Forschungszentrum Karlsruhe
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Analytische Unterstützung zur Vorbereitung des Ausdampf-Versuchs QUENCH-11

Kurzfassung

Im QUENCH-Vorhaben des Forschungszentrums Karlsruhe soll das Fluten eines teilweise zerstörten Kerns untersucht werden. Der zweite LACOMERA Versuch Q-L2 (QUENCH-11) beginnt mit einer Ausdampfphase des Bündels, bis der Wasserspiegel das untere Bündelende erreicht hat. Ein derartiger Versuch wurde bislang noch nicht in der QUENCH-Anlage durchgeführt, so dass mit SCDAP/RELAP5 mod3.2.irs eine Machbarkeitsstudie erforderlich war. Die Ergebnisse zeigen, dass eine Zusatzheizung im unteren Plenum notwendig ist, um den Wasserstand und die Verdampfungsrate (Dampfmassenstrom in der Ausdampfphase) unabhängig von der angestrebten Maximaltemperatur im Bündel zu regeln. Für eine verlässliche Versuchsplanung sowie zur Erstellung der Energiebilanz muss die Zusatzheizung innerhalb des unteren Plenums unterhalb der Wasseroberfläche installiert werden, damit die Heizleistung vollständig in das Wasser eingekoppelt wird. Um die Verdampfungsrate über längere Zeit aufrecht zu erhalten, muss zusätzlich Wasser in das untere Plenum eingespeist werden.

Anhand dieser Rechnungen wird der Testablauf im Detail diskutiert. Eine entsprechende Studie zeigte die Durchführbarkeit eines solchen Ausdampftests und war die Grundlage für die oben erwähnten Änderungen in der Anlage und der Versuchs-Durchführung gegenüber früheren Tests. Eine Reihe von Vorversuche wurde durchgeführt, um die Brauchbarkeit der Änderungen an der Anlage und der geplanten Versuchsführung zu prüfen und um Daten für das thermohydraulische Verhalten der Anlage zu bekommen, an denen die Code-Modelle für die Voraus- und Nachrechnungen von QUENCH-11 getestet werden können. Im Anschluss an die Vorversuche wurden wie bei früheren QUENCH-Tests detaillierte Vorausrechnungen mit verschiedenen Codes zu Versuchsablauf und -steuerung durchgeführt. Drei Forschungseinrichtungen in der EU waren beteiligt. Die berechneten Ergebnisse reagieren empfindlich auf Änderungen der Versuchsparameter wie das anfängliche axiale Temperaturprofil und die eingespeiste elektrische Leistung, wie es auch für die untersuchten physikalischen Bedingungen im Versuch erwartet werden kann.

Analytical Pre-Test Support of Boil-Down Test QUENCH-11

Abstract

The QUENCH program at Forschungszentrum Karlsruhe is focused on the investigation of degraded core reflood. Out of the series of bundle tests, the second LACOMERA test, QUENCH-L2 (QUENCH-11), includes a boil-off phase from the start of the test up to the time, when the water has dropped to the lower end of the bundle. Such a test sequence has not yet been performed in the QUENCH facility so that a feasibility study was necessary. Its results, obtained with SCDAP/RELAP5 mod3.2.irs, show that an auxiliary heater in the lower plenum is required to control the water level as well as the evaporation rate (steam mass flow rate during boil-off) independently of the envisaged rod temperatures. To derive reliable predictions for the test conduct as well as to dress an energy balance, indispensable for analytical work, the auxiliary heater must be installed below the water level in the lower plenum, so that the total electric power is released into the water. To maintain the evaporation rate over a sufficiently long time, additional water has to be fed into the lower plenum.

Based on the calculations, the test sequence is discussed in detail. An initial feasibility study demonstrated the viability of such a boil-down test, subject to the design and operational modifications mentioned above. A series of preparatory tests were performed to qualify the additional features, to demonstrate test control by means of the planned test procedure, and to provide data on the thermal-hydraulic characteristics of the facility for benchmarking of the code models used for test planning and subsequent analysis of QUENCH-11. After the preparatory tests, detailed pre-test calculations with different codes were performed to define the final test protocol, as was done in previous QUENCH tests. Three research institutions in the EU were involved. The calculated results for boil-down are very sensitive to changes of parameters like the initial axial temperature profile and electrical power input as can be expected for the physical conditions in the test.

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Abbreviations and Symbols

ASAP	As Soon As Possible
ASTEC	Accident Source Term Evaluation Code
ECC	Emergency Core Cooling
EPR	European Pressurized water Reactor
EU	European Union
FZK	Forschungszentrum Karlsruhe GmbH, http://www.fzk.de
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH, Garching, Germany
INL	Idaho National Laboratory, USA
INEEL	Idaho National Engineering and Environmental Laboratory, USA
INEL	Idaho National Engineering Laboratory, USA
INRNE	Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
IRS	Institut für Reaktorsicherheit
IRSN	Institut de Radioprotection et de Sûreté Nucléaire, Cadarache, France
ISL	Information Systems Laboratories, http://www.islinc.com
ISP	International Standard Problem of OECD/NEA
ISS	Innovative Systems Software, Idaho Falls, USA
LACOMERA	Large Scale Experiments on COre degradation, MElt Retention And coolability
LOCA	LOss of Coolant Accident
LOOP	LOss-of Offsite Power
LWR	Light Water Reactor
NEA	Nuclear Energy Agency of the OECD
NRI	Nuclear Research Institute Rez, Czech Republic
OECD	Organization for Economic Cooperation and Development
PSA	Probabilistic Safety Assessment
PSI	Paul Scherrer Institut, Würenlingen, Switzerland
PWR	Pressurized Water Reactor
RELAP5	old: Reactor Excursions and Leak Analysis Program now: Reactor Leak and Analysis Program, for LWR transients and SBLOCA
RPV	Reactor Pressure Vessel
QUENCH	Research programme at FZK to investigate material behaviour during LWR reflood conditions
SARNET	Severe Accident Research NETwork
SBLOCA	Small break LOCA
SCD	Severe Core Damage
SCDAP	Severe Core Damage Analysis Package, (USNRC code, developed at INEL), http://www.nrc.gov/about-nrc/regulatory/research/comp-codes.html
S/R5	SCDAP/RELAP5: Coupled SCDAP and RELAP5 code to simulate reactor conditions up to and including SFD conditions
S/SIM	SCDAPSIM
SFD	Severe Fuel Damage
SNL	Sandia National Laboratories, Albuquerque, USA
TRAC	Transient Reactor Analysis Code
TRACE	TRAC/RELAP Advanced Computational Engine (formerly called TRAC-M)
USNRC	United States Nuclear Regulatory Commission, Rockville, MD

1 Introduction

In the QUENCH programme [1] at Forschungszentrum Karlsruhe (FZK), the behaviour of partially damaged fuel rod bundles is investigated to gain insight in the mechanisms of high temperature reflood and of hydrogen and energy release. These processes imply a temperature increase and may influence long-term coolability of a reactor. One objective of the QUENCH programme is therefore to investigate material behaviour under such conditions, among others material interactions that may lead to early formation of liquefied core components significantly below the melting points of the involved ingredients. Other objectives are to investigate the reflood dynamics and to validate and improve codes, used for reactor safety applications and probabilistic safety assessments. When QUENCH-11 was prepared, the QUENCH facility at FZK was the only operational one to investigate a reflood of a severe damaged fuel rod bundle.

A literature review of reflood experiments [2], [9] shows that mostly out-of-pile tests are treated in open literature, and only a few in-pile tests are available. It shows that reflood can stop core degradation and achieve a long-term coolability, if the mass flow rate during reflood is sufficiently high. However, how much is sufficient in this context and what are the most important parameters determining such a threshold level? From the study, the most stringent parameter is the damage state of the bundle; other important parameters are system pressure, injection flow rate, extent of previous oxidation and core size. Effects of core burn-up and MOX-loading are still unknown.

The literature review also shows that, for sufficiently high mass flow rates, core reflood with dedicated emergency core cooling (ECC) systems is considered successful for bottom reflood operation up to a peak core temperature of 2200 K prior to reflood. Beyond this temperature, the data cannot be extrapolated to actual reactor conditions, because localized effects that may lead to local molten pools. Such pools can also grow during reflood and result in uncoolable core regions.

The literature review also shows that a boil-down scenario has not been tackled up to now, i.e. no integral experiment has been performed so far with a controlled steam mass flow rate in the test bundle and a free water surface at the lower end of the test section at the same time. The goal of QUENCH-11 is therefore to investigate a boil-down-reflood test. More precisely, the test is to simulate ceasing pumps, a small break LOCA, or a station blackout with a late depressurization of the primary system. Considering a low system pressure allows to simulate accumulator and low-pressure ECC system injection. A small reflood rate in the final test phase was chosen to address the situation, when only few injection systems are available.

This test scenario was supported the 5th EU Framework programme LACOMERA [3] upon the suggestions of the Institute for Nuclear Research and Nuclear Energy, (INRNE, Bulgaria). The experiment is therefore partially funded by the European Community and is labelled QUENCH-L2 in the LACOMERA context.

The relevance of a boil-down scenario for reactor safety can be explained as follows. Delayed core reflood in the severe fuel damage regime is considered as a suitable accident management procedure. In related integral experiments, performed up to now, the test conditions prior to reflood initiation are representative for the conditions inside the reactor pressure vessel (RPV) in the absence of water. Recent research results have shown that the transition of intact rod geometry to widespread debris or pool formation sharply affects the likelihood of reflood success, e.g. it touches the feasibility of long-term core coolability.

The present experiment addresses this shortcoming. The axial temperature gradient is mainly controlled by the balance of heat generation and convective transfer; the lowest temperature is given by the fluid entrance temperature. Furthermore, this configuration would also allow the simulation of the transient response of the level swell, when subcooled water enters the two-phase pool. This level swell denotes the steam atmosphere above the water that is transported through the reactor by the rising water level; the steam cannot condense, because the temperature of the various structures is too high.

Under boil-off conditions, the presence of water in the different volumes (RPV, downcomer, etc.) of the reactor coolant system modifies the effective dry-out velocity compared with a single channel core simulator. To determine a representative boil-off rate plant calculations are performed for an appropriate reference plant sequence. Results of plant calculations for a range of sequences [6] were used to derive the following target values for QUENCH-11:

- boil-off velocity ~0.1 cm/s,
- decay heat < 1% of the nominal power at the time of core heat-up,
- initial heat-up rate ~ 0.5 K/s up to 1250 K.

Based on the experiences with previous experiments and calculations, a feasible test protocol for these challenging boundary conditions was established. In this report, the preparation of the QUENCH-11 experiment is discussed; the related work was performed at Paul Scherrer Institut (PSI, Switzerland), INRNE, Bulgaria, and at Institute for Reactor Safety (IRS) at FZK with different codes, namely ASTEC, SCDAP/RELAP5 (S/R5) [4], [5], SCDAP-SIM (S/SIM), and MELCOR. The task was prepared and coordinated by FZK/IRS. Their contributions to the test preparation are not marked explicitly.

2 Strategy of Test Preparation

The pre-test support comprised an extensive and coordinated effort in three countries. First FZK/IRS experience with the QUENCH facility dates back to the facility design phase. Since that time, experimental work was supported by calculations, performed with an FZK/IRS in-house version of S/R5.

Typical data for core configuration, boil-off velocity, and ECC flow rates were extracted from reactor calculations with the same code [6]. Typical VVER1000 data were taken into account by INRNE [7]. The first scoping calculations with S/R5, dedicated to achieve an appropriate representation of reactor conditions, showed clearly that the facility had to be upgraded to meet the test requirements [8].

Five issues had to be dealt simultaneously and solved, if possible:

1. Experience of former QUENCH tests shows that quench water is at least partly evaporated in the input pipe and the lower plenum, which are heated in the preceding test phases. Even with maximum pump rate, this process would last more than half a minute. In case of very low makeup rates, i.e. less than about 1 g/s water per equivalent fuel rod surface, this evaporation and hence premature bundle cooling would be strongly adverse to the test goals. To avoid the premature bundle cooling irrespective of the flooding rate, a fast water injection system, based on a gas driven accumulator discharge, has been installed since test QUENCH-06. It has, however, another disadvantage. The rapid injection of water leads to violent transient flows in the bundle with a temporary strong cooling even in the upper bundle region and to a shock wave in the bundle, causing undesired damage. In addition, the fast water injection is difficult to control and difficult to simulate even in its basic features.

2. When a bundle is heated electrically with metallic heaters as in the QUENCH facility, the locally released power depends on local temperature. This effect leads to a significantly different axial power profile compared to the decay heat in a reactor. Whereas its maximum is near the upper end of the heated zone for electrical heating, it is near the centre of the fissile zone for nuclear reactors. In addition, for linear rod power may vary significantly within the heated zone electrical heating: for QUENCH-11, linear rod power in the lower part of the bundle, i.e. when water temperature is near its saturation point, may be as low as only one third of that in the hot zone of the bundle. Due to these physical conditions, energy for boil-off vanishes with decreasing water level. Therefore, the increase of electrical power does not enhance evaporation under these conditions, but increases temperature in the upper sections of the bundle, making the axial profile of linear rod power and temperature even steeper and worsening the situation.

3. In an RPV, the free flow area in the core is similar to the cross section of the downcomer. Therefore, during boil-off a significant amount of water flows from the downcomer into the core, reducing the boil-off velocity for a given core power density. The

amount of this additional water feed has to be taken into account for reactors and should be simulated in the QUENCH test.

4. In typical QUENCH experiments, the mass fluid balance can be dressed rather easily because the inlet fluids are known. During boil-down, the steam mass flow rate can only be deduced by measuring the water level decrease, the increase of condensate mass or, with less uncertainty, by using the mass spectrometer. For the latter method, condensation in the off-gas pipe has to be avoided.

5. An essential issue for the correct modelling of the facility, especially for the energy balance, is the quantification of the heat losses in the lower plenum. Any heat, lost to the containment, does not contribute to the evaporation. Since the start of boiling is sensitive to heat input, the uncertainty should be as small as possible.

The first three issues were tackled in simulating the whole boil-off sequence in a reactor to deduce the development of the free water surface in the QUENCH bundle. Of course, it is not possible to overcome physical conditions as the positive feedback of electrical heating, addressed in item 2, but the calculations may give a solution how to handle them best. In addition, a number of hardware changes were seen to be necessary.

To maintain an appropriate evaporation rate even for a low water level, when most electrical bundle power is released above the water level, an auxiliary heater of about 3 kW was installed in the lower plenum. A fine tuneable water injection into the lower plenum was used to prolong the boil-off phase and in this way to simulate a longer bundle. Since no experience existed for such an experimental conduct, a stepwise preparation was adopted to reduce uncertainties as far as possible.

To avoid condensation in the off-gas pipe, its cooling system was upgraded to a tempering system, allowing a surface temperature beyond condensation temperature. The remaining errors to determine the steam mass flow rate can only be reduced by qualification measurements.

To reduce the heat losses in the region of the lower plenum, an external heating system was attached on the outer surface of the test section in the lower plenum and the inlet pipes, the external heater. After the test, it was, however, assessed [10] that heat losses are dominated by axial heat conduction in the rods to the rod water-cooling.

The QUENCH tests with water quenching normally show a delay of quench water injection after starting the quench pump of about 20 s, letting the bundle in an uncontrollable status during this time. To avoid such a problem in QUENCH-11, it was advised to continue evaporation as before the quench phase and to add the quench water. In this way, the only shortcoming is temperature increase during the delay as in the other QUENCH tests.

After installation of the components and the test bundle, the pre-tests were initiated. First concern was that the heat flux from the auxiliary heater to the water in the lower plenum could lead to flashing effects. Flashing effects are known from transients in boiling water reactors as a sudden and violent boiling at low system pressure. They might occur in the

QUENCH test for high electrical power release in the lower plenum, when water in that region is slightly subcooled, but superheated with respect to the pressure at the top of the bundle. Anything that reduces the hydrostatic head can cause the water at the bottom to become locally superheated and then to flash. In such a case, the electrical energy cannot be transferred to the water fast enough, so that the heater surface temperature increases until the heat transfer mechanisms changes from nucleate boiling to film boiling.

Secondly, the mass flow rate of the additional water injection has to be quantified so that the resulting boil-off process is as close as possible to reactor conditions.

Thirdly, the reflood rate, which is determined jointly by the bundle temperature profile (enthalpy) and the water injection rate, has to be elaborated for assessment of the models.

Fourthly, the typical response time of the facility e.g. of bundle temperature, when electrical heating and hence evaporation rate and convective cooling are changed, at high temperature have to be assessed.

Fifthly, in a separate pre-test a complete reflood scenario has to be simulated so that the successful operation of the upgraded facility is verified, and a quench phase is demonstrated for experimental conditions that differ so much from all previous QUENCH tests. Maximum bundle temperature should be as considered in design basis accidents. By this way, the bundle remains intact for the main test, and, secondly, oxidation can largely be neglected. In addition, data on the boil-down and reflood characteristics are generated that can be used to benchmark the code models.

Therefore, three pre-tests were defined and preformed sequentially before the main test QUENCH-11. They delivered the necessary information to update and optimize the final test protocol (section 5.6).

3 Codes and Facility Models

During the test preparation, three different severe accident codes were used. The codes S/R5 and S/SIM are nearly identical and belong to the category of detailed coupled codes. They are composed of a thermal-hydraulic part, developed for design basis analyses, and a part to simulate component behaviour in a reactor, including material reactions and interactions under severe accident conditions. Their application is restricted to coolant systems, i.e. without detailed containment modelling. The codes MELCOR and ASTEC belong to the second code category, called integral codes. They were specially designed for severe accident analyses and probabilistic safety analyses; they cover all significant phenomena inside the containment and allow for off-site source term estimation. For ASTEC, however, the phenomena inside the RPV are calculated by the DIVA model, which is essentially based on the stand-alone ICARE2 code and its equivalent, the severe accident part of the coupled code system ICARE/CATHARE. Therefore, the quality of the respective physical and chemical models is comparable to the codes of the SCDAP family.

