RELAP/SCDAPSIM/MOD 3.5. ANALYSYS OF KIT'S QUENCH-14 EXPERIMENT

O. DUTKIEWICZ,
K.M. MARCINKIEWICZ
Warsaw University of Technology, Insitute of Heat Engineering,
Nowowiejska 21/25, 00-635, Poland

S. SHUMSKI,
UPC Polytechnic University of Catalonia
Calle Jordi Girona, 1-3, 08-034, Spain

C.M. ALLISON,
J.K. HOKORST
Innovative Systems Software
3585 Briar Creek Ln, 83-406, US

ABSTRACT

The QUENCH-14 experiment was performed within the ACM series (Advanced Cladding Materials) performed by "Karlsrühe Institute of Technology" (KIT), Germany, to investigate the performance of M5® cladding material. During the experiment the peak temperatures exceeded 2000K (the maximum temperature was estimated at 2249K), therefore a local melting of the cladding occurred. The experiment was terminated by reduction in the electrical power followed by water injection from the bottom of the test bundle. There was no breakaway oxidation nor melt relocation. The test conditions used in the QUENCH-14 were comparable to the QUENCH-6 experiment that used Zircaloy-4. Simulations presented in the article were performed with MATPRO Zircaloy-4 properties and both QUENCH-6 and QUENCH-14 experimental conditions.

1. Introduction

1.1 The RELAP/SCDAPSIM/MOD.3.5 code

The RELAP/SCDAPSIM code, designed to predict the behaviour of reactor systems both during normal and accident conditions, is being developed by Innovative Systems Software (ISS) as part of the international SCDAP Development and Training Program (STDP). RELAP/SCDAPSIM uses the publicly available SCDAP/RELAP5 models and correlations developed by the US Nuclear Regulatory Commission in combination with proprietary features developed by ISS and STDP members, which include more advanced models and correlations. RELAP/SCDAPSIM/MOD3.5 contains improved models for LWRs such as improved SCDAP models and correlations for fuel rods, B4C control rods, and electrically heated fuel simulator rods used in the CORA, QUENCH, and PARAMETER experimental facilities in Germany and Russia. MOD3.5 is currently being assessed using representative, large scale integral experiments performed over the past 40 years with results being released in a series of publicly available papers. This assessment is being performed by selected users, ISS, and university students and faculty members participating in the SDTP University Support program. New versions of MOD3.5 will be released as needed based on the results of the on-going assessment activities.

1.2 QUENCH-14 experiment

The QUENCH-14 experiment was performed within the ACM series (Advanced Cladding Materials) performed by "Karlsrühe Institute of Technology" (KIT) in Germany to investigate the performance of M5® cladding material. M5® is a material developed by AREVA (former FRAMATOME). During the experiment the peak temperatures exceeded 2000 K (the maximum temperature was estimated at 2249 K), therefore a local, but only local, melting of the cladding occurred. The experiment was terminated by reduction in the electrical power followed by water injection from the bottom of the test bundle. There was no breakaway oxidation nor melt relocation. The test conditions used in the QUENCH-14 were comparable to the QUENCH-6 experiment that used Zircaloy-4. From the comparison of the two experiments it was concluded that Zircaloy-4 and M5® cladding show comparable behaviour under similar transient test conditions.

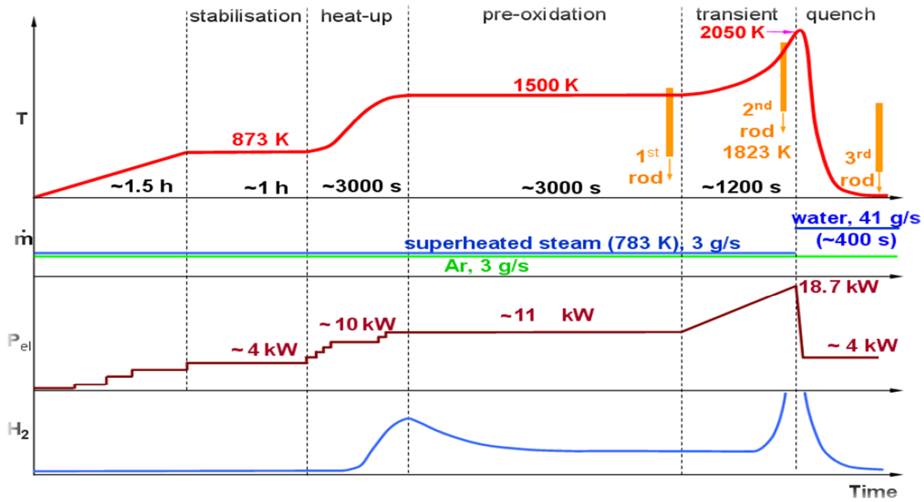

Fig 1. Phases of the QUENCH-14 experiment [1]

