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SIMULATION OF BUNDLE TEST QUENCH-12 WITH INTEGRAL CODE MELCOR

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Abstract

The past NRI analyses cover the Quench-01, Quench-03 and Quench-06 with version MELCOR 1.8.5 (including reflood model), and Quench-01 and Quench-11 tests with the latest version MELCOR 1.8.6. The Quench-12 test is specific, because it has different bundle configuration related to the VVER bundle configuration with hexagonal grid of pins and also used E110 cladding material. Specificity of Quench-12 test is also in the used material of fuel rod cladding – E110. The test specificities are a reason for the highest concern, because the VVER reactors are operated in the Czech Republic. The new input model was developed with the taking into account all experience from previous simulations of the Quench bundle tests. The recent version MELCOR 1.8.6 YU_2911 was used for the simulation with slightly modified ELHEAT package. Sensitivity studies on input parameters and oxidation kinetics were performed.

Introduction

The first NRI activities related to the Quench test simulations were done with the MELCOR 1.8.4 code in 2000. Own NRI input models for MELCOR 1.8.5 (with pre-released reflood model) and later for MELCOR 1.8.6 [1] were developed. The NRI analyses cover the Quench-01, Quench-03 and Quench-06 with version MELCOR 1.8.5 (including reflood model), and Quench-01 and Quench-11 tests with the latest version MELCOR 1.8.6. The Quench related activities were also performed with the latest version MELCOR 2.1 [2], but they were not yet finalized.

The Quench-12 test is specific, because it has different bundle configuration related to the VVER bundle configuration with hexagonal grid of pins. This test is also part of the Advanced Cladding Material testing program of the KIT (former FZK Karlsruhe) which compares available new materials on the oxidation kinetics and cladding behavior under high temperature conditions. Specificity of Quench-12 test is also in the used material of fuel rod cladding – E110. The test specificities are a reason for the highest concern, because the VVER reactors are in operation in the Czech Republic.

The new input model was developed with the taking into account all experience from previous simulations of the Quench bundle tests. The recent version MELCOR 1.8.6 YU_2911 was used for the simulation, but it was slightly modified, because an ELHEAT package, which calculates a power generation in electrically heated rods, was originally prepared for a configuration typical PWR bundles with heated rings no. 2 and 3, but the VVER bundle has heated rings no. 2 and 4.

Simulation performed with the MELCOR code was extended with the sensitivity studies on two very important input parameter definitions, which were not possible to validate on previous tests. The first sensitivity study was done on the input parameter of the rod pitch, because the implemented model in the MELCOR code assumes a square grid of fuel rods, but the VVER bundle uses hexagonal one. This experiment was unique case for validation of an approach which is for long time used in plant inputs – it is based on the presumption of equivalence of ratio of fluid cross area to total cross area of a basic cell. Sensitivity cases used large value (original pitch in hexagonal grid) and smaller value based on a user choice. The second sensitivity study was focused on a study of the best choice of radial discretization in the COR package. The base case is based on the presumption of equalized ratio of fluid flow area per sum of wetted perimeters of all oxidize components (cladding, corner rods, and shroud; spacer grids were neglected). Sensitivity cases used a little different definition of COR radiuses to simulate a little higher or less available atmosphere in contact with heated rings of electrically heated rods. Final effort was focused on oxidation kinetics for the E110 material. Several variants of coefficients were found and tested. The best choice, based on the Quench-12 simulation with the MELCOR code, was application of the KI/RIAR correlation for lower temperatures and Sokolov's correlation for high temperatures.

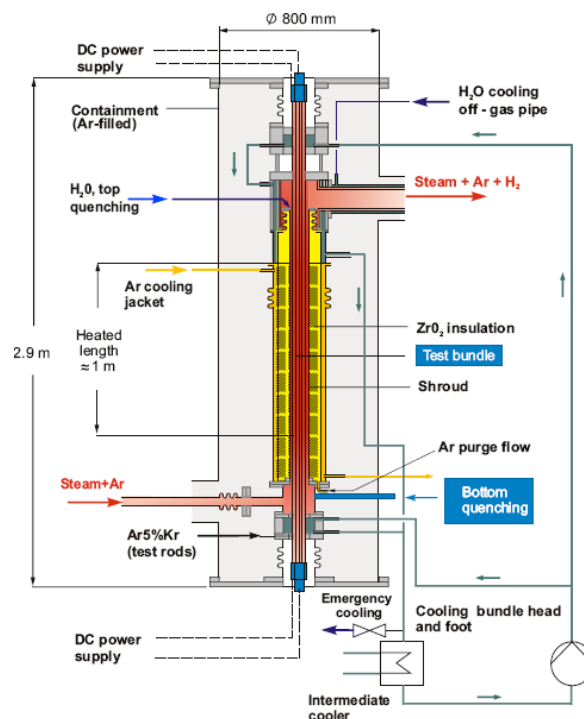


Figure 1 Quench bundle test facility configuration [3].

1. Quench-12 Test Definition

The Quench-12 test was successfully conducted at the KIT (Forschungszentrum Karlsruhe) on September 27, 2006 in the frame of ISTC project 1648.2. The determination of the test protocol was based on numerous calculations with SCDAP/RELAP5, SCDAPSIM and

ICARE/CATHARE. Scheme of the Quench facility for the bundle tests is shown on Figure 1 and consists from heated part of 1.024 m length with isolated shroud and gas and/or water supply from bottom and off-gas pipe on the top of bundle section.

The Quench-12 bundle test [3] is a part of the Advanced Cladding Material testing program (hereafter ACM program) of the KIT institute with the main objective to compare oxidation kinetics of different materials and their behaviour during reflooding of overheated bundle. The Quench-06 test [4] was chosen as the reference test, because this test is very well documented, because it was selected for the OECD ISP-45 [5]. The Quench-06 test used the most usual cladding material for typical western PWRs - Zircaloy-4. But recent fuel assemblies use more and more often advanced cladding materials to replace Zry-4 and those materials were tested within the ACM program with the aim to extend knowledge base to new cladding materials – E110, M5, Zirlo, and Duplex (Zircaloy-4/D4).

