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Pre-test Analytical Support for Experiments Quench-10, -11 and -12

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ABSTRACT

Pre-test analyses using MELCOR1.8.5, SCDAP/RELAP5 and SCDAPSIM have been performed in collaboration of PSI and FZK to support FZK QUENCH programme of electrically-heated bundle tests on reflood of a degraded core. The experiments include QUENCH-10 and -11, recently carried out in the EU 5th Framework LACOMERA programme, with analytical support in the 6th Framework SARNET network of excellence, and QUENCH-12 to be performed in 2006 in support of the project ISTC1648-2. Each test involves novel features that pose challenges in the planning analyses to determine the test protocol and that require code and input changes to accommodate the test conditions.

Special versions of the SCDAP codes were developed to simulate the effect of air on Zircaloy oxidation in the PWR air ingress test QUENCH-10, following pre-oxidation in steam. The analyses highlighted potential difficulties during the air oxidation and reflood phases that were avoided by changes in the test protocol. A more gradual thermal excursion could be achieved, facilitating control of the test, interpretation of data, and minimising the risk of a major excursion during quench. QUENCH-11 involved the steady boildown of an initially water-filled PWR bundle. Additional heating and water supplies were needed to give the desired conditions, and these needed to be tightly specified. Data from pre-tests with lower maximum temperatures were used to benchmark the models for defining the main test.

QUENCH-12 examines the effect of WWER bundle configuration and cladding on heat-up, oxidation, and quench response. The bundle is significantly modified with changes to cladding material (Zr/1%Nb instead of Zry-4), electrical heating, and geometry, hence to radiative heat transfer, hydraulics and oxidation characteristics. Oxidation correlations for Zr/1%Nb in steam were introduced into special versions of SCDAP. Pre-test calculations suggest that the modified kinetics have only a minor effect on the thermal response, but there are larger uncertainties in the oxidation history, which could impact the quench behaviour. Recommendations have been made for the conduct of a low temperature pre-test, and the main test, to be conducted in the summer and autumn of 2006.

The analyses not only support the QUENCH programme, but provide a valuable test of the codes and models. The capability of codes to simulate integral experiments correctly may help to qualify them for reactor purposes in terms of making judgements about accident evolution and management.

1 INTRODUCTION

An important accident management measure to terminate a severe accident in a light water reactor is to inject water to cool the uncovered degraded core. Analysis of the TMI-2 accident [1] and results of integral experiments [2] showed that before core cooling is established, this action may provoke enhanced oxidation, causing a sharp increase in temperature, hydrogen production and fission product release, which may threaten containment integrity and increase the probability of release to the environment.

The QUENCH programme at Forschungszentrum Karlsruhe (FZK) investigates hydrogen generation, material behaviour, and bundle degradation during reflood. The programme provides experimental and analytical data to assist development and validation of models used in reactor accident analysis codes. Integral bundle experiments are supported by separate-effects tests (SET) and code analyses at FZK. PSI contributes complementary pre- and post-test analytical support to help define the test conduct and interpret the experiments. This paper describes the pre-test support to three recent and forthcoming experiments. QUENCH-10 addressed air ingress issues, while QUENCH-11 studied recovery during a boildown transient; these were performed in the EU 5th Framework LACOMERA programme. QUENCH-12 will investigate the effect of WWER fuel assembly configuration and materials, and is being conducted as a contribution to ISTC1648-2. The analytic support is provided under the EU 6th Framework SARNET programme.

The paper concentrates on how judicious application of code models, typically two or more independent codes, has enabled to define the test protocols to promote the achievement of experimental objectives in a safe and reliable manner.

2 QUENCH FACILITY AND TESTS

The QUENCH programme at FZK started in 1996 as the successor of the CORA programme in which material interactions under the conditions of a hypothetical severe nuclear accident were investigated, with increased emphasis on quantifying hydrogen production during reflood. The main component of the QUENCH facility is the bundle, which in all past tests comprises typically 21 fuel rod simulators about 2.5 m long, of which 20 are heated over a length of 1024 mm by 6 mm diameter tungsten heaters in the rod centres, surrounded by annular ZrO_2 pellets to simulate fuel. The geometry and most other bundle components (Zry-4 cladding, grid spacers) are prototypical for Western-type PWRs. The central rod is unheated and is used for instrumentation or to simulate a control rod. The heated rods are filled with argon-krypton or helium at about 0.22 MPa to allow rod failure detection by the mass spectrometer. The pressure in the test section is around 0.2 MPa. Four Zircaloy corner rods are installed to improve the thermal hydraulic conditions and to mount additional thermocouples. Two of these rods can be withdrawn during the test to determine the axial oxidation profile at critical phases. The bundle is surrounded by a Zircaloy shroud, a 37 mm thick ZrO_2 fibre insulation, and a double-walled stainless steel cooling jacket. The shroud provides encasement of the bundle and simulates surrounding fuel rods in a real fuel element (Fig.1). The whole set-up is enclosed in a steel containment.

The test bundle, shroud, and cooling jacket are extensively equipped with thermocouples at different elevations and orientations. The test section incorporates pressure gauges, flow meters, and a water level detector. Hydrogen and other gases are analyzed by a mass spectrometer at the off-gas pipe about 2.7 m behind the test section. A redundant hydrogen detection system, based on heat conductivity measurement of binary Ar-H_2 mixtures (Caldos), provides data when no gases other than Ar, H_2 and steam are present.

A QUENCH experiment typically consists of the following phases: heat-up, pre-oxidation, transient, and quenching or cool-down. During heat-up the bundle reaches temperatures at which cladding oxidation begins at the upper elevations. The temperatures are then controlled at a roughly constant level to achieve the desired oxidation before a further excursion is initiated, usually by an increase in electrical heating. The excursion can result in maximum bundle temperatures of well above 2000 K and is accompanied by increased hydrogen generation. During most of the test, a flow of 3 g/s steam and 3 g/s Ar as carrier gas for H_2 measurement is typically maintained. During the last phase, water or saturated steam is injected at the bottom of the test section, and power is reduced to simulate decay heat.

