QUENCH-14, QUENCH-16 and QUENCH-ALISA analysis with RELAP5/SCDAPSIM MOD3.5(KIT) and MOD3.5+(KIT)

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Special thanks to: dr Martin Steinbrück, dr Chris Allison
Outline

1. Introduction: title, outline, overview.
2. QUENCH-14 analysis with RELAP5/SCDAPSIM MOD3.5, and MOD3.5+ both using M5+ oxidation rate.
3. QUENCH-16 analysis with MOD3.5.
4. Pre-test calculations for QUENCH-ALISA with MOD3.5, and MOD3.5+
5. Post-test calculations for QUENCH-18 / QUENCH-ALISA in MOD3.5+
6. Summary and conclusions.
8. References.
9. The end.
Overview

- KIT’s QUENCH – experiments, using electrically heated simulator rods, and investigating the behavior of materials, for example cladding or absorber, under accidental conditions;
- QUENCH focuses on oxidation, hydrogen production, melting, coolability;
- QUENCH-14 and QUENCH-ALISA / 18 – both have M5® cladding;
- QUENCH-16 and QUENCH-ALISA – both are air ingress tests.
QUENCH-14 with M5*

Fig. QUENCH-14 test bundle. [1]

QUENCH-14 used M5. In the analysis we use M5 oxidation rates (according to [2]) instead of standard MATPRO Zircaloy oxidation rates.

Fig. QUENCH-14 nodalisation in RELAP5/SCDAPSIM.
Temperatures at elevation 850 mm in Q-14 experiment and from calculations in RELAP5/SCDAPSIM

- Experiment, centerline of central rod, 850 mm
- SCDAP 35, Centerline central rod 850 mm
- SCDAP 35+, Centerline central rod 850 mm
Total hydrogen production [g] in QUENCH-14

- **Hydrogen integral, SCDAP 35, Zry**
- **Hydrogen integral, SCDAP 35+, M5**
- **Hydrogen integral production, Experiment**
In this experiment there was a significant shroud melt at elevations between ~500 and ~700 mm. The shroud failure lead to water leakage in an amount of 7264 g, found post test in the ZrO₂ fiber [3].

Fig. QUENCH-16 bundle cross sections at 530 mm, 550 mm, 630 mm and 650 mm. [3]

Fig. 3D QUENCH-16 model representation. The shroud failure, with water leaking from the bundle, is simulated using valves and a pipe of a volume equal to the volume available in the ZrO₂ fiber. Please note that sources and sinks are not drawn here.

Fig. QUENCH-16 bundle withdrawn from cooling jacket. [3]
QUENCH-16 with MOD3.5, total hydrogen production

The experiment, over 140 g

The simulation, over 85 g
ALISA: pre-test

In case of QUENCH-ALISA pre-test calculations we did not assume leakage from the shroud, thus the used physical model was simpler, compared to QUENCH-16.

The boundary conditions according to the Pre-test simulations of QUENCH-ALISA in the frame of the NUGENIA QUESA project [6] presentation from 4th NUGENIA-SARNET TA2.1 Review Meeting.

Fig. QUENCH-ALISA bundle composition. [5]

Fig. QUENCH-ALISA model cross-section.

Fig. 3D QUENCH-ALISA model, without sources and sinks.
Pre-test ALISA temperatures at 700 mm in MOD3.5. (model 1) and MOD3.5+ (model 2)
From [6] pre-test calculations:

<table>
<thead>
<tr>
<th></th>
<th>ATHLET-CD</th>
<th>MAAPS</th>
<th>SCDAPSim (JB)</th>
<th>RELAP/SCDAPSIM (LEI)</th>
<th>SOCRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total H$_2$ generation (g)</td>
<td>end of preoxidation</td>
<td>11.0 g</td>
<td>10.7 g</td>
<td>14.9 g</td>
<td>6.8 g</td>
</tr>
<tr>
<td></td>
<td>end of reflood</td>
<td>28.2 g</td>
<td>23.5 g</td>
<td>17.9 g</td>
<td>11.8 g</td>
</tr>
</tbody>
</table>

Pre-test ALISA in MOD3.5 (model 1) and MOD3.5+ (model 2) - total hydrogen production
ALISA: post-test in MOD3.5+

The physical model remains the same, the timeline changes.