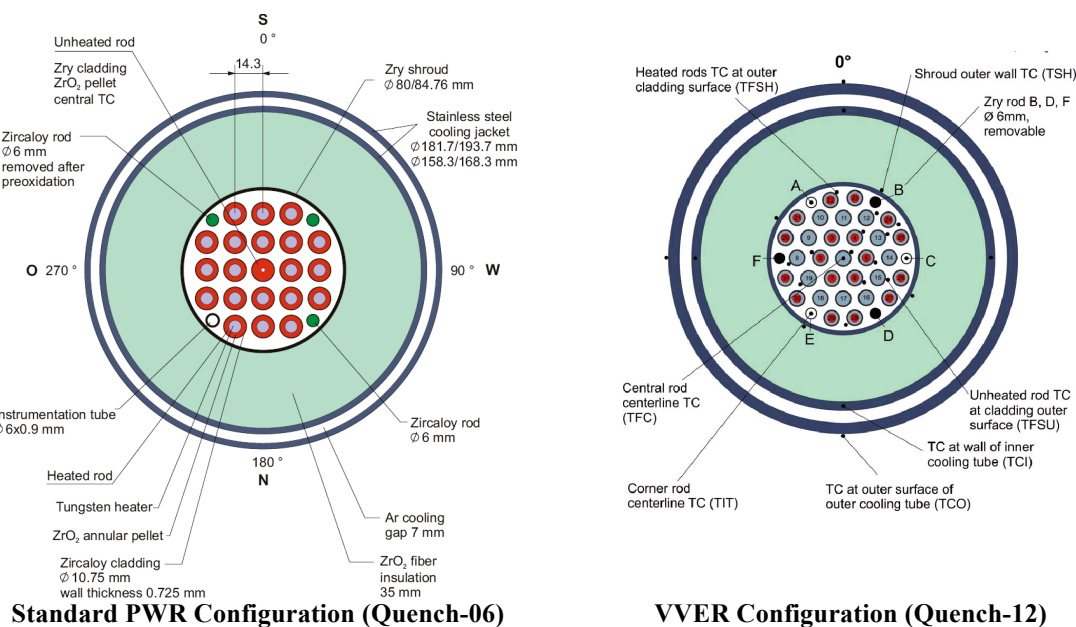


Figure 2 Cross-sections of bundles used in the Quench-06 test (typical western PWR) [4] and Quench-12 test (VVER bundle) [3].

The QUENCH-12 experiment investigated the effects of VVER materials and bundle geometry on core reflood, in comparison with test QUENCH-06 (ISP-45) with western PWR geometry (comparison of cross-sections is on Figure 2). While the PWR bundle uses a single unheated rod, 20 heated rods, and 4 corner rods arranged on a square lattice, the VVER bundle uses 13 unheated rods, 18 heated rods and 6 corner rods, arranged on a hexagonal lattice. The test was conducted with broadly the same protocol as QUENCH-06 [6], so that the effects of the VVER characteristics could be more easily observed. This involved pre-oxidation to a maximum of about 200 μm oxide thickness at a temperature of about 1200 $^{\circ}\text{C}$, followed by a power ramp until a temperature of 1800 $^{\circ}\text{C}$ was reached, then reflood with water at room temperature was initiated.

The principal objection [7] of the comparison of geometrical parameters of the QUENCH-12 bundle with the QUENCH-06 bundle was to reach as identical relations as possible, so:

- 1) coolant channel area relationship Quench-12/Quench-06 = 1.09 $\Rightarrow$ the fluid flow rate should be 9% higher for the Quench-12 bundle than for the Quench-06 bundle to provide the same flow velocity
- 2) metallic surface relationship Quench-12/Quench-06 = 1.22 $\Rightarrow$ higher chemical energy production for the VVER bundle due to exothermic steam-metal reaction;
- 3) bundle material mass relationship Quench-12/Quench-06 $\approx$ 0.97 $\Rightarrow$ the electrical power for the VVER bundle should be lower than for the Q06 bundle.

The experiment started with an application of electrical bundle power of ca. 3.5 kW (Figure 3 [7]), which was ramped step-wise to 9.9 kW over ca. 2000 s to achieve the desired pre-oxidation temperature at bundle peak position of 1200 °C, in a flow of 3.3 g/s argon and 3.3 g/s steam. Pre-oxidation was continued to 6000 s. The power was then ramped at a rate of 5.1 W/s to cause a temperature increase until the desired maximum temperature before quench of 1800 °C was reached, then reflood with 46 g/s water at room temperature was initiated, following rapid filling of the lower plenum. The electrical power was reduced to 4 kW during the reflood phase, approximating effective decay heat levels.

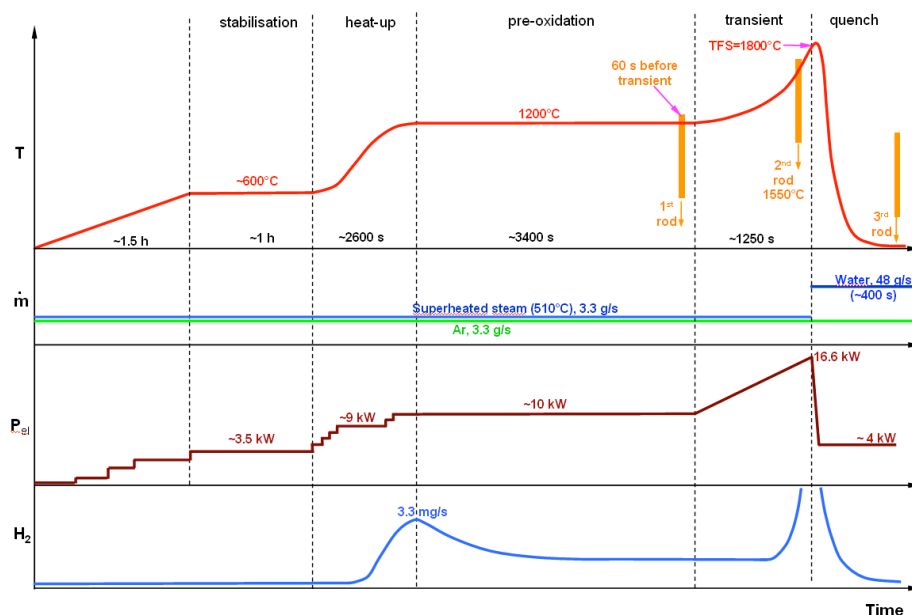


Figure 3 Quench-12 test conduct – evolutions of maximum temperature, argon, steam, and water supply, electrical power, and hydrogen generation rate [7].

Two corner rods were withdrawn during the test to estimate the oxidation extent: the first corner rod was withdrawn at the end of pre-oxidation phase, the second corner rod was withdrawn during the transient phase before begin of the moderate temperature escalation. Both rods showed intensive spallation of oxide scales. The lower part of the third corner was withdrawn after the test. At the position of breach of this rod at the bundle elevation of 880 mm melting of the inner β -Zr structure was observed.

