Kokshaga river

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Post-Test Calculation of the QUENCH-17 Bundle Experiment with Debris Formation and Bottom Water Reflood Using Thermal Hydraulic and Severe Fuel Damage Code SOCRAT/V3

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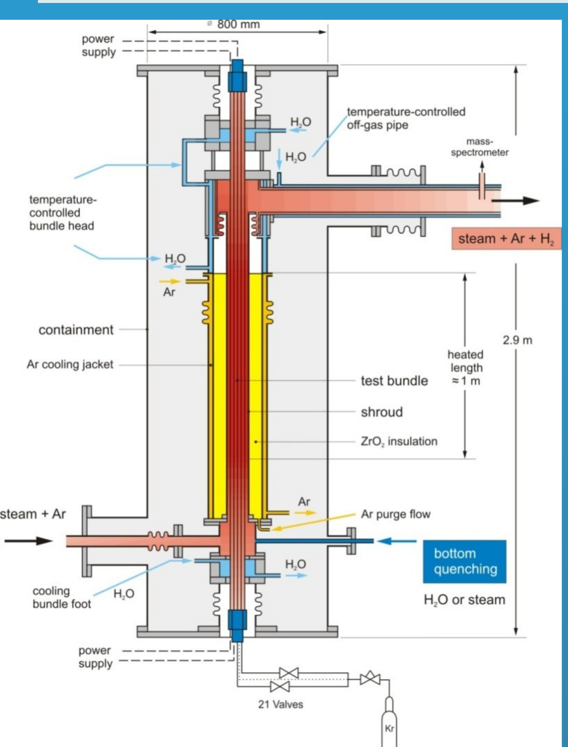
Schwarzwald

1. Purpose

The purpose of this work is using of the computer modelling code SOCRAT/V3 for post-test evaluation of bundle test QUENCH-17 with debris.
The QUENCH-17 test conditions simulated a representative scenario of LOCA (Loss of Coolant Accident) nuclear power plant accident sequence in which the overheated up to 1800K core would be reflooded from the bottom by ECCS (Emergency Core Cooling System).
The test QUENCH-17 was successfully conducted at the KIT, Karlsruhe, Germany, in January 30-31, 2013. The objective of this test was to examine the formation of a debris bed inside the completely oxidised region of the bundle without melt formation and to investigate the coolability behaviour during the reflood.
The important feature of QUENCH-17 test was the massive porous debris bed formation just before bottom water reflood initiation.

2. QUENCH-17 Facility

- The QUENCH-17 test bundle (Fig. 1,2) was made up of 21 fuel rod simulators with a length of approximately 2.5 m. The rods are placed in the square set.
- Only 12 periphery fuel rod simulators were heated over a length of 1024 mm.
- 9 unheated fuel rod simulators were located in the inner part of bundle.
- Heating was carried out electrically using 6-mm-diameter tungsten heating elements installed in the centre of the periphery rods and surrounded by annular ZrO_2 pellets.
- Massive porous debris formation in the inner part of the bundle was not influenced by the presence of tungsten heaters
- The high melting temperature of Hf ensured that the claddings withstood high temperature phase of the test.
- 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.



Periphery rods claddings, corner rods and shroud made of hafnium!

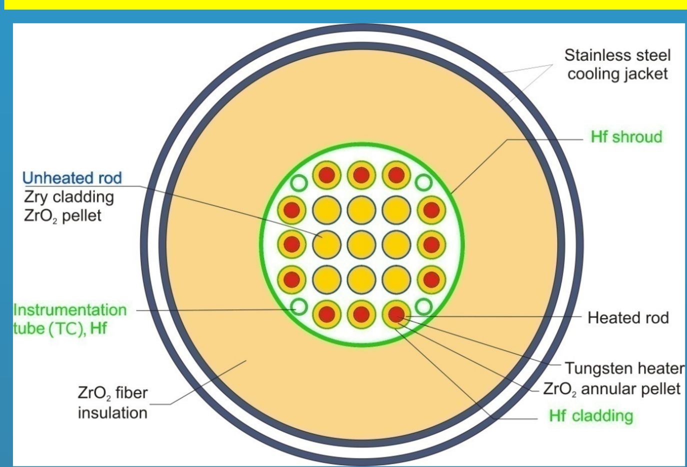


Fig. 1. QUENCH-17 test bundle

3. QUENCH-17 Phases

1. Heat-up phase, mass flow rates 2 g/s and 2 g/s (steam and argon), the heat-up to T≈1900 K in hot region;
2. Pre-oxidation phase, the peak cladding temperature T≈1800 K, with debris bed formation at about 77,500 s in the end of phase;
3. Bottom flooding phase, water mass flow rate 10 g/s.