3.1 SCDAP/RELAP5

3.1.1 Code Description

RELAP5 is a six equation thermal-hydraulic model with a gas mixture model to track several non-condensable species. For thermal-hydraulics, the one-dimensional form of the six-equation two-fluid model is solved for the volume fraction, velocity and temperature of each phase, using a semi- or nearly-implicit numerical method. The liquid and gaseous phases are treated as being homogeneously mixed within each individual fluid cell. Closure is provided by algebraic relations for the exchanges of mass, momentum and energy between the phases and at solid structures, while one- or two-dimensional heat conduction is calculated within the structures. Quenching is calculated node by node according to the local fluid conditions and surface temperature, using the built-in heat transfer package. Spatial resolution is typically achieved by means of a rather detailed axial subdivision. Special component models address reactor systems such as pump, separator, steam dryer, and accumulators.

SCDAP was originally developed at then INEL now INL, as a stand-alone code and sponsored by the USNRC. It had a simplified thermal-hydraulics model to address analyses of in-pile and out-of pile facilities for severe accident conditions. Some improvements were made to represent the features of out-of-pile reflood experiments correctly [5].

To analyse nuclear power plants, SCDAP was coupled to the thermal-hydraulic code RELAP5. The coupled code S/R5 also contains the COUPLE code for a finite-element model of the lower head. It can be used to simulate LOCAs and other transient accident scenarios and to simulate operator interactions.

In the present version, the SCDAP part includes component models for fuel rods, control rods, shroud, grid spacers etc. Chemical reactions such as oxidation and eutectic material interactions, failure models, material dissolution and melting, and melt relocation are simulated. Transition from rod-like geometry to large debris and molten pools with subsequent relocation into the lower head are considered, too. To simulate the QUENCH facility, a detailed electrical heater rod model has been developed [5]. The electrical power, released in the bundle, is calculated from the electrical properties of the heater elements for the local temperature to consider the positive feedback of electrical heating. In the QUENCH tests, electrical rod power is derived from electrical current and voltage measurement. Voltage measurement is, however, outside the bundle, and the electrical power, released outside the bundle, e.g. at the sliding contacts of the rods cannot be neglected. Lacking better information, this is done by introducing a constant user-input resistance, called external or static resistance. Since the electrical resistance of the rod increases with temperature, the portion of the total electrical power that is calculated to be released in the rods increases with temperature. The energy balance in S/R5 refers to the bundle only; the electrical power, released outside the bundle, is therefore not included. The S/R5 approach for electrical bundle power about positive feedback and about the external resistance has been adopted in other codes.

The parabolic correlations of Cathcart-Pawel and Urbanic-Heidrick are used for Zircaloy oxidation in the temperature ranges below and above 1853 K, respectively. The core degradation models seek to provide a mechanistic treatment of the cladding behaviour, interactions between materials and relocation processes. The models include meltdown of fuel rods and structures, fragmentation of embrittled fuel rods, the formation of a molten pool of core material, crust formation and failure, and the slumping of molten material to the lower head, debris/melt behaviour therein and the lower head structural response.

S/R5 applications are restricted to the RPV and coolant circuits, and end with the failure of the lower head due to melting. Due to the USNRC consolidated code programme, the development of S/R5 was stopped. The code is further developed by ISS under the name S/SIM (see section 3.2); the RELAP5 code is replaced by TRACE, developed by ISL under USNRC contract.

3.1.2 Facility Model

The input deck is based on the standard QUENCH input deck as used for pre-test support of the QUENCH facility. It includes all significant thermal-hydraulic systems of the QUENCH facility and has the best blind calculation capability, presently available for degraded core reflood simulations. It also takes into account the facility dynamics outside the bundle under transient conditions.

Fine meshes are a prerequisite for an appropriate simulation of reflood processes, since the code does not include a mesh refinement technique for quench conditions. The test section is therefore divided into 32 axial zones, namely 6 meshes (each 7.5 mm long) in the lower electrode zone, 20 meshes in the heated zone (each 50 mm long), and 6 in the upper electrode zone (each 10 mm long). With respect to the bundle environment, the shroud and all adjacent components up to and including the containment are modelled. The central (unheated) rod, the inner, and the outer ring bundle are modelled by three different fuel rod components; the corner rods are modelled as hollow fuel rods. Due to the restrictions of the code, the corner rods have the same length as the heater rods. For fast calculations, a simplified model is available which includes only the test section with the shroud, shroud insulation and inner cooling jacket.

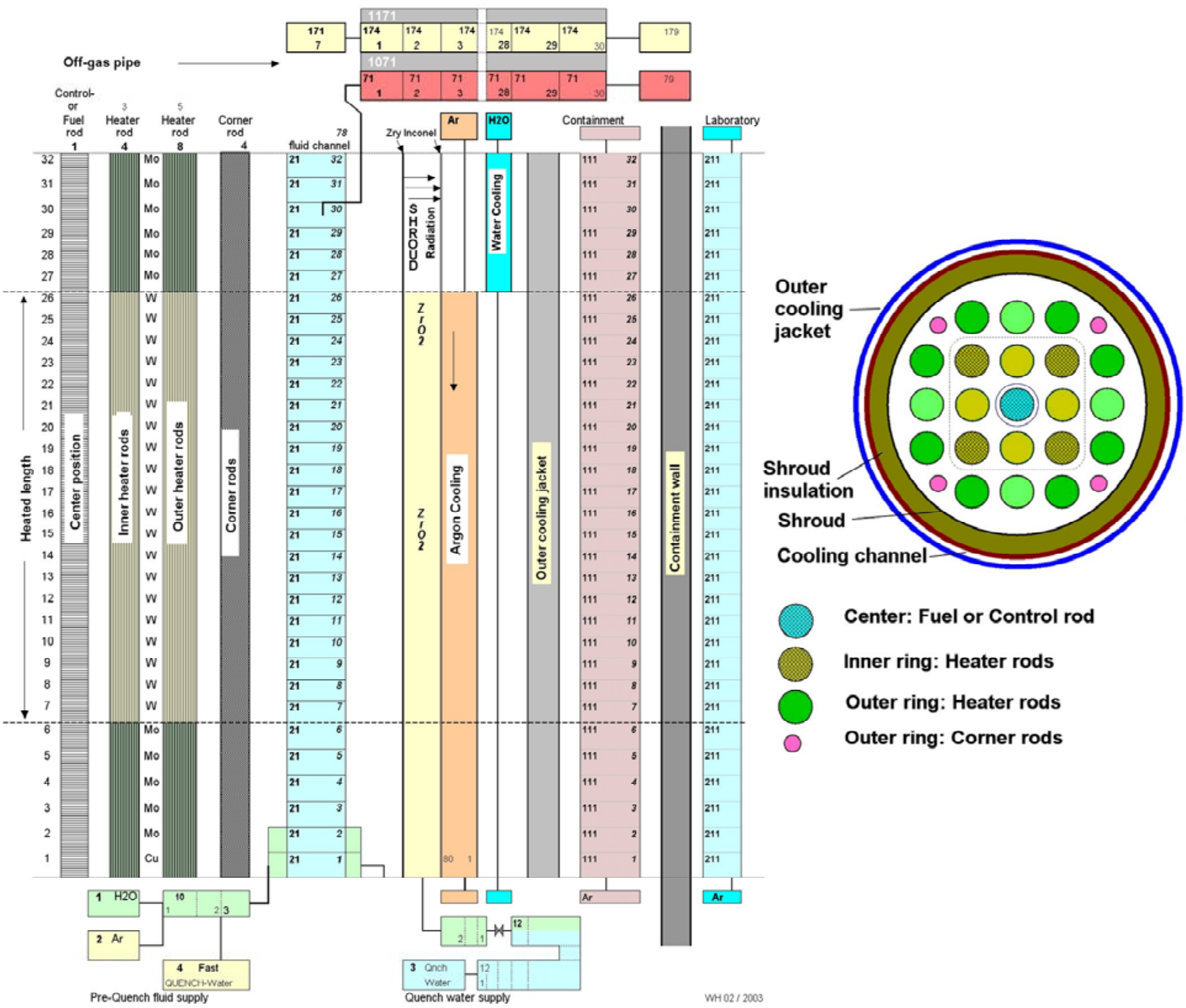

Fig. 3-1 Schematics of the complete S/R5 facility model

For QUENCH-11, the auxiliary heater was modelled as a RELAP5 heat structure in the lower plenum, connected to two lowermost axial volumes between the bundle (vol 21 in Fig. 3-1) and the adjacent annulus (vol 40 and vol 50). To account for heat losses to the containment, the containment temperature as well as the outer heat transfer coefficient was adjusted to meet experimental conditions of the pre-tests.

3.2 SCDAPSIM

3.2.1 Code Description

S/SIM is supplied by ISS and is based on one of the later releases of S/R5 mod 3.2, with further improvements in numerical treatment and inclusion of graphics interfaces that facilitate its application to transient analyses. The electrical heater rod model for QUENCH is similar to S/R5.

S/R5 and S/SIM have been used extensively for analytical support to the QUENCH experiments. The use of S/SIM gives results independent from the analyses performed by FZK using their in-house version of S/R5 and detailed model and in this way enhances the reliability of pre-test support. A feature of S/SIM is accommodation of the axial variation of the shroud configuration, not provided by S/R5. Use of S/SIM to support the QUENCH experiments is an important step in its qualification for plant analyses.

3.2.2 Test Section Model

The input is based on the model used by ISS in their participation in ISP-45 (pre- and post-test calculation of QUENCH-06). The computational domain is restricted to the main experimental components and comprises three fluid circuits. The first one includes the lower plenum, the heated test section, and the upper electrode zone up to its top end. Therefore, it encompasses the tungsten, molybdenum and copper sections of the heater rods. The details of the water and gas supply lines, and the off-gas pipe are not included. The second and third systems refer to the two cooling circuits in the annulus between the inner and outer cooling jackets to remove heat from the heated section and the upper electrode zone, respectively. In the test section, a single fluid channel is used, subdivided into 20 axial nodes, each of which corresponds to one axial node of the SCDAP components. The heated section (tungsten heaters) is represented by ten nodes, the lower and upper molybdenum sections by four nodes each, and the lower and upper copper electrodes by one node each. In S/SIM, specified boundary temperatures are imposed at the two extreme nodes of the heater elements (i.e. the Cu electrodes), specified here as that of the local fluid. Five SCDAP components represent the bundle: fuel rods represent the unheated central rod, the inner ring of eight heated rods, the outer ring of twelve heater rods, and the four corner rods, respectively; the Zircaloy shroud, zirconia insulation and stainless steel inner cooling jacket are modelled as a shroud component. The facility configuration is thus represented in a much simpler way and with a coarser discretisation than in the detailed S/R5 model used by FZK, as described in section 3.1.2.

The auxiliary heater in the lower plenum that is being used for the first time in QUENCH-11 is represented by a hollow cylindrical stainless steel heat structure with an internal heat source corresponding to the nominal heating. A user-defined multiplier (nominally 1.0) may be applied to allow for possible heat losses that are not modelled. Nominal boundary conditions are used for the bundle power, the additional water, the reflood water, the fluid supply to the cooling jacket, and outside sink temperature for the outer cooling jacket. Calculations started with nominal temperatures for the empty test section, which was then filled to the top of the tungsten-heated section by injection of water at 90 ˚C.

3.3 MELCOR

3.3.1 The MELCOR Code 1.8.5

MELCOR is designed to simulate the relevant phenomena and components in a nuclear power plant during all phases of a severe accident. A main objective of the code is to concentrate on the major characteristics and parameters important for plant safety rather than to capture the processes in detail. MELCOR comprises, typically, simple empirical correlations or parametric approaches; it is frequently used in conjunction with coarse-mesh input models. The simplified treatment of many individual processes and whole plant capability is complemented by use of the more detailed modelling provided by codes such as S/SIM.

The thermal-hydraulic module furnishes the thermal and fluid conditions for all of the process and component models — degradation, fission product transport, corium-concrete interaction, etc. The masses of liquid water, steam and each non-condensable gas species in each cell are calculated, while a simplified, one-dimensional treatment of momentum balance is used for the flows. Closure is provided via correlations for the mass, energy and momentum exchanges. Heat conducting structures provide the physical and thermal boundaries for the hydraulic system; the structures can ablate or undergo failure through thermo-mechanical loads. The core models describe the heat-up, oxidation, fuel dissolution, bulk melting, and relocation. The core components include fuel rods, absorber rods, cladding, non-supporting structures such as guide tubes, and supporting structures. These are frequently subdivided into a number of radial and axial cells within a single fluid volume. The Urbanic-Heidrick correlation for Zircaloy oxidation is normally used at all temperatures, but alternative correlations may be specified through input. Quenching is represented in recent versions of MELCOR by a semi-empirical model for quench front propagation which has performed successfully in QUENCH simulations, provided the bundle was not significantly damaged prior to reflood, for example as in QUENCH-06.

The controlled temperature history in the QUENCH experiments provides a good opportunity to assess various oxidation models. MELCOR has therefore been used successfully by a number of organisations including SNL, NRI Rez, and PSI, to analyse the QUENCH experiments. Features of the test section, notably the Zircaloy shroud and the electrical heater elements, require a modelling and a discretisation that differ somewhat from those used in typical plant models. However, MELCOR is sufficiently flexible to represent the essential features of the QUENCH facility.

3.3.2 Test Section Model

The MELCOR hydraulic model comprises one channel for the bundle, with four axial nodes spanning the tungsten heated section, one cell each for the upper and lower molybdenum sections and one each for the upper and lower copper electrodes. In contrast to S/SIM, MELCOR allows the core or bundle components to be modelled in more detail than the corresponding hydraulic region. Thus, 22 axial nodes are used for the bundle components. Ten nodes are used to model the tungsten-heated section while the remainder represent the molybdenum and copper sections of the heater rods. As in S/R5 and S/SIM, the bundle the central rod, the two rings of heater rods and the corner rods are treated separately. Since there is no specific shroud component in MELCOR, the Zircaloy shroud is represented as a canister component. Outside the shroud, the insulation and inner cooling jacket are represented as heat structures. The outer surface of the inner cooling jacket is modelled as a boundary condition rather than as a hydraulic system.

In a similar manner to S/SIM, the total time-dependent power supply and the (fixed) external resistance are input by the user. The auxiliary heater is represented by a heat structure within the lower plenum, in an analogous manner to S/SIM model, as are the remaining initial and boundary conditions for initial filling, additional water, and reflood water.

3.4 ASTEC

3.4.1 The ASTEC Code V 1.2

The computer code system ASTEC is developed in a joint effort of French IRSN and its German equivalent GRS to simulate severe accidents in Light Water Reactors from the initiating event up to the possible release of radionuclides (so-called "Source Term") outside of the containment. It is intensively used for PSA level 2 analyses, for evaluating the severe accident management procedures and for preparing and interpreting experimental programmes. It is the reference European code in the Network of Excellence SARNET in the 6th FWP of the European Commission.

ASTEC, which covers almost all severe accidents phenomena, is composed of dedicated modules e.g. DIVA for reactor behaviour under severe accident conditions. A number of such modules can be run as stand-alone codes. This structure facilitates the validation of a module by comparison against experiments. Each module concerns the phenomena that occur in a part of the reactor or during a stage of the accident, for instance: two-phase thermal-hydraulics flows in the primary and secondary circuits, transport of fission products and aerosols in the primary and secondary circuits, a "lumped-parameter" approach (using 0D volumes) for the containment thermal-hydraulics and aerosol behaviour, and interactions of the molten corium with concrete in the cavity after RPV failure. The core degradation models are directly issued from the IRSN detailed code ICARE2, for which that institute has made very important efforts since more than 10 years. The situation is the same for the containment models (thermal-hydraulics and aerosols) that take benefit of the GRS work on the former containment codes.

3.4.2 Test Section Model

The QUENCH-11 input deck is based on that for QUENCH-06, adjusting the initial temperatures and adding the auxiliary heater in the lower plenum. Temperature at the end of the rods is set to 353 K. In the radial direction, the test section up to and including the inner cooling channel, is modelled. In the axial direction, the computational domain starts at –0.47 m and ends at 1.5 m elevation, as given in Fig. 3-1 for S/R5. The central rod, the two rings of rods to be heated independently, the four Zircaloy corner rods, and the shroud up to the inner cooling jacket wall are considered. Three corner rods are modelled as tube structures, the removable corner rod as a solid structure, taking into account the reduced length as can be seen in Fig. 3-2. The ZrO_2 fibre insulation of the shroud is modelled from above the lower plenum up to the end of the heated zone at the level of 1.024 m. At the outer boundary, stationary temperatures are used based on measurements.

