NENE-2012, September 5-7, 2012, Ljubljana, Slovenia

Post-Test Calculation of Air Ingress Experiment QUENCH-16 Using Thermal Hydraulic and Severe Accident Code SOCRAT/V3

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1. Purpose

The purpose of this work is using of the computer modelling code SOCRAT/V3 for post-test evaluation of air ingress experiment QUENCH-16.

The QUENCH-16 test conditions simulated a representative scenario of LOCA (Loss of Coolant Accident) nuclear power plant accident sequence in which the overheated up to 1870K core would be reflooded from the bottom by ECCS (Emergency Core Cooling System).

The test QUENCH-16 was successfully conducted at the KIT, Karlsruhe, Germany, in July 27, 2011, The primary objective of this test was to investigate the oxidation of Zircaloy in the air following a limited pre-oxidation in the steam and to achieve a long period of oxygen starvation to promote the interaction with the nitrogen.

The important feature of QUENCH-16 test was the air ingress phase during which the air was supplied to the working section of experimental installation.

2. QUENCH-LOCA Facility

- The QUENCH-16 test bundle was made up of 21 fuel rod simulators with a length of approximately 2.48 m (heated rod simulators). The rods are placed in the square set (Fig. 1).
- The rod cladding was identical to that used in LWRs: Zircaloy-4, 10.75 mm outside diameter, 0.725 mm wall thickness.
- Heating was carried out electrically using 6-mm-diameter tungsten heaters. Tungsten heating elements were installed in the centre of the rods and surrounded by annular ZrO2 pellets.
- The test bundle was instrumented with thermocouples attached to the cladding and the shroud at 17 different elevations with an axial distance between the thermocouples of 100 mm.

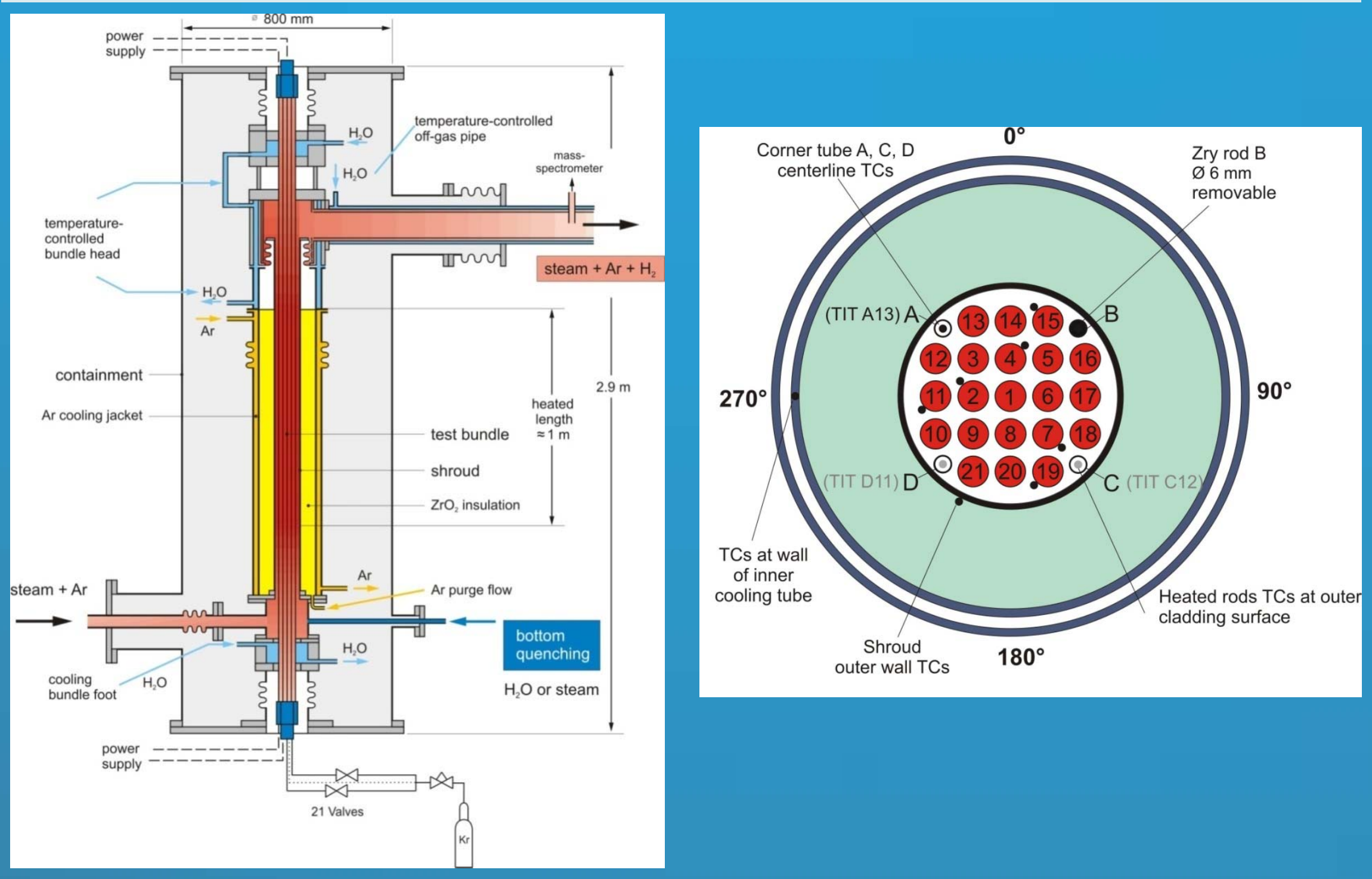


Fig. 1. QUENCH-16 test bundle

3. QUENCH-16 Phases

1. First heat-up phase in the flow of steam/argon mixture (mass flow rates 3/3.4 g/s , the heat-up to T≈1260°K in hot region;;
2. Pre-oxidation phase, the cladding temperature T≈1380°K in hot region;
3. Cooldown phase (preparation to air ingress) with temperature drop to ~930°K;
4. Air ingress phase with air mass flow rate 0.2 g/s at inlet, the heat-up to T≈1870°K in hot region
5. Bottom flooding phase, water mass flow rate 50g/s.