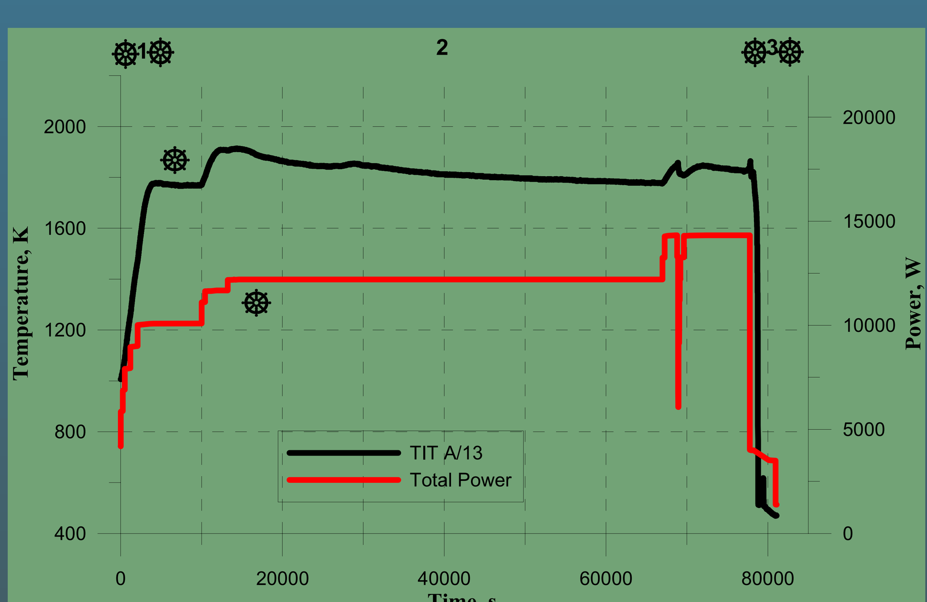


Fig. 2. QUENCH-17 temperature behaviour, power history. The numbers of phases are indicated

I only know that I know nothing…

SOCRAT 470 BC-399 BC

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.*

Fig. 3. SOCRAT nodalization for QUENCH-17

Mass flow rates are presented in Fig. 4. Debris module block-scheme is in Fig. 5.