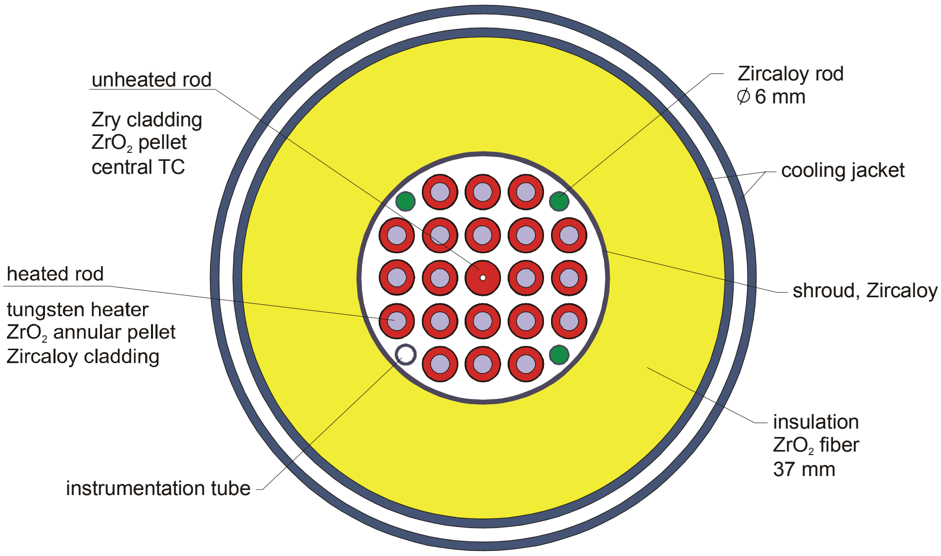

Figure 1: Cross-section of the QUENCH facility with a PWR bundle

Eleven bundle experiments have been performed to date [3], with varying degrees of pre-oxidation, mode of reflooding/cool-down, and rates of flow and steam/gas composition through the bundle. Experience has shown that the thermal response of the bundle can be very difficult to control, particularly during transition phases of the tests such from heat-up to pre-oxidation and the reflooding/cool-down. Indeed, the challenges arise for the very reason that the tests are needed, namely to eliminate limitations in current knowledge of phenomena that pose safety concerns to nuclear plants. The experiments performed recently and planned for the future include modifications to the bundle materials, configurations and operation, thus making more difficult the protocol definition and conduct.

3 PRE-TEST ANALYSIS FOR QUENCH EXPERIMENTS

Planning analyses were and are being performed at PSI for QUENCH-10, -11 and -12 and for QUENCH-10 and -11 at FZK, using MELCOR [4], ASTEC [5] and SCDAP versions SCDAP/RELAP5 (S/R5) [6] and SCDAPSIM (S/Sim) [7] in tandem. The planning support includes intensive cooperation amongst FZK and PSI staff.

3.1 Air Ingress Experiment QUENCH-10

QUENCH-10 was conducted at FZK on 21 July 2004 [8] to address issues related to cladding oxidation during exposure to air, possibly during a reactor transient or spent fuel accident. In many ways QUENCH-10 complements the AIT2 test performed in the CODEX facility [9]. It is expected that air oxidation would most likely take place in conditions of low flow following a prolonged period of heating and oxidation in steam. As in previous experiments, therefore, the bundle was to be significantly pre-oxidised prior to switching from steam-Ar flow to air-Ar flow. The early phases would follow the majority of previous QUENCH tests. The switch from 3g/s steam to 1 g/s air would imply a sharp reduction in convective heat transfer plus an increase in heat generation rate due to the more energetic reaction between Zircaloy and oxygen and the potentially faster kinetics.

PSI performed planning analyses using MELCOR and S/R5. The standard versions of S/R5 cannot simulate the QUENCH heater rods, while the code also does not model the air oxidation kinetics or the consumption of oxygen. Modifications by FZK to accommodate QUENCH and by PSI to simulate the heat release and air oxidation kinetics were included (though it was not possible to represent oxygen consumption). MELCOR contains the features necessary for QUENCH-10 although other limitations of the code dictate that some approximations were needed in the QUENCH model. MELCOR also adopts a simplified treatment of the two-phase hydraulic processes. Preliminary calculations confirmed the fear that rapid escalation would occur immediately after the switch to air, with a short time interval only before reaching the reflood initiation criterion of 2073 K. Further analysis indicated that reducing the power by about 50% after the pre-oxidation would allow the bundle to cool, and hence achieve a more gradual heating during the air phase: This would provide more time in which to obtain data on the establishment of air oxidation kinetics and to prepare the approach to reflood more effectively. Bundle temperatures calculated with

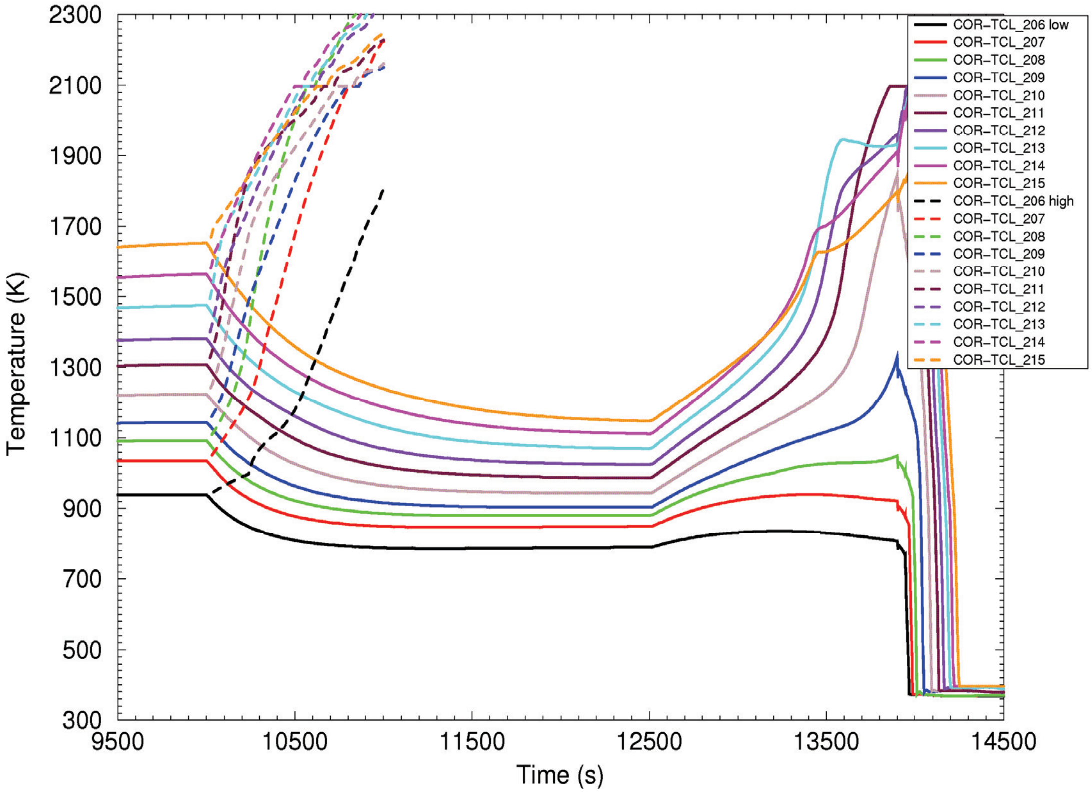

Figure 2: QUENCH-10 – Axial temperature distribution showing effect of temperature reduction on the subsequent air ingress transient

MELCOR are shown in figure 2, thus demonstrating the benefit of the power reduction. It was to be expected, in any case, that the oxidation would eventually become oxygen starved.