Based the experiment several conclusions were made. Measured hydrogen production was equal to 34 g during pre-oxidation and transient phases; 6 g in quench phase. In reference QUENCH-6 experiment has given 32 g and 4 g of hydrogen in corresponding phases [1], [2], [6]. Post experiment examination showed significant cladding inner oxide layers with thickness up to 20% of outer oxide layers [2] and partially oxidized cladding melt [2]. It can be concluded that M5® and Zircaloy-4 claddings showed comparable behaviour during reflood. M5® shows superior oxidation resistance over wide temperature ranges and the lower hydrogen uptake in comparison to Zircaloy-4, while at temperatures above 1650 K Zircaloy reveals lower oxidation rate [1]. The pre-oxidation phase bundle temperature peaked at 1500 K, for duration of 3000 s, at height 950 mm. Maximal oxide thickness was equal to 170 µm (corner rod) [1]. Maximum bundle temperature during transient was equal to 2073 K, with maximal oxide layer thickness of 470 µm (corner rod). Rod failure was observed 15 s before reflood initiation [1]. Shroud failed during reflood and the maximal oxide layer thickness raised up to 630 µm [1]. Post-test investigations showed no breakaway oxidation of M5® cladding nor melt relocation. Some melting occurred at elevations between 900 and 1100 mm. Maximal oxide thickness was equal to 860 µm (at elevation 950 mm) [1]. Internal oxide layers were formed as result of steam penetrating cladding cracks [1]. Three corner rods made of Zry-4 were withdrawn during the course of the experiment to check their oxidation level and analyse how it develops in various stages of the experiment.

1.3 QUENCH-14 simulation with RELAP/SCDAPSIM

The assessment of MOD3.5 for QUENCH-14 is being performed in several phases. The results are being published in a series of publicly available papers including this paper. First, the QUENCH-6 experiment was re-analysed using the latest version of MOD3.5(dp), where (dp) is the configuration control number. This analysis included a careful independent review of the original QUENCH-6 input model that was used to test and validate the improved electrically-heated fuel rod simulator model, the re-analysis of the experiment, with the addition of sensitivity studies, and the publication of the results in a series of publicly available papers. Second, original QUENCH-6 input model was modified to incorporate the QUENCH-14 features and boundary conditions, MOD3.5(dp) was then run using the standard “MATPRO” Zircaloy-4 material properties, and the calculated and measured results were compared. To validate the choice of nodalisation used in the simulation sensitivity study has been conducted. It confirmed that the choice was right and accurate. Also the code did not show relevant dependence on the radial nodalisation changes between 13 and 19 radial nodes. These comparisons shown in this paper include the influence of both the slight changes in test conditions between QUENCH-6 and QUENCH-14 as well as the differences in cladding material.

2. Simulation

2.1 Model

Our model consists mainly of two parts – RELAP5 hydraulic structure and core created in SCDAP. Created model for this simulation based on input developed in KIT by H. Madokoro [7] for QUENCH-6 reference experiment. The updated model has included new heated rods model introduced in RELAP5/SCDAPSIM/MOD 3.5 as well as necessary changes in geometry and boundary conditions. Before updating to QUENCH-14 experiment our new model has been evaluated by comparison with QUENCH-14 [1] report and other various papers analysing this experiment [2], [3], [4]. As seen in Fig 2 the general trends of temperature were well represented and new model is correctly reflecting the bundle behaviour. It is to be noted, that during the experiment some thermocouples failed (i.e. at 950 mm) and during the reflood some thermocouples were flooded, thus showing sudden drops in measured temperatures (i.e. at 1150). Changes in the input model included, but were not limited to: adjusting bypass elevation and collapsed liquid level calculation; also the nodalisation was changed. Of course, we also implemented updated heated rod model.

