTEC–ICARE2 H2 Sequence Calculation
Base case, comparison between the codes
Impacts on hydrogen production

Variability of hydrogen production kinetics and total mass obtained in the calculations of different accidental transients is in the same range.

Kinetics varies from 0.02 and 0.22 kg/s (mean flow rate).

Mass varies from 100 to 800 kg.
Impacts on fission product release

- Modification of ICARE2 to allow semi-volatile fission product release when the fuel is liquefied
- Fission product release is strongly correlated to the quantity of fuel liquefied
- Dissolution up to the solidus temperature lead to increase:
  1. Semi-volatile fission product release by a factor of 3 (Barium and Molybdenum)
  2. Volatile fission product release by a factor of 1.5 (Iodine and caesium)
Impacts on fission product releases

- Maximum fission product release (80%) is obtained with the same values of parameters that maximum $H_2$:
  - mixture oxidation
  - oxidation kinetics limited by the gain in $O_2$ mass

- Main ASTEC calculations results:
  - Mo combines with Cs and Rb
  - less important quantities to combine with I
  - I combines with other compounds to form organic iodine and gaseous caesium iodine
Impacts on the corium composition

- Great variability of corium composition: proportion between the oxide and metallic phases can vary by a factor of 3

- Composition mainly results from the oxidation rate of core materials and the quantity of fuel dissolved by liquid Zircaloy:
  - Low oxidation rate: large mass relocation of metallic materials before UO$_2$ and ZrO$_2$ relocation
  - Important fuel dissolution (threshold temperature equal to solidus temperature): large mass of UO$_2$ is relocated to the lower plenum and conducts to reduce metallic materials fraction.
Impact on the corium composition

Dissolution threshold temperature impacts on corium composition: solidus temperature conducts to important UO₂ dissolution and a decrease of metallic materials fraction.
Conclusions

- **Impacts of main uncertain core degradation parameters**
  - Almost a factor of 2 on mass $H_2$ produced
  - A factor of 4 on $H_2$ flow rate
  - Fission product release is strongly correlated to fuel liquefied quantity
  - A factor of 3 on semi-volatile fission product release
  - A factor of 1.5 on volatile fission product release
  - Variation of the iodine gaseous release and of caesium airborne from the primary circuit break
  - Metallic materials fraction can vary from a factor 3

- **The most influential uncertain parameters**:
  - U-Zr-O mixture oxidation
  - Dissolution limit of fuel and oxidized cladding