The new timeline:

- instead of 7300 s, at 7542 s into the experiment the steam flow is set to 0.3 g/s and argon flow to 1.0 g/s;
- at 7542 s the air flows at 0.2 g/s rate, and thus the air ingress phase begins;
- at 12030 s the quench begins, instead of 11341 s - QUENCH-16 case;
- 12180 s is the end of the quenching phase;
- 12300 s is the end of simulation.
Post-test ALISA in MOD3.5+ at 700 mm, model 1: \( W(1)=0 \), model 2: \( W(1)=1 \) and M5*
Post-test ALISA in MOD3.5+, model 1: $W(1)=0$, model 2: $W(1)=1$ and M5*

**Model 1:** $W(1)=0$ at card 40000170.

**Model 2:** $W(1)=1$ at card 40000170 and M5 oxidation rate instead of Zircaloy’s oxidation rate.
Model 1: $W(1)=0$ at card 40000170.

Model 2: $W(1)=1$ at card 40000170 and M5 oxidation rate instead of Zircaloy’s oxidation rate.
Summary

- QUENCH-14 simulation results are satisfying. However, it has been the least challenging experiment to model. The M5* oxidation rate in MOD3.5, gives similar peak value of hydrogen generation rate to the experimental value.

- QUENCH-16 is an experiment difficult to model, due to several phenomena. Concerning hydrogen production, the air ingress contributed into 5 g produced in re-oxidation of nitrides in claddings and 2 g in shroud; oxidation of melt has given 19 g of H₂ from claddings and 14 g from shroud. Total contribution of claddings in hydrogen production during reflood was 81 g [3], in our simulation we have obtained about 85 g.

- The pre-test calculations for QUENCH-ALISA were until 8700s very similar to those presented as “JB_SCDAPSIM” in [6]. In our simulation we did not have a temperature escalation during air ingress as in [6]. On the other hand our quench phase has been more pronounced.

- In the post-test calculations for QUENCH-ALISA we have analyzed different oxidation models available in RELAP5/SCDAPSIM. We have used M5* in model 2. The difference between models 1 and 2 is evident. In model 1 quench phase with fast temperature increase may be observed. In model 2 there is a temperature increase in air ingress. The total hydrogen production is bigger for model 1, for model 2 it is about 10 g smaller.

Fig. Photo taken yesterday (17.10.2017) at the Quench Workshop; Presentation by dr Juri Stuckert

Fig. Our post-test QUENCH-ALISA results with model 2.
Conclusions

❖ RELAP5/SCDAPSIM model for electrically heated rod is a good tool to model QUENCH experiments. At the very beginning, we have compared the results between simulations using resistance calculated by the code and from the table, and those results were almost identical.

❖ RELAP5/SCDAPSIM has given very good results for QUENCH-14. In case of air ingress tests: QUENCH-16 and QUENCH-ALISA, the complex reactions between nitrogen and Zircaloy need be introduced to the code, and for that reason nitrogen should be separated from air.

❖ The chemical reaction of Zircaloy with nitrogen, as described in [8], is an exothermic reaction, where $\Delta h$ is about $4.056 \times 10^6$ J/kg$_{Zr}$. This value translates into such an example: if 6.79% of Zr present in QUENCH-16 bundle reacted with $N_2$, then the power difference between QUENCH-16 and QUENCH-14, since 8000 s till the quench, would be compensated.
Conclusions

❖ There is a need for a quantification of nitride formation during air ingress and energy release due to that process.

❖ In QUENCH-16 simulation we did not obtain the temperature measured in the experiment on the shroud. Our shroud (Zircaloy) did not melt, thus its contribution to the hydrogen production was smaller. Concerning hydrogen production from claddings, our result (85g) is very close to the one mentioned in the report (81g) [3].

❖ Modelling of QUENCH-18 seems less challenging than QUENCH-16, considering the quenching phase. It may be a result of steam being injected together with air in air ingress phase in ALISA.

❖ QUENCH-ALISA post-test and pre-test differ notably, due to different timeline. In post-test calculations we managed to apply M5* oxidation rate (model 2). Temperatures from model 2 reach higher values in air ingress phase than those from model 1.

Fig. Chemical interactions and formation of liquid phases in a LWR fuel rod bundle with increasing temperature. [7]
Future plans

Applying all the phenomena observed in QUENCH-16 to RELAP5/SCDAPSIM:

❖ nitridation;
❖ re-oxidation of the nitrides;
❖ melt oxidation.
References:


References:


[8] C. Bals, T. Hollands, New Results of Post-test Calculation of Quench-16 with ATHLET-CD, June 14, 2016, Budapest
Thank You for Your attention.