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

Alexander Vasiliev  
Nuclear Safety Institute (IBRAE)  
B.Tulskaya 52  
115191 Moscow, Russia  
vasil@ibrae.ac.ru

Juri Stuckert  
Karlsruhe Institute of Technology (KIT)  
Kaiserstrasse 12  
76131 Karlsruhe, Germany  
juri.stuckert@kit.edu

ABSTRACT

The thermal hydraulic and SFD (Severe Fuel Damage) best estimate computer modelling code SOCRAT/V3 was used for the calculation of the QUENCH-17 experiment which was the first test in the QUENCH tests series simulating debris behaviour.

The QUENCH-17 test conditions simulated a representative scenario of nuclear power plant severe accident sequence with debris bed formation in which the overheated up to 1800 K core would be reflooded from the bottom by ECCS (Emergency Core Cooling System). The QUENCH-17 test included the following phases:

- Heat-up phase (heat-up rate up to 0.25 K/s);
- Oxidation phase (the cladding temperature T\approx 1800 K in hottest region, steam mass flow rate 2 g/s);
- Bottom flood phase (characteristic cooling time \approx 600 s, water mass flow rate 10 g/s).

The test QUENCH-17 was successfully conducted at the KIT, Karlsruhe, Germany, on 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 QUENCH facility is designed for studies of the PWR fuel assemblies behaviour under conditions simulating design basis, beyond design basis and severe accidents.

The test bundle for the QUENCH-17 test was intentionally changed in comparison to basic QUENCH tests with the emphasis to investigate debris behaviour phenomena. Only 12 periphery fuel rod simulators were heated. 9 unheated fuel rod simulators were located in the inner part of the test bundle. This is why the massive porous debris formation in the inner part of the bundle was not influenced by the presence of tungsten heaters.

The SOCRAT/V3 computer modelling code was used for the calculation of basic thermal hydraulic, oxidation and thermal mechanical behaviour during all phases of the experiment.

The calculated results are in a good agreement with experimental data which justifies the adequacy of modelling capabilities of the SOCRAT code system.
INTRODUCTION

The heat-up, melting, relocation and hydrogen generation phenomena, relevant for high-temperature stages in a reactor severe accident are governed in particular by heat and mass transfer in porous debris and molten pools which are formed in the core region. The rods eventually lose their mechanical holding and collapse into heaps of particles named “porous debris bed”. The accurate modelling of its behaviour is very important for adequate description of accident dynamics.

The analysis of the TMI-2 accident [1] and the results of integral out-of-pile (CORA [2], QUENCH [3]) and in-pile experiments (PHEBUS [4], PBF [5]) have shown that the debris zones are formed in high temperature regions of the core. It has also been found in reflood tests that before the water succeeds in cooling the fuel pins, there is an enhanced oxidation of the zircaloy cladding that in turn causes a sharp increase in temperature, hydrogen production and fission product release.

It is assumed that new metallic surfaces are formed by cracking and fragmentation of the oxygen-embrittled cladding tubes as a result of the thermal shock during flooding leading to enhanced oxidation and hydrogen generation.

Unfortunately, the physical processes taking place during the late phase of severe accidents are still very complicated and rather far from complete understanding. The main phenomena important for adequate description of debris behaviour are as following: debris formation, coolant flow through debris and corresponding heat transfer, mass and energy transfer in debris, phase transitions and chemical reactions, decay and chemical heat generation, convective and radiative heat transfer, solid crust formation and disappearance on region boundaries.

Cladding melt relocation occurred laterally and axially within the confinement of the scale by which the surface area is diminishing and the thermal contact to the pellets is improving [3]. This contributes to the development of large temperature variations. Together with the embrittlement of bare scale (without contact to metallic cladding but in contact with the steam) this can result in scale cracking and triggering of internal oxidation and outward melt penetration, which will accelerate the steam oxidation. The analysis of QUENCH-02, QUENCH-03 [3] and QUENCH-09 [6] experiments shows that the major hydrogen release took place in debris and melt regions formed in the upper part of the fuel assembly.

The factors which complicate the problem are eutectics formations between interacting materials typical of reactor technology (UO$_2$, ZrO$_2$, Zr, Fe, Cr, Ni, B$_4$C) and a lack of thermophysical data for the high temperature region (in the course of an accident, the temperature reaches the value 3100 K and higher).