The heated bundle section is divided axially into 11 cells, 9 nodes each 0.10 m long and 2 cells at the upper end of the heated rod, both 0.062 m long. In the lower electrode section, the length of 0.47 m is divided into five equidistant nodes. In the upper electrode zone, the first node is 0.086 m long; the four subsequent ones are 0.1 m long. This discretisation allows a better representation of the high temperature region prior to reflood and reduces discretisation errors on the electrical and oxidation energy release. For the static electrical resis-

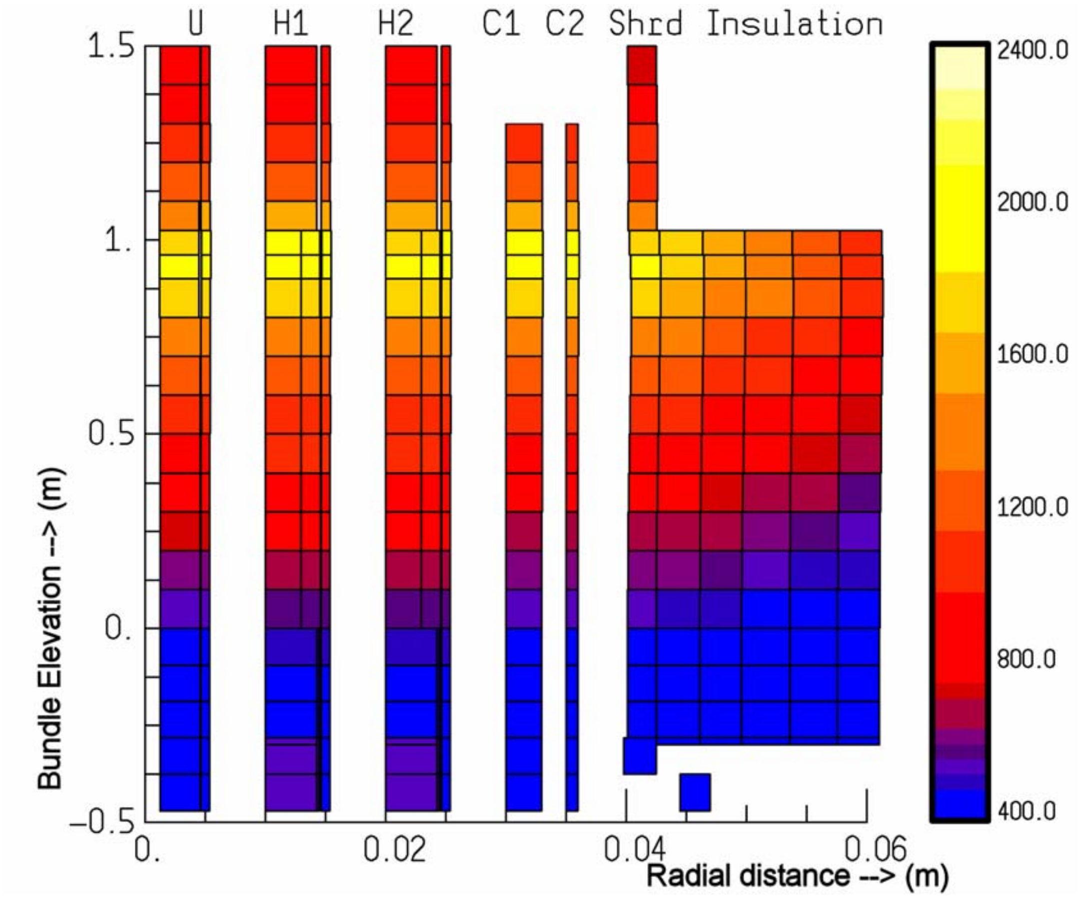

Fig. 3-2 Modelling of the QUENCH facility with ASTEC V1.2

Only the inner half of the fibre insulation in the shroud is shown.

tance of the circuit outside the electrical heater rod a value of about 4.2 mΩ per rod is applied based on experiences from other experiments.

The bundle fluid is modelled as a single channel. Necessary boundary conditions such as pressure and mass flow rates are provided by dedicated structures (CONNECTI). Due to code limitations, no pipes connecting the test section to the gas supply or the off-gas pipe are modelled. After the corner rod has been removed, its oxidation is no longer simulated. The input for the radiation exchange in the heated zone and the upper electrode has been extended to calculate radiation exchange between fuel rods and corner rods correctly. Since there the lower plenum is always filled with water, calculation of radiation exchange between fuel rods and shroud is suppressed in this region.

Fig. 3-2 represents an intermediate bundle state at about 5000 s. The interfaces between the different material layers in the heater rods are shown by vertical lines. The hollow corner rod is given by its thin Zircaloy wall thickness. The radial positions, given on the x-axis, represent roughly the bundle composition. The figure reflects clearly, how the heat penetrates into the shroud insulation; in the upper half of the heated section, the steep axial temperature gradient of more than 1500 K/m is visible.

4 Pre-Tests

In the following section, the three pre-tests Q11-v1, Q11-v2, and Q11-v3 are discussed with respect to the new hardware installations, the operation procedures, response times and sensitivities. Main emphasis is put on their relevance for pre-test calculations of the main test QUENCH-11. The pre-tests tackle instrumentation, qualification, and handling of the new installations. In addition, the two latter ones also serve as qualification of the pre-test calculation capability for the main test QUENCH-11.

4.1 Pre-Test Q11v1

Systems like data acquisition, auxiliary heater and additional water injection, necessary to perform a QUENCH test, were tested under quasi steady state conditions. Q11v1 gave information about the heat balance and heat losses in the lower plenum and entry pipes. No pre-test calculations were performed for Q11v1. The bundle was filled with water up to the elevation of 1.0 m and heated up close to saturation temperature with the auxiliary heater only. The following tasks were performed:

1. Check for steady state conditions.
2. Start evaporation with auxiliary heater and compensate evaporation losses with the additional water injection.
3. Check amount of condensation in the upper plenum and the off-gas pipe.

The following results were obtained.

1. No component showed essential problems.
2. External heating power of 190 W is OK. Temperature T 511 rather stable (36 V, 6.8 Ω)
3. No flashing observed with the auxiliary heater power of 3.2 kW.
4. Stable steam production rate of 1 g/s +/- 10% (boil-off velocity about 0.3 mm/s) for P_{aux} = 3.2 kW and water level between -300 mm and 600 mm.
5. Power control was reliable and benign.
6. Water level L 501 includes offset or drift of about –50 mm, when the auxiliary power exceeds 3 kW. The reason is unclear.
   Water level will be checked by water balance, using initial level, injected and evaporated (condensed) water.
7. Lowest tolerable water level in test –250 mm (L 501 without correction), no sign of hazardous overheating of the auxiliary heater, i.e. the heater is completely wetted.
8. Temperature in off-gas pipe > 114 °C, hence above T_{sat} due to 3 g/s Ar at 142 °C; heating time to reach that temperature ~ 2 h

9. External heater for additional water delivers inlet temperature of 95 °C. Switch on heater about 30 min before water is injected.

4.2 Pre-Test Q11v2

An objective of Q11v2 was to check whether flashing occurs during boil-off and core heat-up. Furthermore, the interplay between bundle heating system and auxiliary heater should be elaborated. Besides, it was to prepare the pre-test Q11v3, where a reflood test should be performed in a manner similar to QUENCH-11, but with a maximum temperature as considered in design basis accidents.

In Q11v2, the bundle is initially filled with water and heated up with the bundle heating system and the auxiliary heater for about 1000 s, as can be seen in Fig. 4-1. Afterwards, the bundle power is reduced to about 1 kW and the auxiliary power increased to about 2 kW, so that the boil-off is controlled by the auxiliary heater alone. The minimum water level above the upper end of the auxiliary heater has to be evaluated. During this period, the power of the auxiliary heater is adjusted to match the desired boil-off velocity. When the water level (L 501) drops below –150 mm, additional water is injected to maintain a constant water level for the heat-up phase. To avoid any oxidation in the bundle reflood is initiated at about 580 K.

Some pre-calculated temperature curves are shown in Fig. 4-1 bottom. The steep temperature increase up to 300 s is caused by local heating at locations above the water level, not yet cooled by steam. This situation ends, when saturation is reached and evaporation starts (Fig. 4-1 centre). After 750 s, core uncovery starts when the water level drops below 0.9 m.

With decreasing water level, evaporation falls below 1 g/s at around 2700 s. This is the signal to start the additional water injection compensating the evaporation losses so that the water level remains nearly stationary at the lower electrode zone. The test is terminated by flooding the test section with 18 g/s water at around 3450 s.

In the first calculations performed with S/R5, flashing was observed for low water levels and high auxiliary heater. A closer check of the modelling of the auxiliary heater revealed that for the effective surface area the inner surfaces of the heater ribs were not taken into account.

The various pre-test calculations as well as the pre-tests itself revealed that the defined scenario can be simulated in the QUENCH facility. The risk of flashing events cannot be excluded, when only the auxiliary heater is active. It can be practically excluded, if both heating devices, the bundle and auxiliary heater, are active. The S/R5 results are sensitive to small changes in the initial temperature profile and hence to changes in the enthalpy of the test section, as it is quite comprehensible for the experimental conditions in question. The boil-off velocity was larger, because in that calculation the full power of the auxiliary heater was released into the water and the radial and axial heat losses were underestimated as can be seen in Fig. 4-2. The stepwise increase of the auxiliary power is uncritical with respect to flashing for the given experimental conditions.

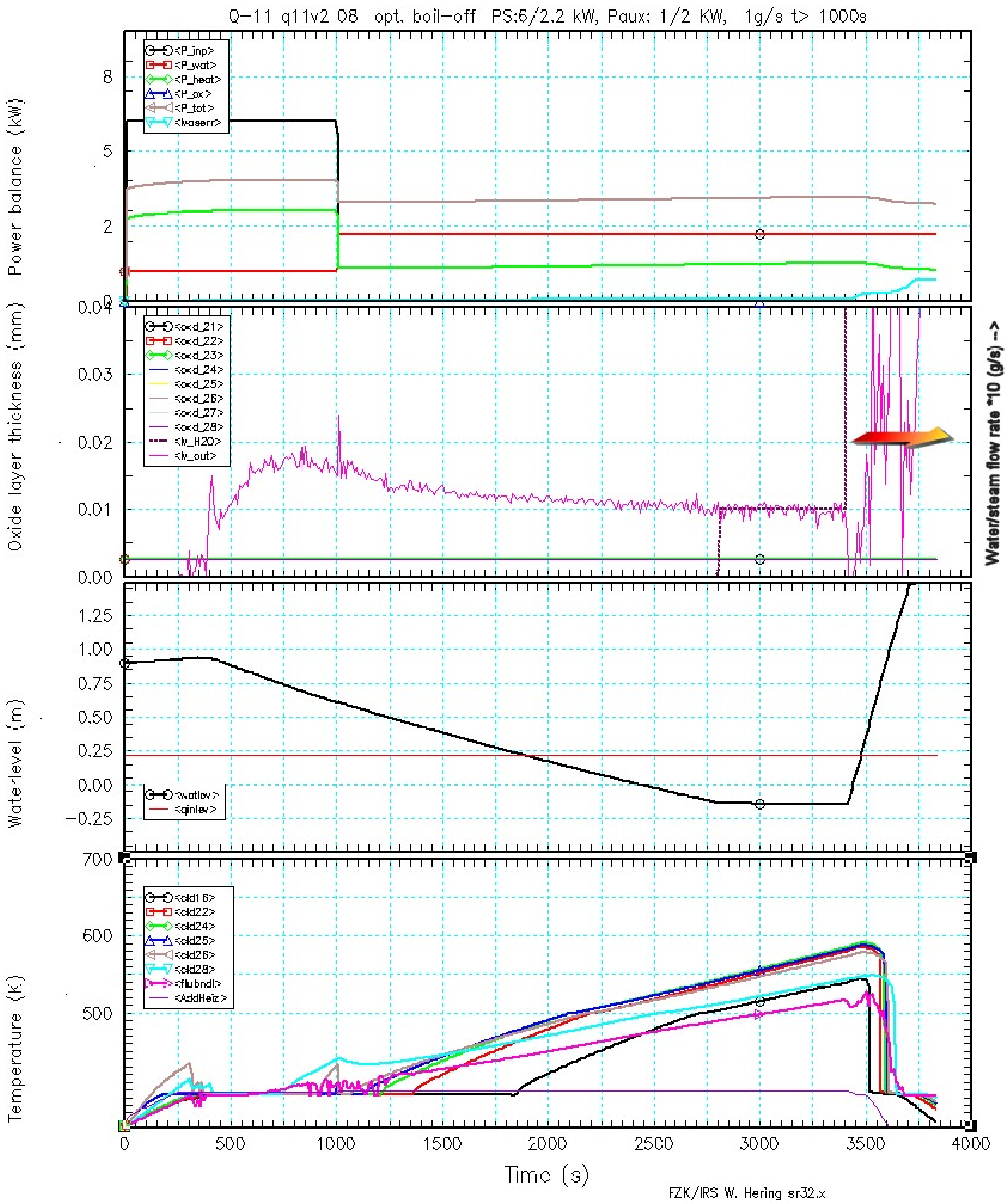

Fig. 4-1 Final scenario for pre-test Q11v2 (08)

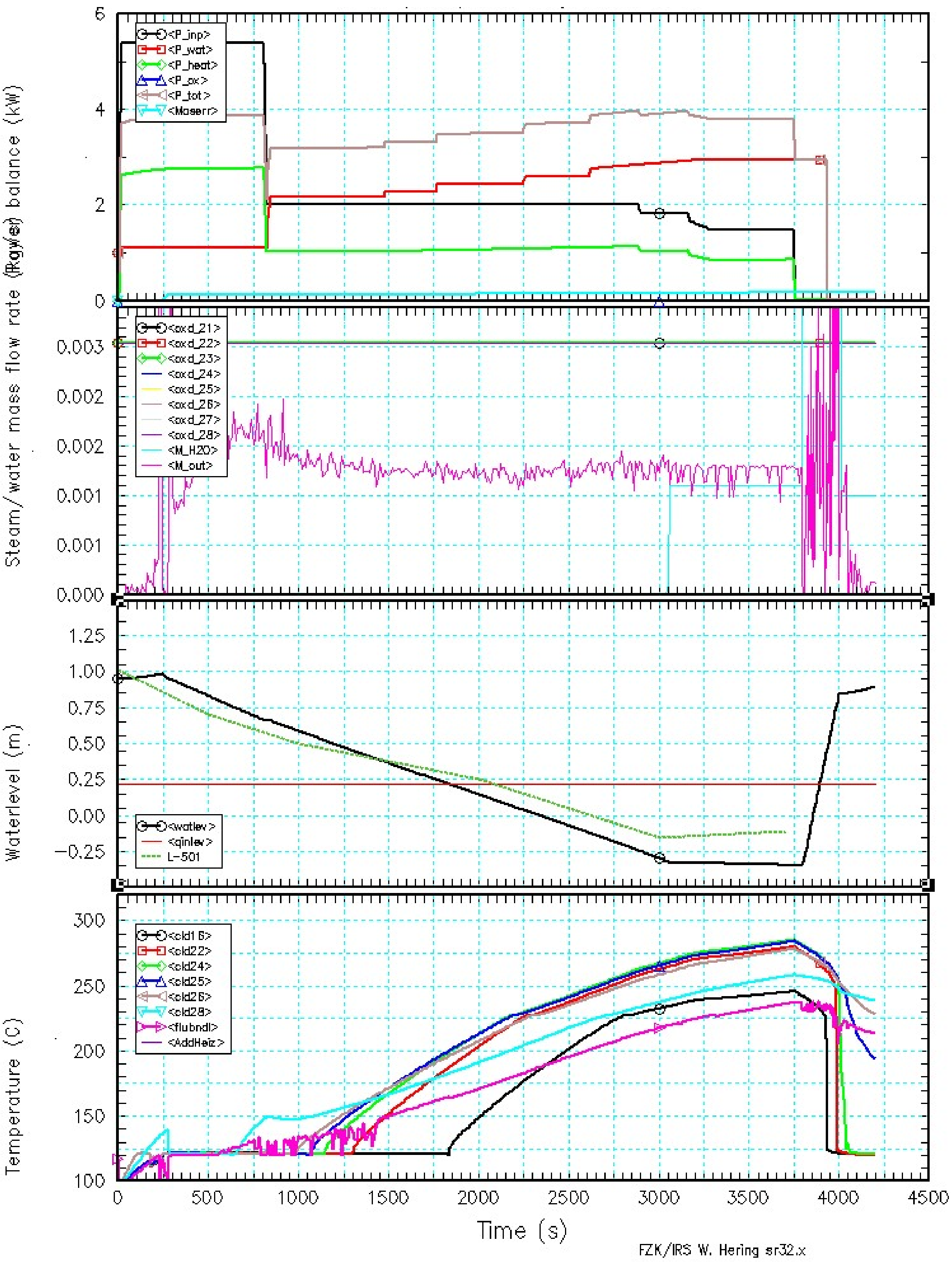

Fig. 4-2 Post test calculation using experimental power data Q11v2 (a03)

4.3 Pre-Test Q11v3

The third pre-test Q11v3 is intended to perform QUENCH-11 as close as possible, but at lower temperatures so that oxidation can be neglected largely. Therefore, the initial phases i.e. boil-off and heat-up, should be the same, only the reflood phase is initiated earlier at about 1350 K to avoid any fuel rod damage. During the test, system behaviour, bundle response, controllability, and operator response time margins are checked.

Q11-v3 scenario:

Start with steady-state conditions of Q11v2:
water at about 353 K, filled up to about 1.2 m, external heater active

1. Initialization phase:
   Heat-up using bundle power to reach saturation at 0.2 MPa,
   and monitor evaporation rate (mass spectrometer, water level)
2. Boil-off and bundle heat-up phase
   Investigation of the experiment control and system response up to 1350 K (similar to design basis conditions).
   - Take heat-up scenario from the QUENCH-11 test,
   - boil-off velocity of about 0.3 cm/s (water injection rate:1 g/s), controlled by bundle power)
   → heat-up phase ends, when T_{max} ~ 1350 K is reached,
3. Plateau phase
   1. Maintain temperature for about 5 min, and
   2. Initiate slow reflood as defined for the QUENCH-11 (20 g/s water).
   3. Check water level to avoid dry out of auxiliary heater.

   If in phase 3 temperature rises beyond 1450 K, initiate reflood ASAP.

4.3.1 Pre-test Calculations with S/R5

Based on the Q11v2 experiences and related input decks, several S/R5 calculations were performed with parameter variations as indicated in Table 4-1. To meet the measured data, the efficiency of the auxiliary heater was decreased, thus increasing the simulated heat losses to the containment; the value of the external resistance was left unchanged. Best results were obtained with case a04, as can be seen by comparison with the results of Q11v3, added in the last row of the table.