A second concern was that the oxidation in air would render the cladding more susceptible to oxidation during reflood. Initial plans were to simulate the limited availability of coolant in the event of an air ingress scenario. S/R5 calculations, shown in figures 3 and 4, indicated the risk of a significant excursion if the reflood rate was reduced from the customary 40-50 g/s to ca. 15 g/s as originally intended, even though the models could not fully take account of the effects of air oxidation.

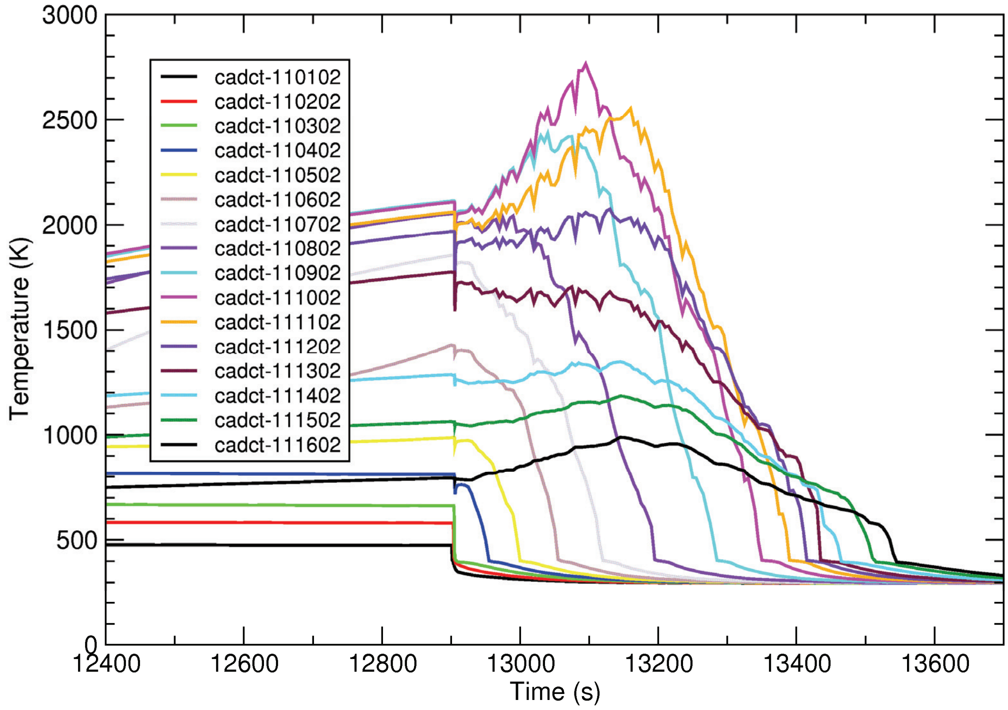

Figure 3: QUENCH-10 – Axial temperature distribution after reflood with 15 g/s water

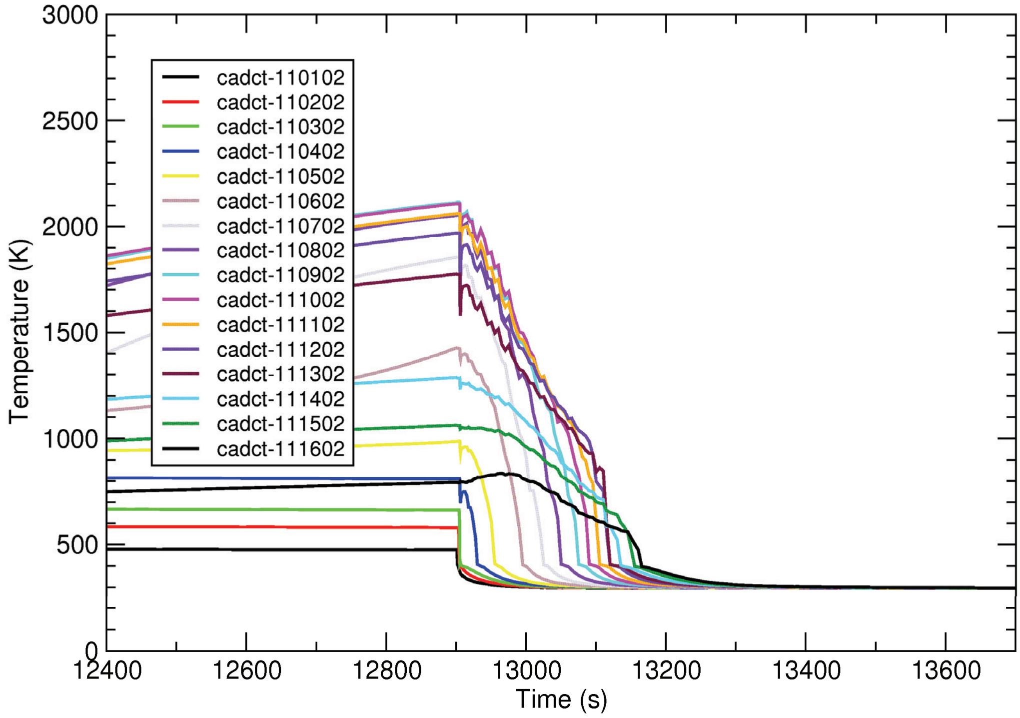

Figure 4: QUENCH-10 - Axial temperature distribution after reflood with 50 g/s water

The risk could be avoided completely by cool-down in an inert gas, but at the cost of sacrificing to opportunity to gain important knowledge on recovery from an air ingress sequence. Reflood was carried out using 50 g/s water, despite a remaining slight risk.