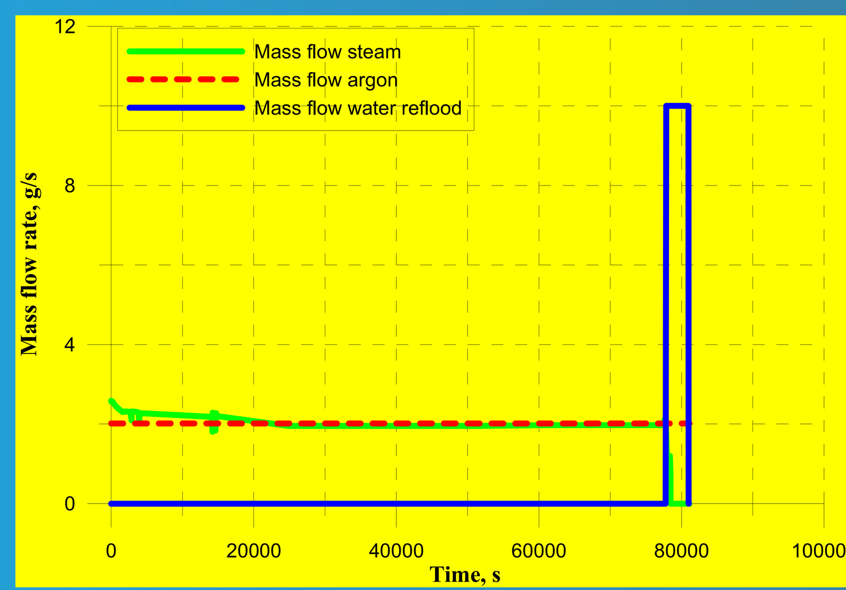


Fig. 4. QUENCH-17 mass flow rates of argon, steam and flood water

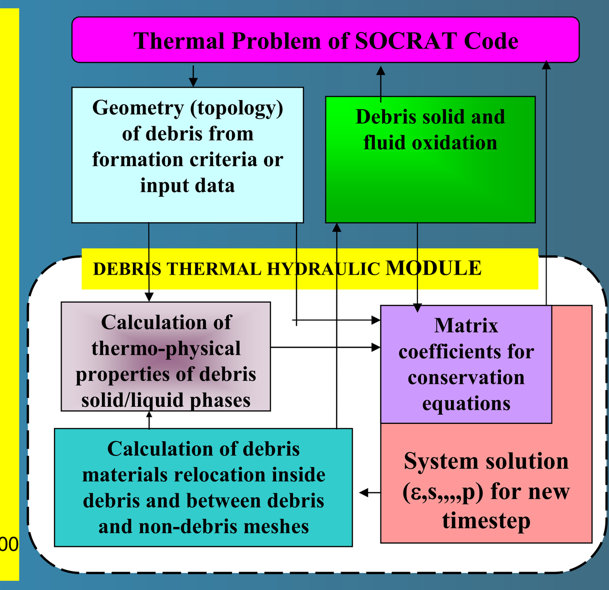
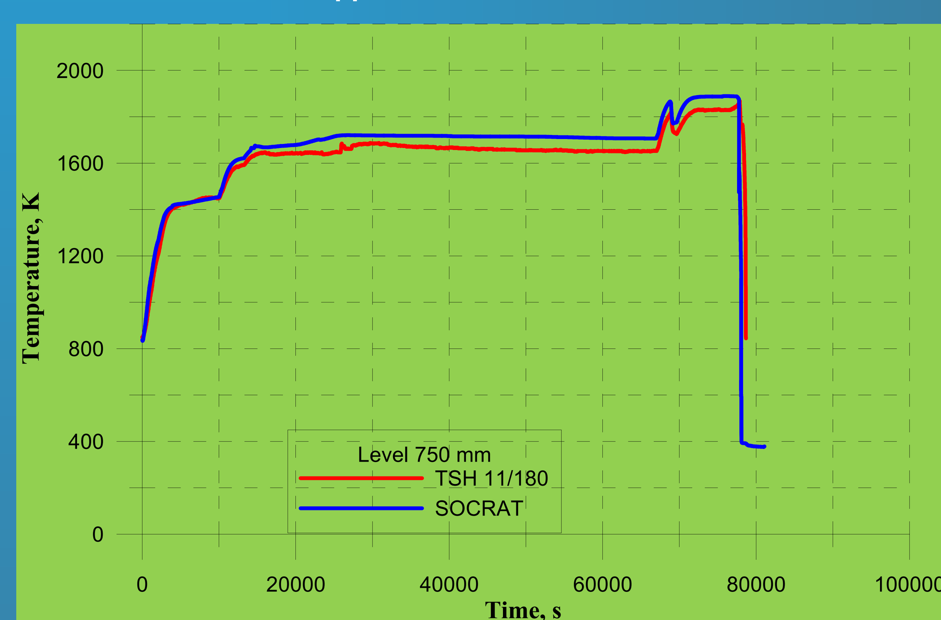


Fig. 5. Block-scheme showing relations between different sub-modules of SOCRAT debris behaviour module