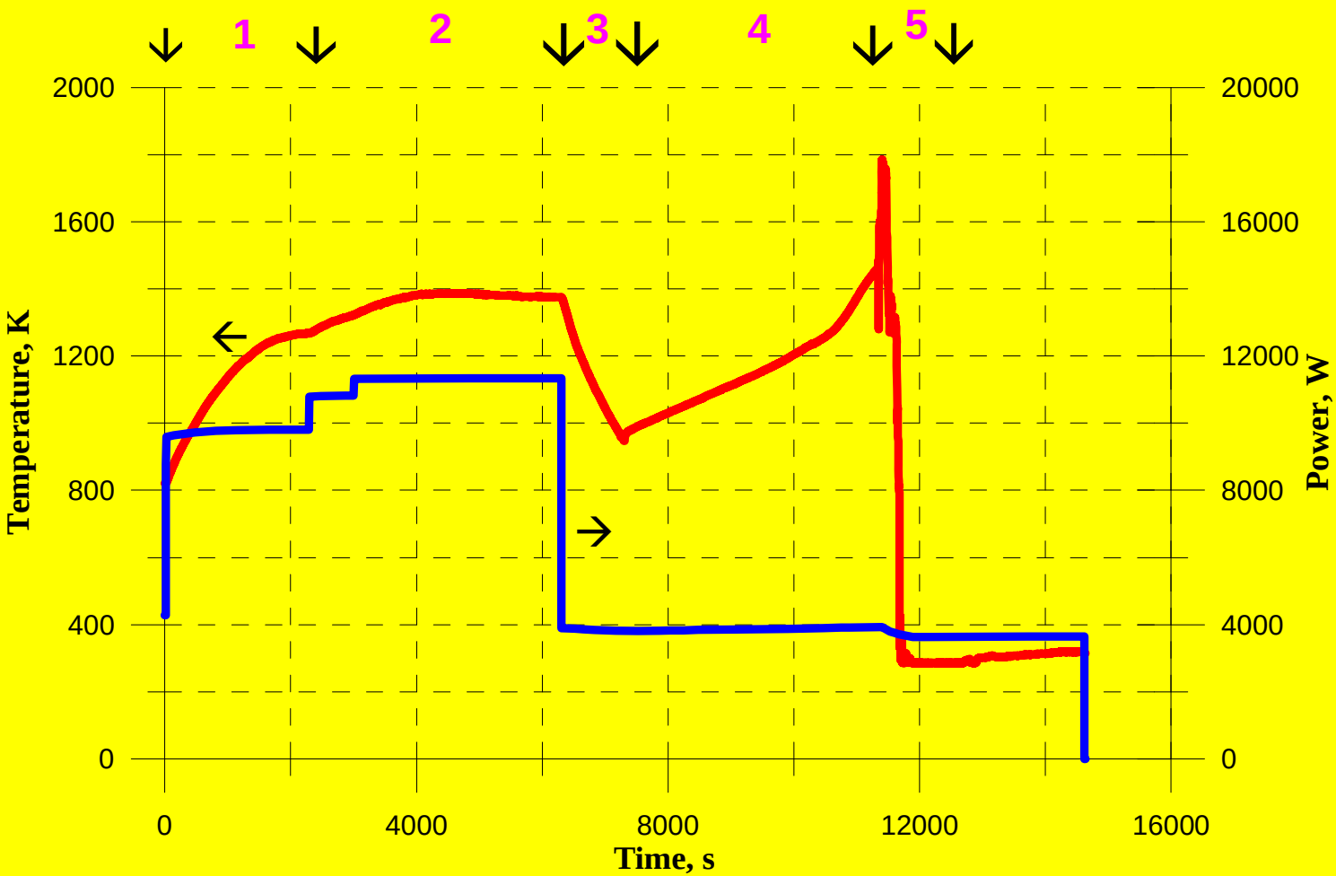


Fig. 2. QUENCH-16 temperature behaviour, power history. The numbers of phases are indicated

4. SOCRAT – Russian Best Estimate Computer Modelling Code

Things to do in application to NPP accidents:

Thermal hydraulics;
Severe accident phenomena (oxidation, melting, relocation *etc*.);
Thermal mechanics;
Containment processes;
Lower plenum and “core-catcher” behavior;
Aerosoles release and transport *etc.*

I only know that I know nothing…

SOCRAT

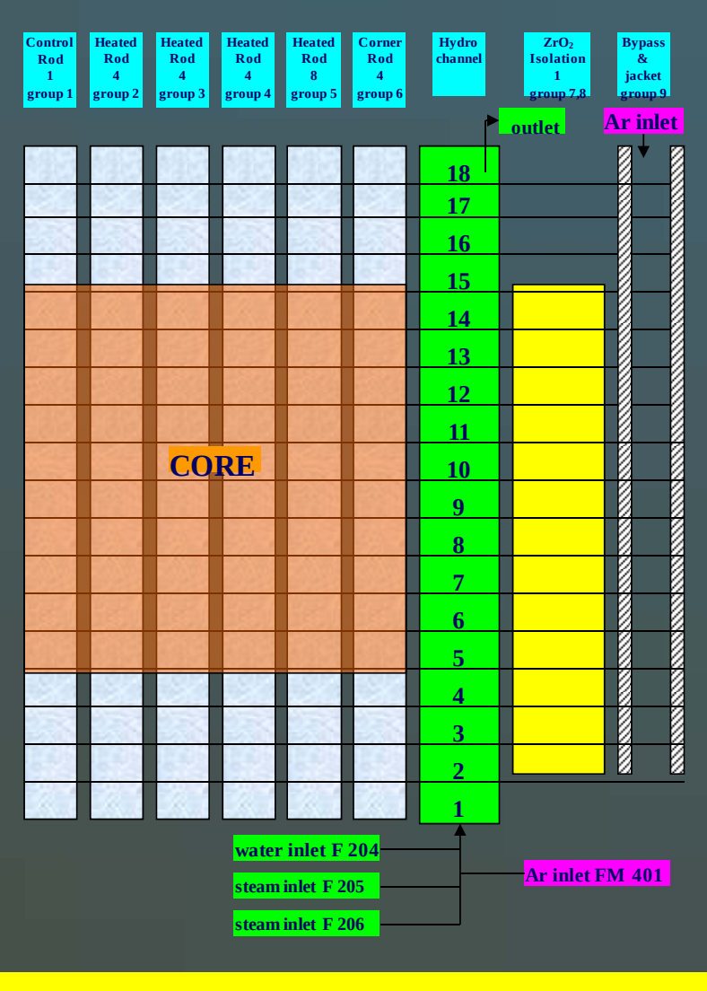


Fig. 3. SOCRAT nodalization for QUENCH-16

5. Experiment

Main input and boundary conditions are presented in Figures 4-6. Temperature dynamics is shown in Fig. 7