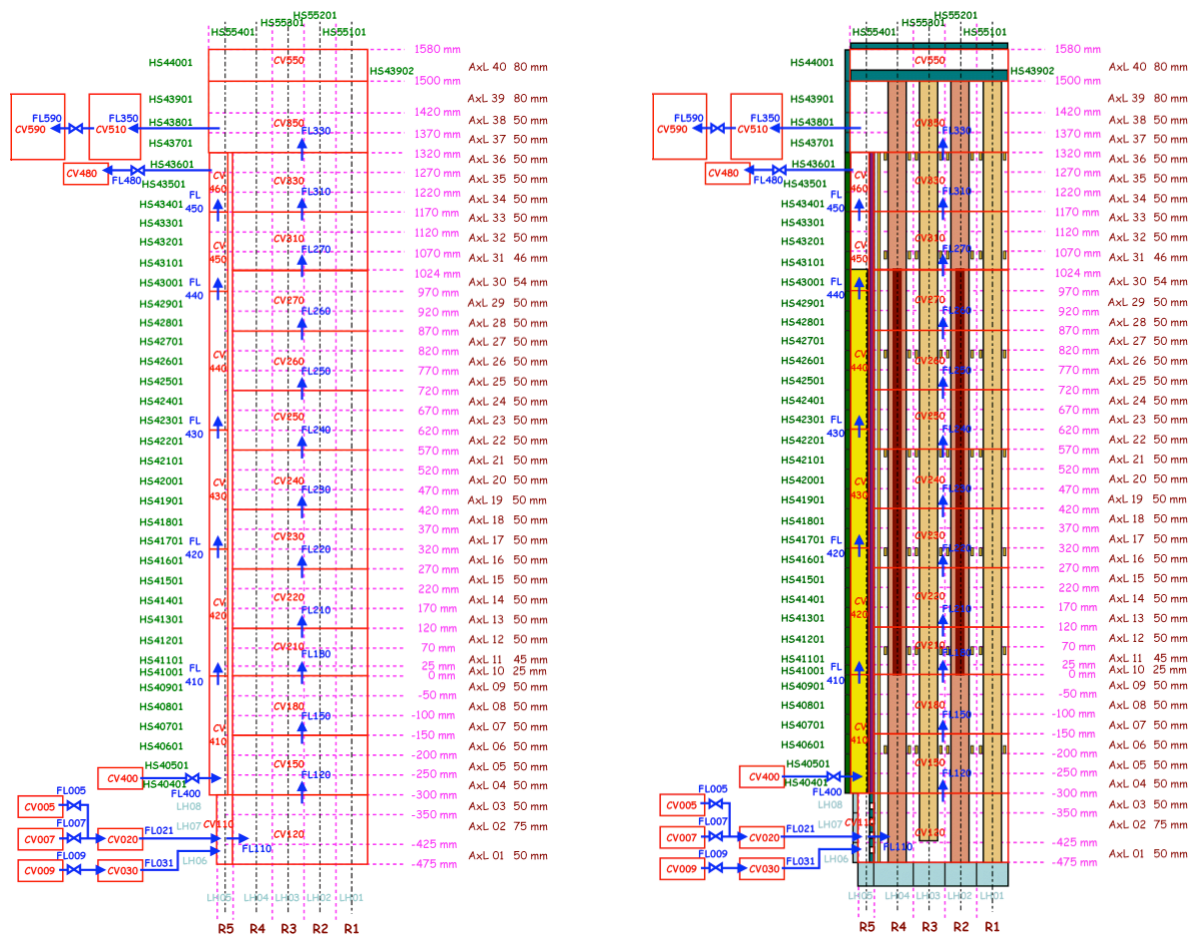


Figure 4 Nodalization of the Quench-12 test input model for the MELCOR code; left figure shows only thermal-hydraulics components, right one includes also COR ones.

Following reflood initiation, a moderate temperature excursion about 50 K was observed, over a longer period than in QUENCH-06. Preliminary figures for hydrogen production are 34 g in the pre-oxidation and transient phases, and about 24 g in the quench phase, the amount released in the quench phase being six times higher than seen in QUENCH-06. This is linked to the longer excursion time. The hydrogen content inside of corner rods reached 35 at% at the bundle elevation of about 1100 mm.

2. MELCOR Code Used for Simulation of Quench-12 Test

The MELCOR code is an integral code for the analysis of a severe accident progression and source term estimation. Simulations of the Quench-12 test presented in this paper were performed with the first version – MELCOR 1.8.6 release YU_2911 with linked routines for calculation of electrical power produced by electrical heaters. Development of routines for electrical heaters specific for the Quench-12 test was done in the NRI based on the version prepared for the previous simulations of the Quench bundle tests. The principal difference between Quench-12 and other tests is that in the standard PWR test has only one (central) unheated or control rod surrounded with two rings of heated rods with independent power

control per ring. The VVER configuration has also unheated central rod, but it is surrounded with three rings of rod and the only inner and outermost rings are heated.

3. Development of Input Data for Quench-12 Test Simulation with MELCOR Code

The input data for the MELCOR code were fully developed at NRI with application of experience from previous simulations of other Quench bundle tests. Input file could be subdivided into several parts – definition of thermal-hydraulics, fuel simulators – bundle plus surrounded shroud, sources and sink of media, boundary conditions, and material definitions. Figure 5 shows two visualizations of the input model nodalization. The left visualization includes only thermal-hydraulics components – control volumes (red boxes with red notation in form CVnnn, where nnn is user defined number), flow paths (blue arrows with blue notation in form FLnnn, where nnn is user defined number), heat structures (here indicated only with their notations in green colour and form HSnnnn, where nnnnn is user defined number), net of radial and axial discretization of COR package defined with dashed pink lines and pink values of axial elevation of axial borders, and bottom head segments (here indicated only with their notations in light blue colour). The right visualization includes the same components like left one plus green boxes for heat structures and light blue boxes for bottom head segments and also other components of COR package – unheated rods in ring 1 and 3 represented with full height sand boxes (rod in ring R3 starts in axial level 2), heated rods in rings R2 a R4 represented with full height light brown boxes with emphasised heater section with dark brown colour, spacer grids represented as small sand boxes, corner rods represented as tall and slim sand box in ring R4, shroud represented with violet tall and slim box in ring R4, and shroud insulation is represented with yellow box. Generally colours represent material of components, so sand and brown colour represents Zr based alloy, green and blue represents steel structures, and yellow represents ZrO₂ fibers.

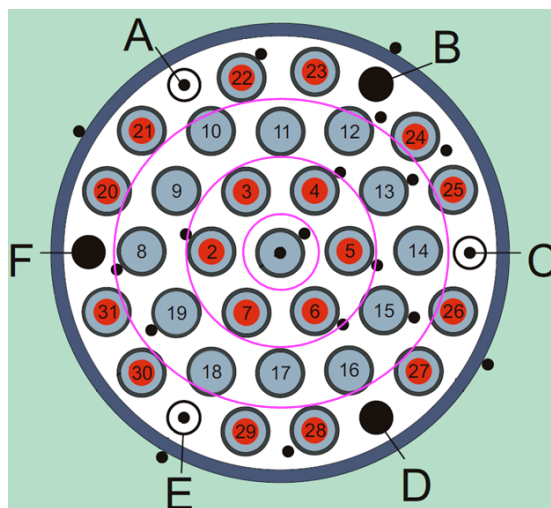


Figure 5 Radial discretization of fuel rod bundle in Quench-12 test input model

The main principles of the input model used very extensive experience from the development of input models for other Quench bundle tests. Main focus is done on the bundle section, sources for gas and water supply and sink are simplified. Modelling of gas and water sources

uses control volumes with time-dependent state values and flow through flow paths from source volumes uses approach with time-dependent velocity, which is calculated via. control functions to keep correct mass rate. Sink control volume also uses time-dependent state values, mainly pressure is controlled to predict correctly its evolution in bundle. Fluid space in the bundle is subdivided into control volumes with main assumption – three axial levels are merged into one control volume in channel, but in bypass more axial levels are merged into bypass control volume. Bypass control volumes are filled with argon and the model of bypass includes also source control volume and sink control volume with the aim to control mainly pressure. Heat losses from a system of bundle and shroud are defined via. boundary condition definitions for outer surface of boundary heat structures which model inner cooling jacket and their values are measured for sufficient number of axial levels.