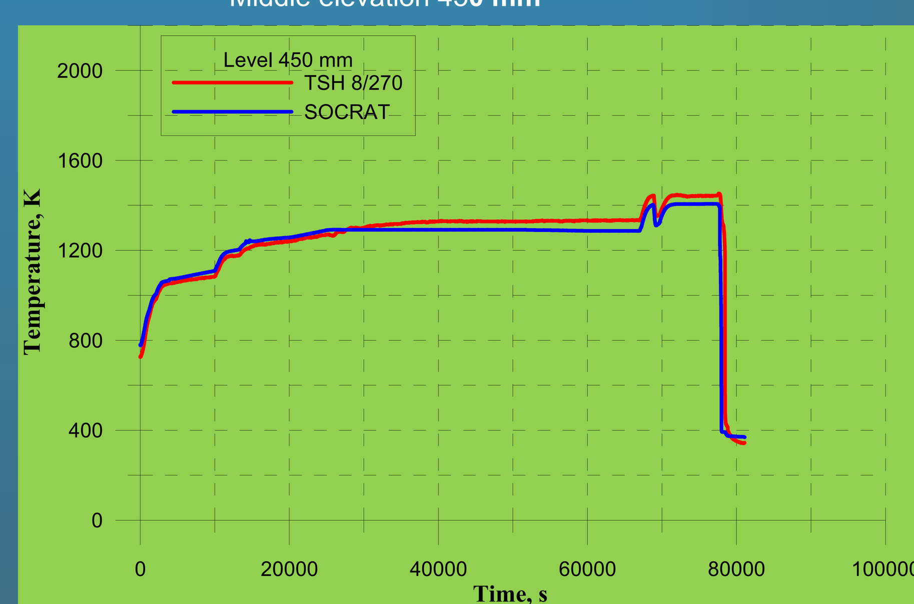
5. Results of QUENCH-17 Test Modelling

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. 6. Overall core heat balance – Fig. 7.
Hydrogen production is in Fig. 8.

Upper elevation 750 mm



Middle elevation 450 mm



Lower elevation 150 mm

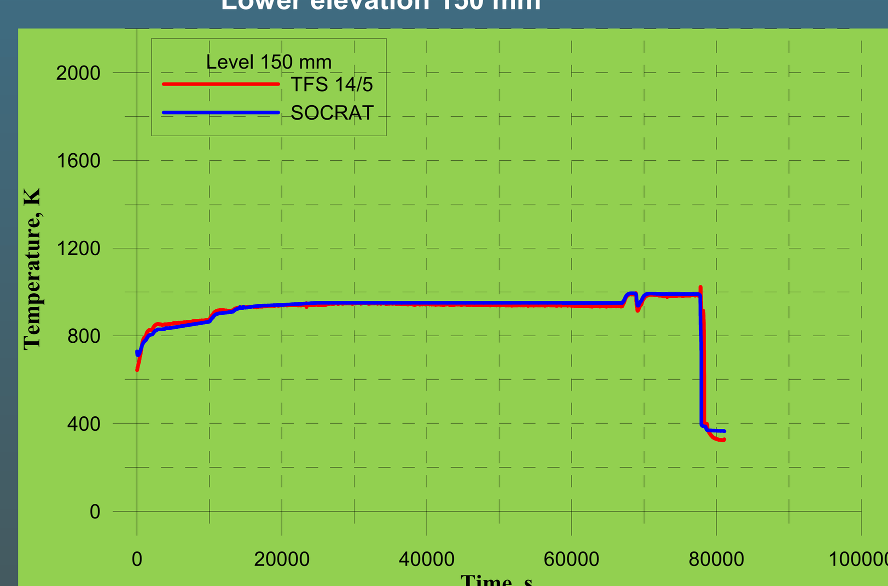


Fig. 6. Temperature dynamics at different elevations

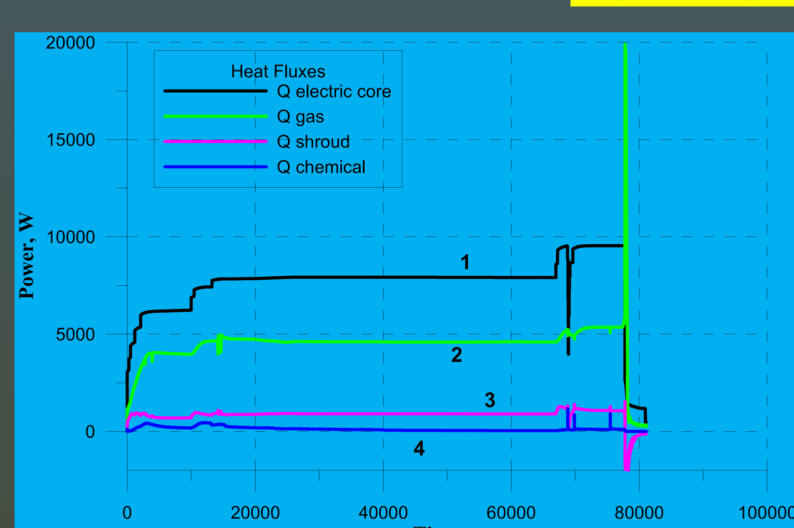


Fig. 7. QUENCH-17 calculated heat balance:
1 – total electric power,
2 – power transferred by gas,
3 – heat flux to shroud,
4 – chemical power