QUENCH-10 was conducted according to recommendations based on the planning calculations, without problems. There was a progressive heat-up during the air phase, with eventual oxygen starvation, and minor oxidation during reflood but no excursion. The data revealed aspects of air oxidation that are stimulating complementary SETs and model development.

3.2 Boil off Experiments QUENCH-11

QUENCH-11 [10] was designed to investigate boildown and degraded core quenching at low reflood rate of less than 20 g/s. The low reflood rate was to simulate the situation in a commercial reactor, when only one pump can be activated or when the pumps cease due to pressure increase in the system. Due to peculiarities of the facility such as large plenum and piping volumes, this cannot be achieved with the normal test procedure; the experiment was to be conducted in a completely novel manner. Therefore, QUENCH-11 would start with an initially flooded test section. Steam flow would be provided by the boil off process; respective heating would not only be performed by normal bundle power, but also by an auxiliary heater in the lower plenum, designed for that purpose. With decreasing water level, the latter would become more and more important. For mass spectrometer calibration, Ar would be injected at the upper end of the test section. To finally provide a quasi stationary water level in the lower electrode zone and to prevent the auxiliary heater from dry-out, additional water would be injected into the lower plenum Another key feature would be the absence of a controlled period of pre-oxidation designed to achieve an oxide layer at the initiation of reflood. Instead, pre-oxidation would be determined from thermal evolution of the heated rods during boiloff.

Three trial tests (Q-11v1 … Q-11v3) were performed to verify the functioning of the modified facility and new features and to characterise the thermal-hydraulic behaviour under conditions relevant to the main test. The last trial, Q-11v3, involved the complete test sequence as the main test, but heat-up was limited to about 1050 ˚C. The trial provided data to benchmark the code models before final planning analyses for the main test. It also meant that the main test would be performed with a mildly pre-oxidised bundle.

FZK performed pre-test calculations for QUENCH-11 using S/R5 and the European integral code ASTEC V1.2. Among the objectives were to define electrical power for bundle and auxiliary heater as well as the mass flow rate for the additional water injection. With an updated input deck, based on the results of Q-11v3, six S/R5 pre-test calculations were performed to investigate the sensitivity to this scenario. It turned out that the thermal escalation prior to reflood is sensitive to small changes in bundle and auxiliary power, due to the positive temperature dependencies of resistance heating and Zry oxidation and the rather low steam flow rate. Figure 5a shows the Q-11v3 and the QUENCH-11 alternative bundle and auxiliary power histories. Figure 5b compares the calculated temperatures with the Q-11v3 experimental data, showing the similar evolution up to the Q-11v3 power reduction at 2930 s, and subsequently the effect of power history on the escalation. Figure 5c shows the water level to be insensitive to power history; the diverging water levels between Q-11v3 and the pre-test calculations are due to a valve malfunction in Q-11v3.

An advantage of ASTEC is that the code runs much faster than S/R5, even with a fine axial mesh, enabling further calculations to be performed readily. The calculations started with Q-11v3 and then were extended to QUENCH-11. After optimizing the input deck, the results agreed very well with those of S/R5 (figure 6, figure 7). Data indicated by TCR are located at fuel rod centreline, TFS at the fuel rod cladding and TSH at the inner shroud surface.

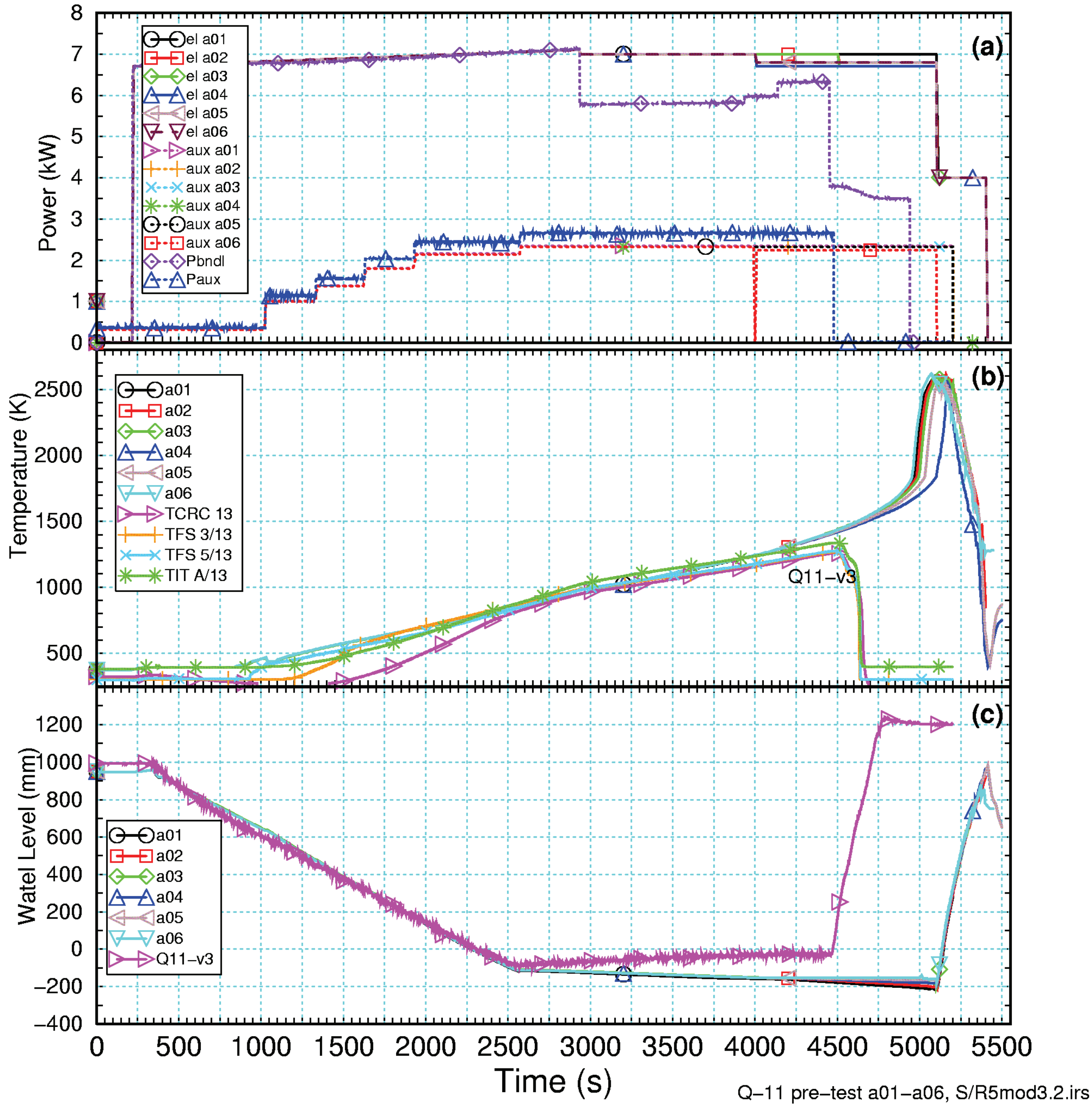

Figure 5: S/R5 pre-test calculations for Q-11: a(upper) bundle and auxiliary power; b(middle) bundle temperatures at 950 mm elevation; c(bottom) water level in bundle. TC readings refer to Q-11v3.