Because the Quench-12 test investigated behaviour of the VVER bundle with hexagonal lattice, it is a unique opportunity for sensitivity cases on definitions of two key input parameters, which can play important role in the input model preparation for real energetic VVER reactors. The first important parameter is PITCH, which defines pitch between fuel rods and the basic assumption of the MELCOR code modelling assumes square lattice. The usual approach for definition of this PITCH parameter for VVER reactors used in the NRI is based on the assumption of equal ratio of fluid cross area to total cross area of cell (see Figure 6) with the equation (1). The base case calculation uses value of parameter PITCH calculated from equation (1) $PITCH = 0.010721$ m and this calculation uses acronym v24. Sensitivity cases use the original value of pitch in the hexagonal lattice ($P_{TR} = 0.01275$ m with acronym v24b) and user choice of smaller value (0.009 m with acronym v24c).

$$PITCH = \sqrt{\frac{P_{TR}^2}{\sqrt{2}}} \quad (1)$$

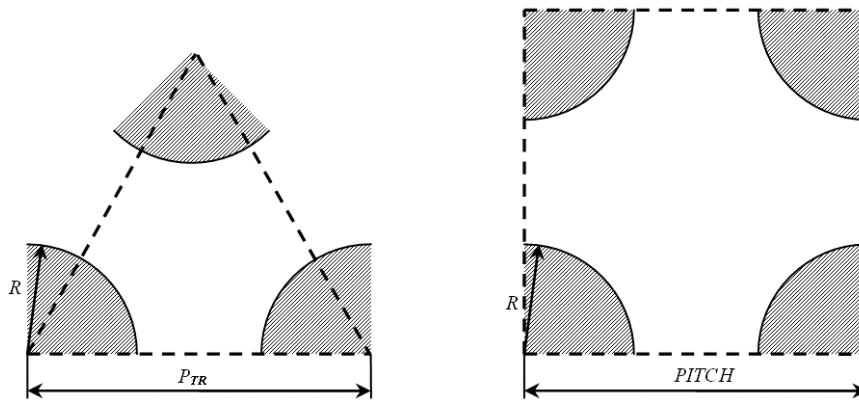


Figure 6 Scheme of VVER cell (hexagonal lattice) and standard PWR cell (square lattice)

The second sensitivity study was focused on the definition of radiuses of radial rings of bundle discretization. The base case values were determined with the assumption of equalized ration of fluid flow area per sum of wetted perimeters of all components, which can be oxidized (cladding, corner rods simulated as non-supporting structures, and shroud; grid spaces were neglected). Table 1 summarizes definition of radiuses for all rings in base case

(again with acronym v24) and two sensitivity cases – the first one with increased ration for radial rings with heated rods (R2 and R4; acronym v25) and the second one with decreased ration for radial rings with heated rods (R2 and R4; acronym v26). Those modifications influence mass of steam available in individual rings for the component oxidation.

Ring	v24 Base Case		v25 increased R2 and R4		v26 decreased R2 and R4	
	Radius [m]	Ration [m ² /m]	Radius [m]	Ration [m ² /m]	Radius [m]	Ration [m ² /m]
R1	0.0071	0.0033	0.0068	0.0028	0.0074	0.0037
R2	0.0188	0.0033	0.0200	0.0042	0.0170	0.0020
R3	0.0310	0.0033	0.0300	0.0023	0.0340	0.0057
R4	0.0455	0.0035	0.0455	0.0039	0.0455	0.0021

Table 1 Definition of radial ring radiuses in base and sensitivity cases

4. Results of Quench-12 Test Simulations with MELCOR Code

This chapter is subdivided into three sub-chapters. The first one describes results of the Base Case simulation, the second one is focused on the first sensitivity study on the impact of parameter PITCH modifications, and the third one on the second sensitivity study on definition of radial.

The main concern of the analytical simulation of the Quench experiments was to compare prediction of temperature histories, hydrogen generation, and final configuration of bundle. Result post-processing of the MELCOR code simulations could use different approaches and at the NRI two main tools for post-processing of the Quench simulations are – the HISPLTM tool, which was distributed with older versions of the MELCOR code (till version MELCOR 1.8.5, but it correctly operates also with versions MELCOR 1.8.6 and also MELCOR 2.1), and the ATLAS tool, which was developed by GRS (Germany) [8] and which is used for graphical visualization. The first tool – HISPTLM – is used for preparation of time histories of selected parameters, their comparison with measured values, and comparison of results from more calculations. The second tool – ATLAS – is used for preparation of figures with snapshots of temperature or mass profiles, for temperatures also in comparison with measured values. But this tool cannot be used for comparison of two and more calculation results due to its limitations.

4.1 Base Case Simulation

The first simulation is the base case (it uses also acronym v24, but mainly on figures with comparison with sensitivity runs). This simulation was also used for the tuning up of external resistivity parameter, which simulates the resistance of top and bottom parts of heated rod which are not simulated in the calculation, i.e. part above 1580 mm and below -475 mm. Final value of this parameter was 4.8 mΩ/rod.