The degradation is non-homogeneous and the core exhibits, at the same time, both damaged and undamaged regions. The important part of porous debris numerical analysis is the modelling of radiative heat transfer in the debris and between debris and non-debris (initial geometry) meshes. Some approaches are used in the literature to describe the radiative heat transfer in the core [7,8].

Heat and mass transfer in porous media have been investigated intensively during the last three decades due to their extremely wide applications including not only nuclear engineering but also geothermal energy, oil industry, pollutant migration in waters, different types of heat exchangers, thermal isolation in buildings and tubes etc. [9-11]. A detailed review of the subject of flow in porous media has been recently done by Pop and Ingham [12].

The new concepts which are now used in the development of best-estimate computer modelling codes include the detailed self-consistent modelling of a wide spectrum of physical phenomena typical of the late stage of a severe accident. This is why the adequate calculation
of porous debris behaviour is now a very important part of severe accident analysis using best-estimate computer codes.

Porous debris models will allow more realistic physical modelling of the core degradation, and move the sophistication of the thermal evaluations more parallel to other processes simulations. This is an incremental improvement to a code customized to thermal-hydraulic and severe fuel damage evaluations.

The debris models have been implemented into known severe accident codes such as RELAP/SCDAP [13], MELCOR [14] and CATHARE/ICARE [15]. In particular, a very detailed advanced model of debris behaviour was developed by F. Fichot from IRSN, France. This model is an important constituent part of the French severe accident code ICARE. Comprehensive analysis of debris modelling is presented by F.Fichot et.al. [16].

CATHARE/ICARE was recently applied to a debris bed experiment at the PRELUDE facility [17]. On the basis of that investigation, ICARE debris models were improved to better describe thermal hydraulics of debris during reflood.

Another experimental program planned at the PEARL facility [18] will also help to get a deeper understanding of the debris related phenomena characteristic for beyond design basis accidents in PWRs.

The objective of the QUENCH-17 bundle test was the investigation of thermo-hydraulic, thermo-mechanical and physico-chemical phenomena under severe accident conditions with debris formation. All ambitious experimental programs on debris phenomena will definitely elucidate many questions about porous debris behaviour and allow to upgrade existing debris models in different configurations including a bundle geometry.

The basic distinctive features of the model used in the SOCRAT computer modelling code [19] compared to another existing debris bed models implemented into severe accident numerical codes listed above include the unified approach to the description of flowing objects for different stages of degradation (drop, stream, debris, pool), the possibility for application to the constructive and geometrical features of VVER, and the choice of the mechanisms of debris formation.

The results of the SOCRAT/V3 calculation of basic thermal hydraulic, oxidation and thermal mechanical behaviour during all phases of the experiment QUENCH-17 are presented in this paper.

2 QUENCH FACILITY

The QUENCH facility at KIT is designed for studies of the Light Water Reactor (LWR) fuel assemblies behaviour under conditions simulating design basis and beyond design basis accidents at the nuclear power plants (NPP).

The test bundle (Figures 1, 2) was made up of 21 fuel rod simulators with a length of approximately 2.5 m. 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 the test bundle.

Due to such geometry, the porous debris formation in the inner part of the bundle was not influenced by the presence of W heaters as it would be in the old geometry.

The rod cladding for 9 inner rods was identical to that used in LWRs: Zircaloy-4, 10.75 mm outside diameter, 0.725 mm wall thickness. The unheated rod simulators were filled with segmented ZrO₂ pellets (without centre holes). The rod claddings for 12 outer heated rods were made of hafnium. The test bundle was surrounded by a Hf shroud, followed by a 37 mm thick ZrO₂ fibre thermal insulation axially extending from the bottom to the upper end of the heated zone. The high melting temperature of Hf ensured that the claddings withstood the high temperature phase of the test. Special Hf corner rods, inserted between the bundle and shroud, additionally reduced the coolant channel area to a representative value.
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\textsubscript{2} pellets. The tungsten heaters were connected to electrodes made of molybdenum and copper at each end of the heater.

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 for most locations.

Figure 1: Schematic representation of QUENCH test section facility
Figure 2: Cross-section of QUENCH-17 test bundle (12 heated, 9 unheated, 4 corner rods)

3 QUENCH FACILITY MODELING

The nodalization scheme of the QUENCH test facility for the SOCRAT/V3 computer modelling code is presented in Figure 3. The radiative heat transfer is calculated in SOCRAT/V3 taking into account the square geometry of the rod bundle.