Table 4-1 Parameters and results of S/R5 pre-test calculations and results of Q11v3

Scenario	Paux	Static resistance	$K_{(ZrO2)}$ (%)	mH2O (g/s) t> 4200s	max Temp (K)	d_{max}(ZrO2) (µm)	m_{tot} (H2) (g)
a01	80%	3,6 mΩ	+40%	1,00	1450	58	4,29
a02	100%	4,2 mΩ	+40%	1,00	1300	32	2,08
a03	100%	4,2 mΩ	+80%	1,00	1280	24	1,56
a04	80%	4,2 mΩ	+80%	1,00	1280	27	1,71
a05	91%	4,2 mΩ	+80%	1,00	1250	23,5	1,46
a06	85%	4,2 mΩ	+80%	1,05	1275	30	1,59
Q11v3	-?-	-?-	-?-	1,05	1275	21	1,69

4.3.2 INRNE Post-Test Calculations

Based on the initial conditions as well as the results of the pre-test the INRNE team performed pre-test calculation of boil-off test using MELCOR and the following conditions: The maximum applied bundle power was 7.1 kW; the maximum power of the auxiliary heater in the lower plenum was 2.7 kW.

1. ***Preconditioning phase:***

- Test section was fill up for 80 s at approximately 1.0 m of water level with saturated temperature approximately 395 K (pressure in bundle is 0.2 MPa).

- The flow rate of FW during the fill in phase was 100 g/s. The temperature of feed water was 368 K.

Therefore, the pre-test conditions in the bundle are:

- Water level of 0.99 m has been reached in 75 s. Afterwards, there the water level decreased by 7–8 cm for the next 80 s and went back of level to 1.0 m. Fluctuation of the water level could be explained by initial conditions – coolant was saturated and the water level in upper part in bundle was very sensitive.

- Coolant temperature in bundle was stabilized at 394 K - 395 K;

- Pressure in bundle 0.2 MPa.

During the whole transient, 3 g/s argon were injected at the top of the bundle. The temperature of argon injected at the top was 415 K.

2. ***Boil-off phase:***

The decrease of the water level starts at approximately 230 s. After 80 s, there was no feeding of test section until 2550 s.

The boil-off phase started at 230 s and lasted at 2550 s, then the auxiliary water of 1.1 g/s (by 4200 s switched to 1.0 g/s) was supplied at the bundle bottom with temperature of 368 K (95 C), and the water level was stabilized at elevation of -100 mm.

Switch on auxiliary heaters with a power between 1.0 and 2.7 kW. The auxiliary heaters are located at the lower plenum of the test facility.

- Speed of bundle uncovering during Boil-off phase 0.48 mm/s.

- Heat-up rate 0.58 K/s in the interval of 900 s to 2300 s.

3. ***Start of reflood phase:***

- Peak core temperature of 1495 K was reached at 4300 s.

- Injections of 19 g/s reflood water from quenching pump.

- Temperature of reflood water approximately 295 K.

The bundle was flooded with the water rate of 19 g/s with 295 K by 4468 s and maximum fuel cladding temperature of 1495 K was reached.

The total hydrogen mass, produced during the calculation, was 9 g. Oxidation started approximately at 1600 s. Most of hydrogen mass was generated during the stabilization of water level at –100 mm. During this time, there was injection of water with 368 K.

4. *Conclusions:*

To avoid significant higher hydrogen generation some corrections are needed. First of all, it is necessary to start supplying of feed water before 2550 s and so to maintain a higher water level. At this time (2550 s), the temperature is just above 1200 K. Therefore, oxidation is negligible after that time. There is need of increasing of auxiliary heat power above 2.7 kW to 3.0 kW and decreasing to 6.5 kW bundle power between 2000 s and at the end of calculation.

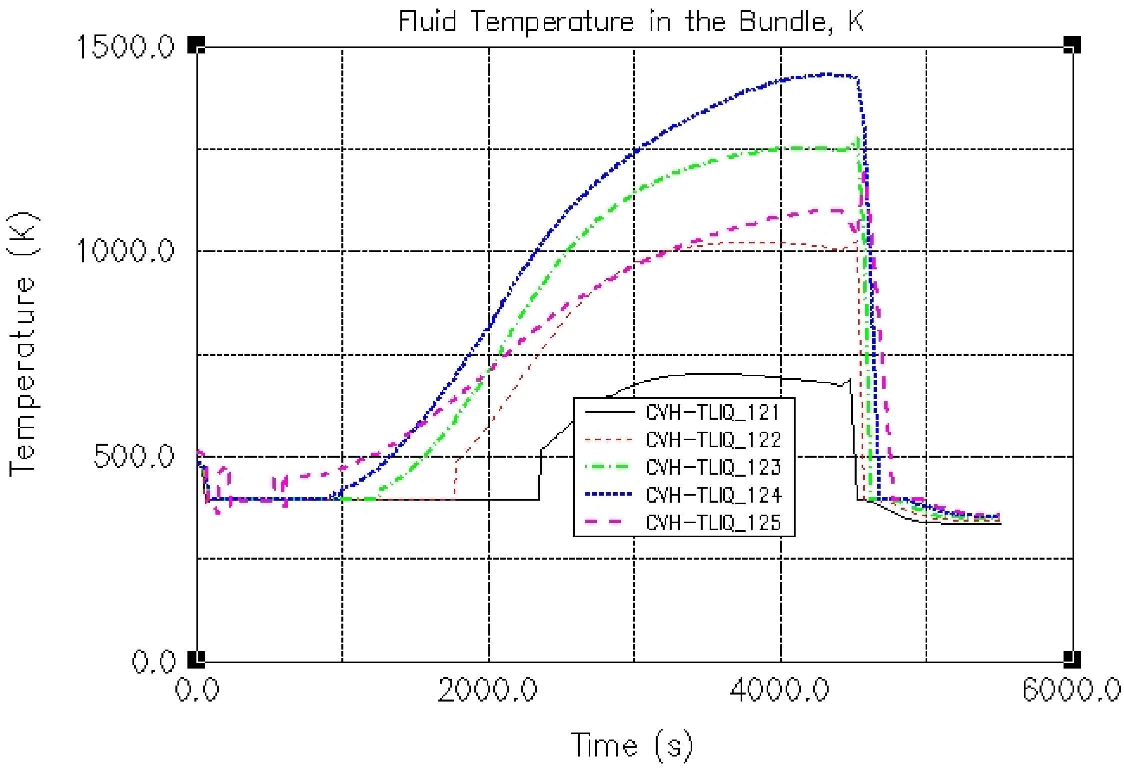

Fig. 4-3 Q11v3 bundle fluid temperature at various axial levels

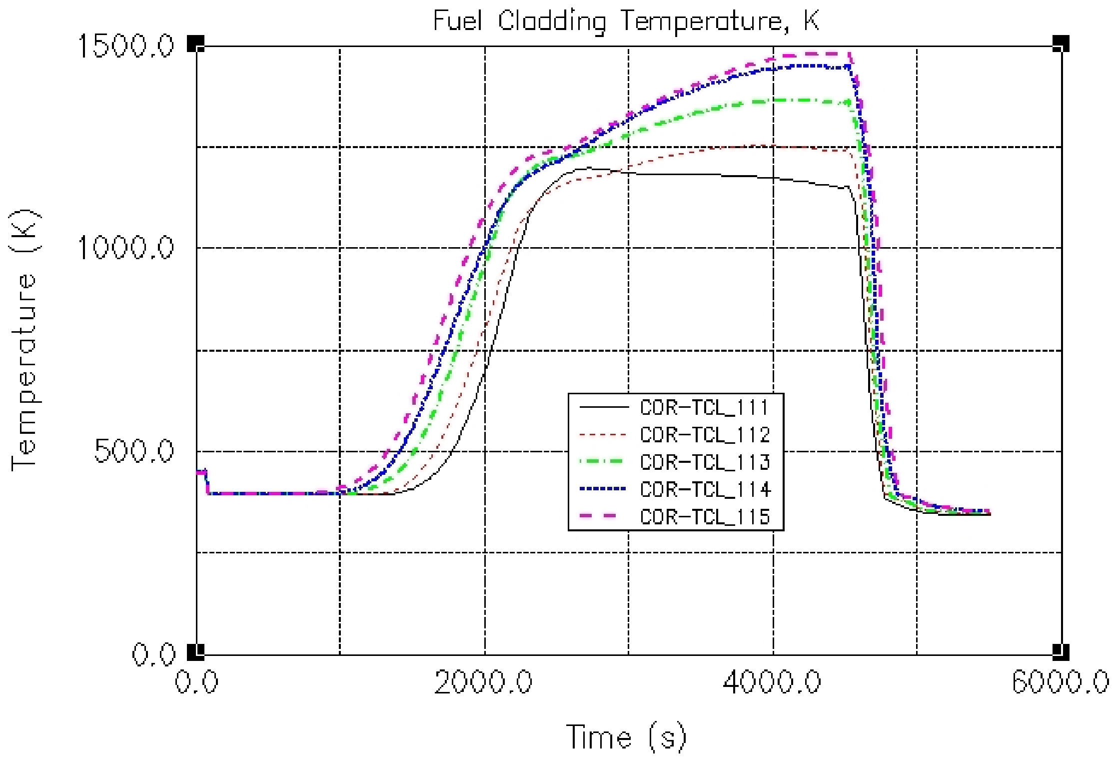

Fig. 4-4 Q11v3 fuel clad temperature at various axial levels

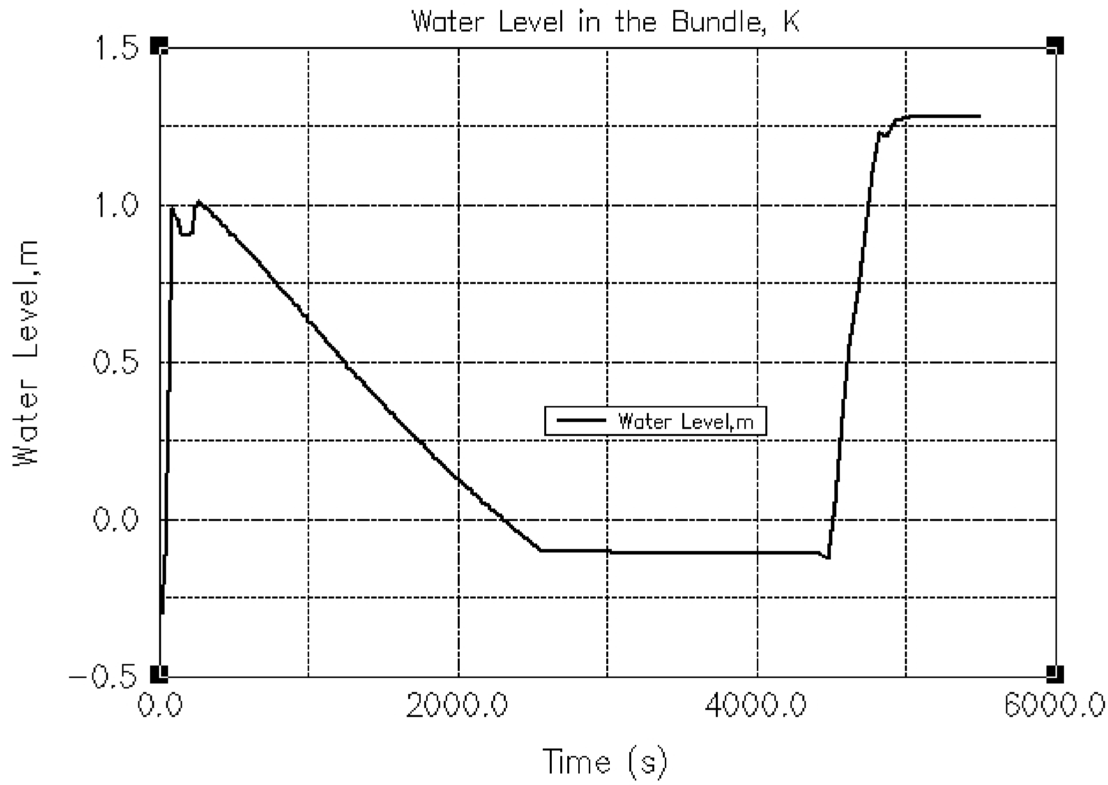

Fig. 4-5 Q11v3 water level

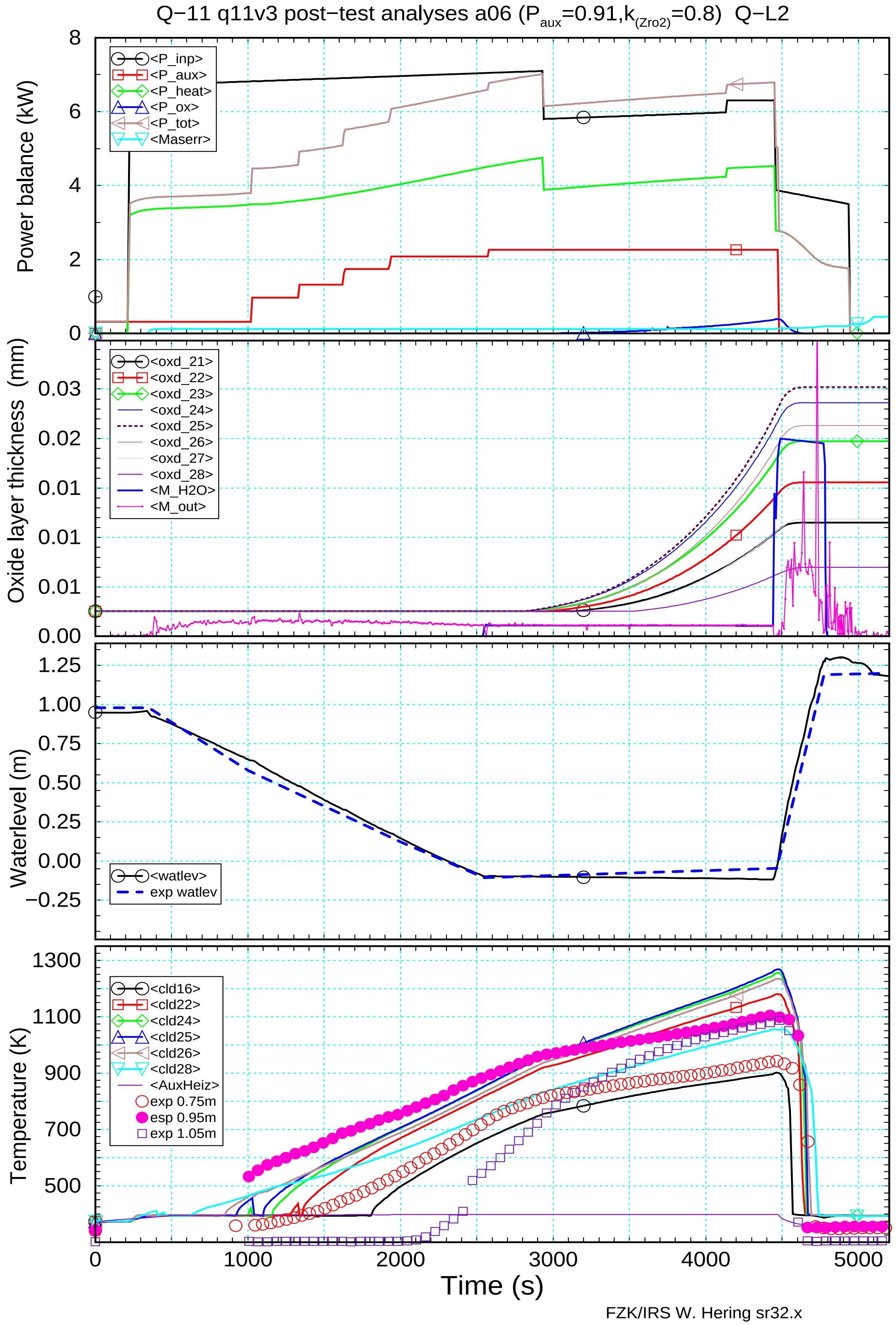

Fig. 4-6 S/R5 post test calculation for Q11v3

4.3.3 Post Test Analyses with S/R5

The Q11v2 experiment revealed that the pre-test calculations have to be qualified by experiments because of the observed sensitivity of the facility. Based on the input deck from pre-test calculations the heat losses in the lower plenum were adapted by varying the heat transfer conditions and the responsible surface area. The thermal conductivity of the fibre insulation was increased for saturation temperature to better simulate the lack of insulation in the lower plenum. The efficiency of the auxiliary heater was reduced to about 85% in the calculations shown in Fig. 4-6.

4.3.4 Post-Test Calculations with S/SIM (PSI)

Results of a single post-test calculation (Q11v3jb13d) are presented (Table 4-2 and Table 4-3), following trial cases in which the external resistance and the multiplier on the additional heating were adjusted. The other trial cases showed essentially similar behaviour; the main differences were in event timings.

Table 4-2 Parameters of Q11v3 post-test calculation using S/SIM

Case	**P_{aux} (%)**	**R_{ext} (mΩ)**	**P_{el} (kW)**	**T_{oxfail} (K)**	**m_{H2O} (g/s)**	**T_{clad} (K)**	**d_{max} (µm)**	**m_{tot} (g)**
Q11v3jb13d	78	3.4	experi-mental	2200	experi-mental	1340	35	3.4

P_{aux} auxiliary heater power
R_{ext} external resistance
P_{el} electrical bundle power
T_{oxfail} clad failure temperature
T_{quench} temperature for quench initiation
t_{quench} time of quench initiation
m_{H2O} steam mass flow rate
T_{clad} maximum clad temperature
d_{max} maximum oxide scale
m_{tot} cumulated hydrogen mass

Table 4-3 Event sequence for Q11v3 using S/SIM

	Value / Condition	Time (s)
Auxiliary water switched on	level < -50 mm	2570
Onset of oxidation	rate > 1 mg/s	3550
Quench initiation	1335 K	4533
Peak temperature	1342 K	4565
Bundle quenched	T_{max} < 500 K	5480

The results for bundle collapsed water level, temperatures, steam exit flow rate, and hydrogen generation are shown in Fig. 4-7 to Fig. 4-11. The Q11v3 calculation generally followed measured decrease of water level (L 501) and progressive uncovery of the bundle, although there were some discrepancies in the behaviour during the early stages, when the boil-down and heat-up rate near the top of the bundle were underestimated. The evaporation rate was underpredicted at the start of the boil-down, consistent with the deviation of the water level at the start of bundle heat-up. Possibly, there were heat sources in the upper region that were not represented in the model. Agreement improved as the bundle uncovery progressed, at least until the power was reduced at about 3000 s.