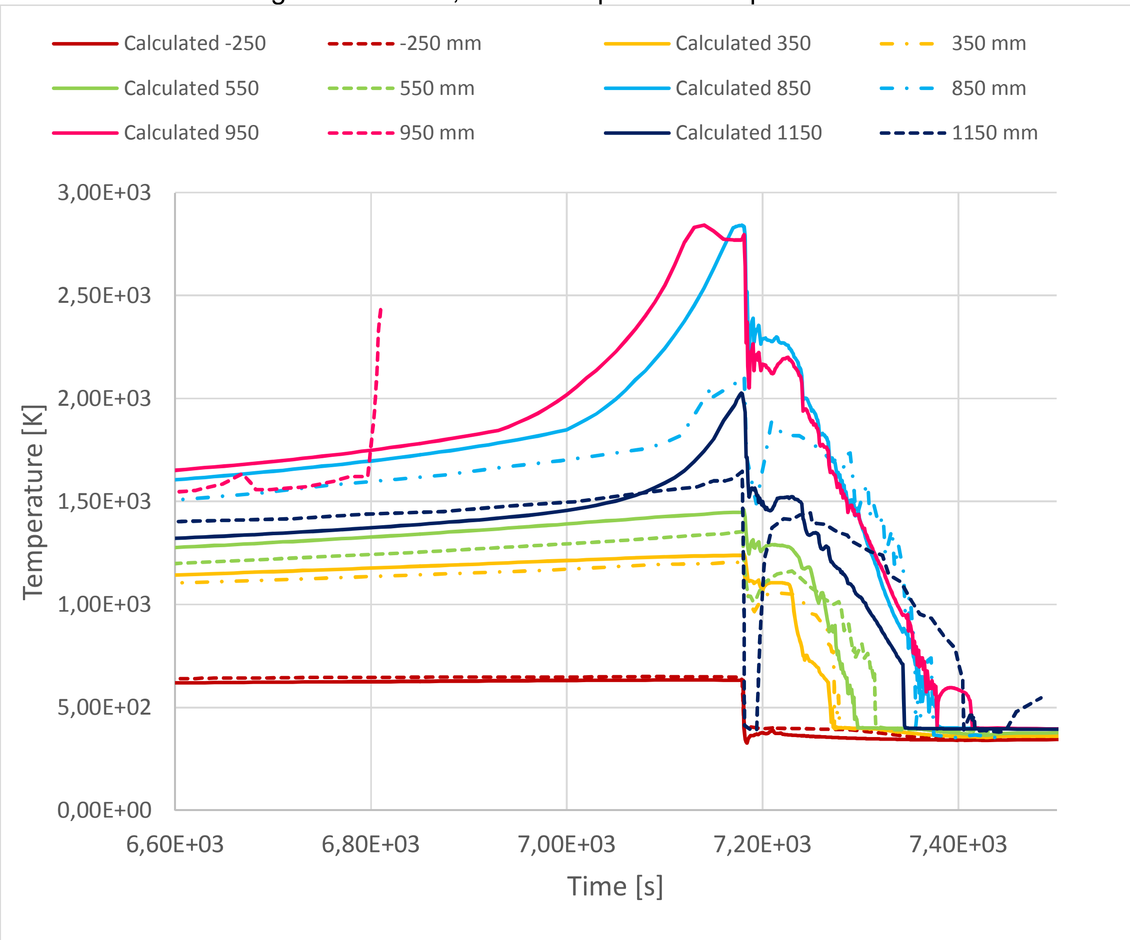

Fig 2. Comparison of experimental and calculated temperatures of inner fuel rod surface temperature. Continuous lines show values calculated in RELAP5/SCDAP, while dashed lines represent measured data in the experiment.

The transition from the QUENCH-6 to QUENCH-14 experiment, considering input model started with changes in the geometry, dimensions and thermohydraulic boundary conditions.