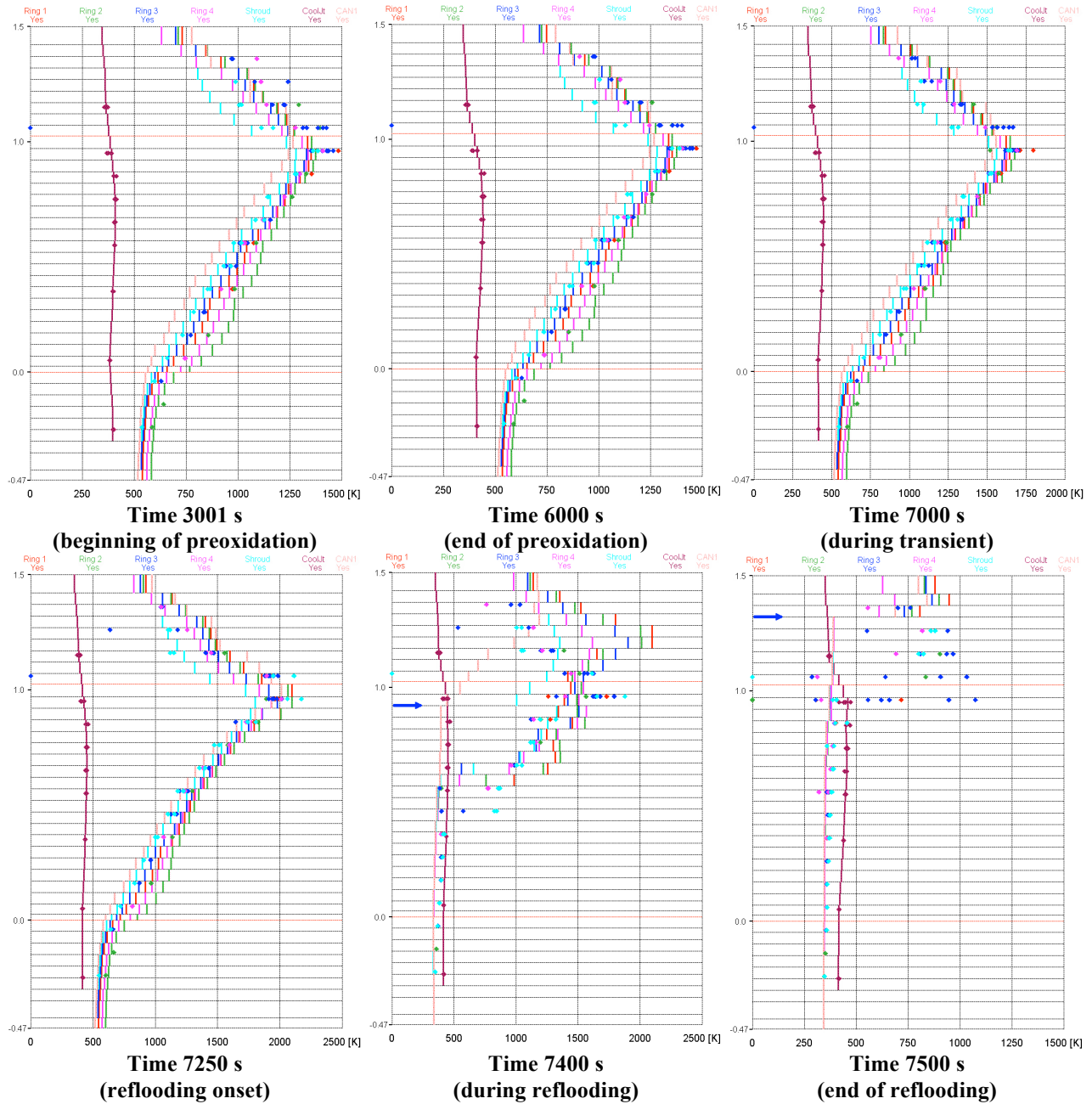


Figure 7 Evolution of temperature profiles in Base Case simulation
(dots – measured values, lines – calculated values)

Figure 7 summarizes evolution of temperature profiles of the most important components represented with different colours and compared with measured values. Measured values are represented with dots of appropriate colour in comparison with component in the simulation with the MELCOR code. Bordeaux colour represents temperature of inner cooling jacket, which is boundary condition for radial heat losses from bundle and shroud. Red colour represents cladding of unheated rod in ring 1, green colour represents cladding of heated rod in ring 2, blue colour represents cladding of unheated rod in ring 3, magenta colour represents cladding of heated rod in ring 4, cyan colour represents shroud, and light pink colour fluid in

radial ring R1, but during the visualization user can choose any of radial rings. Horizontal red lines emphasize heated section between elevations from 0.0 m to 1.024 m. Prediction of temperatures in the Base Case simulation matches measured values very well from beginning till the transient phase. Also the comparison at the reflood onset matches measured values relatively well, the only difference is for the hot spot, where the hottest temperatures were measured for the shroud, but in simulations they are predicted for cladding of rings R1 and R2. During reflooding phase at time 7400 s the axial position of the quenched front is predicted very well, because axial position of dropped temperatures is in very good agreement although the axial position of swollen water level in the simulation is in significantly higher elevation (marked with blue arrow). But the upper part of bundle is predicted as over heated. The most likely reason is an absence of simulation of shroud penetration, which was observed in the experiment (see figure 8). This explanation is also in accordance with other results – at time of 7275 s the shroud thermocouple at elevation 1.050 m failed and at time 7290 s prediction of temperatures in upper part of bundle in the simulation starts to be higher than measured values (for elevations from hot zone and above it). The last snapshot at time 7500 s also support this theory, because measured thermocouples were quenched only below elevation 0.950 m and all measured values from elevation above are unquenched, but simulation predicted quench front position at 1.350 m, i.e. in the same position like swollen water level (again marked with blue arrow). As a conclusion, an inclusion of the shroud break modeling should result in more realistic prediction of upper bundle temperature during and after reflooding in the Quench-12 test simulation with the MELCOR code.

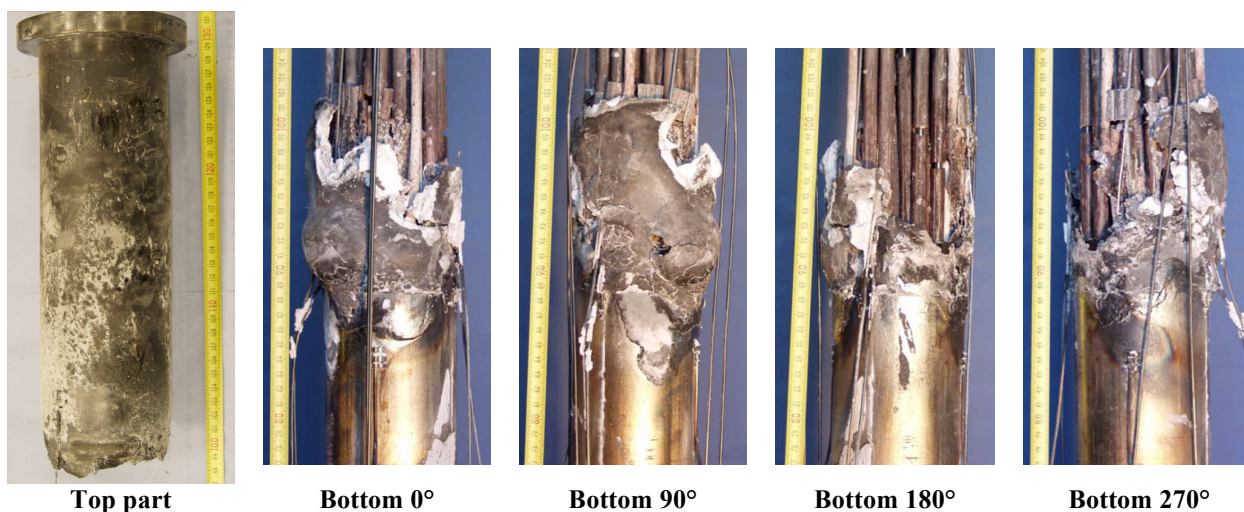


Figure 8 Posttest appearance of piece of upper shroud and the hot zone of shroud and test bundle (~750-1150 mm) at orientations 0, 90, 180, and 270 degrees [3]

Hydrogen generation was predicted in very good agreement with measured data. Measured hydrogen generation during pre-oxidation phase (until 6500 s) was 14.2 g and prediction in the Base Case simulation with the MELCOR code was 13.97 g. Measured hydrogen generation at the end was 57.8 g and prediction 53.36 g. This value is a little less, but it corresponds with the absence of modelling of shroud outer surface oxidation and also with absence of oxidation of non-prototypic materials (heaters), which contributes with relatively low, but non-zero hydrogen generation. Last but not least contributor is the underestimation of

the MELCOR code of the oxidation of the relocating material – candling melt and solid particulate debris.