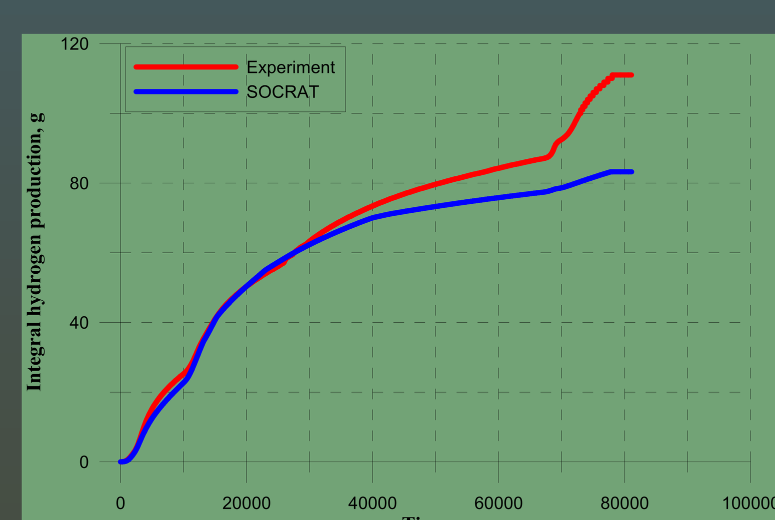


Fig. 8. QUENCH-17: integral hydrogen production

6. Reflood Features in QUENCH-17

In the course of QUENCH-17 test the fuel rods experience two stages of rods destruction status as accident progresses:
•Undamaged (initial) geometry;
•Debris geometry.
All three types of heat transfer (conduction, convection, radiation) experienced a sharp change after transition from undamaged geometry to debris bed geometry. Reflood in QUENCH-17 was in porous debris geometry.
Continuity, momentum and energy equations for each phase are used to describe the porous debris dynamics. For example, a generalized momentum equation for a porous medium is written in the following form:

$$\frac{\rho_f}{\varepsilon s}\frac{\partial\langle\bar{u}_f\rangle}{\partial t}+\frac{\rho_f}{\varepsilon s}\left(\langle\bar{u}_f\rangle\cdot\bar{\nabla}\right)\left(\frac{\langle\bar{u}_f\rangle}{\varepsilon s}\right)=-\bar{\nabla}\langle p\rangle^f+\rho_f\bar{g}+\frac{\mu_f}{\varepsilon s}\Delta\langle\bar{u}_f\rangle-\frac{\mu_f}{K}\langle\bar{u}_f\rangle-\frac{C_E}{K^{1/2}}\rho_f\left|\langle\bar{u}_f\rangle\right|\langle\bar{u}_f\rangle$$

$\bar{u}_f$ is the velocity vector, ρ_f the fluid density, μ_f the dynamic viscosity, ε the porosity, s the saturation, p the pressure, g the gravity, K the permeability and C_E the Ergun constant

Fig. 9 QUENCH-17: debris between Zry and Hf rods

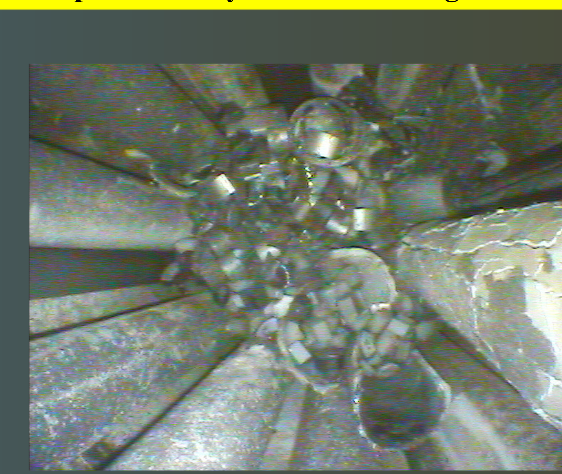
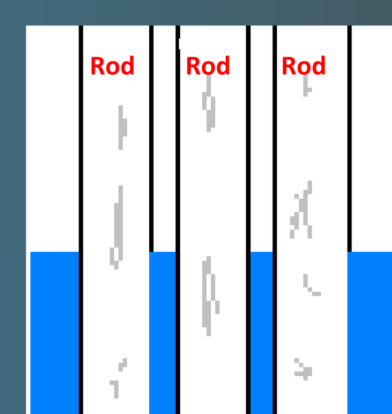