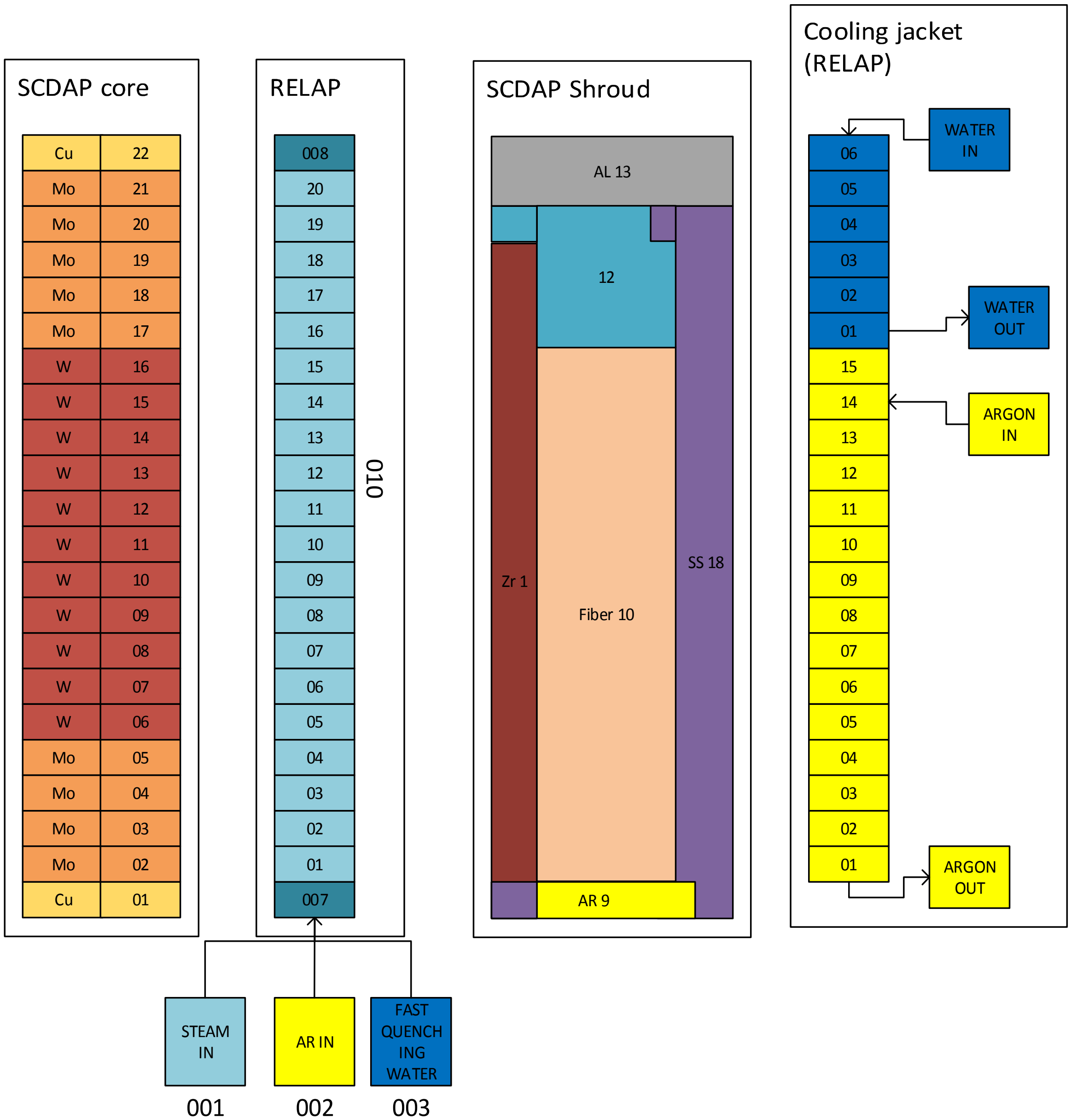

Fig 3. QUENCH-14 test bundle nodalisation for RELAP5/SCDAP simulation

In our model the RELAP5 elevation begins from 0.00 m, what refers to the -0.475 m in the test bundle. SCDAP and RELAP are two separate parts of the model, though the corresponding volumes in both those parts are at the same elevations. In RELAP5 a pipe was created to simulate experimental vessel in which the test bundle was placed. There is one to one correspondence between SCDAP axial odes and RELAP5 volumes, in compliance with the MOD 3.5 manual. At the bottom of the pipe there is a lower plenum, simulated by a branch. It is connected with three time dependant volumes setting boundary conditions. RELAP5 is also used to model the outer cooling jacket. It consists of two parts: one with argon as working fluid and second with water. Those two pipes are connected to sources and sinks setting boundary conditions for proper fluids.

SCDAP model consists of 5 components: unheated central rod, 8 inner rods, 12 outer rods, 4 corner rods and a shroud.