The nodalization scheme used for the calculation of the QUENCH-16 experiment had 8 radial groups of heat structures and 18 axial meshes, most axial meshes are 0.1 m long in axial direction. The total modelling length was 1.875 m (corresponds to the zone heated by molybdenum/tungsten heaters, from the lowest level -0.475 m up to the highest level 1.4 m where the level 0 m corresponds to the low boundary of the heated region). The nodalization scheme includes necessarily the spacer grids and the periphery corner rods.
The thermal problem is mainly influenced by heat fluxes in a system. The thermal conductivity of the shroud isolation is one of the most pronounced factors. The thermal conductivity data for the ZYFB-3 isolation [20] was used in the modelling.

4 SYSTEM OF GOVERNING EQUATIONS

The SOCRAT code uses a special model for the calculation of debris behaviour. The model features are summarized below.

4.1 Main Assumptions of Analysis

On the basis of existing experimental data the different mechanisms of porous debris formation from initial rod-like geometry are considered. The criteria for debris formation were derived from the existing physical notions and validated by the computational analysis of severe accident experiments like QUENCH-03, PHEBUS B9+ (PWR specific) and CORA-W2 which reproduced VVER-type geometry and materials.

The SOCRAT porous debris model is based on the following assumptions:

- We deal with non-Darcian porous medium in the presence of internal heat generation;
- The viscous dissipation is neglected;
- The fluid is assumed to be viscous and heat-generating;
- The solid is assumed to have a different temperature and is also heat-generating;
We use conservation equations for mass, momentum and energy for debris dynamics; Two-dimensional problem is considered with axial symmetry.

4.2 Basic Equations

Continuity, momentum and energy equations for each phase are used to describe the porous debris dynamics. The approach is based on the phenomenology from the works [21-26] and presented in the paper [27].

For example, a generalized momentum equation for a porous medium is written in the following form:

\[
\frac{\rho_f}{\varepsilon_S} \frac{\partial \langle \vec{u}_f \rangle}{\partial t} + \frac{\rho_f}{\varepsilon_S} \left( \langle \vec{u}_f \rangle \nabla \right) \left( \frac{\langle p \rangle}{\varepsilon_S} \right) = - \nabla \langle p \rangle + \frac{\mu_f}{\varepsilon_S} \Delta \langle \vec{u}_f \rangle - \frac{\mu_f}{K} \langle \vec{u}_f \rangle - \frac{C_{\varepsilon}}{K^{1/2}} \rho_f \left[ \langle \vec{u}_f \rangle \right] \left[ \langle \vec{u}_f \rangle \right]
\]

(1)

where \( \vec{u}_f \) is the velocity vector, \( \rho_f \) the fluid density, \( \mu_f \) the dynamic viscosity, \( \varepsilon \) the porosity, \( s \) the saturation, \( p \) the pressure, \( g \) the gravity, \( K \) the permeability and \( C_{\varepsilon} \) the Ergun constant [21].

4.3 Numerical Realization

The system of equations mentioned above was represented in integral form and in two-dimensional geometry for the application of a finite volume (FV) approach. Then, this system was solved using time discretization to find the general independent porous debris parameters (\( \varepsilon_S \), \( \varepsilon \), \( \langle \vec{u}_f, s \rangle \), \( \langle \vec{H}_f, s \rangle \), \( H_f \) and \( H_s \) and \( p \)) for the current time step based on parameters values at the previous time step. Here, \( H_f \) and \( H_s \) denote specific enthalpies for liquid and solid part of debris, respectively. Gradient and divergence terms are approximated by ordinary methods typical of FV technics.

The momentum equation in the integral form has the property that the momentum in any control volume (microscopic or macroscopic) is changed only by flow through the surface, forces acting on the surface, and volumetric body forces. This important property is inherited by the discretized equations if the FV approach is used and the surface fluxes for adjacent control volumes are identical. If this is done, then the integral over the entire domain, being the sum of the integrals over the microscopic control volumes, reduces to a sum over the surface of the domain. Overall mass conservation and energy conservation follow in the same way from the continuity and the energy equations, respectively.

The important part of the module (Figure 4) is the interface sub-module for the heat- and mass transfer between debris and non-debris (initial geometry) meshes. The linkage between different types of meshes (intact, debris, melt pool) should be done with great accuracy ensuring the total heat- and mass balance in a system.

