Reflooding of a degraded core:
Modeling and experimental needs

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Objectives - Safety Issues

1. Quantify the risks associated with reflooding
2. Optimize the strategy of water injection
3. Estimate the conditions of corium relocation into the lower plenum and the consequences for the subsequent steps of the accident

State of the core:

- Intact or slightly damaged rods
- Relocated melt along the rods
- Collapsed debris
- Molten pool in the core
- Molten pool in the lower plenum

Need for a realistic and non conservative approach

⇒ Improve the accuracy of safety assessments
Status of knowledge - Experimental data

Synthesis made by FZK (Hering & Hommann, 2004), based on QUENCH data and earlier results.

Lack of data for more damaged states: debris, molten pool.
Modeling in 3 steps

1. Characterize the geometry of the core

2. Understand the physics at the local scale

3. Derive models for flow and heat transfers at the reactor scale
Description et characterization of the damaged core
An evolutive porous medium (1)

Relocated melt between rods

(Tomographies of PHEBUS-FPT1 bundle)
An evolutive porous medium(2)

Dissolution and fragmentation of pellets

(Tomographies of PHEBUS-FPT1 bundle)
Variations of the average particle size

\[ l_p = 4.4 \frac{(1 - \varepsilon)}{A_v} \]
Variations of the surface density
Impact of reflooding on the damaged rods

What happens when water is injected?

The collapse of rods is likely to occur at 2000K (ISTC 1648 results)
Experimental observations

Analysis of PBF-SFD 1.4 et LOFT LP-FP2

- Bottom of core: Quasi-intact rods, with a reduced flow section because of relocated melt.

- Top of core: high temperature rods which are partly dissolved which have collapsed and formed debris. Observations indicate a limited compaction and the size of particles ranges from 1 to 5mm, corresponding to the « natural » fragmentation.

- Existence of a « dense » zone at the bottom of the debris bed resulting from the accumulation of relocated melt.
## Synthesis

### Schematic evolution of a fuel rod

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1700K</td>
<td>No rupture</td>
</tr>
<tr>
<td>2000K</td>
<td>Rupture under reloading (cf. PBF-LOC et ISTC 1648.2)</td>
</tr>
<tr>
<td>2100K</td>
<td>Natural fragmentation</td>
</tr>
<tr>
<td>2300-2500K</td>
<td>Rupture before reflooding, Liquid Zr relocation</td>
</tr>
<tr>
<td>2800K</td>
<td>Total melting</td>
</tr>
</tbody>
</table>

The various configurations may be classified

Lack of experimental data to better characterize the debris bed and the criteria for fuel rod collapse
Two-phase flow in a damaged core

Multi-dimensional effects
Upscaling and main assumptions

1. The medium, not homogeneous at a small scale, is represented by an continuous medium.

2. The small scale geometry is taken into account through effective transport properties

3. Thermal non equilibrium between the fluid and the debris

4. Two velocities: gas and liquid
A debris bed is assumed to have formed in the «hot part of the core. It is surrounded by non-damaged rods.
ICARE/CATHARE V2.0 - Debris Bed Reflooding

radial velocity field in the vessel (m/s)
2D Debris Bed Reflooding (1): lower plenum

Initial temperature field

Water injection
2D Debris Bed (2) : Void Fraction Evolution
2D Debris Bed (3) : Temperature evolution
It is possible to « cool » the debris bed, even after dry-out:
A stable temperature is reached.
2D Dry-out « cooling » (2)

<table>
<thead>
<tr>
<th>No cooling</th>
<th>Dry-out cooling</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000</td>
</tr>
<tr>
<td>600</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td></td>
</tr>
<tr>
<td>900</td>
<td></td>
</tr>
</tbody>
</table>

Debris Temperature
Center of the bed
Conclusions from SARNET WP 11.1

1. SARNET - WP 11.1: Core and Debris coolability during reflooding
   Sub-topic coordinator: M. Burger (IKE)

   - Participants: IKE (DEBRIS, WABE), KTH (POMECO + DEFOR), VTT (STYX)
     and IRSN (ICARE/CATHARE)

   - Model validation based on simple configurations (homogeneous medium,
     low temperatures, 1D, non prototypic materials)

   - Agreement on the importance of multidimensional models to improve the
     accuracy of code predictions for safety studies (multi-dimensional effects
     are likely to increase the chances of successful quenching)
Impact of oxidation (1)

ICARE/CATHARE V2.0 - Debris Bed Reflooding
Steam Temperature

No oxidation → Oxidation → melting of Zr

Initial composition: UO2-80% + Zr-13% + ZrO2-7%
Initial temperature: 1273K
Impact of oxidation (2)

The oxidation front is located downstream of the quench front.

No kinetics data for the oxidation of melts.
General Conclusions

1. The geometry of a damaged core can be characterized as well as the conditions of debris formation, although not very accurately with the existing data.

2. Multi-dimensional models for reflooding are available (WABE, ICARE/CATHARE, ...) but they have been mainly validated with 1D experiments and at low temperatures.

3. Oxidation may have a significant impact to prevent a complete reflooding and lead to the formation of a local molten pool. But hardly any experimental data are available.
Project proposal for FP7: In-Vessel coolability

- Reflooding of a damaged core (FZK, IRSN and IKE experiments)
- Corium progression and molten pool formation in case of unsuccessful quenching (LIVE-3). This is also related to the objectives of the OECD CORTRAN project, with real materials
- Reflooding of a debris bed in lower plenum (KTH, IKE)
- Melt retention: external cooling (LIVE-2 and maybe CEA)
- More analytical studies on debris bed characterization (KTH)
- Numerical studies of 2D effects (IKE and IRSN)

In parallel, definition of typical accident scenarios for which the code predictions (in case of reflooding) may vary over a wide range
- Selection of important physical parameters
- Development of models, in particular for ASTEC
IRSN experimental project: PEARL

- Study the effects of multidimensional flow on the quenching of a non homogeneous debris bed
- Provide experimental data to validate models

60 cm