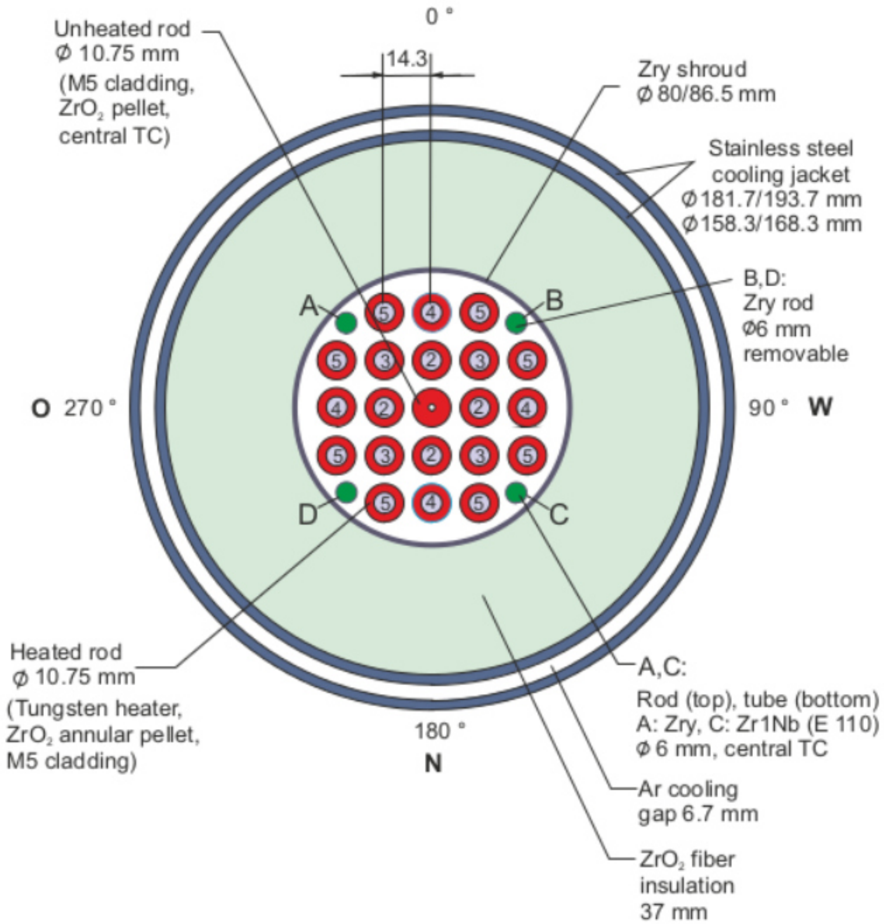

Fig 4. Fuel rod simulation bundle - cross section [1]

The boundary conditions for this experiment are as follows: flow of steam and argon equal to 3 g/s, flow of quenching water is equal to 41 g/s. Our simulation starts at the beginning of heat-up phase. The temperature is rising from the point of 873K. At 3110 s of experiment time pre-oxidation phase occurs. At 6010 s the bundle goes into transient phase to be quenched at 7214 s by initiation of fast water injection. Total available heating power is equal to 70 kW, of which 40% is within inner heated rods and 60% in outer rods. Power history used in the simulation is presented in the Fig **5**.