In parallel with FZK, PSI performed pre-test calculations for Q-11v3 using MELCOR and S/Sim in order to set up and exercise the models, and to indicate what to expect during the trial. Preliminary calculations indicated that the additional heating should be applied gradually while the bundle is already partly uncovered to avoid a sudden boiling up and expulsion of water, the so-called "geyser effect". Some changes to the model were made to reflect the actual boundary conditions used in Q-11v3. Figures 8 and 9 compare MELCOR and S/Sim calculations with the Q-11v3 data for bundle temperatures and water level, respectively. There were some difficulties associated with modelling of the upper part of the bundle, but the depletion and uncovery are generally in excellent agreement, suggesting the models were suitable for planning the main test. The Q-11v3 results confirmed that the mode of additional heating would provide stable conditions, as indicated by the Q-11v3 pre-test calculations.

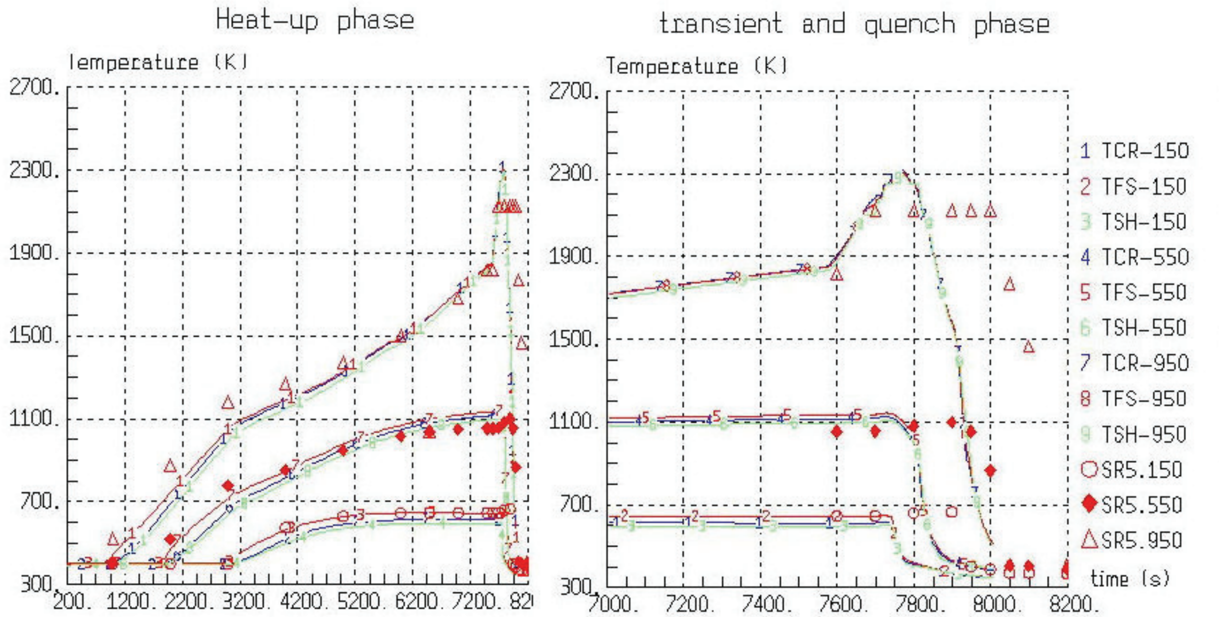

Figure 6: S/R5 (symbols) and ASTEC (lines) pre-test analyses of QUENCH-11: temperatures at lower, middle and upper elevations: left, during heat-up and right, during transient and quench

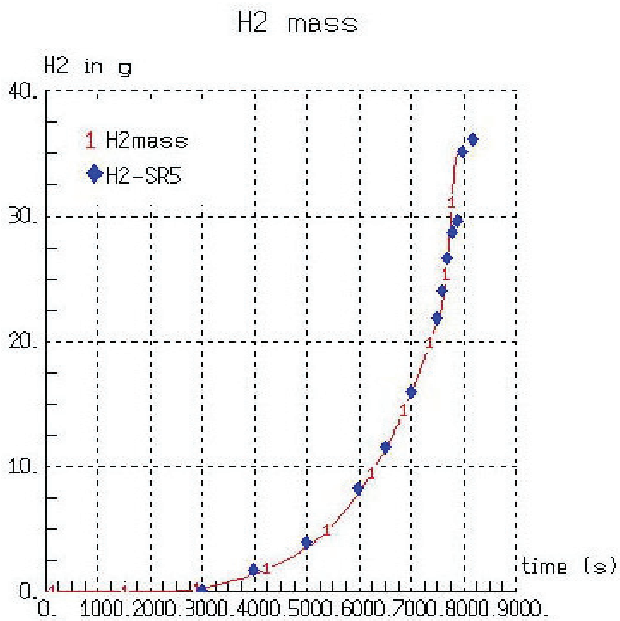

Figure 7: S/R5 (symbols) and ASTEC (lines) pre-test analyses of QUENCH-11: hydrogen mass

Pre-test calculations for the main test were performed both as follow-on and stand-alone simulations, indicating a slightly later and slower escalation in the first case due to the prior oxidation but no significant impact regarding test conduct. Figure 10 shows results of several sensitivity studies indicating probable steam starvation shortly before reflood and risk of a severe excursion, if reflood is delayed beyond the planned initiation temperature of 1800 ˚C.