After about 3000 s, the rate of heat-up was overestimated, with the result that the temperatures at the upper locations, having been underestimated during the early period, came into good agreement by the time quench was initiated. However, agreement for the temperatures at the lower locations worsened following the power reduction. This aspect of the result is rather surprising, and perhaps points to a rather delicate energy balance at many locations that became perturbed by the change in electrical power. A possible reason might be the reduced auxiliary power, used in the calculation to match the liquid level; this led to an underestimate of steaming rate and perhaps cooling of the rods. The calculated onset of hydrogen generation was later than observed, possibly due to the slower heat-up during the early stages. However, the generation rate was significantly overpredicted, once the oxidation began.

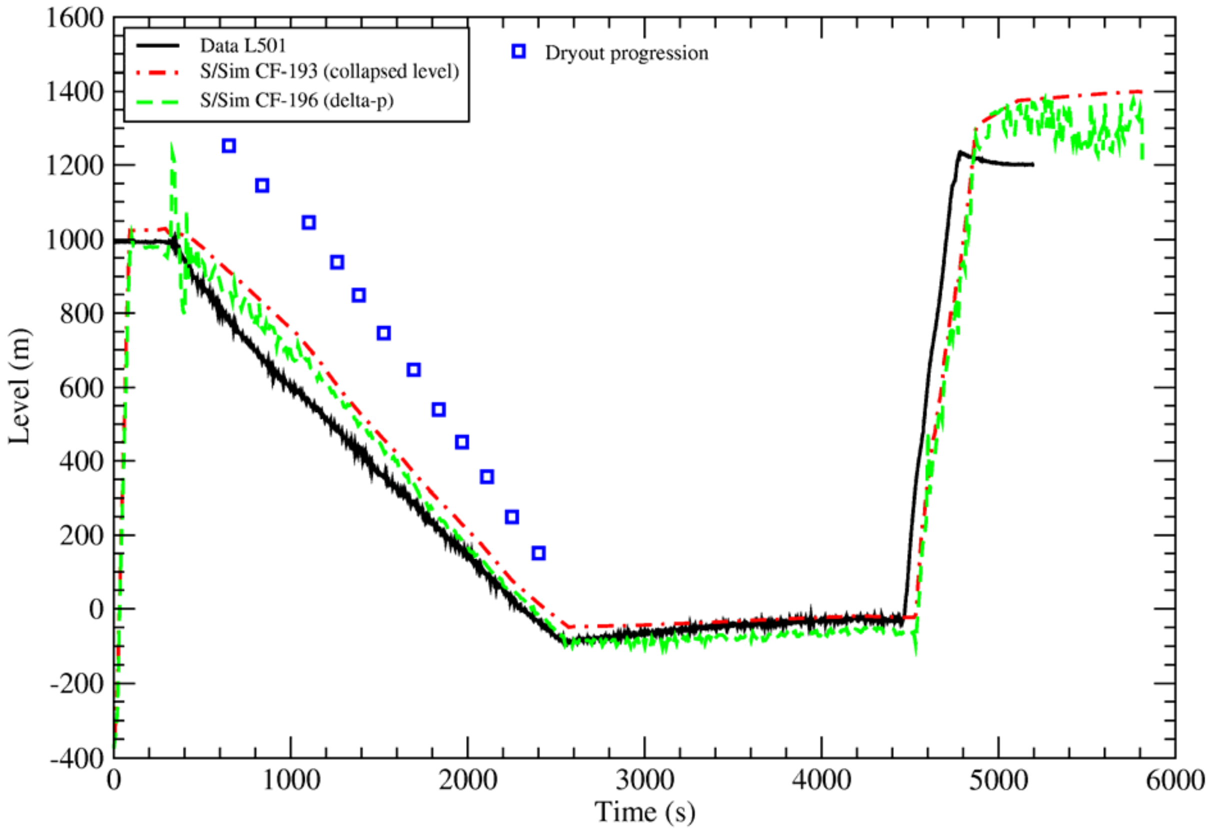

Fig. 4-7 S/SIM Q11v2 collapsed water level

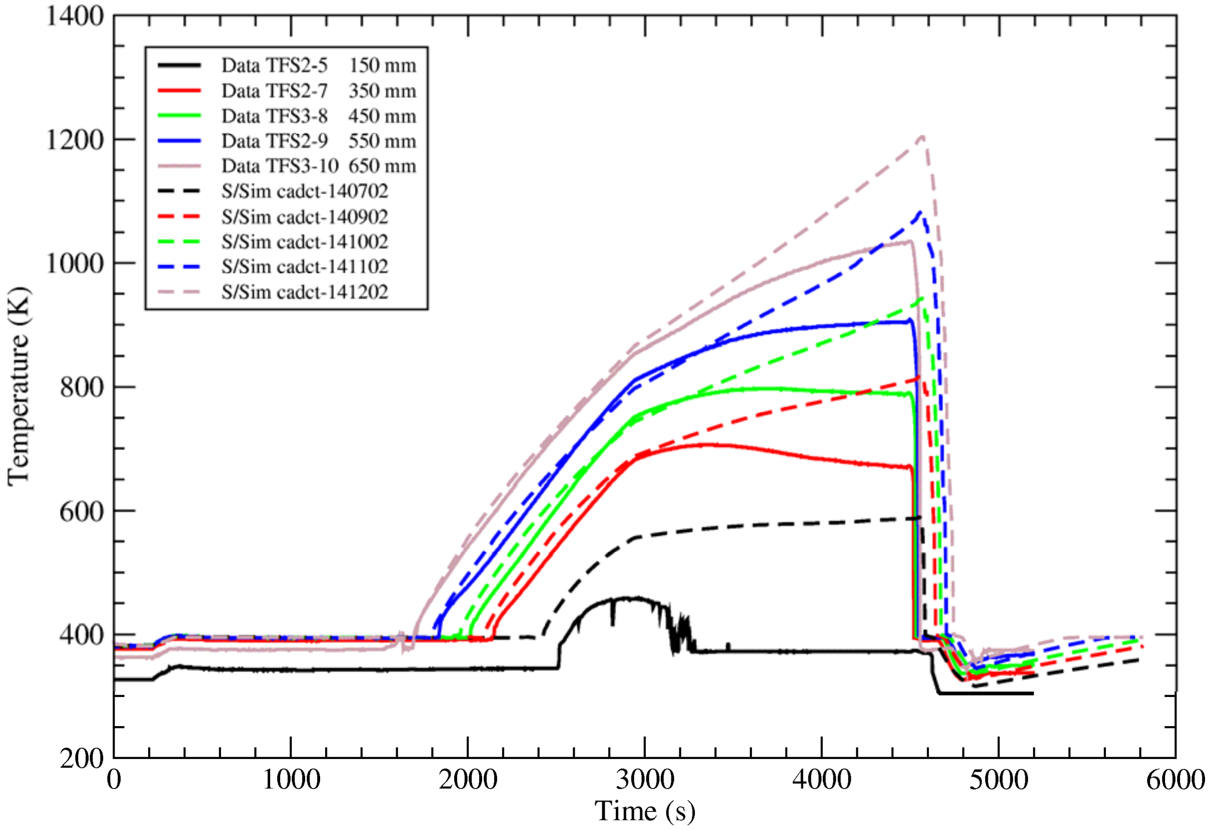

Fig. 4-8 S/SIM Q11v3 heater rod surface temperatures (lower part of the bundle)

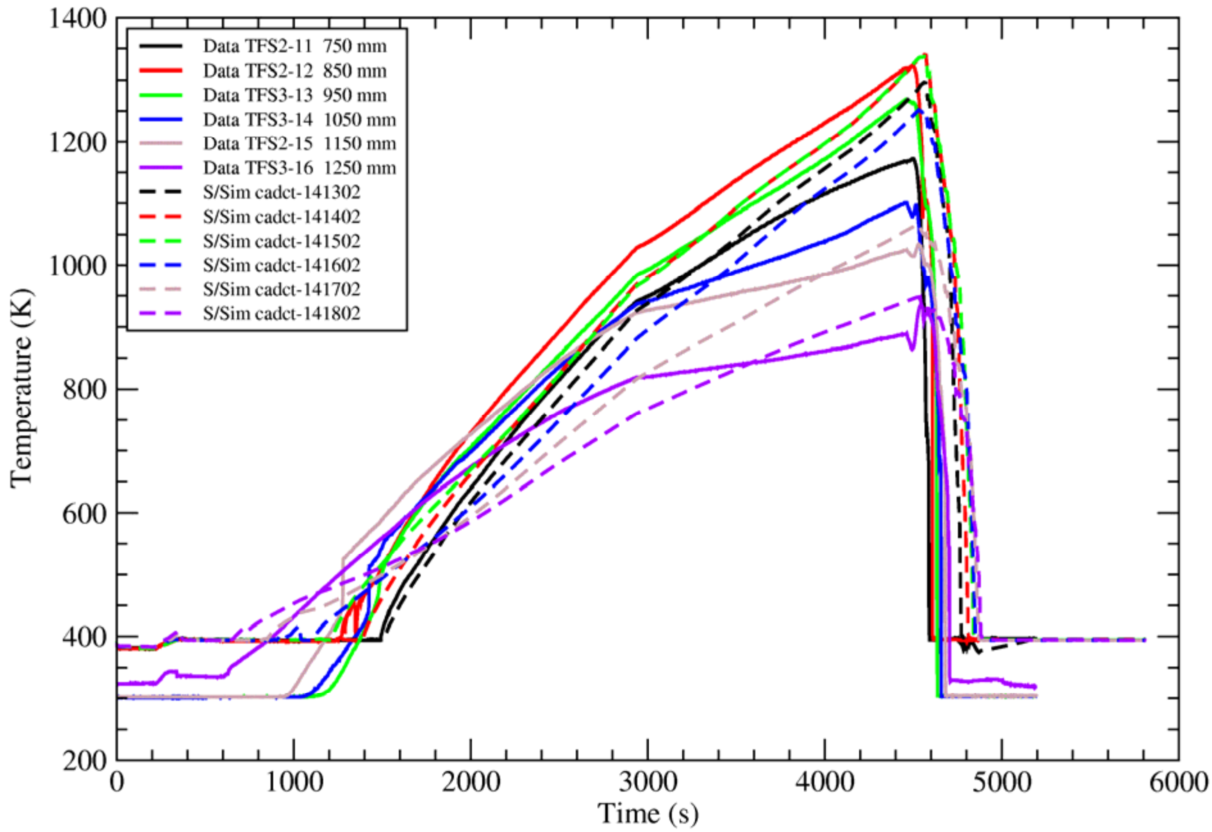

Fig. 4-9 S/SIM Q11v3 heater rod surface temperatures (upper part of the bundle)

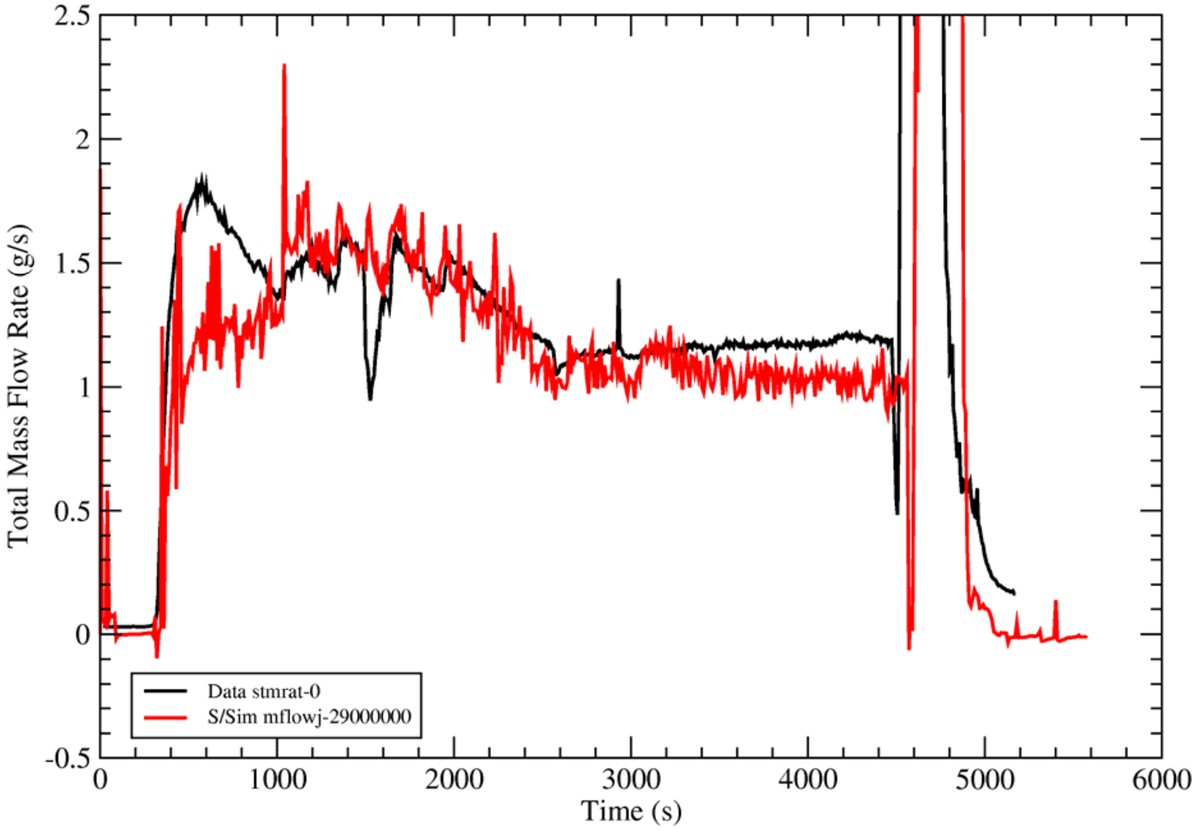

Fig. 4-10 S/SIM Q11v3 steam exit flow

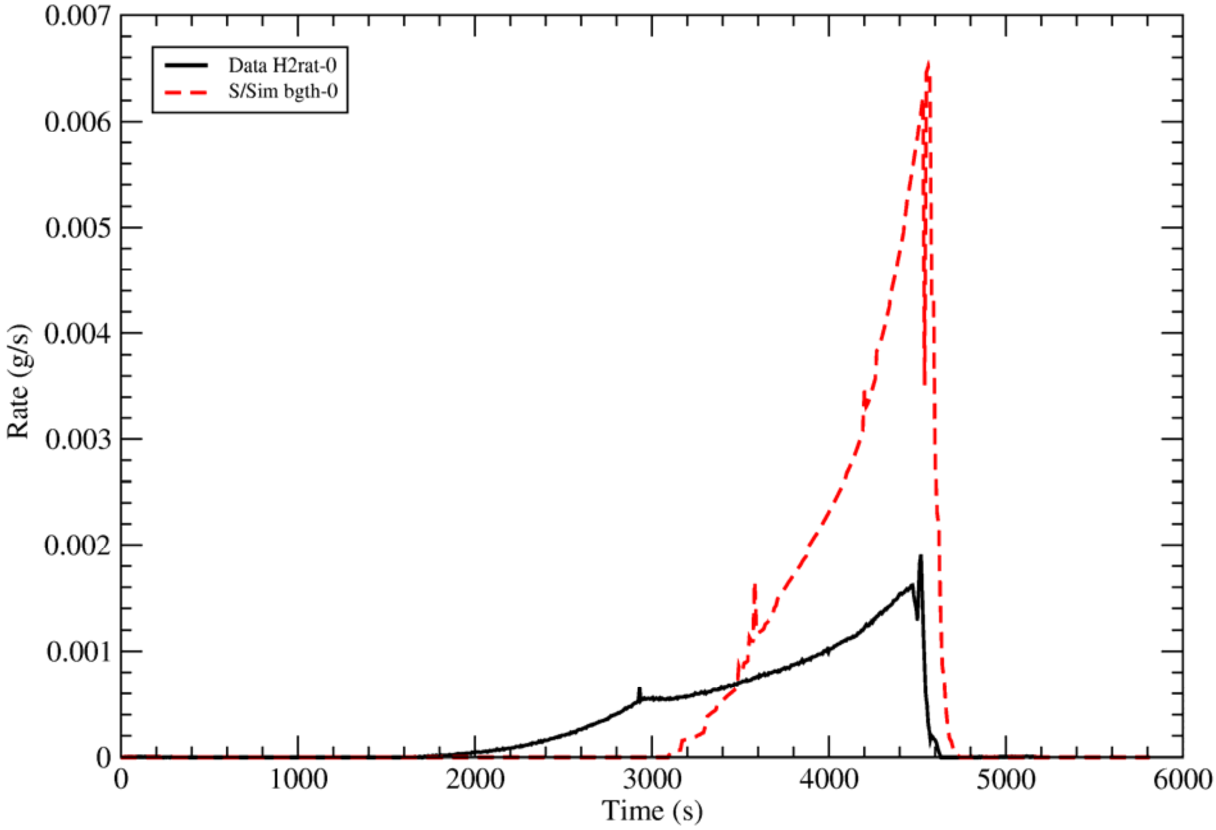

Fig. 4-11 S/SIM Q11v3 Hydrogen generation rate

4.3.5 Post-test Calculations with MELCOR (PSI)

The results of the MELCOR 1.8.5 calculations showed almost identical behaviour compared with the PSI S/SIM calculation (section 5.4.2). A series of calculation was performed using different values for the external resistance and different multipliers for the auxiliary heater power. Main differences were the event timings, while the key data (e.g. total hydrogen production, steam flow and temperature behaviour) were similar.