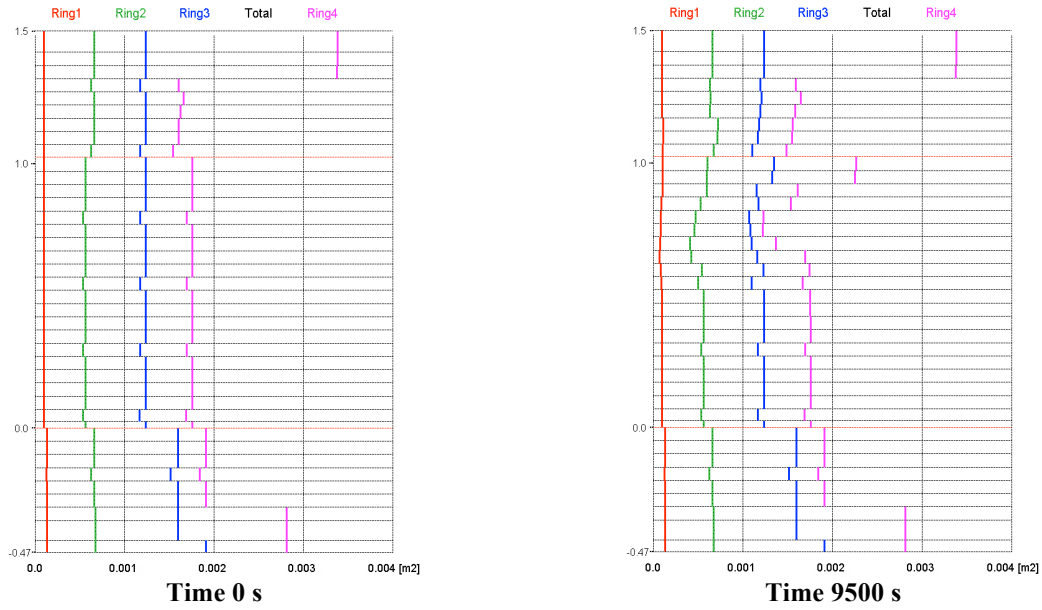


Figure 9 Axial profiles of fluid flow area in rings at the beginning and end of simulation

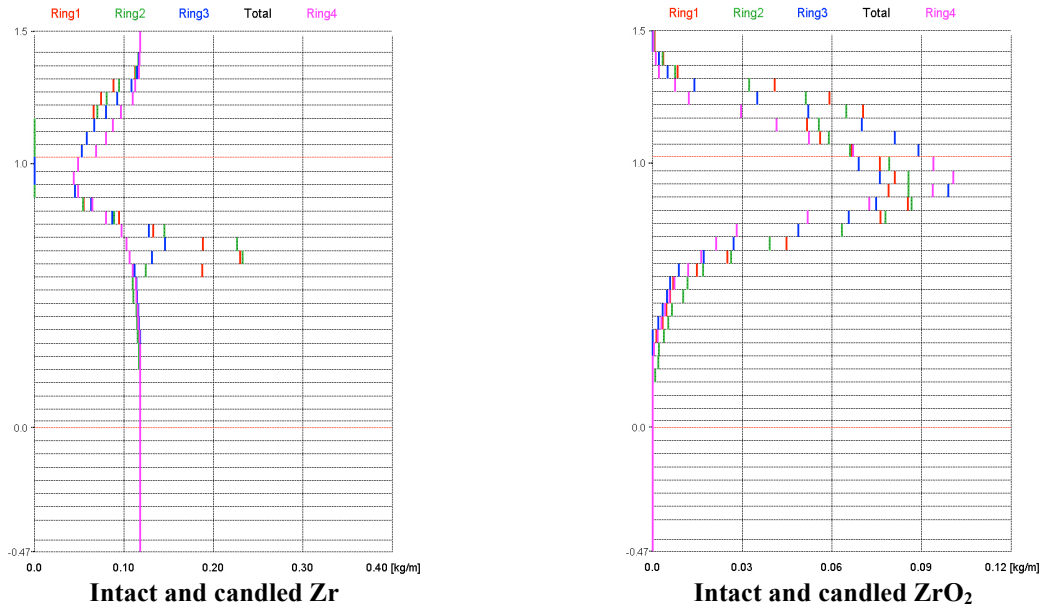


Figure 10 Axial profiles of specific mass of intact and candled Zr and ZrO₂ per rod in rings at the end of simulation

Evolution of bundle configuration could be compared on the axial profiles of fluid flow areas for individual rings for times at the beginning and end of simulation (figure 9). These figures could be supported with the axial profiles of specific masses of intact and candled Zr and ZrO₂ for individual rings at the end of simulation (figure 10) and also specific masses of intact and candled Zr and ZrO₂ in component shroud (figure 11). All three figures illustrate very good prediction of main location of flow blockage (between elevations 0.6 to 0.9 m).

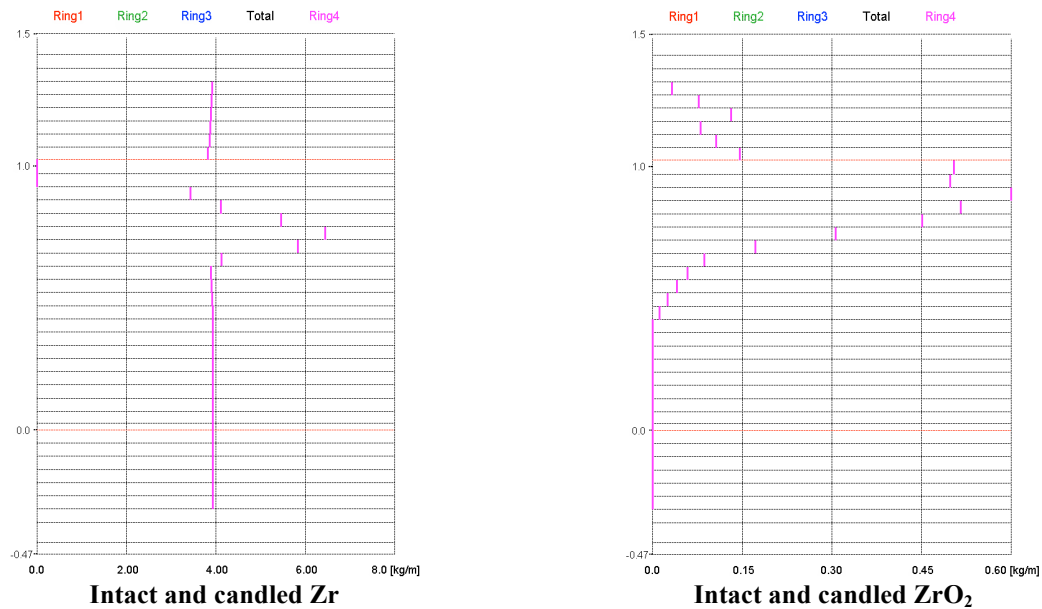


Figure 11 Axial profiles of specific mass of intact and candled Zr and ZrO₂ in shroud component at the end of simulation

4.2 Sensitivity Study on Parameter PITCH

Two sensitivity cases were calculated with MELCOR code and compared with the Base Case described in the chapter 4.1. The first sensitivity case (it uses acronym v24b) uses for the parameter PITCH the value in the hexagonal lattice of the VVER bundle (12.75 mm) and the second sensitivity case (it uses acronym v24c) uses the user defined smaller value 9 mm. Original value used in the Base case (it uses acronym v24) was 10.721 mm and this value was calculated using the equation (1).

Figure 12 compares the evolution of cladding temperature at elevation 0.95 m of the rod in the radial ring R3, i.e. unheated rod, and also evolution of hydrogen generation during the test. Differences in the predicted temperature evolution are really very small and the only detailed checking of results identified a little greater temperature in case v24c and a little less temperatures in case v24b, both in comparison with the Base Case v24. Prediction of a little greater or less temperatures resulted in the greater or less prediction of hydrogen generation in both phases – pre-oxidation and transient with reflooding. As mentioned above differences are very small, but their source comes from different treatment of the radiation heat transfer, because lower value of the pitch results in more intensive heat exchange in comparison with the greater value of pitch. In any time this study showed that wrong definition of the PITCH parameter for the VVER bundle with the hexagonal lattice did not results in principally wrong prediction of the Quench-12 test, but application of PITCH value based on equation (1) is the correct definition for the VVER plant applications as observations from this study confirmed.