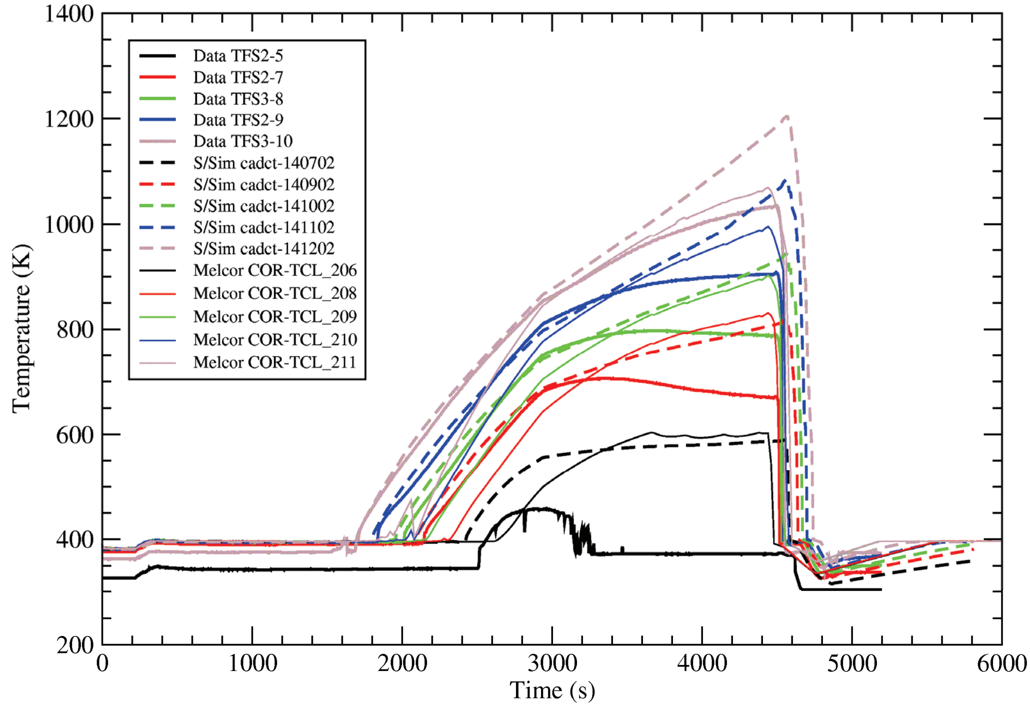

Figure 8a: Comparison for QUENCH-11/v3 bundle temperatures: lower

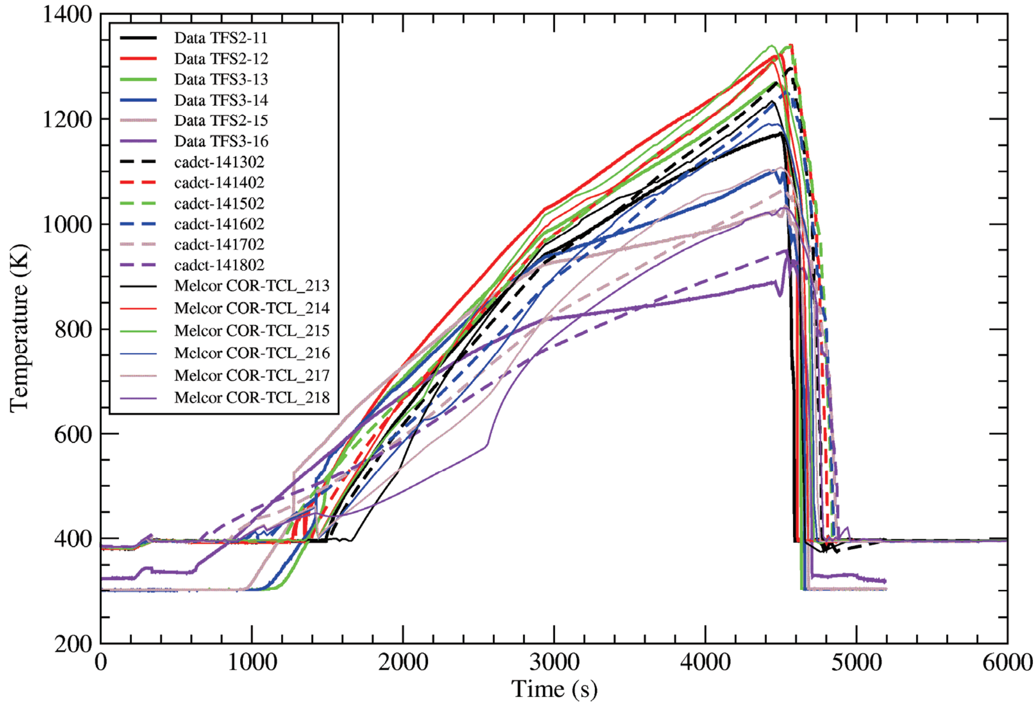

Figure 8b: Comparison for QUENCH-11/v3 bundle temperatures: upper

Based on the experiences with Q-11v3 and the collective pre-test calculations with the various codes, a detailed test protocol was elaborated, including alternatives in case of any malfunction of systems. To achieve a more stable operation during boildown, it was recommended to enhance the convective heat transfer by increasing the evaporation rate to at least 1 g/s steam. Due to the uncertainties regarding the escalation phase, the onset of reflood was defined at 5100 s or earlier when the peak bundle temperature exceeds 1800 K. It was also recommended to continue the additional water injection during the quench phase, to maintain stable conditions at the bundle inlet in the event that quench water injection is delayed (as occurred in most previous QUENCH tests). The experiment was conducted as planned, exhibiting the expected smooth heat-up and significant oxidation during reflooding.