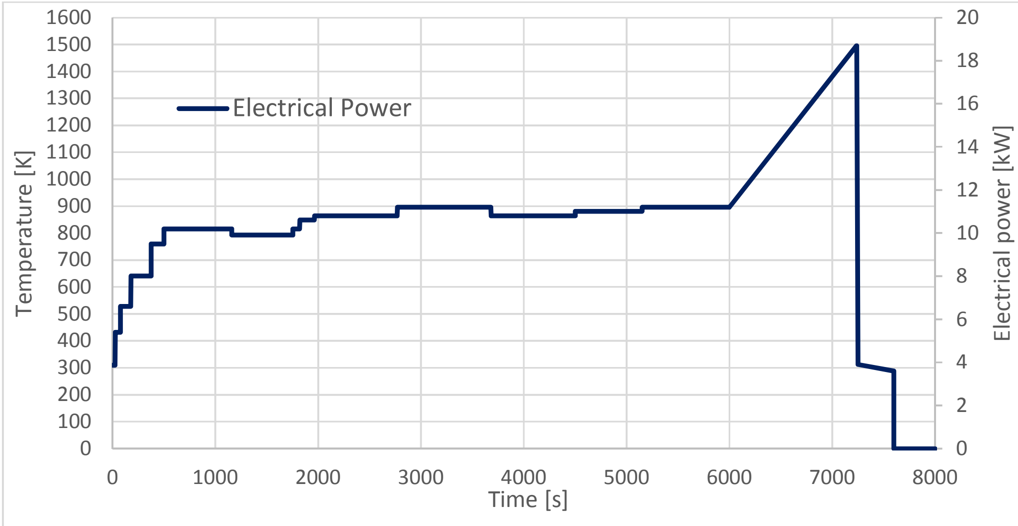

Fig 5. Power history used in the simulation

3. Results of the analysis and comparison with experiment

In general the RELAP5/SCDAPSIM/MOD3.5 has proven itself as a good tool for analysis of such problems. It should be noted that following convention has been assumed for next graphs: dashed curves represent data derived from the KIT report [1], while continuous lines represent data calculated by the code.

There is good agreement between results obtained in the simulation and the experiment, especially the axial temperature profiles were impressively similar as in Fig 6.

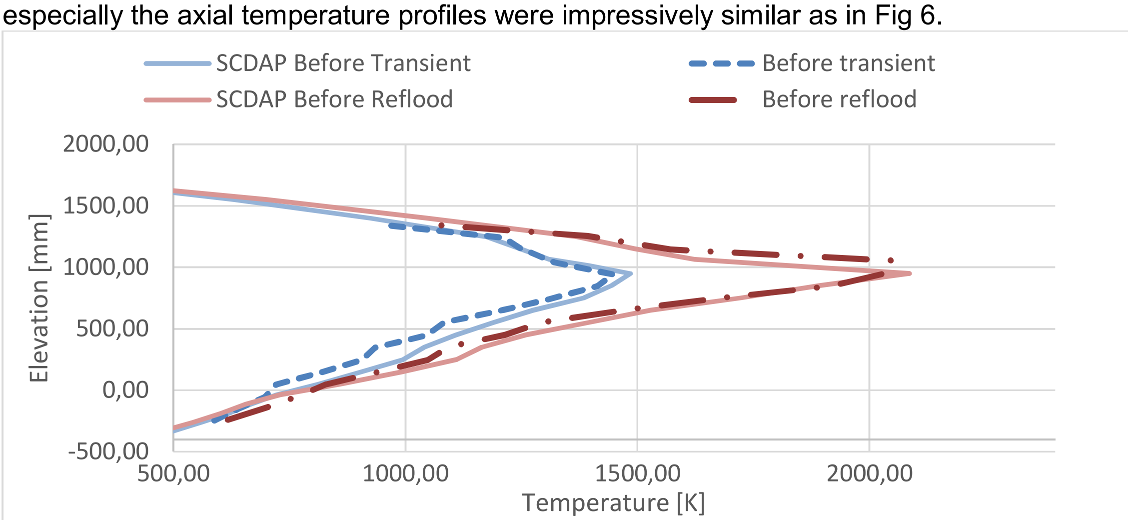

Fig 6. Axial bundle temperature profiles before transient and before reflood

There is also good agreement of temperature trends with the experiment in heat-up and transient phases. During reflood the temperature trends are properly represented, though there are possible small differences due to low resolution of data taken from KIT report or issues with thermocouples themselves (i.e. thermocouple inertia).