5 BASIC PHASES OF QUENCH-17 TEST

The time sequence and main parameters of QUENCH-17 phases are presented in Figure 5 and in the Table 1.

The QUENCH-17 experiment consisted of three basic phases:
1. Heat-up phase, mass flow rates $A_{\text{steam}} = 2.0 \text{ g/s}$ and $A_{\text{argon}} = 2.0 \text{ g/s}$, the heat-up to $T \approx 1900 \text{ K}$ in hot region;
2. Pre-oxidation phase, the peak cladding temperature $T \approx 1800 \text{ K}$, 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.

The steam, argon and flood water mass flow rate are represented in Figure 6.

Figure 4: Block-scheme showing relations between different sub-modules of debris behaviour module

Figure 5: QUENCH-17 phases. Numbers of phases are indicated. Debris bed was formed about 270 s before phase 3 initiation

Figure 6: Mass flow rates of steam, argon and flooding water

During heat-up transient, pre-oxidation and cool-down phases, superheated steam together with the argon as carrier gas entered the test bundle at the bottom end and left the test section at the top together with the hydrogen that was produced in the zirconium-steam and in
the hafnium-steam reactions. Both argon and steam flows entered the working section during heat-up transient, pre-oxidation and cool-down phases.

Table 1: Phases of QUENCH-17 experiment

<table>
<thead>
<tr>
<th>Phase</th>
<th>Main parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FA temperature, K</td>
</tr>
<tr>
<td>1. FA preliminary heating-up in steam-argon flow</td>
<td>820-1900</td>
</tr>
<tr>
<td>2. Stabilization of main parameters and FA preoxidizing. Debris formation in the end of phase</td>
<td>1900-1800</td>
</tr>
<tr>
<td>3. FA cool-down</td>
<td>1800-400</td>
</tr>
</tbody>
</table>

The cool-down phase was preceded by formation of massive debris zone at levels 350-950 mm (above the grid spacer at 350 mm) and small debris zone on the grid spacer at 1050 mm. The axial mechanical load was applied to the bundle at about 77,500 s to form a debris bed because the bundle kept the rod geometry even under total oxidation conditions at levels 650-1100 mm. The average diameter of big debris particles was about 1-2 cm which were mixed with small fragments of cladding remnants with characteristic sizes of 0.01-5 mm (see Figures 7, 8).

The quench phase was initiated by turning off the argon and air flow, filling the lower plenum with quench water at a low rate with the aim to save the same status of debris bed.

![Figure 7: Debris between Zry and Hf rods](image1)
![Figure 8: QUENCH-17 blockage at 910 mm (top view)](image2)
6 RESULTS OF OF QUENCH-17 EXPERIMENT MODELLING

6.1 Modelling of Thermal Hydraulic Behaviour

The calculated and experimental bundle temperature at 950 mm elevation (near the upper part of heated zone) versus time for QUENCH-17 is presented in Figure 9. The maximum temperature about 1850 K was reached at this axial level. Figures 9-18 show the temporal dependence of temperature for different axial locations. SOCRAT reproduces the temperature behaviour very well.

The calculated heat fluxes in a heated region is presented in Figure 19.
Figure 15: Temperature at elevation 350 mm
Figure 16: Temperature at elevation 250 mm
Figure 17: Temperature at elevation 150 mm
Figure 18: Temperature at elevation -50 mm
Figure 19: Calculation heat balance:
1 – total electric power,
2 – power transferred by gas,
3 – heat flux to shroud,
4 – chemical power
6.2 Modelling of Oxidation

The calculated hydrogen generation rate and integral production in comparison to experimental data for QUENCH-17 is presented in Figures 20-21. SOCRAT underestimates hydrogen generation at the second part of the test. The possible reason for it is not adequate taking into account the oxidation of Hf. Note, that oxidation characteristics of Hf are still not very well studied.

There was no debris oxidation in QUENCH-17 because it consisted of completely oxidised components.

In general case, the oxidation in molten pools and in molten parts of debris regions has some peculiarities in comparison to oxidation in solid. The oxidation of metallic melts is not described by application of usual kinetic correlations. Melt oxidation together with melt relocation, dispersion and fragmentation are obviously some of the most important debris and pool phenomena.