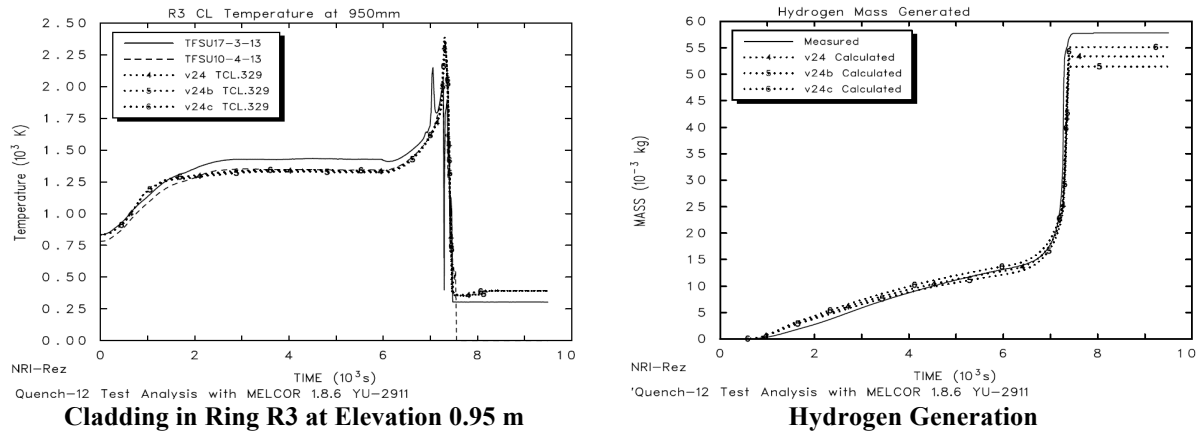


Figure 12 Comparison of cladding temperatures in radial ring R3 at elevation 0.95 m and comparison of hydrogen generation in sensitivity study on parameter PITCH

4.3 Sensitivity Study on Radiuses of Radial Rings

Again two sensitivity cases were calculated with MELCOR code and compared with the Base Case described in the chapter 4.1 in this second sensitivity study. The first sensitivity case (it uses acronym v25) uses the increased values for rings R2 and R4 and the second sensitivity case (it uses acronym v26) uses the decreased values for rings R2 and R4 – for details see table 1. Original values used in the Base case (it uses acronym v24) were defined with the assumption of equalized ration of fluid flow area per sum of wetted perimeters of all components, which can be oxidized.

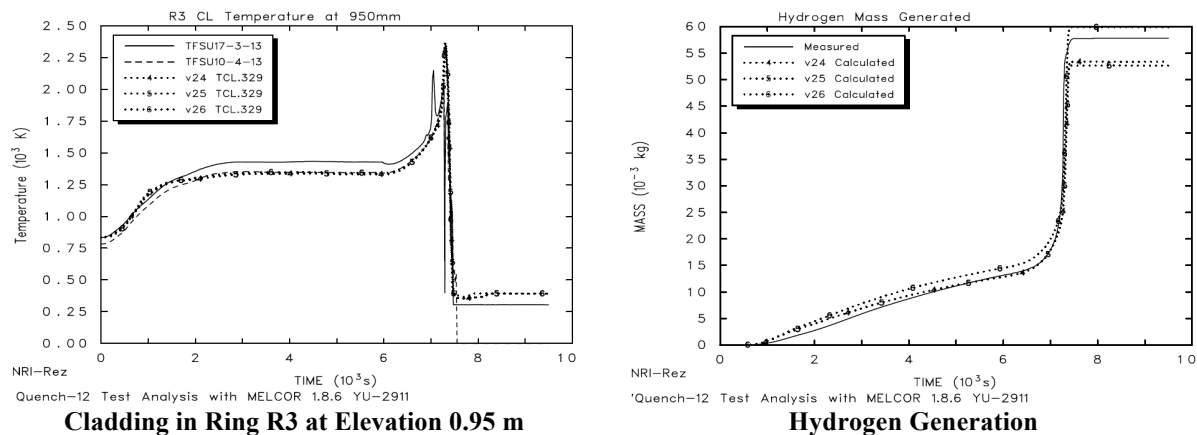


Figure 13 Comparison of cladding temperatures in radial ring R3 at elevation 0.95 m and comparison of hydrogen generation in sensitivity study on definition of ring radiuses

Figure 13 compares the evolution of cladding temperature at elevation 0.95 m of the rod in the radial ring R3, i.e. unheated rod, and also the evolution of hydrogen generation during the test. Differences in the predicted temperature evolutions are really very small and the only detailed checking of results identified a little greater temperature in case v26 and a little less temperatures in case v25, both in comparison with the Base Case v24. Prediction of a little greater or less temperatures resulted in the greater or less prediction of hydrogen generation in both phases – pre-oxidation and transient with reflooding. Mainly in case v26 the prediction

of hydrogen generation during reflooding was greater and resulted in the overestimation of total hydrogen generation. The reason of differences is a different total heat capacity of coolant in rings, because the total heat capacity of coolant in rings with heated rods in case v26 was less and it causes higher cladding temperature and oxidation rate. Concerning the plant applications, usual approach to definition of radial rings does not depends so strongly on the exact choice like in such small bundle. But this study showed that the inclusion of the additional bypass flow into the bundle channel could negatively influence predicted results, because different prediction of oxidation results also in the different prediction of heat generation due to the metallic component oxidation.

4.4 Sensitivity Study on E110 Oxidation Kinetics Correlation

The above mentioned simulations were done with the default definition of oxidation kinetics in the MELCOR code – Urbanic-Heidrick [1], which was developed for the Zircaloy-4 material, but the Quench-12 test uses the E110 alloy. The table 2 summarizes the definitions of various correlations for low and high temperature oxidations available in the open literature, converted to the formulation needed in the MELCOR code – mass gain of oxidized Zr. All correlations from table 2 are also shown on Figure 14, again in comparison with the U-H (red lines). It is obvious that the kinetics correlations for the E110 predict slower oxidation for lower temperatures (below about 1300 K), but more intensive oxidation for higher temperatures (including high temperature range above 1850 K). This conclusion was fully confirmed in all of performed simulations, which used various choices of correlations from table 2.