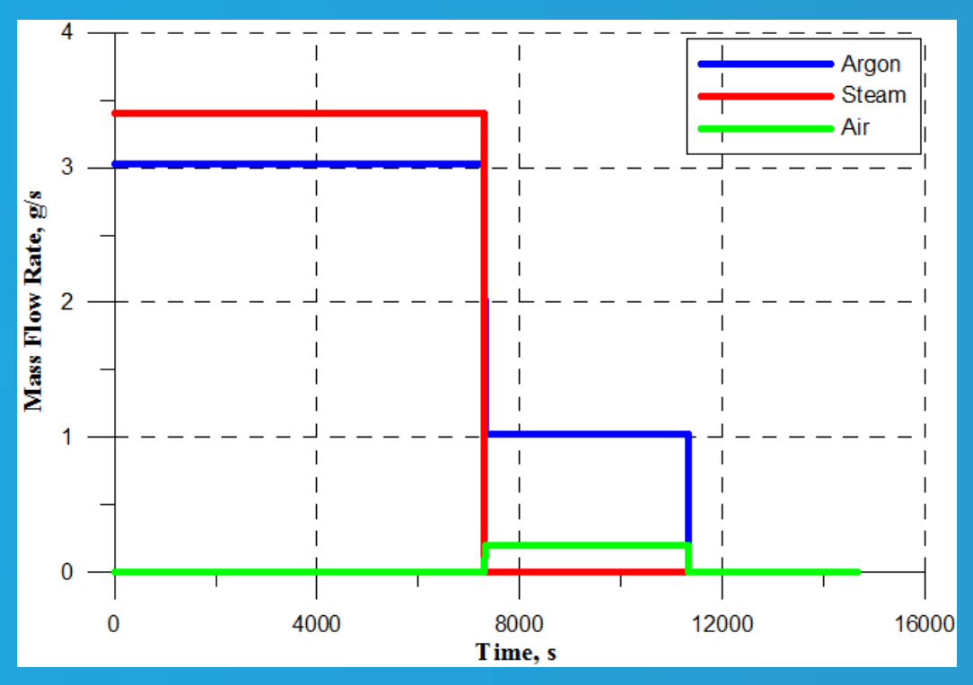


Fig. 4. QUENCH-16 mass flow rates of argon, steam and air

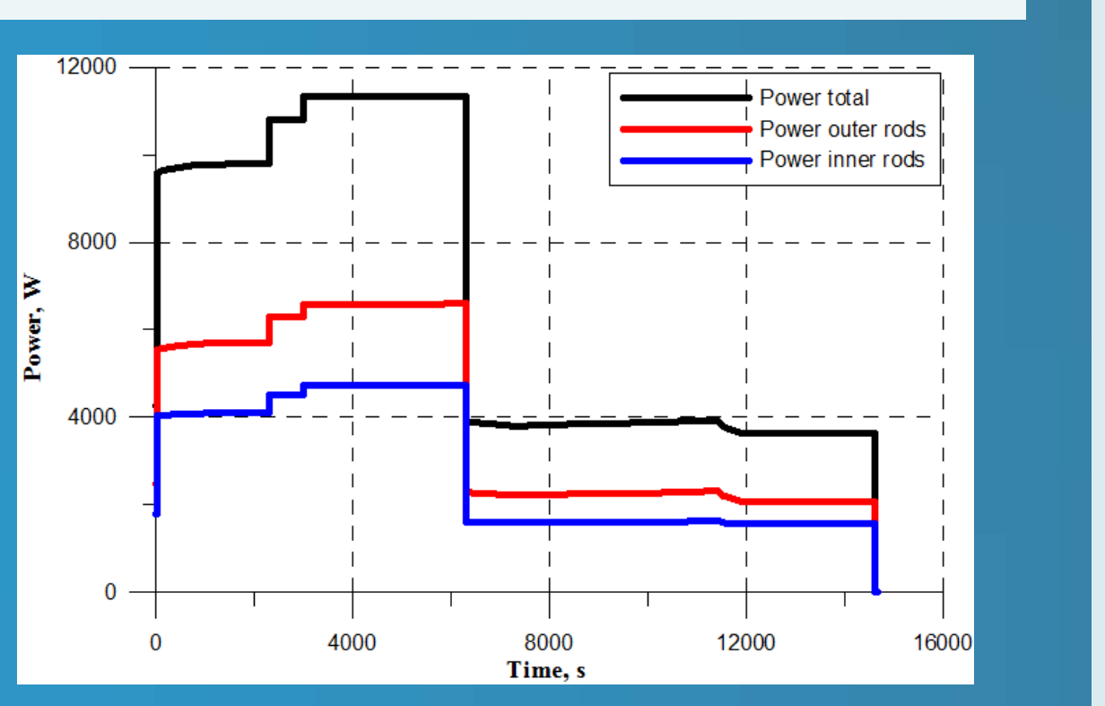


Fig. 5. QUENCH-16 electric power history

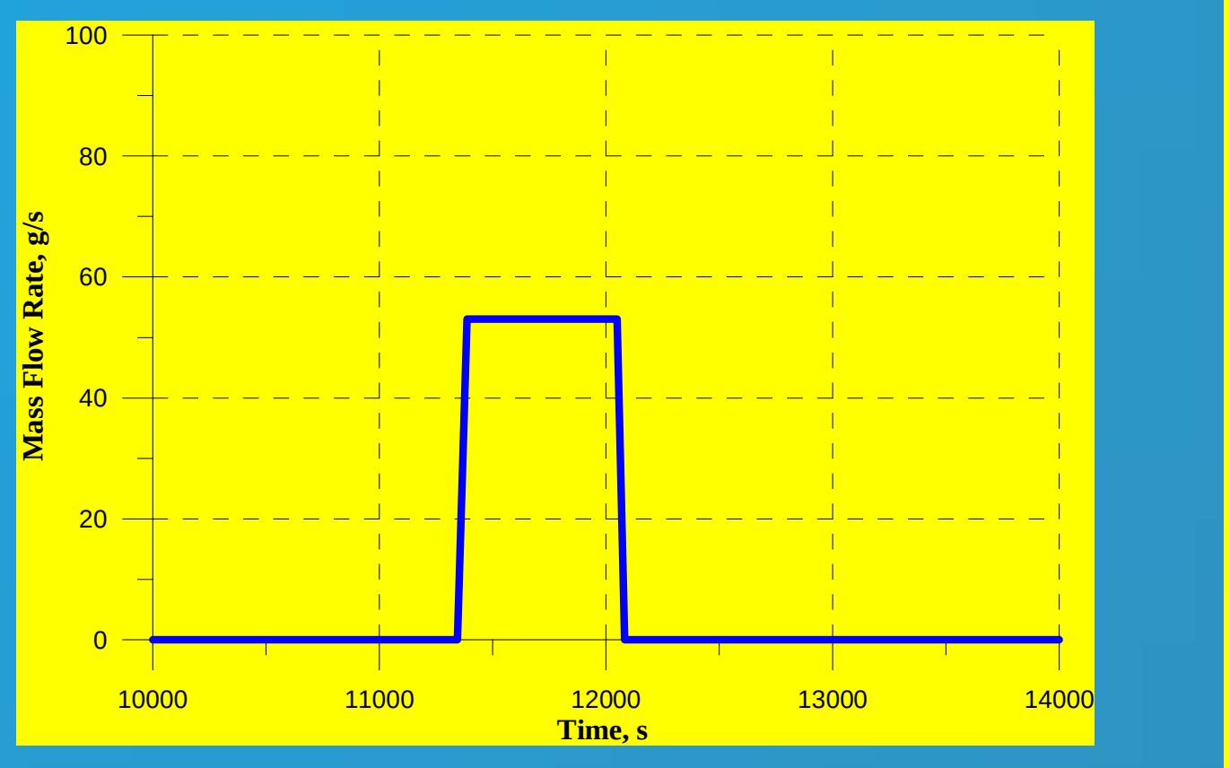


Fig. 6. QUENCH-16 water mass flow rates at reflood

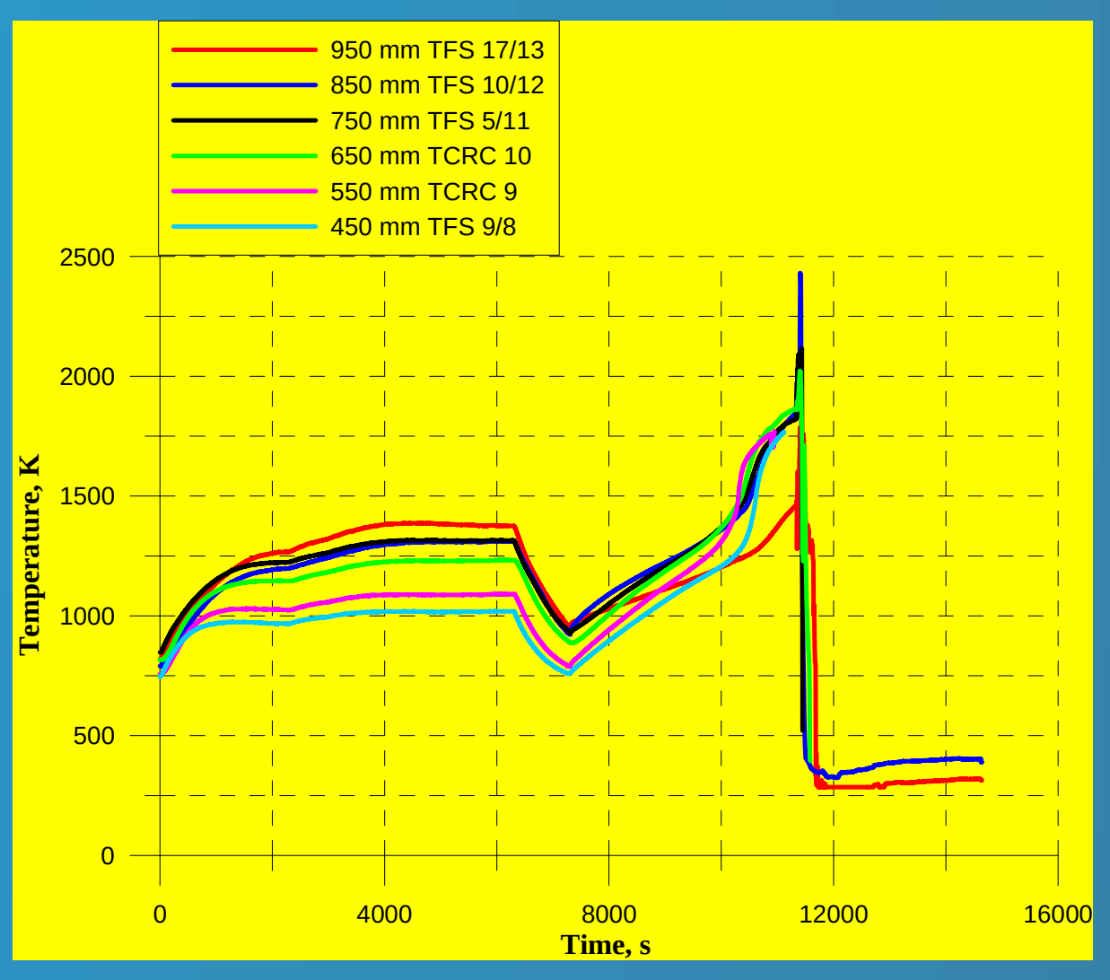


Fig. 7. QUENCH-16 experimental temperatures at different elevations

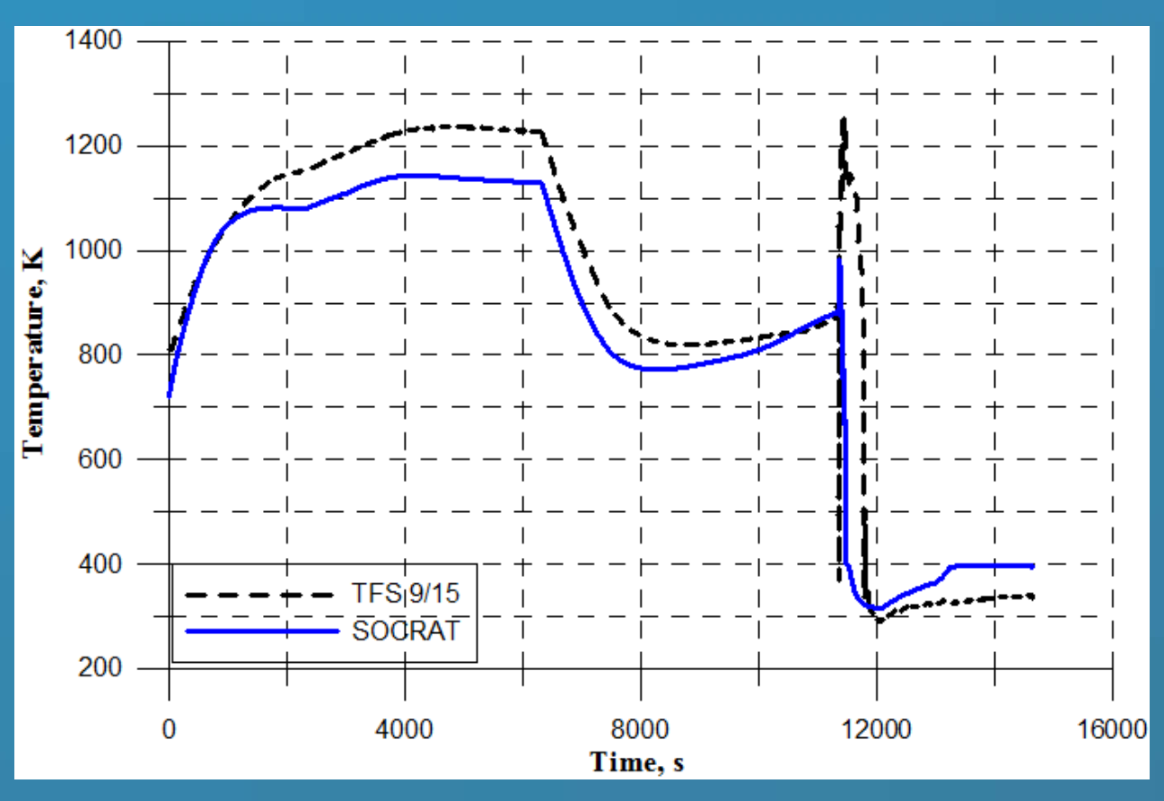