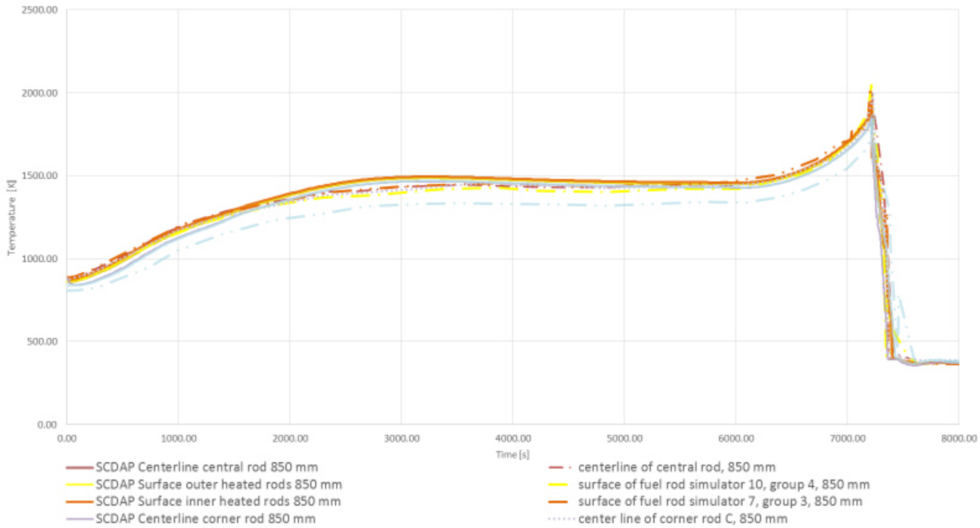

Fig 7. Thermocouple readings at elevation 850 mm

After verifying that the temperature graphs have proper correlation and seem to correctly represent physical phenomena occurring in the bundle, the focus can be redirected to main issue of QUENCH tests, the hydrogen factor. It appears that general trend of hydrogen generation is properly represented, though there is higher generation rate during heat-up and transient process than in the experiment. During reflood there is an opposite phenomena – hydrogen generation rate is lower than in experiment. It may be caused by presence of thicker protective oxide layer and lower amount of material to produce oxide, since oxide production was higher in heat-up phase.

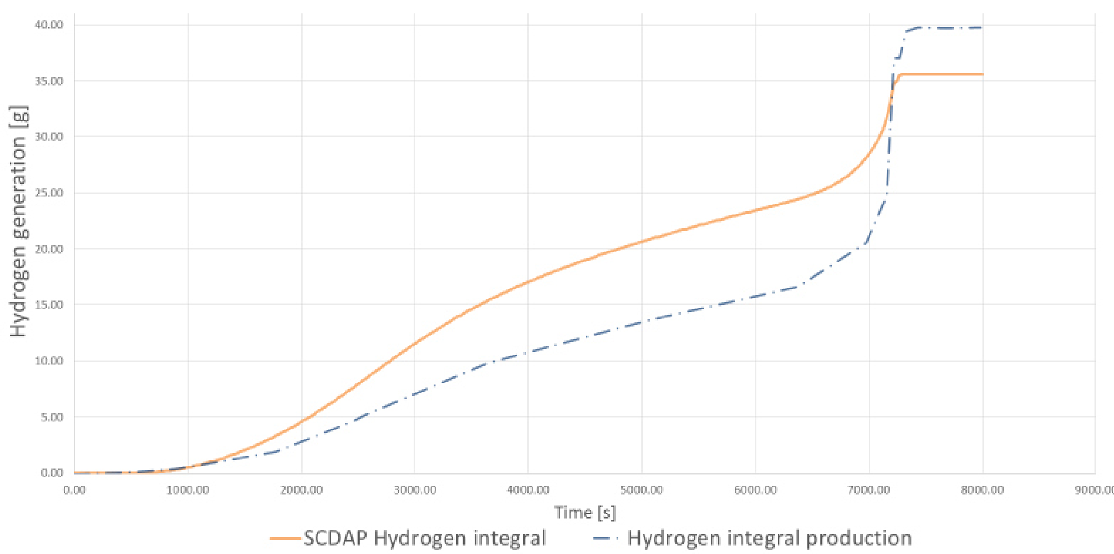

Fig 8. Comparison of integral hydrogen production

The difference in hydrogen production is connected to the usage of Zircaloy-4 material in code input instead of M5® that was in the test.

Shape of axial oxide thickness distribution has been properly represented, though in the experiment the maximum values were higher. Oxide thickness is directly connected to the production of hydrogen – therefore conclusions may be linked with those about hydrogen production. Since there is higher hydrogen production in the heat-up phase, also the oxide layer is thicker in SCDAP at the time. The corner rods in the experiment were made out of

Zry-4, thus comparison between the oxide thicknesses for those rods seemed the most reasonable. For the corner rods, after the test the axial profile is a little bit different, but the cumulative oxide thickness is basically the same, as seen in the Fig 9.