Table 4-4 and Table 4-5 show, respectively, the main parameters and event sequence calculated by MELCOR, using 3.8 mΩ as external resistance and 78 % of the nominal auxiliary heater power. Fig. 4-12 to Fig. 4-15 shows the calculated water level, temperatures, steam exit flow rate and hydrogen generation rate. The steam production was underestimated at the start of the experiment, but then followed the measured decrease of the collapsed water level. In the calculation, feed water input started when the water level reached an elevation of -100 mm, hence later than in the test. Afterwards, the water level was underestimated. The heater rod temperatures were underestimated up to a time of about 3000 s, but overestimated afterwards in the lower part of the bundle. These trends are similar to SCADPSIM. The hydrogen generation started at 2800 s and was overestimated by a factor of two. The steam generation after about 3000 s was underestimated by about 20 %. In the calculation, the quench phase was initiated, when the maximum bundle temperature reached 1335 K. The timing of initiation of the quenching was in good agreement with the experiment.

Table 4-4 Parameters of Q11v3 post-test calculation using MELCOR

P_{aux}	R_{ext} (mΩ)	P_{el} (kW)	T_{quench} (K) t_{quench} (s)	m_{H2O} (g/s)	T_{clad} (K)	m_{tot} (g)
78%	3.8	experi-mental	1335 4463	experi-mental	1351	3.3

Table 4-5 Event sequence for Q11v3 using MELCOR

	Value / Condition	Time (s)
Auxiliary water switched on	level < -100 mm	3005
Onset of oxidation	rate > 1 mg/s	3200
Quench initiation	1335 K	4463
Peak temperature	1342 K	4515
Bundle quenched	T_{max} < 500 K	4780

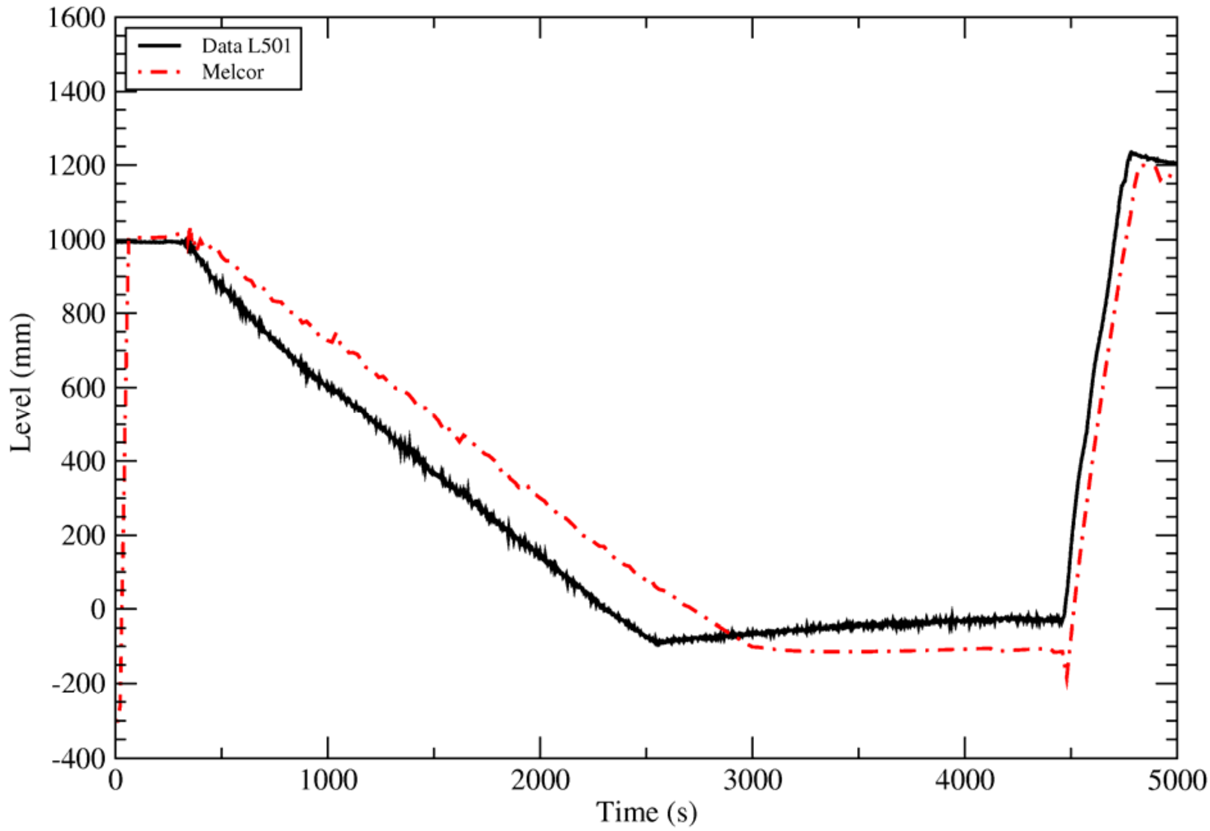

Fig. 4-12 MELCOR Q11v3 collapsed water level

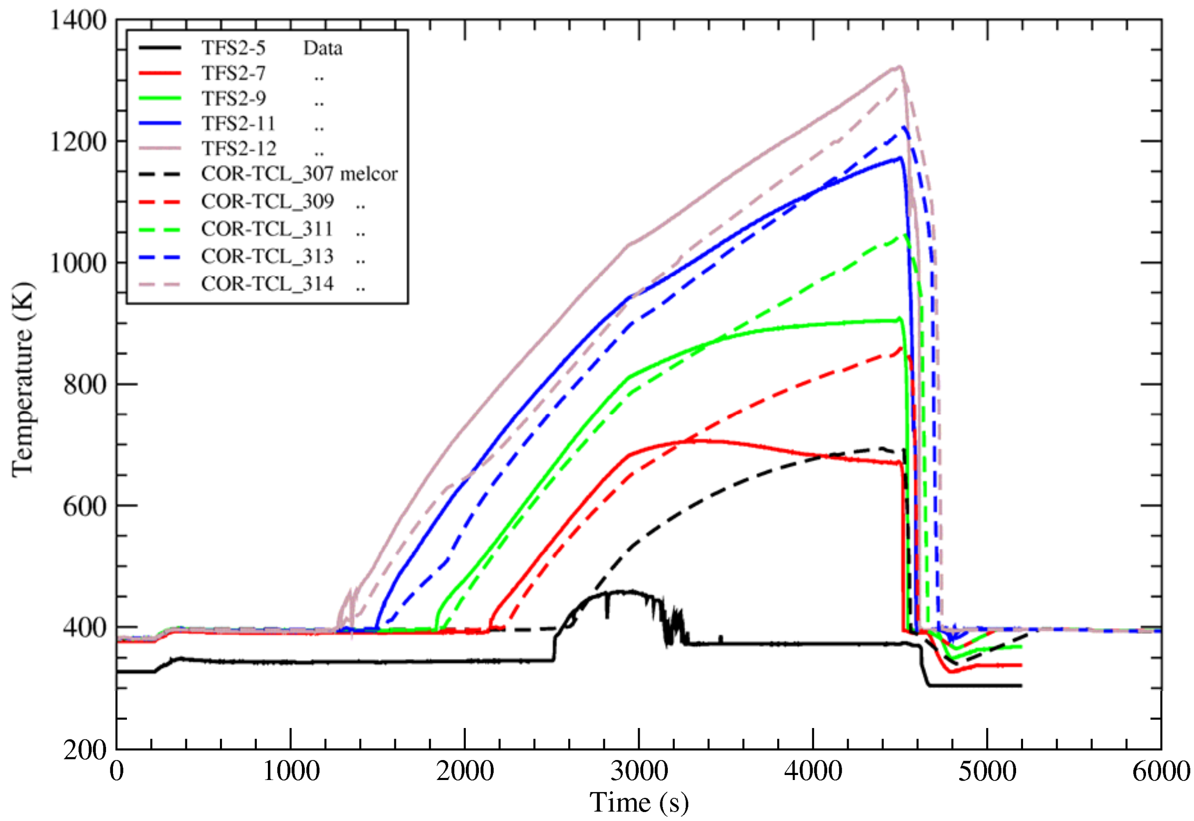

Fig. 4-13 MELCOR Q11v3 heater rod surface temperatures

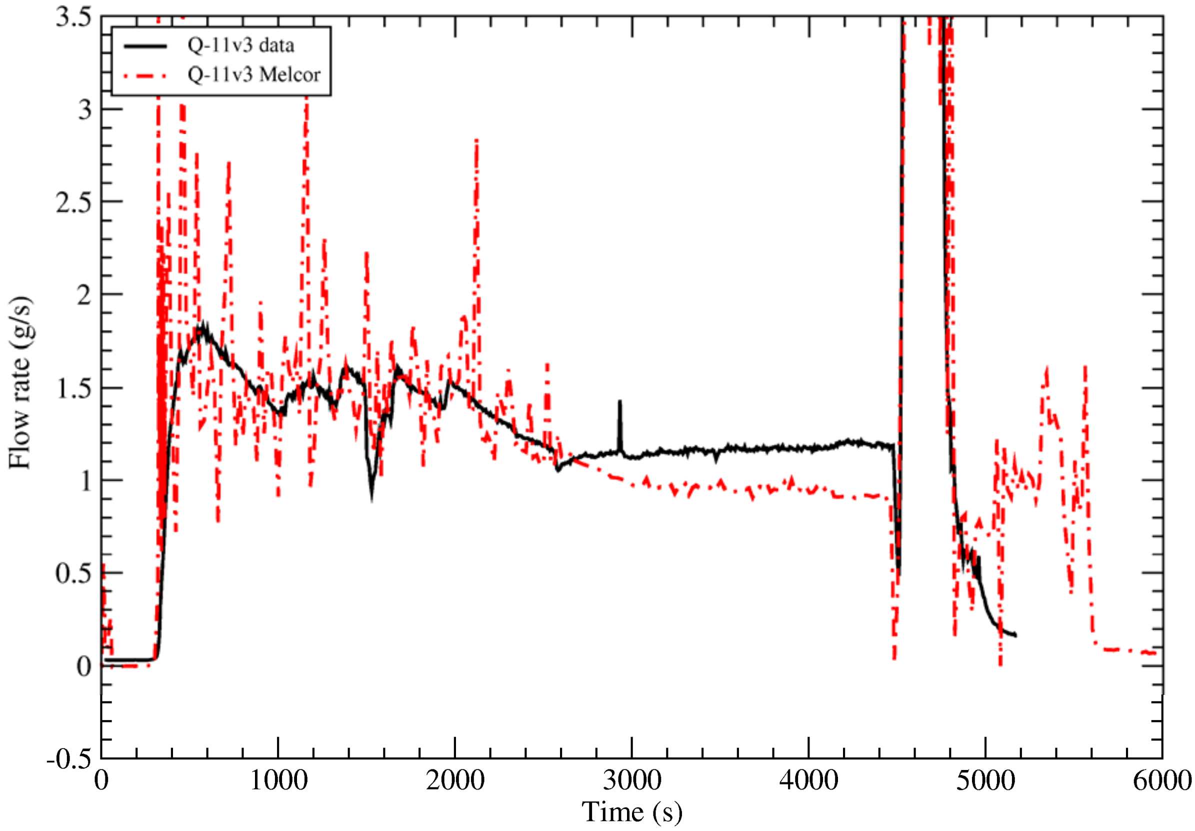

Fig. 4-14 MELCOR Q11v3 steam exit flow

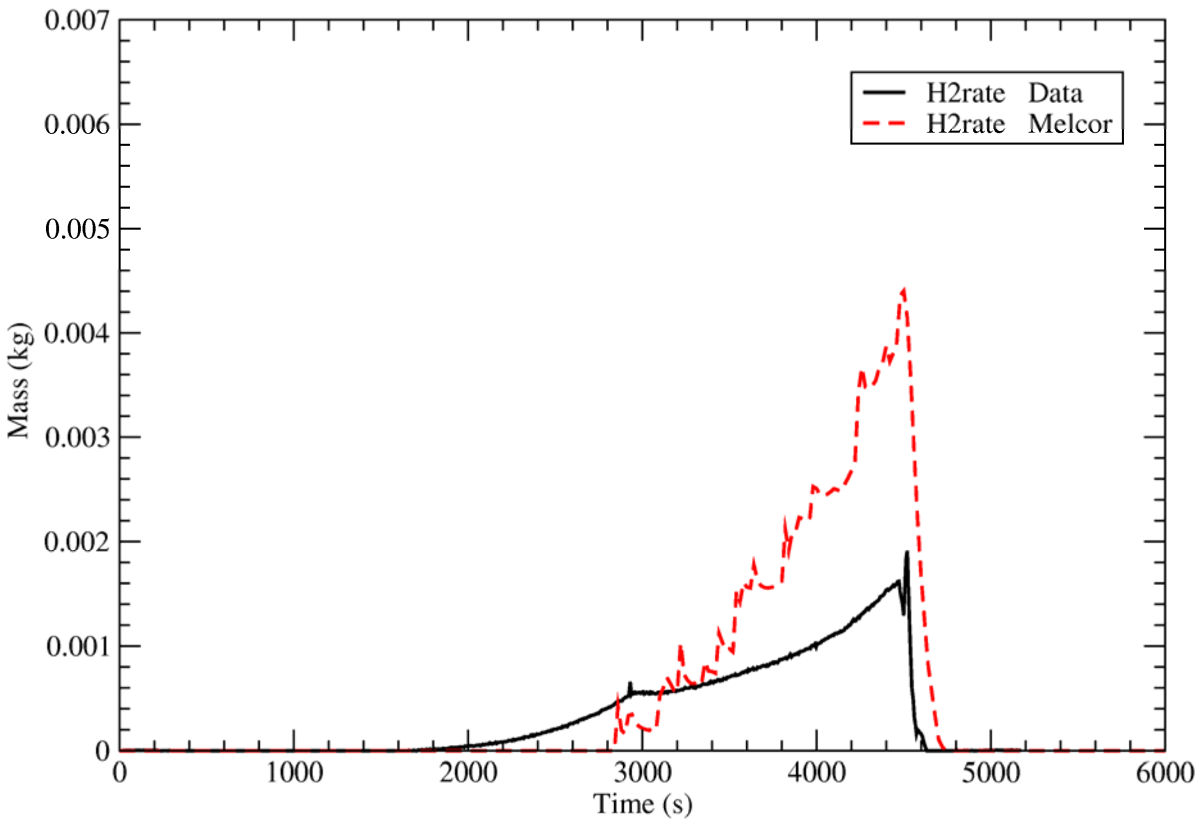

Fig. 4-15 MELCOR Q11v3 hydrogen generation rate

5 Main Test QUENCH-11

5.1 Pre-Test Calculations with MELCOR (PSI)

The predicted results for the main test QUENCH-11 are summarised in Table 5-1 and Table 5-2. Results for the collapsed water level in the bundle, cladding temperatures in the inner ring, and hydrogen generation are shown in Fig. 5-1 to Fig. 5-3. The same parameters as for the calculation of the pre-test Q11v3 are used as base case for the pre-test calculation for the QUENCH-11 experiment (78 % of the nominal auxiliary heater power and 3.8 mΩ for the external resistance). The timing for the initiation of the quench phase was controlled by the maximum bundle temperature of 2073 K. Sensitivity of the results was studied, when the auxiliary heater power was increased to 88 %, when the higher external resistance was increased to 4.2 mΩ, and when the Prater-Courtright (P-C) correlation was used instead of the Urbanic-Heidrick (U-H) correlation for the Zircaloy oxidation in the temperature region above 1900 K.

Table 5-1 Parameters of QUENCH-11 pre-test calculations using MELCOR

P_{aux}	R_{ext} (mΩ)	Oxidation model	P_{el} (kW)	T_{quench} (K) t_{quench} (s)	m_{H2O} (g/s)	T_{clad} (K)	m_{tot} (g)
78%	3.8	(U-H) (default)	experi-mental	2073 5170	1.0	2170	20.0
78%	4.2	U-H	experi-mental	2073 5620	1.0	2085	18.5
78%	4.2	U-H < 1800 K P-C > 1900 K Interpolation 1800 – 1900 K	experi-mental	2073 5515	1.0	2382	19.0
88%	3.8	U-H	experi-mental	2073 5430	1.0	2165	21.6
88%	3.8	U-H < 1800 K P-C > 1900 K Interpolation 1800 – 1900 K	experi-mental	2073 5332	1.0	2400	23.8

Table 5-2 Event sequence for QUENCH-11 (base case) using MELCOR

	Value / Condition	Time (s)
Auxiliary water switched on	level < -100 mm	2780
Onset of oxidation	rate > 1 mg/s	3690
Quench initiation	2073 K	5170
Peak temperature	2170 K	5290
Bundle quenched	T_{max} < 500 K	5460

The earliest initiation of the quenching was calculated to be at 5170 s in the base case. When the auxiliary power was increased, evaporation rate and hence convective cooling of the rods were increased, delaying the initiation of quenching. The increased external resistance lowered the heating power of the bundle, hence led to a lower temperature increase in the hot zone and in this way delayed the initiation of quenching. Using the model of the faster oxidation (Prater-Courtright correlation), the temperature excursion was accelerated and the initiation criterion (maximum bundle temperature 2073 K) of the quench phase was reached earlier.

The total amount of hydrogen production was almost the same in all calculations and rather less than that calculated by S/SIM using the same quench initiation temperature (Table 5-1 and Table 5-3). Higher hydrogen production would probably have been calculated if the quenching had been initiated at higher temperatures (see chapter 6.2.2); otherwise, the total oxidation was insensitive to the input assumptions.