6. Results of QUENCH-16 Test Modelling

The basic thermal parameters of experiment QUENCH-LOCA-0 are reasonably reproduced by the code. SOCRAT overestimates temperatures at medium levels during air ingress phase.

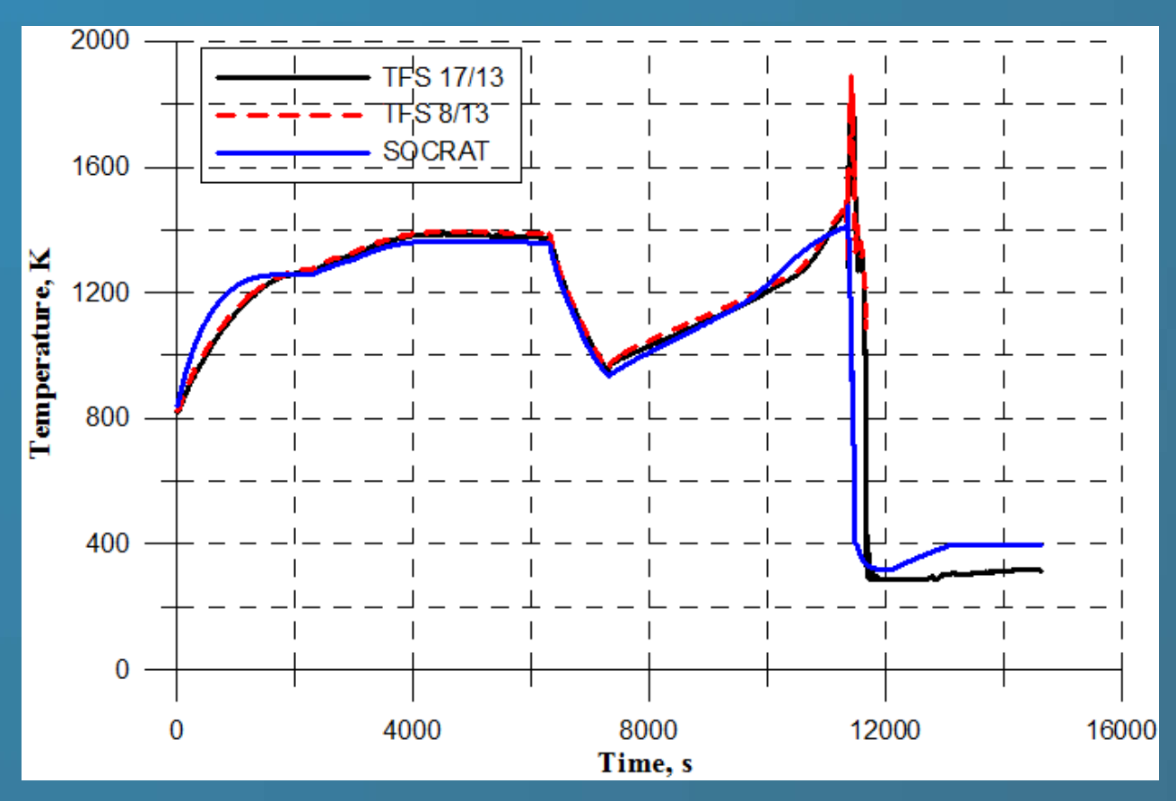
Cladding temperatures are presented in Fig. 8. Overall core heat balance – Fig. 9.

Calculated zirconia layer thicknesses (Fig. 10) are in a satisfactory agreement with the experimental values.