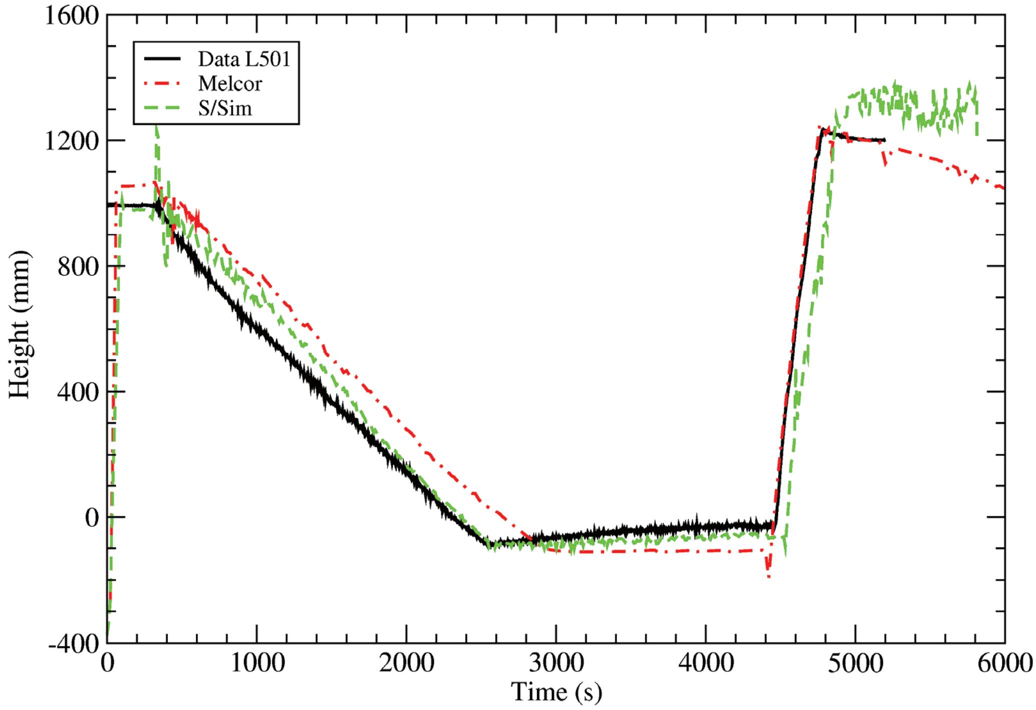

Figure 9: Comparison for QUENCH-11/v3 water level in the bundle

3.3 WWER Simulation QUENCH-12

QUENCH-12 will be performed in 2006 as a counterpart to QUENCH-06 [11], ISP-45 to investigate the effect of WWER fuel assembly configuration and materials. Major differences are as follows: Zr-1%Nb is used in place of Zry-4 for the cladding and shroud, and the rods are arranged on a hexagonal rather than on a square pitch. The number of heater rods is reduced from 20 to 18, the number of unheated rods increased from 1 to 13 (the diameter of each reduced from 10.75 mm to 9.13 mm), while the number of corner rods is increased from 4 to 6. The modifications mean that, again, the transient and reflood behaviour will differ from past experience. To preserve, as far as possible, the bundle thermal-hydraulic conditions the steam, argon, and reflood water flows are increased slightly according to the larger hydraulic flow area, but the maximum bundle temperature before reflood initiation, the duration of pre-oxidation, transient and reflood phase as well as the reflood initiation criterion are to be the same as in QUENCH-06.

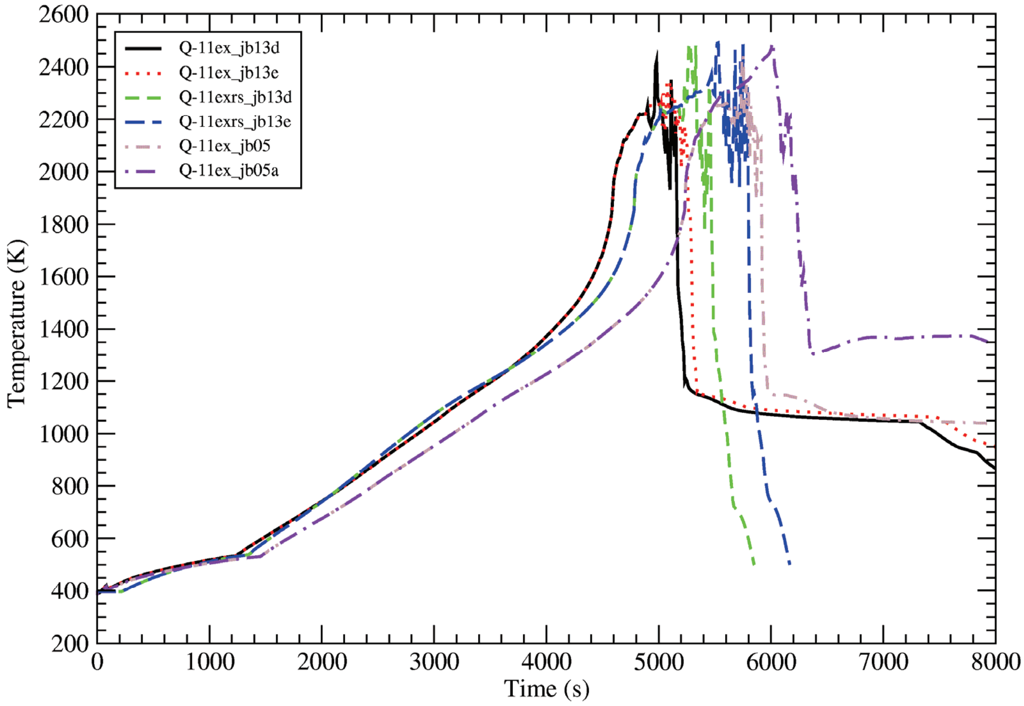

Figure 10: Sensitivity predictions for QUENCH-11 maximum temperatures

Due to the novel features of the bundle, a limited pre-test trial (Q-12PT) was performed to characterise the thermal-hydraulic response and provide data to benchmark code models. Here, the conditions were limited to the early stages of initial heat-up to avoid any oxidation that might compromise the main test, important since a major objective is to investigate the oxidation characteristics of the Zr-1%Nb cladding.

Analyses were performed with S/Sim and S/R5, starting from the models developed in post-test analyses of previous QUENCH tests and incorporating the changes to the bundle configuration, with a provisional value for the additional resistance assumed based on available estimates. View factors have been modified for hexagonal bundle geometry, based on calculations of [12]; the method has been described in [13]. A correlation, [14], [15] for Zr-1%Nb oxidation kinetics was incorporated into both codes to indicate how the new material might affect the oxidation. Preliminary calculations established viability of the planned test conduct and gave the necessary indications for the power history.

The model was adjusted slightly in the light of results of the pre-test trial. Figure 11 compares the temperatures at the top of the bundle calculated using S/R5 and S/Sim with results from the pre-test trial, after a small adjustment to the additional resistance and boundary conditions. The same input model was then used to predict the temperature in the main test, with the power based on the nominal scaling from QUENCH-06. The results are compared with the QUENCH-06 data in figure 12, where the close similarity confirms the scaling and provides a guideline power history for QUENCH-12. The temperatures during most of the transient are only slightly affected by the choice of oxidation model, although the final escalation before reflood is more rapid with the Zr-1%Nb correlation. There is only a slight difference between the S/R5 and S/Sim results at this location.