The current version of SOCRAT code includes the melt oxidation model for the next configurations: a) the melt in the form of drops or rivulets on rod; b) the debris with a liquid part; c) the melt pool. The approaches to model the melt oxidation were described in the literature [28]. However, the melt oxidation is a very intensive and complicated process and the adequate solution of this problem in a code is very difficult. This is why the SOCRAT code basically underpredicts the hydrogen production at the phase of debris and pool formation (see, for example, [29]).

7 REFLOOD PHASE FEATURES IN QUENCH-17 EXPERIMENT

In the course of the QUENCH-17 test the fuel rods experience two stages of rods destruction status as the accident progresses:

- Undamaged (initial) geometry;
- Debris geometry.

So, for many QUENCH tests (for example, in classical QUENCH-06 test) the water reflood took place in indamaged geometry (Figure 22). Contrary to QUENCH-06, the water reflood in QUENCH-17 was performed in porous debris geometry (Figure 23).

All three types of heat transfer experience a sharp change after transition from undamaged geometry to debris bed geometry.
Figure 22: Schematic representation of flood in undamaged rod geometry relevant of basic QUENCH tests

Figure 23: Schematic representation of flood in porous debris geometry relevant of QUENCH-17

For example, the convective heat transfer is described by the following dependence of Nusselt number $Nu$ [30]:

$$Nu = \frac{hd}{\kappa} = Nu_j \frac{(1 - \varepsilon)}{0.28\varepsilon^{0.9}}$$

(2)

where $d$ is the debris particle diameter, $\varepsilon$ is the debris porosity, $\kappa$ is the thermal conductivity of the coolant. $Nu_j$ is determined here:

$$Nu_j = 0.14 \text{Re}_j^{0.65}, \text{Re}_j=2\times10^3\div10^4,$$

$$Nu_j = 0.088 \text{Re}_j^{0.7}, \text{Re}_j=10^4\div3\times10^5,$$

$$\text{Re}_j = \frac{Vd_{eq}}{\nu}, \quad d_{eq} = d \frac{\varepsilon}{6(1 - \varepsilon)}, \quad V = \frac{V_{sup}}{\varepsilon},$$

where $V_{sup}$ is the superficial coolant velocity.

The convective heat transfer coefficient described above and the enlarged coolant-solid interface area in debris result in enhancement of steam generation during reflood of the debris region.

Presumably, this is why the steam generation rate in QUENCH-17 was enhanced noticeably when the reflood water level went up through axial levels 350-950 mm.

Figures 24 and 25 show the temperature behavior during reflood in the experiment and in calculations respectively. Figure 26 demonstrates the experiment and SOCRAT temperature dynamics in the same graph. SOCRAT strongly underestimates the time of bundle quenching. The possible reasons for disagreement may be not taking into account of the thermo-hydraulic influence of spacer grids, a not adequate flow regime map description near the boiling curve and inaccuracies in porous debris thermal hydraulics in SOCRAT models.
So, the characteristic experimental time of quenching in QUENCH-17 was equal approximately 800 s. It is much longer than the quench time in the QUENCH-06 test (about 300 s) with undamaged geometry at reflood. However, it is necessary to take into account that the 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 2200 K in QUENCH-06.

Figure 24: Experimental temperatures at different elevations during reflood

Figure 25: Calculation temperatures at different elevations during reflood

Figure 26: Comparison between calculation and experimental temperatures during reflood
8 CONCLUSIONS

A long-term oxidation scenario was realized to get a massive high temperature porous debris zone in the QUENCH-17 test. The massive debris bed was formed at axial elevation from 350 to 950 mm.

The SOCRAT/V3 computer modelling code was used for the 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 the SOCRAT code system.

The coolability of massive debris bed was supported by experimental and calculation results.

The performed QUENCH experiments showed the importance of detailed taking into account of processes in porous debris regions for adequate description of heat and mass transfer in a bundle.

SOCRAT/V3 underestimates the 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.

The QUENCH-17 test results will help in more detailed understanding of debris related phenomena and its influence on reactor severe accident dynamics. Such important issues as debris oxidation and relocation phenomena as well as the coolability of massive debris bed can be investigated more thoroughly.

NOMENCLATURE

ECCS emergency core cooling system
FA fuel assembly
LOCA loss-of-coolant accident
NPP nuclear power plant
Nu Nusselt number
Pr Prandlt number
PWR pressurized water reactor
Re Reynolds number
VVER Russian type of pressurized water reactor
ε debris porosity

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REFERENCES