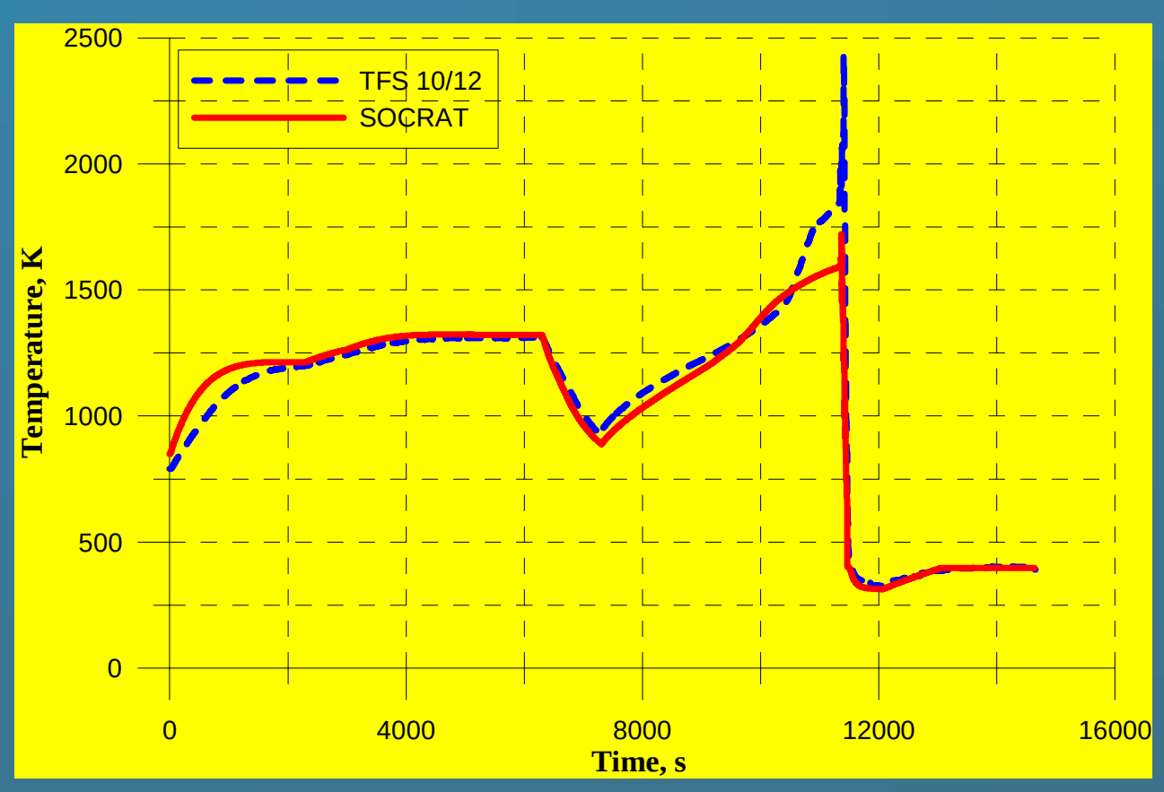
1150 mm



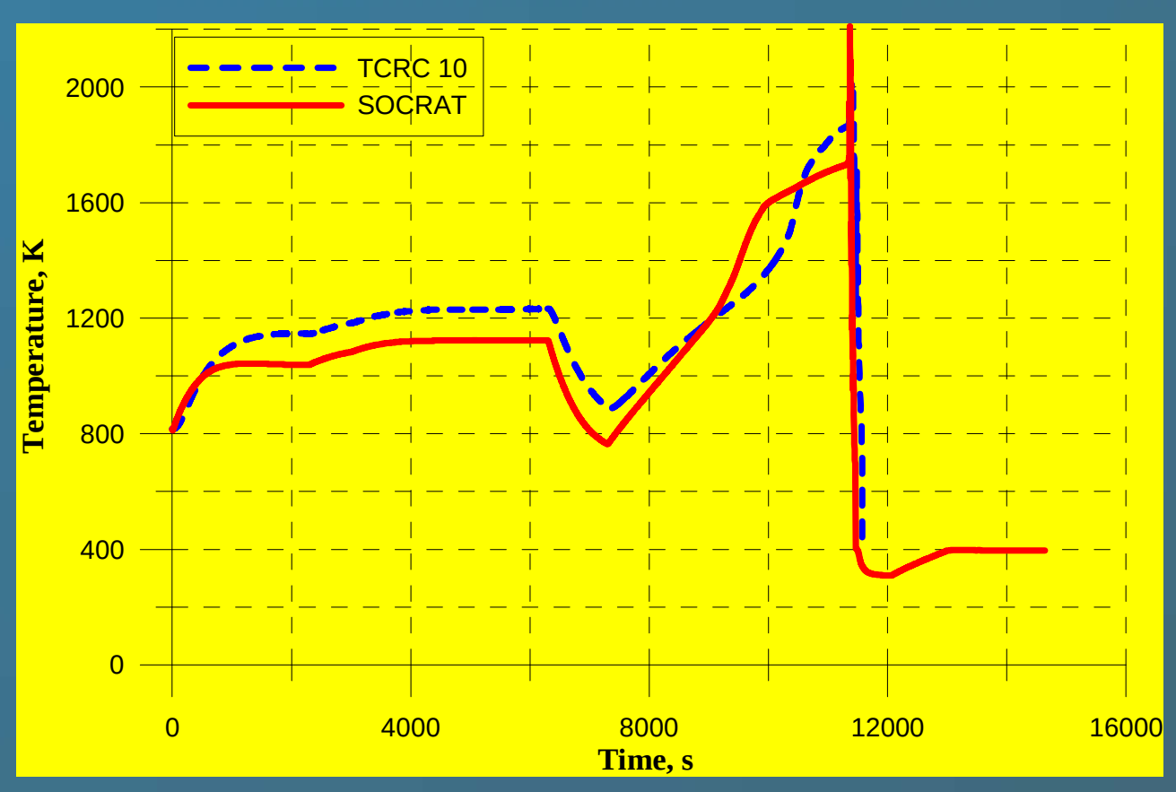
950 mm



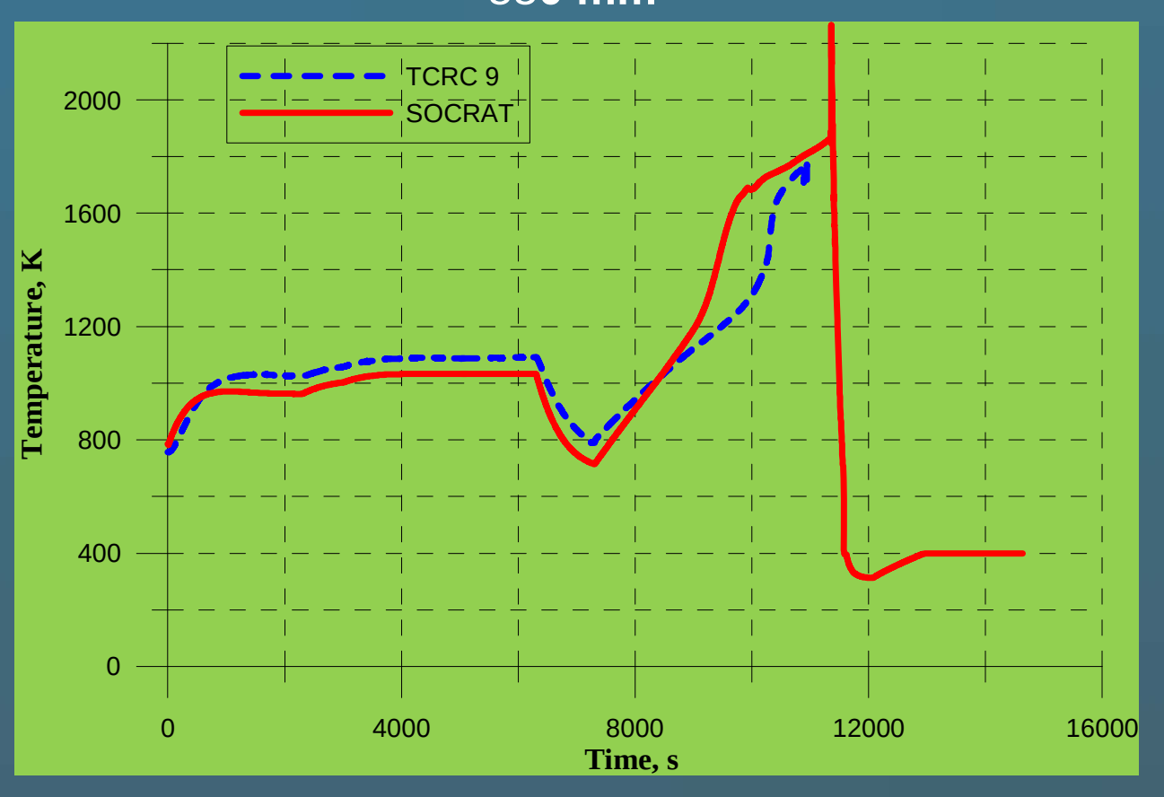
850 mm



650 mm



550 mm



50 mm

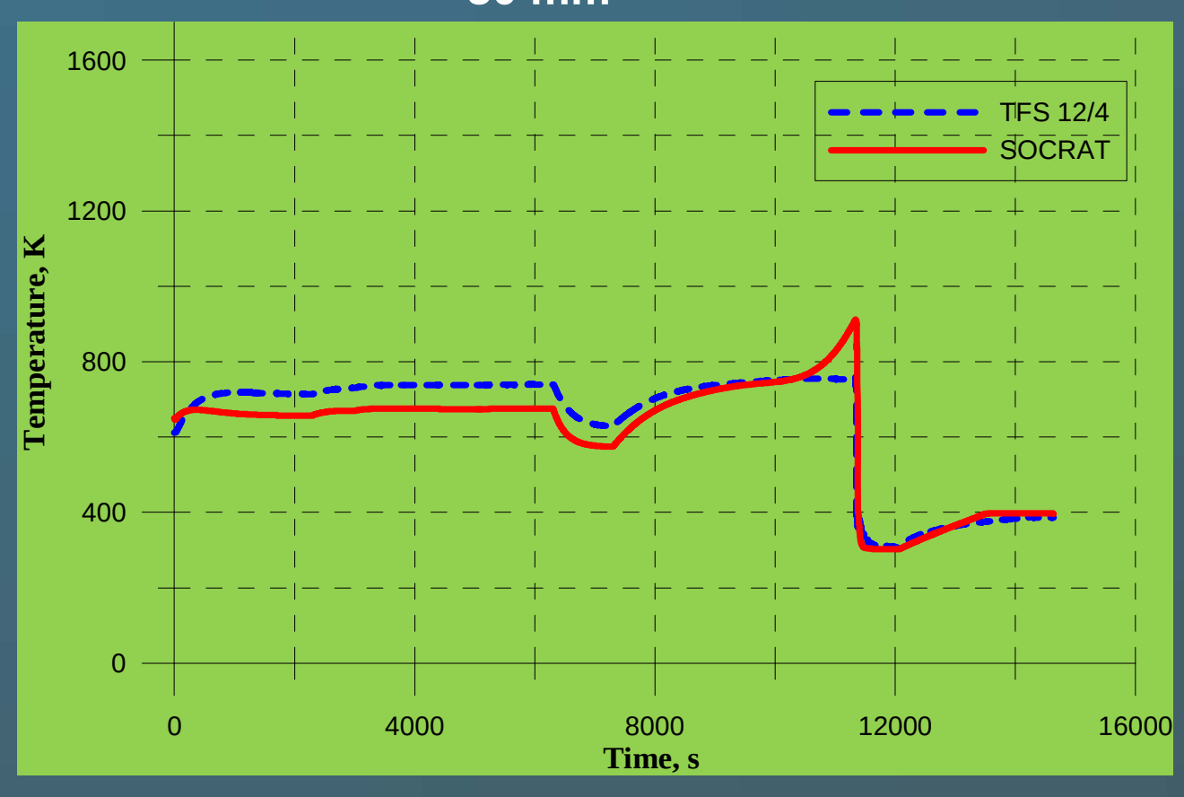