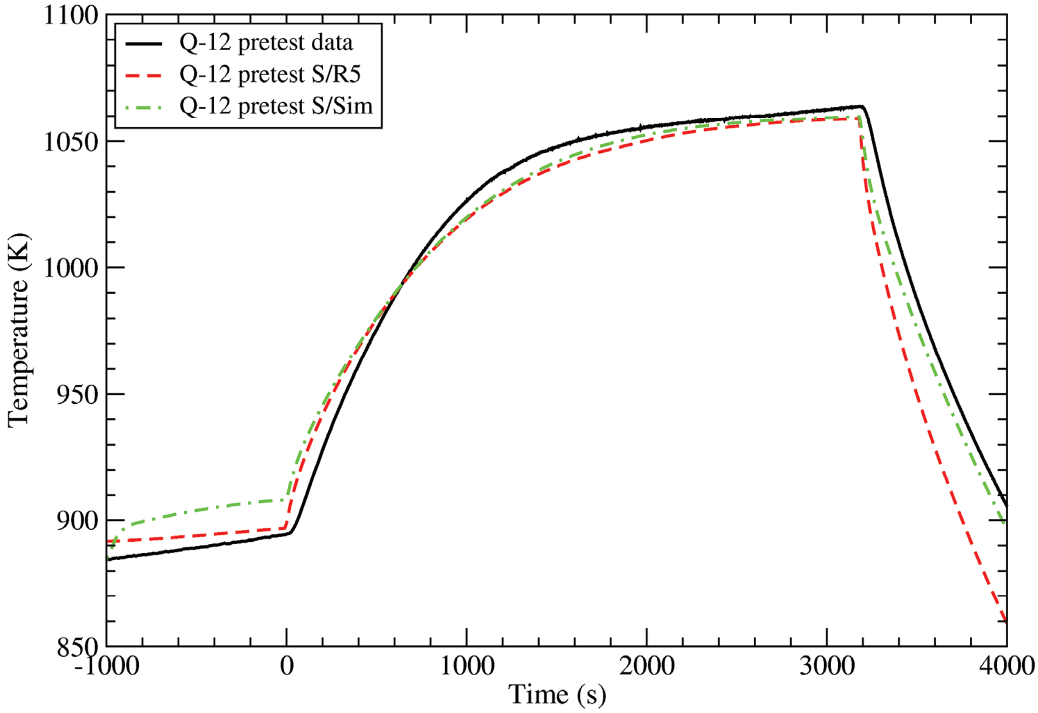

Figure 11: S/R5, S/Sim and data comparison for Q-12PT maximum temperature

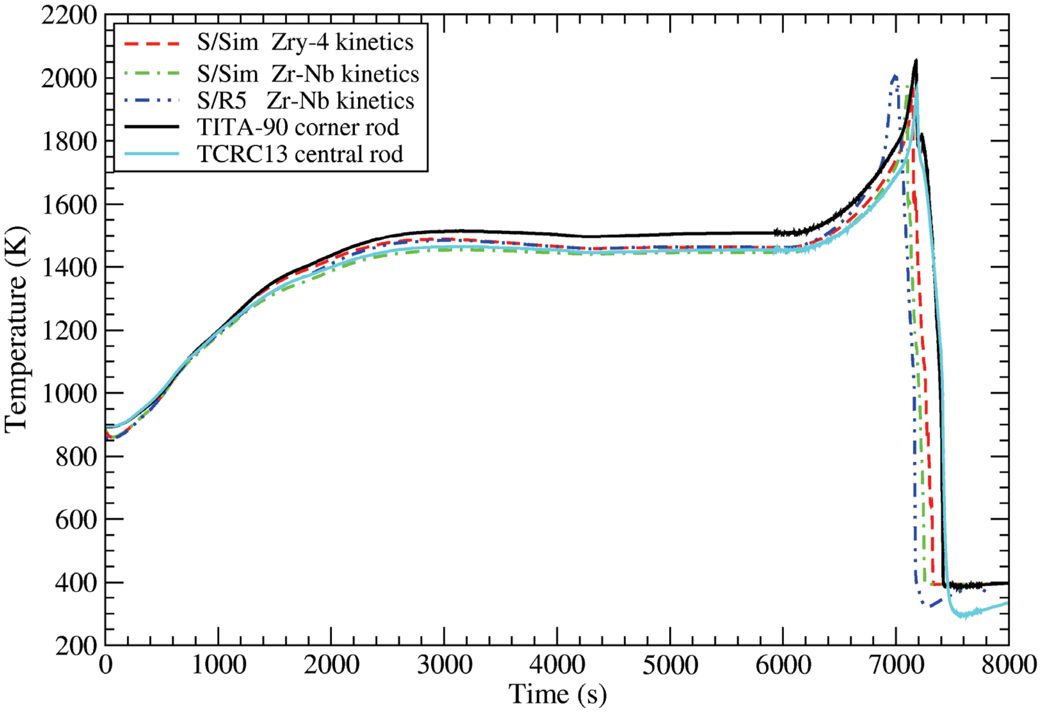

Figure 12: Comparison of unheated rod predicted temperatures at 950 mm for QUENCH-12 with QUENCH-06 data

4 CONCLUSIONS

The paper has demonstrated how the use of integral severe accident analysis codes, in some cases specially adapted for specific experimental conditions, has enabled the definition and safe conduct of experiments. The experiments cover the effects of air ingress, boildown followed by reflood and the effects of VVER compared with standard Western PWR geometry; thus they provide a good test of code capabilities and so lend confidence regarding the use of these codes in reactor applications. The pre-test computational support is being followed by a programme of post-test interpretative analysis that provides further insights into code capabilities, needs for model improvement, and resolution of remaining safety issues.

The strategy based on independent analyses, use of different codes and comparison with data minimises the potential impact of model limitations in individual codes, and provides additional confidence for defining test conditions. The effectiveness of analytical support depends critically on dialogue with the experimental team and the experience of the code users familiar with the QUENCH facility and experiments.

Several of the questions to be answered in the present context are analogous to those arising in reactor analyses, for example in the definition of criteria for water injection as an accident management measure. The experience of performing analytical support for experiments of this kind provides a spin-off benefit to reactor application, helping to make the most effective use the available tools in addressing plant safety issues.

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