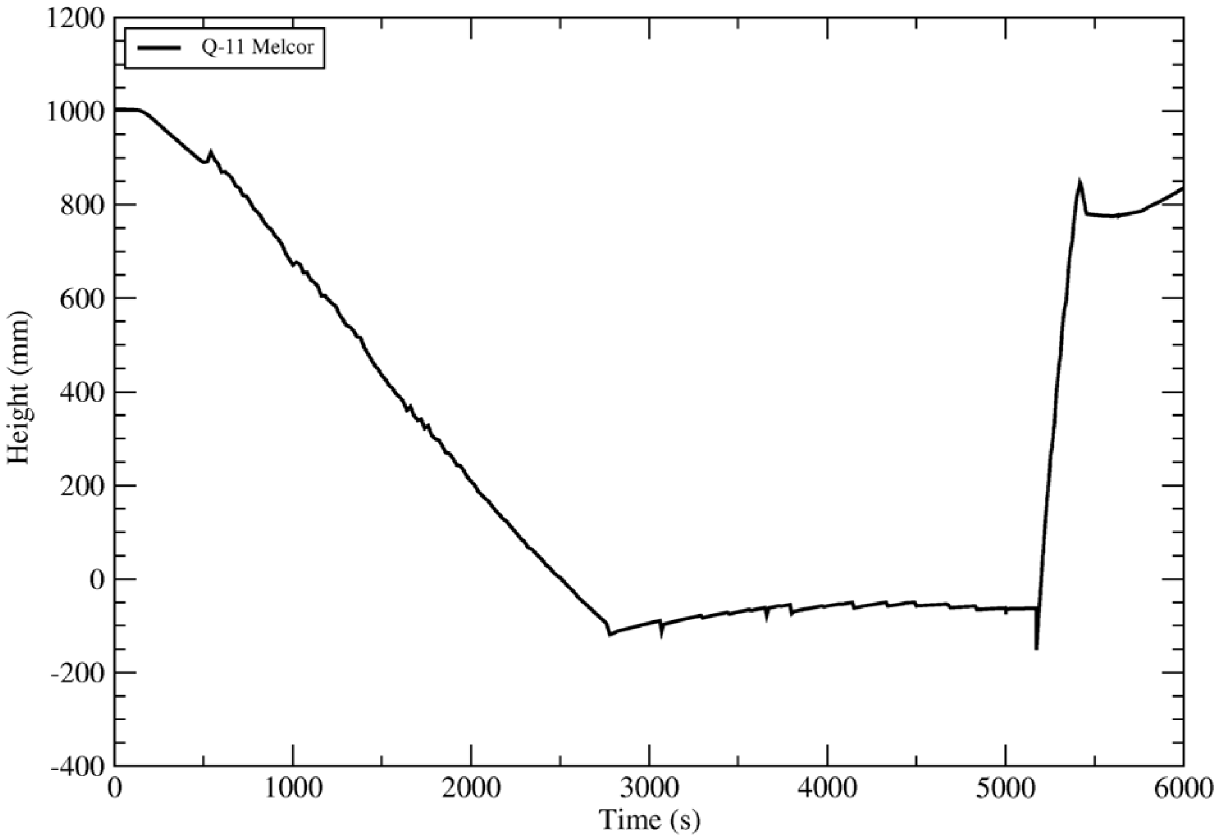

Fig. 5-1 MELCOR QUENCH-11 predicted collapsed water level

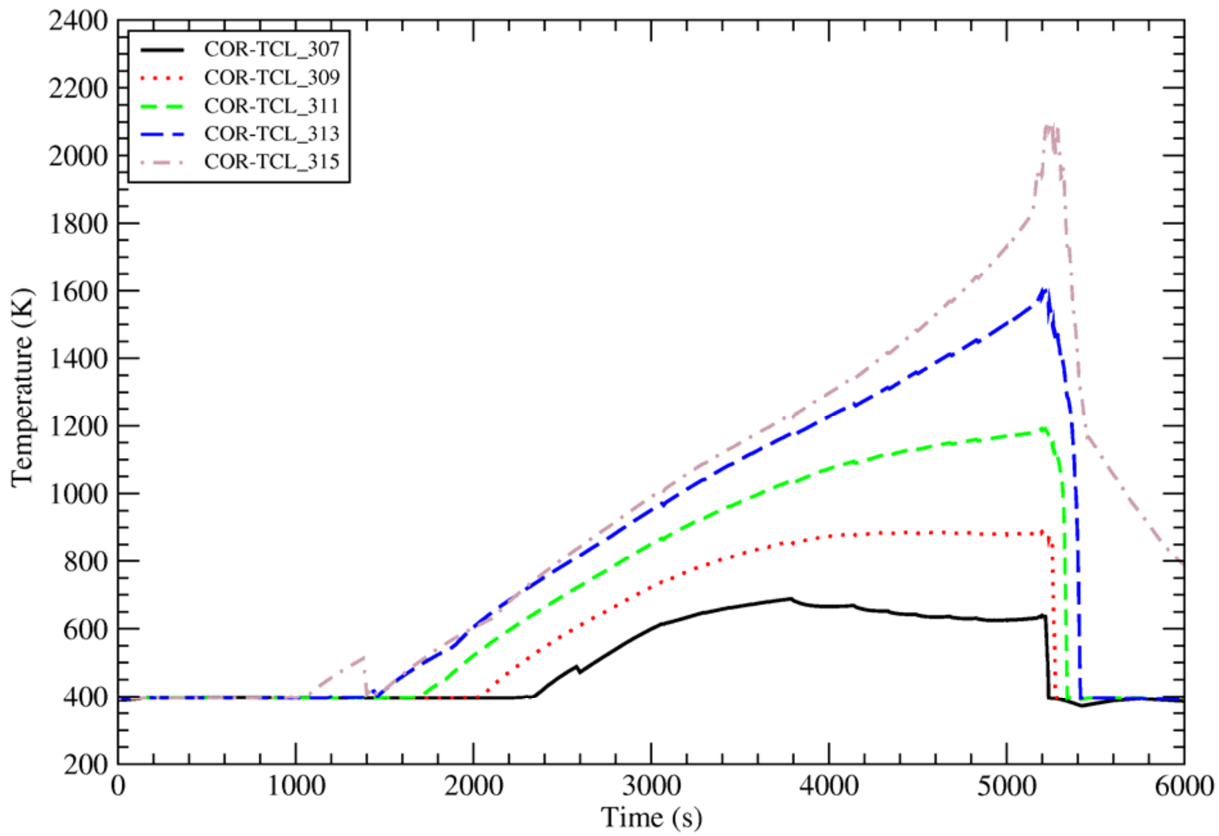

Fig. 5-2 MELCOR QUENCH-11 predicted heater rod surface temperature

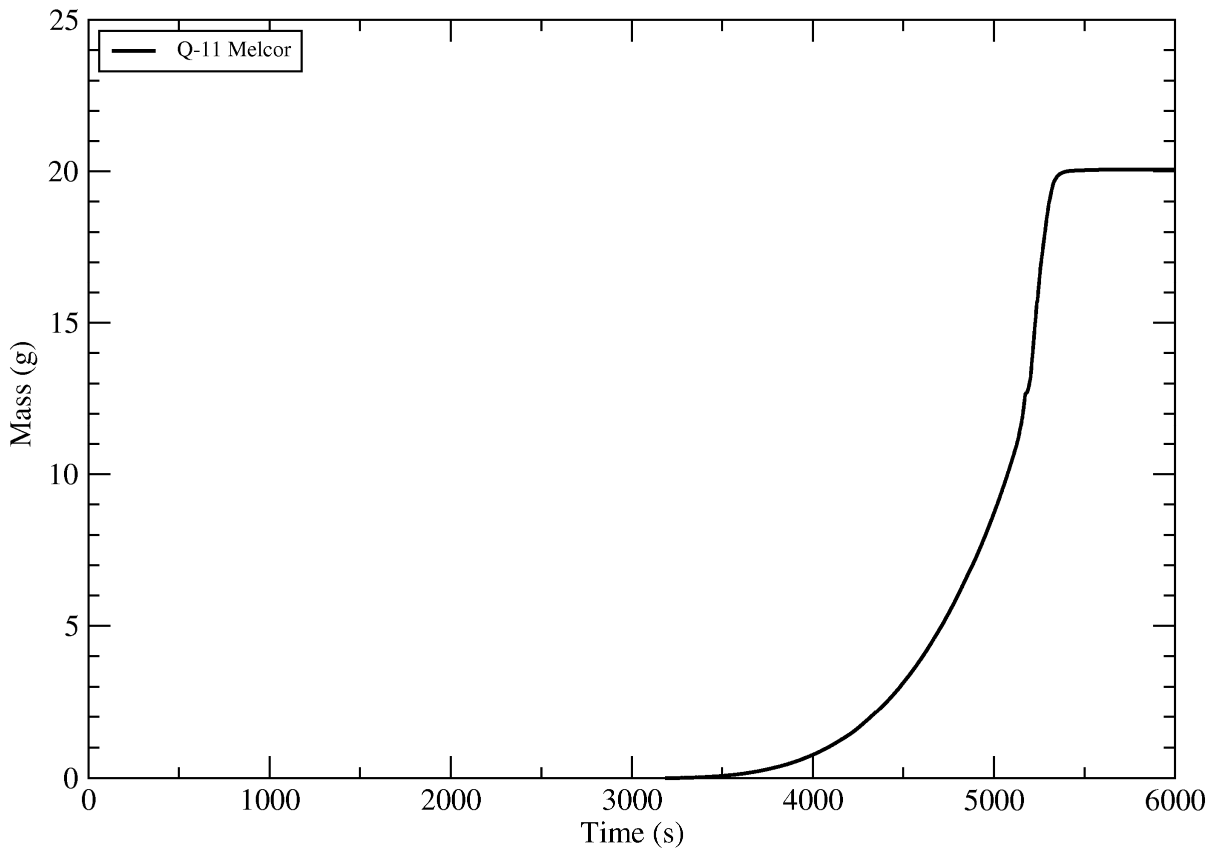

Fig. 5-3 MELCOR QUENCH-11 predicted hydrogen generation

5.2 Pre-Test Calculations with S/SIM (PSI)

On the understanding that QUENCH-11 conduct would follow closely Q11v3, up to the time of reflooding in the pre-test, the same model was used for the main test. The actual pre-test conditions were used as far as possible for the Q11v3 post-test calculations. The post-test calculation for Q11v3 which gave the best agreement for rate of boil-down, stabilisation of the water level and timing of criterion for quench initiation was chosen as the starting point for predictions of the main test, and then modified according to the planned conduct to define the final base case, Q11exrsjb13f. In order to take into account the possible effect of pre-oxidation during Q11v3, calculations for QUENCH-11 were performed with and without the preceding pre-test. The cases, which were restarted from the Q11v3 simulation, are indicated with “rs” in the identifier in Table 5-3. Additional sensitivity tests were run to examine the effect of variations in auxiliary heating, the criterion for quench initiation and oxide shell failure temperature. Following the preliminary pre-test calculations performed at FZK, most of the cases used a high value of the temperature criterion for quench initiation. The final base case used a temperature of 2073 K.

The QUENCH-11 calculated results are summarised in Table 5-3 and Table 5-4. Results for the bundle collapsed water level, the maximum cladding temperature temperatures, and the hydrogen generation are shown in Fig. 5-4 to Fig. 5-6. Fig. 5-7 shows the cladding temperatures along the heated rods of the inner ring, for the final base case.

A point should be made concerning the water level. An oversight meant that, in the non-restart simulations, the same injection period was used as in Q11v3. Due to the higher temperatures this was not enough to completely refill the bundle. The error was redressed in the restart cases where complete refill was achieved. This shows clearly the effect of bundle temperature on the quantity of injected water required.

Apart from timings, the overall behaviour was not strongly dependent on the external resistance or the multiplier on the additional heating. However, the comparison showed that stabilisation of the water in the lower plenum depends on a match between heat input and water injection, suggesting a need for the experimenters to monitor the level and exercise control. There was some effect of prior calculation of v3. Setting up of exactly the same conditions at the start of boil-down is not possible, but the differences are minor during the boil-down, until the escalation due to rapid oxidation. The restart from v3 shows the pre-oxidation delayed the escalation by about 200 s.

All the calculations, in which a high temperature criterion for quench was selected, 2250 or 2500 K, showed significant oxidation before quench initiation. In addition, all the cases showed a period of steam-starvation. There was also significant oxidation during reflood, probably due to the rather low reflood rate (18 g/s) and which was assumed the same as in Q11v3. The limited time interval of 335 s in the four cases that did not follow on from v3 also resulted in incomplete flooding. Considering the elevated temperatures and conditions favourable for oxidation, a longer period of injection is in order (assumed in the v3 follow-on cases). As might be expected, the pre-quench and reflood oxidation were generally greater in the cases of higher temperature criterion. A somewhat surprising result was the more extensive oxidation in two cases that followed the v3 calculation. In all cases except

Q11exjb05a, where there was the largest pre-oxidation, the reflood oxidation was comparable with the pre-oxidation. In that one case, the relocation was effectively prevented by specifying a high (2500 K) value for the oxide shell failure temperature. Similarly, there was only moderate oxidation in the final base case, where no degradation of the heater rods occurred. According to the S/SIM, candling of metallic-rich material did not inhibit the continued oxidation; it is noted that the temperatures were rather high and there was a sufficient flow of steam.

Table 5-3 Parameters of QUENCH-11 pre-test calculations using S/SIM

Case	**P_{aux}**	**Rext (mΩ)**	**$\lambda_{(ZrO2)}$ (%)**	**P_{el} (kW) t>4000s, $t>t_{quench}$**	**T_{oxfail} (K)**	**T_{quench} (K) t_{quench} (s)**	**m_{H2O} (g/s)**	**T_{clad} (K)**	**d_{max} (µm)**	**m_{tot} (g) $t=t_q$ total**
preliminary calculations										
Q11exjb13d	78%	3.4	+ 0%	6.80 4.00	2200	2250 4902	1.10	2421	* 385 @ 1578	50 118
Q11exjb13e	78%	3.4	+ 0%	6.80 4.00	2200	2500 5007	1.10	2345	* 451 @ 1553	61 129
Q11exjb13drs	78%	3.4	+ 0%	6.80 4.00	2200	2250 5183	1.10	2487	* 471 @ 1888	& 61 147
Q11exjb13ers	78%	3.4	+ 0%	6.80 4.00	2200	2500 5474	1.10	2490	* 457 @ 1643	& 97 222
Q11exjb05	88%	4.2	+ 0%	6.80 4.00	2200	2500 5627	1.10	2442	* 424 @ 1494	64 148
Q11exjb05a	88%	4.2	+ 0%	6.80 4.00	2500	2500 6014	1.10	2491	693	118 149
final calculation										
Q11exrsjb13f	78%	3.4	+ 0%	6.80 4.00	2200	2073 4856	1.10	2292	465	& 25 55

* max depth of intact, in-place cladding oxide
@ max total depth including relocated cladding+oxide
& including v3

Table 5-4 Event sequence for QUENCH-11 (case Q11exrs_jb13f) using S/SIM

	Value / Condition	**Time (s)**
Auxiliary water switched on	level < -50 mm	2450
Onset of oxidation	rate > 1 mg/s	3560
Quench initiation	2073 K	4856
Peak temperature	2292 K	4970
Bundle quenched	T_{max} < 500 K	5470