Fig. 8. Temperature dynamics at different elevations

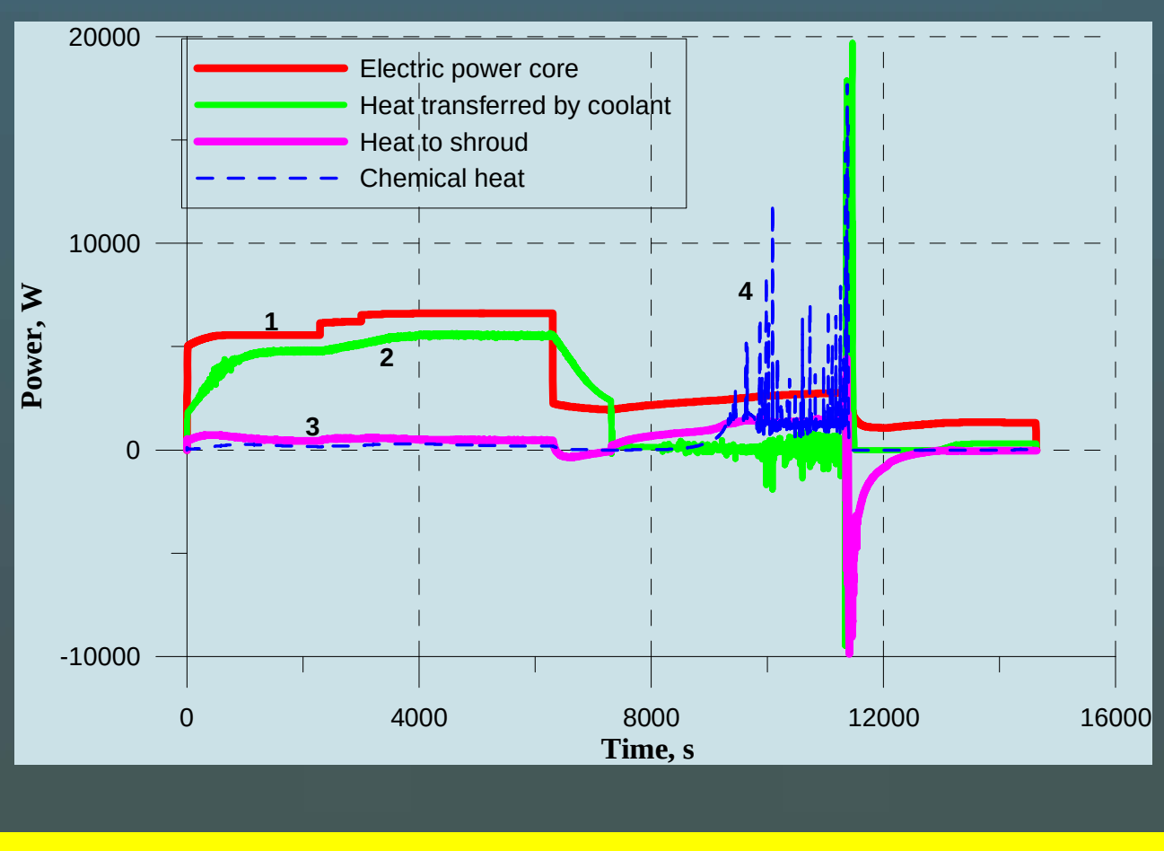


Fig. 9. QUENCH-16 calculated heat balance:
1 – total electric power, 2 – power transferred by gas, 3 – heat flux to shroud, 4 – chemical power