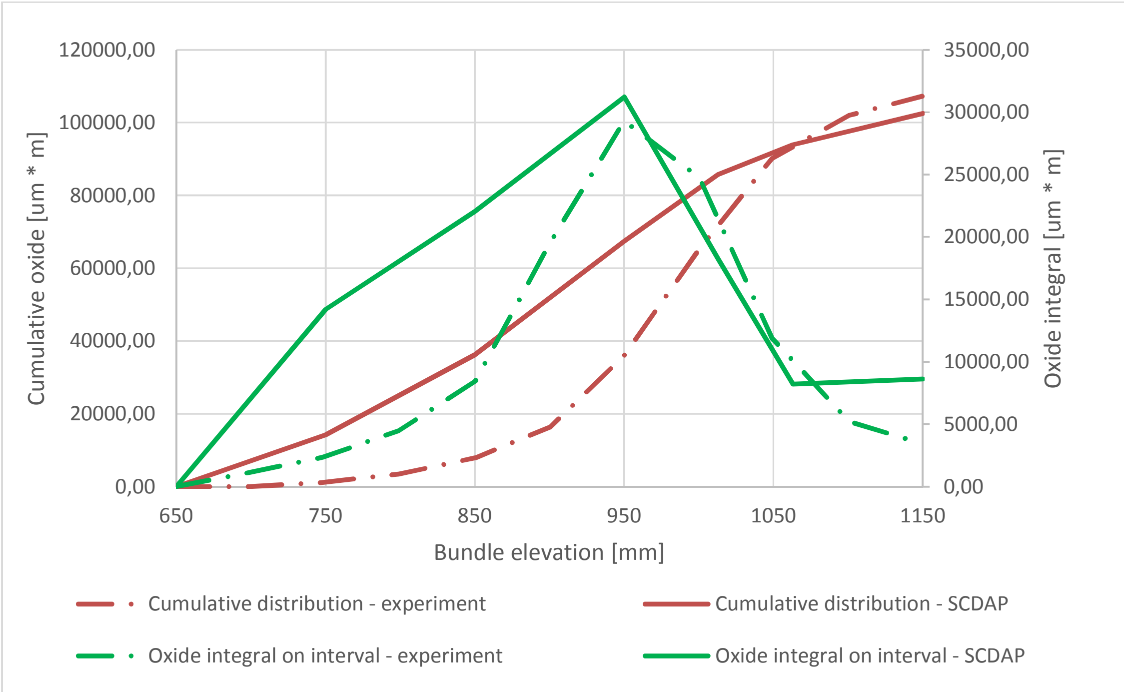

Fig 9. Cumulative distribution and integrated oxide thickness of corner rod after test made out of Zry-4

4. Summary and conclusions

QUENCH-14 as an experiment of ACM series aimed in investigation of industrial materials, in this case M5®, especially their properties considering the hydrogen production factor. Simulation presented in the article was using Zircaloy-4 material in QUENCH-14 conditions, which gives a chance for a comparison of the materials behaviour in similar temperatures. The model reflected the experiment set-up as well as possible, but some events that occurred during the experiment were not included, such as: simulator rod failure 15 s before reflood initiation, shroud failure during the reflood causing argon flow into annulus between shroud and cooling jacket.

The simulation was performed using RELAP5/SCDAPSIM/MOD3.5 with updated simulator rod model. Input was prepared basing on proven QUENCH-6 deck prepared by H. Madokoro [7] with necessary changes connected to different set-up of the test. Before modifying it for the sake of QUENCH-14 analysis, the input was revaluated and properly adjusted.

The results of the analysis are very satisfying. Temperature trends and profiles are represented correctly. It is to be noted, that data from thermocouples in experiment is not always to be trusted, because of flooding, inertia and other physical phenomena – therefore trends and profiles should be the main point of concern. And since the agreement is very good, a conclusion can be made that this version of the code is well suited for such analysis and able to perform calculations with good accuracy.

The model uses Zry-4 instead of M5® and the previously done analysis, by different authors (i.e [2], [4]) as well as the KIT report, state that M5® cladding and Zry-4 should present similar behavior except for the slight differences in heat-up (circa 870 K) and transient phase (precisely above 1650 K) – M5® has accordingly higher and lower hydrogen generation. This fact may cause differences in integral hydrogen production (as in Fig **8**) and in oxide profiles for heater rods from post-test analysis. Those arguments suggest that with M5® cladding correlations code would predict the bundle behavior with even higher accuracy.

5. References

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