Material	Correl.	Ref.	Rate Coeff. K [kg(Zr) ² /(m ⁴ *s)]	Exp. Coeff. Q [K]	Temperature Range [K]
Zry-4	UH	[1]	29.6	16820.0	< 1853.0
Zry-4	UH	[1]	87.9	16610.0	≥ 1873.0
E110	Sok-LT	[9]	2584.3	23040.0	< 1773.0
E110	Sok-HT	[9]	1596.9	20800.0	> 1773.0
E110	Sok-LT	[10]	1292.1	23033.4	< 1773.0
E110	Sok-HT	[10]	798.4	20796.2	> 1773.0
E110	Sok-LT	[11]	687.8	20821.3	823.0 ÷ 1473.0
E110	Sok-MT	[11]	1292.2	23041.4	1473.0 ÷ 1773.0
E110	Sok-HT	[11]	798.1	20801.3	1773.0 ÷ 1873.0
E110	VV	[11]	455.9	21427.2	873.0 ÷ 1723.0
E110	BDL	[11]	192.7	20523.2	973.0 ÷ 1373.0
E110	KI/RIAR	[11]	79.6	19106.1	1073.0 ÷ 1473.0
E110	AEKI	[11]	351.9	20401.3	773.0 ÷ 1473.0
E110	FZK	[11]	1296.3	22665.4	1323.0 ÷ 1673.0

Table 2 Definition of oxidation kinetics coefficients used in the study

Application of selected correlations to the simulation of the Quench-12 test was done and compared with the original Base Case simulation. Figure 16 shows the comparison of a cladding temperature at elevation 0.95 m for fuel rod in ring R3 with the measured data and also Base Case simulation. All simulations have very similar evolution of this temperature, the only difference is predicted Sok-LT [9] Sok-HT [9] (long dashed line) and AEKI [11]

Sok-HT [11] (medium dashed line), which predicted a little earlier temperature escalation in comparison with other simulations, but in better agreement with the measurements. But those two simulations resulted in significant overestimation of hydrogen generated – mainly for the transient and reflooding phases. All simulations underestimated hydrogen generation with

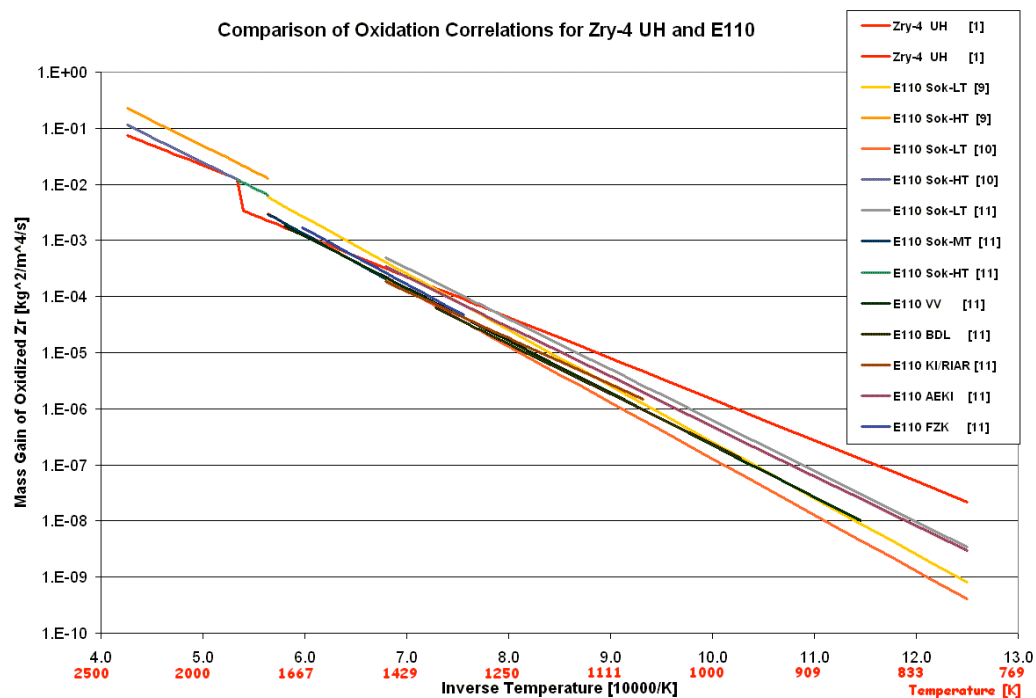
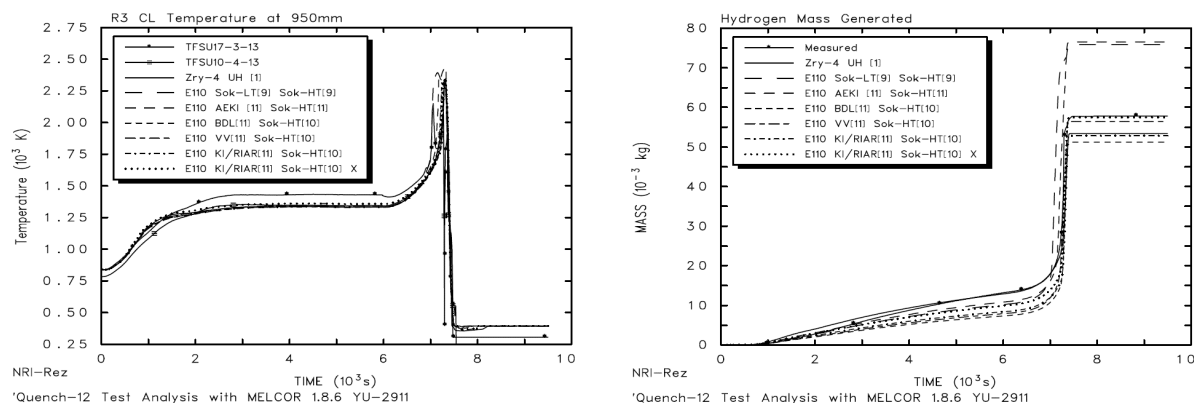


Figure 14 Comparison of open oxidation correlations for E110 material with Urbanic-Heidrick correlation for Zry-4 (default in MELCOR code)



Cladding in Ring R3 at Elevation 0.95 m

Hydrogen Generation

Figure 15 Comparison of cladding temperatures in radial ring R3 at elevation 0.95 m and comparison of hydrogen generation in sensitivity study on oxidation correlations for E110 material

E110 (figure 15) during pre-oxidation phase and very slightly overestimated hydrogen generation during transient and reflooding phases. Based on the comparison of tested combinations of correlations it could be chosen one variant as the best choice – KI/RIAR [11]

Sok-HT [10], because this combination predicted the highest production during pre-oxidation phase and the acceptable agreement during transient and reflooding phases. More over this combination was recalculated (dotted line on Figure 15) with the modified external resistivity input value – all simulations were done with 0.0048 mΩ/rod and the last calculation with 0.0038 mΩ/rod.

5. Conclusions

Simulation of the Quench-12 bundle test was performed with the MELCOR 1.8.6 code as the independent contribution of the NRI Rez to the validation of the code. The highest interest in this test was done by its configuration, because this test simulated the VVER bundle with hexagonal lattice and with the cladding using Russian E110 material. Both those specific features are relevant for the nuclear power plant operated in the Czech Republic. Analytical simulation of this test also enabled to perform some sensitivity studies on definitions of important input parameters, which studying was not possible on other experiments – definition of modelling parameter PITCH and correlation for oxidation kinetics for the E110 material. Sensitivity studies confirmed correctness of approaches which are for long time used in the input decks for the VVER reactors and they also enabled to define best choice of the oxidation kinetics for the E110 material. Based on the simulation of the Quench-12 test, the choice of KI/RIAR [11] Sok-HT [10] correlations seems to predict the best agreement with measured data and can be recommended for the VVER plant applications of the MELCOR code. Some disagreement in hydrogen production during transient and reflooding phases could be improved with the modelling of shroud failure and atmosphere/water overflow.

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