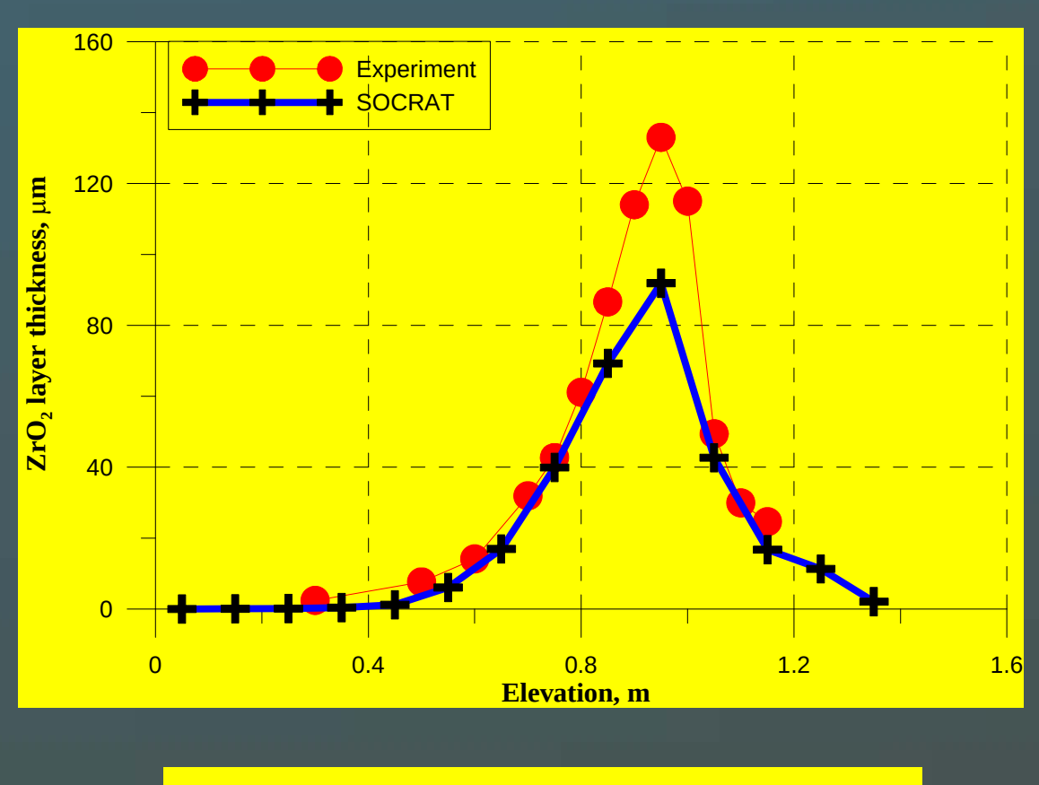
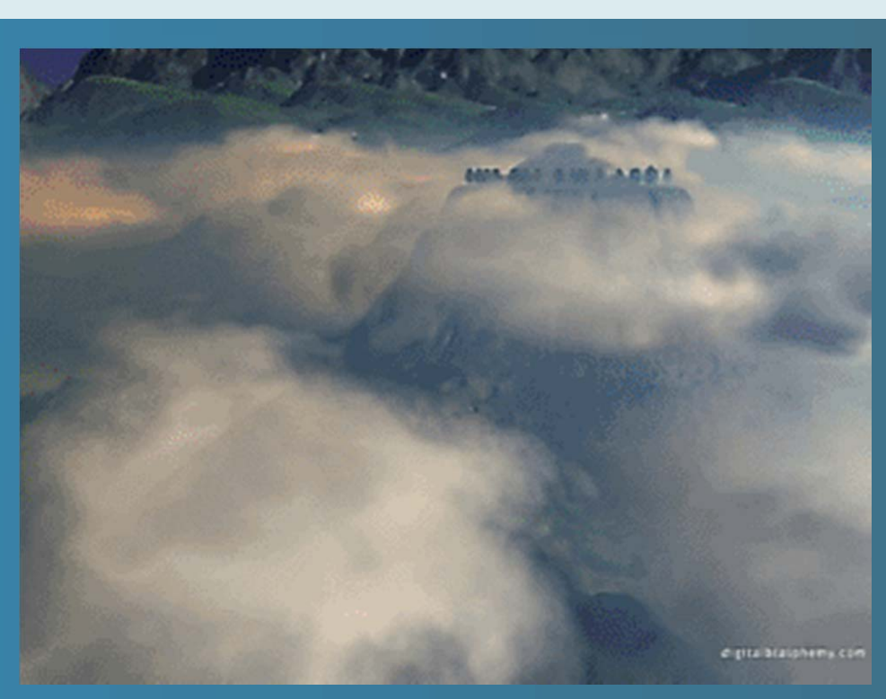


Fig. 10. QUENCH-16: corner rod B ZrO_2 layer thickness at time 7300 s

7. Air Ingress Features in QUENCH-16 compared to PARAMETER-SF4 and QUENCH-10

The air ingress phase (phase 4, Fig. 2) was very important phase of SF4 experiment. The oxidation of zirconium claddings in the air behaves in different way compared to oxidation in the vapour. First, the heat effect of the chemical reaction of oxidation in the air is approximately two times larger than in the vapour. Second, the kinetics of oxidation in the air is non-parabolic (approximately linear, that is more strong) in contrast to parabolic kinetics of zirconium oxidation in the vapour. So, the zirconium oxidation in air is very aggressive.

This is why the temperature behaviour at different elevations (Fig. 7) is that there is the tendency to reach highest temperatures at medium or even at bottom elevations (300-500 mm from the bottom of heated region). This fact is in contrast to oxidation in the vapour QUENCH tests where the highest temperatures were reached definitely at highest elevation 950 mm from the bottom of heated region.



Complicated nature of Aephiros

$$Zr+2H_2O=ZrO_2+2H_2+Q_{chemical,1}$$

$$Zr+O_2=ZrO_2+Q_{chemical,2}$$

$$Q_{chemical,2} \cong 2Q_{chemical,1}$$

Aggressive oxidation in Air!

SOCRAT is ready to calculate oxidation in air!

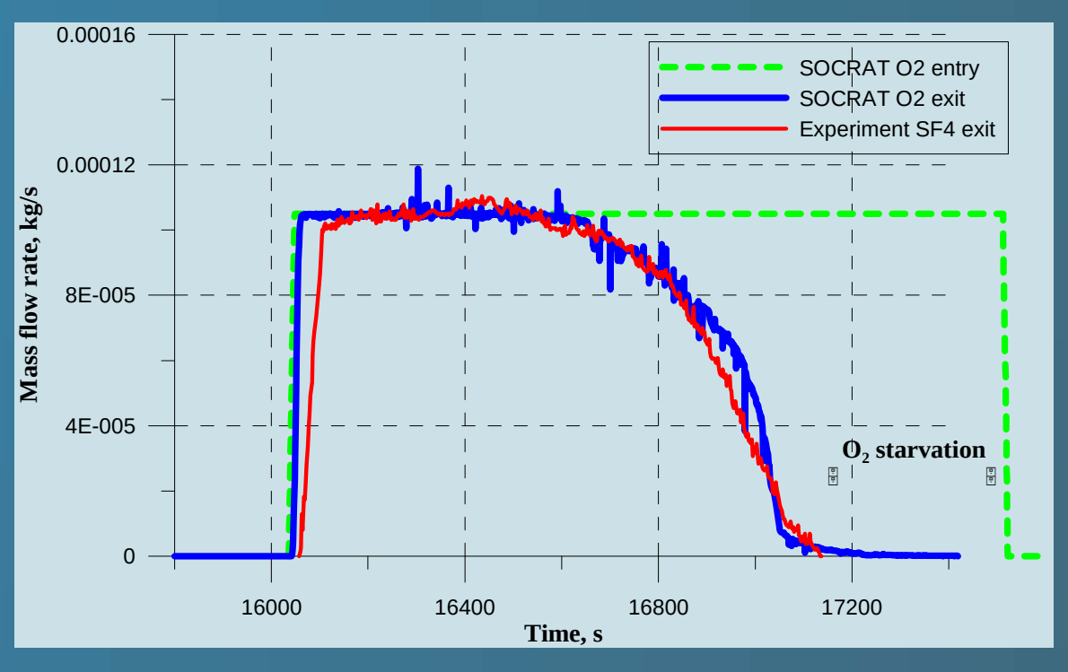


Fig. 11. PARAMETER-SF4 O_2 mass flow rate at the inlet and the outlet of test section. The oxygen starvation region is indicated