Fig. 10 QUENCH-17: debris accumulated on spacer grid

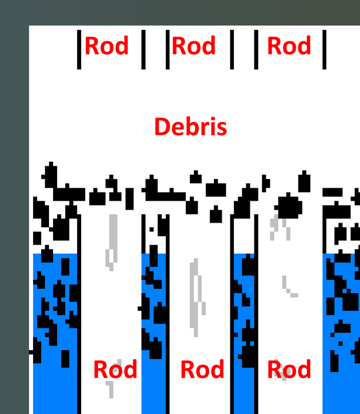
SOCRAT

Reason & intellect
Undamaged geometry



CYCLOPE

Destruction & chaos
Debris geometry



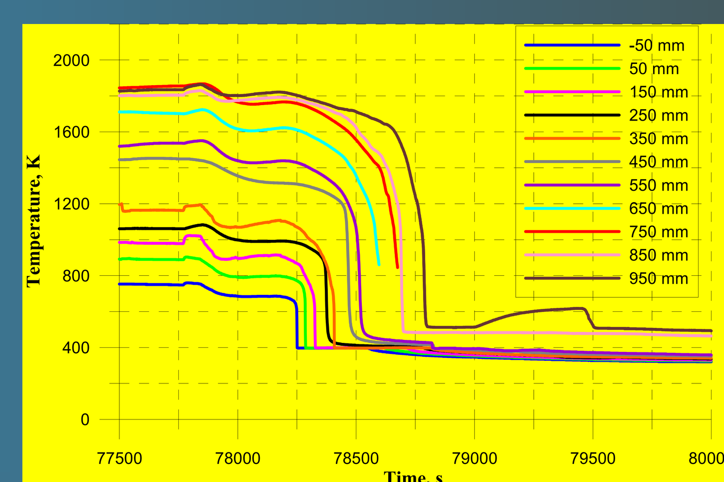


Fig. 11. QUENCH-17: experimental temperatures at different elevations during reflood

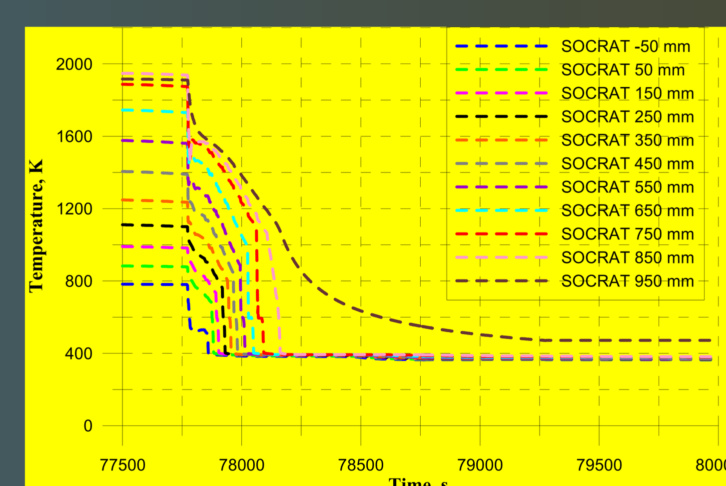


Fig. 12. QUENCH-17: calculation temperatures at different elevations during reflood

So, the characteristic experimental time of quenching in QUENCH-17 was equal approximately 800 s. It is much longer than quench time in classical QUENCH-06 test (about 300 s) with undamaged geometry at reflood. It is necessary to take into account, however, that reflood mass flow rate in QUENCH-06 was 40-50 g/s (opposite to 10 g/s in QUENCH-17). Also, the temperatures at reflood initiation were different for these tests - 1800 K in QUENCH-17 against 2100 K in QUENCH-06.

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 debris formation conditions.

A long-term oxidation scenario was realized to get massive high temperature porous debris zone in QUENCH-17 test. The massive debris bed was formed at axial elevations from 350 to 950 mm.
SOCRAT/V3 computer modelling code was used for calculation of basic thermal hydraulic, oxidation and thermal mechanical behaviour during all phases of the experiment.
In general, the calculated results are in a good agreement with experimental data which justifies the adequacy of modelling capabilities of SOCRAT code system.
The coolability of massive debris bed was supported by experimental and calculation results.
SOCRAT/V3 underestimates characteristic time of quenching. Presumably, possible reasons for it are of thermo-hydraulic nature: neglecting of spacer grids, flow regime map description near boiling curve and incorrectness of porous debris hydraulics. The upgrading of models is currently underway.