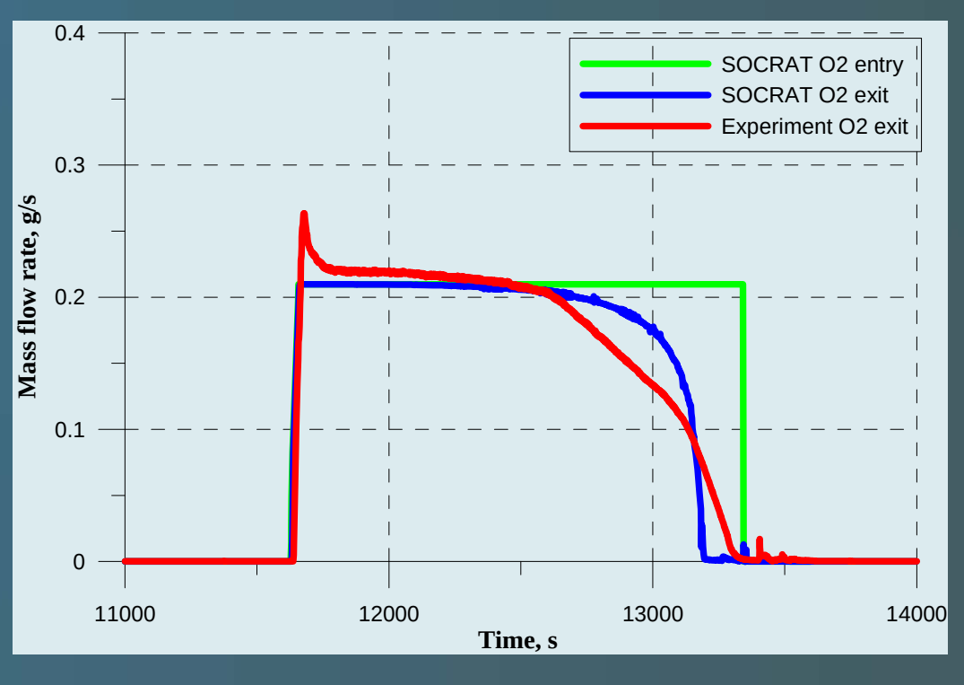
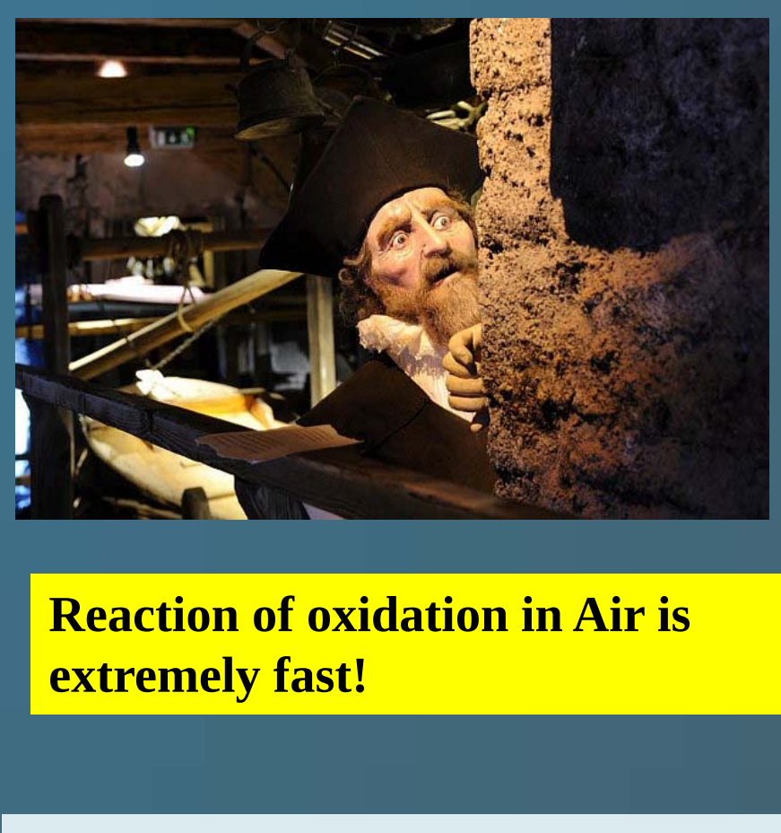


Fig. 12. QUENCH-10 O_2 mass flow rate at the inlet and the outlet of test section.



Reaction of oxidation in Air is extremely fast!

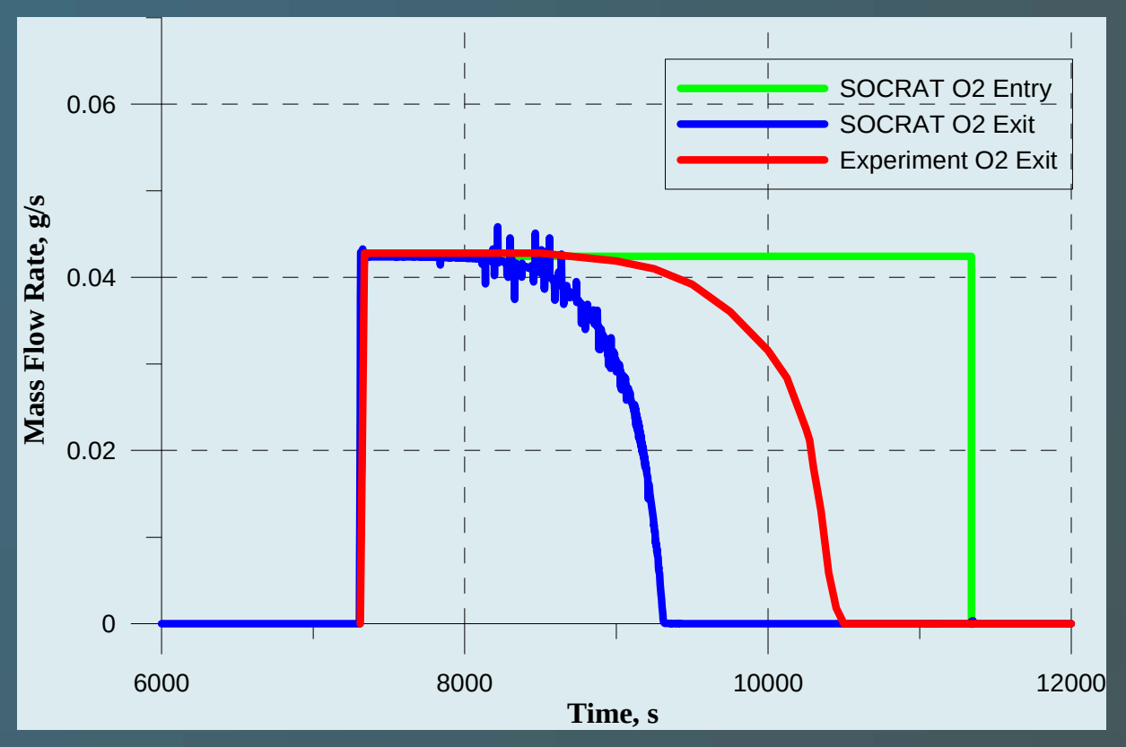


Fig. 13. QUENCH-16 O_2 mass flow rate at the inlet and the outlet of test section

Indeed, after pre-oxidation and cooldown phases the zirconium dioxide layers on rods surfaces at the bottom elevations were not thick enough to protect from intensive oxidation reaction in the air. When the air began to enter the fuel assembly, the strong oxidation was initiated at lower and medium elevations to result in fast temperature escalation.

Figures 11-13 show the oxygen (which is a constituent part of the air) mass flow rate at the inlet and at the outlet part of the fuel assembly in tests. One can see that the oxygen consumption grows as long as the cladding temperature becomes higher. Finally, the situation arises when all the oxygen entering the fuel assembly is consumed for oxidation of zirconium claddings. This state is called as total oxygen starvation.

ACKNOWLEDGMENTS

The work has been performed in the frame of the cooperation agreement between IBRAE and KIT in the field of nuclear energy research.

8. Conclusions

The lessons learned from severe nuclear accidents at Three Mile Island, US, 1979; Chernobyl, USSR, 1986, and Fukushima, Japan, 2011, showed the very high influence of severe accident processes on beyond design basis accident dynamics.

To get a realistic description, the deep understanding of hydraulic, mechanical and chemical processes taking place under NPP accident conditions is necessary, in particular, during air ingress conditions.

Posttest numerical modelling of QUENCH-16 test was performed using SOCRAT/V3 code. Results of thermal hydraulics and air ingress modelling are presented.

The calculated and experimental data are in a reasonable agreement. SOCRAT underestimates the time of oxygen starvation which may be connected with overestimation of oxidation by air at fuel assembly medium levels in calculations.