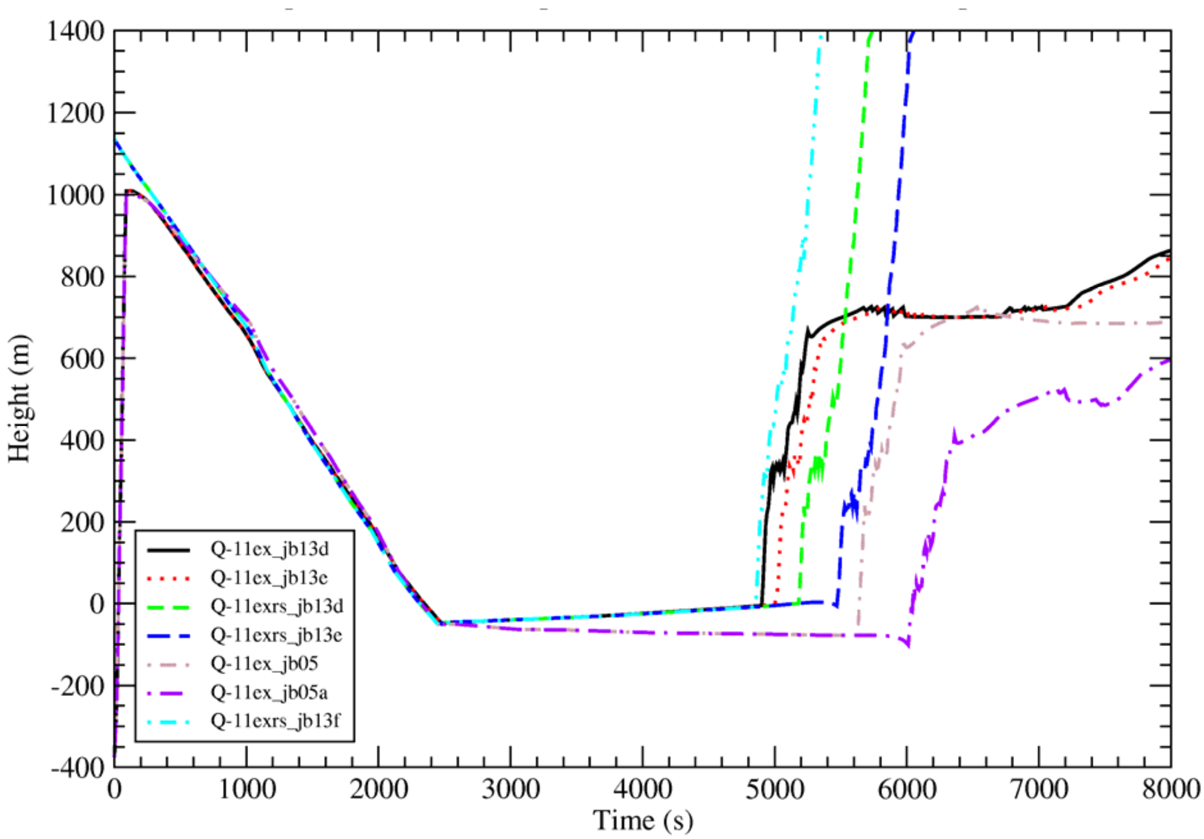

Fig. 5-4 S/SIM QUENCH-11 predicted collapsed water level

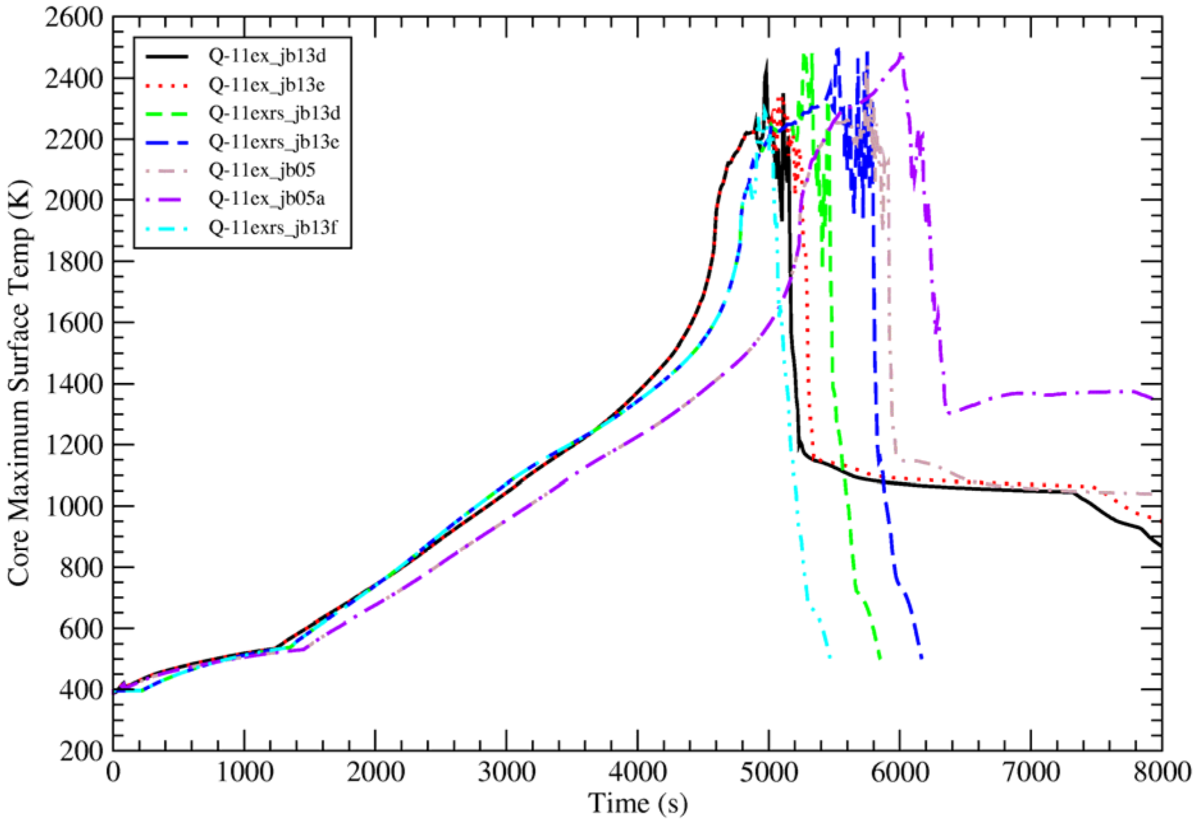

Fig. 5-5 S/SIM QUENCH-11 predicted maximum bundle surface temperatures

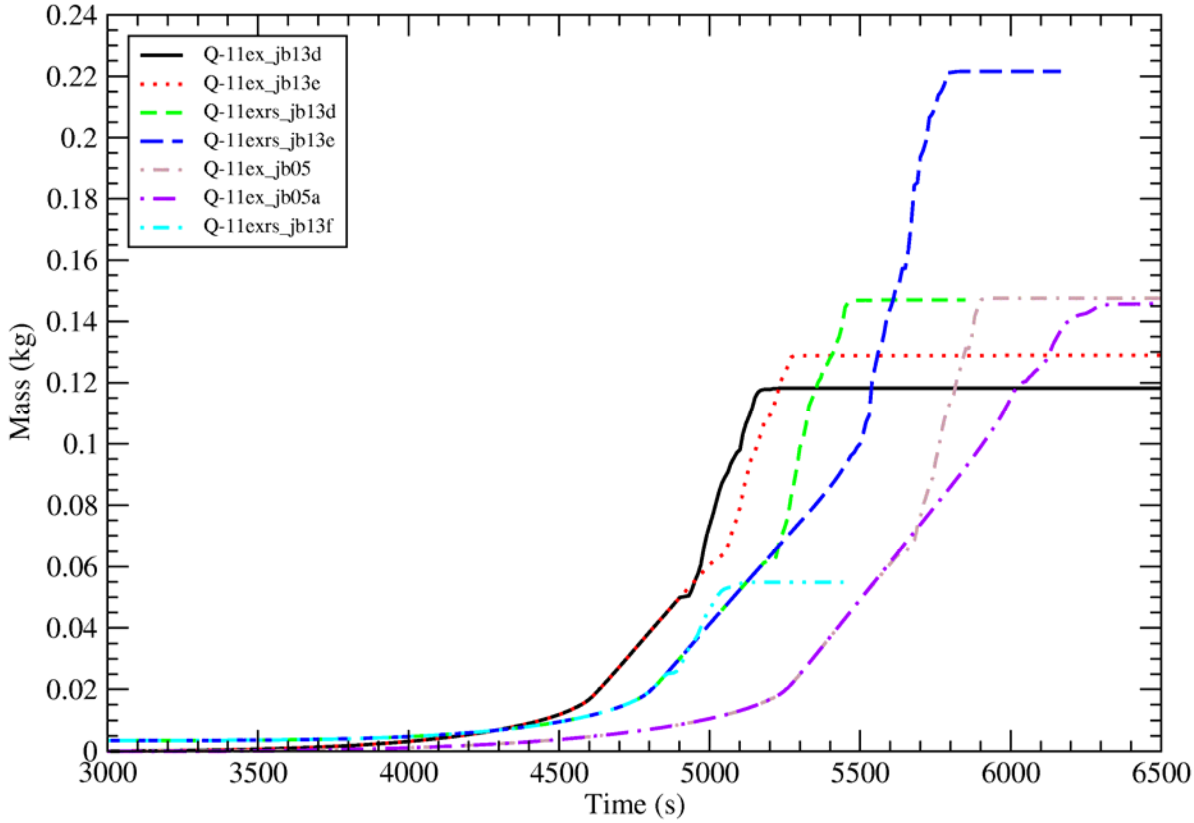

Fig. 5-6 S/SIM QUENCH-11 predicted hydrogen generation

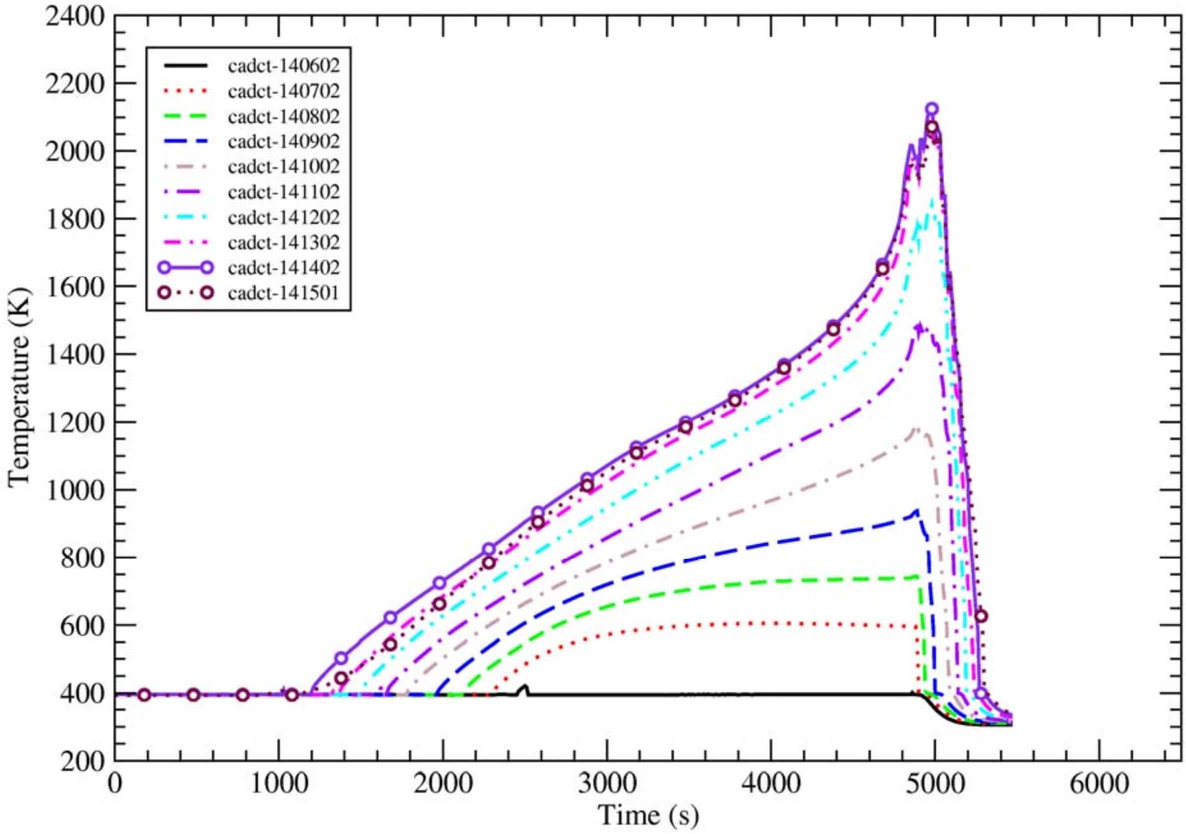

Fig. 5-7 S/SIM QUENCH-11 predicted heater rod surface temperature

5.3 Pre-test Calculations with S/R5

5.3.1 Scoping Calculations

In the QUENCH-11 pre-test calculations with S/R5 mod3.2.irs, the Leistikow-Schanz correlation was used as proposed during a COLOSS meeting. As clad failure criteria, a temperature of 2550 K and 60 % oxidation were used. The calculations started with simulating metallic surfaces of the rods, i.e. the influence of the oxide layer after the pre-test Q11v3 was not considered. The uncertainty of the predictions that is due to the oxide layer after the pre-test will be discussed in section 5.3.2. The calculations were stopped when the maximum temperature drops below 1700 K.

Fig. 5-8 indicates the difficulty to simulate a complete axial power profile of typical reactor conditions within the 1.5 m, available in the QUENCH facility. In the first pre-test calculations (Table 5-5), the bundle power was not reduced from 7 kW to 6.8 kW but after 4500 s. This was too late, so that the exothermal power drove the clad temperatures (Fig. 5-8, bottom) far beyond 2600 K after 5000 s. In favour of a higher steam mass flow rate, a partial boil off is taken into account as can be seen in Fig. 5-8, lower centre. This should also overcome the uncertainty of the water leakage observed during q11v3 (see above). To avoid the early temperature escalation, the power was reduced 500 s earlier (cases: v03 - v06), reducing the heat-up rate slightly and increasing the oxide layers before temperature escalation. The integral results maximum clad temperature, maximum oxide layer thickness, and total H_2 mass are given in Table 5-5 on the right side.

Table 5-5 Parameters of QUENCH-11 pre-test calculations using S/R5

Scenario	P_{aux}	Static resistance	$K_{(ZrO2)}$ (%)	Pel (kW) t>4000s	Pel (kW) t>4500s	Pel (kW) t>5100s	m_{H2O} (g/s) t> 4200s	max T(K)	d_{max}(ZrO2) (µm)	m_{tot} (H2) (g)
v01	89%	4,2 mΩ	+80%	7,00	7,00	4,00	1,00	2605	440	37,8
v02	89%	4,2 mΩ	+80%	7,00	6,80	4,00	1,00	2608	690	86,9
v03	89%	4,2 mΩ	+80%	6,70	6,70	4,00	1,05	2598	630	82,7
v04	88%	4,2 mΩ	+80%	6,70	6,70	4,00	1,10	2546	530	22,7
v05	88%	4,2 mΩ	+80%	6,80	6,80	4,00	1,10	2536	540	49,6
v06	85%	4,2 mΩ	+80%	6,80	6,80	4,00	1,10	2615	620	66,6

From all results, the variation in the electric bundle power after 4000 s is rather sensitive:
- below 6.7 kW, the escalation is inhibited, leading to a design basis reflooding, and
- above 6.8 kW, the temperature escalation occurs too early.

In the latter case, the reaction time for the operators to initiate reflood at the pre-defined criteria is very short. If this time interval is exceeded, undesirable high temperatures and large bundle damage will occur. This can be accepted if the bundle is reflooded by rapid injection. However, for the low reflood mass flow rate in QUENCH-11, this is not appropriate at all.

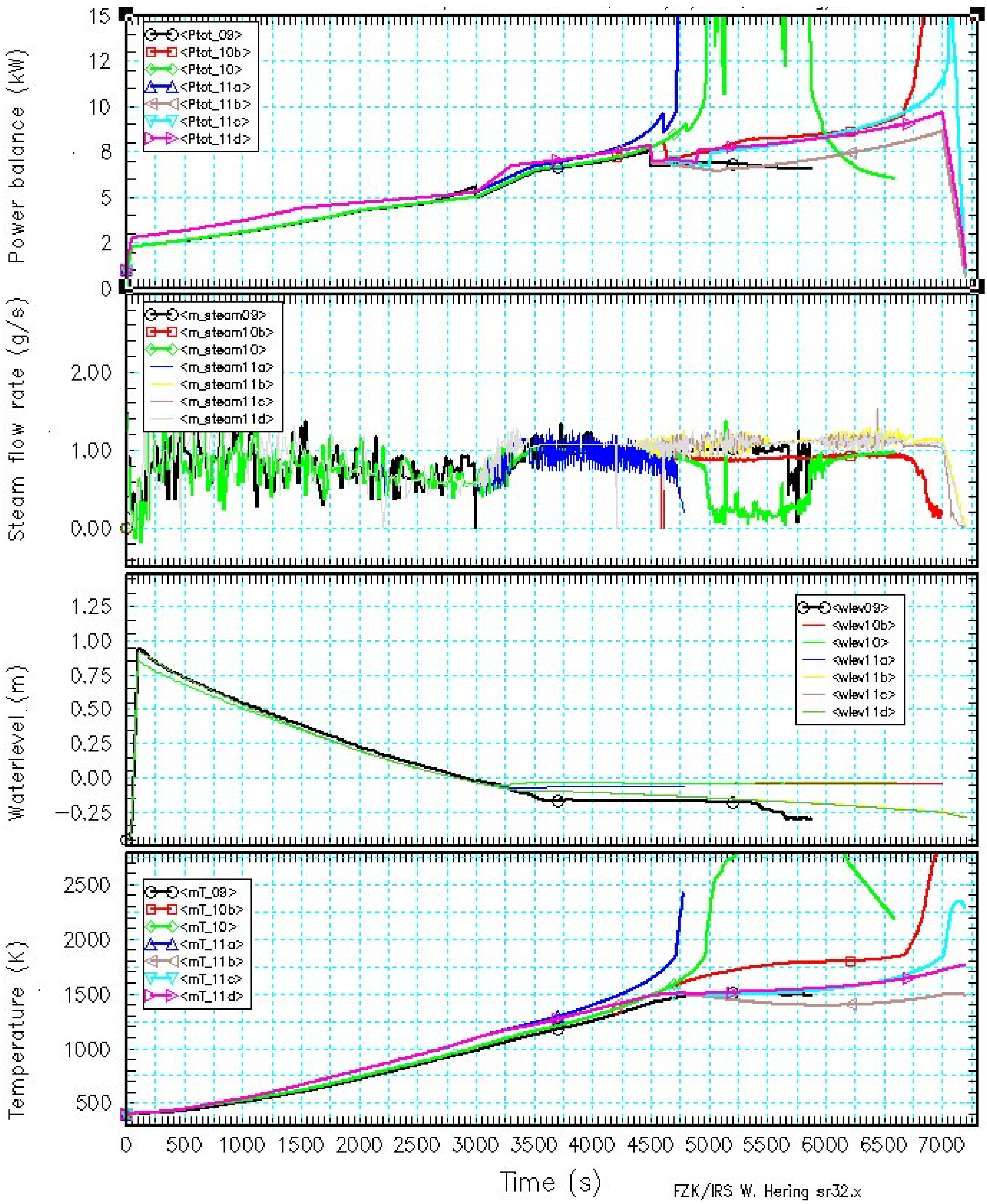

Fig. 5-8 Summary of the last seven scoping calculations for QUENCH-11 with S/R5
Top: Power (total, auxiliary heater, electrical heater, oxidation), steam flow rate at bundle exit, collapsed water level, and peak core temperature

5.3.2 Influence of Pre-Oxidation

To assess the uncertainty of the pre-test calculations for the main test that is due to the oxide layer after the pre-test, a special simulation was performed. It starts with a post-test calculation for Q11v3 to calculate the oxide scale at the start of the main test. A cold fill-up of the

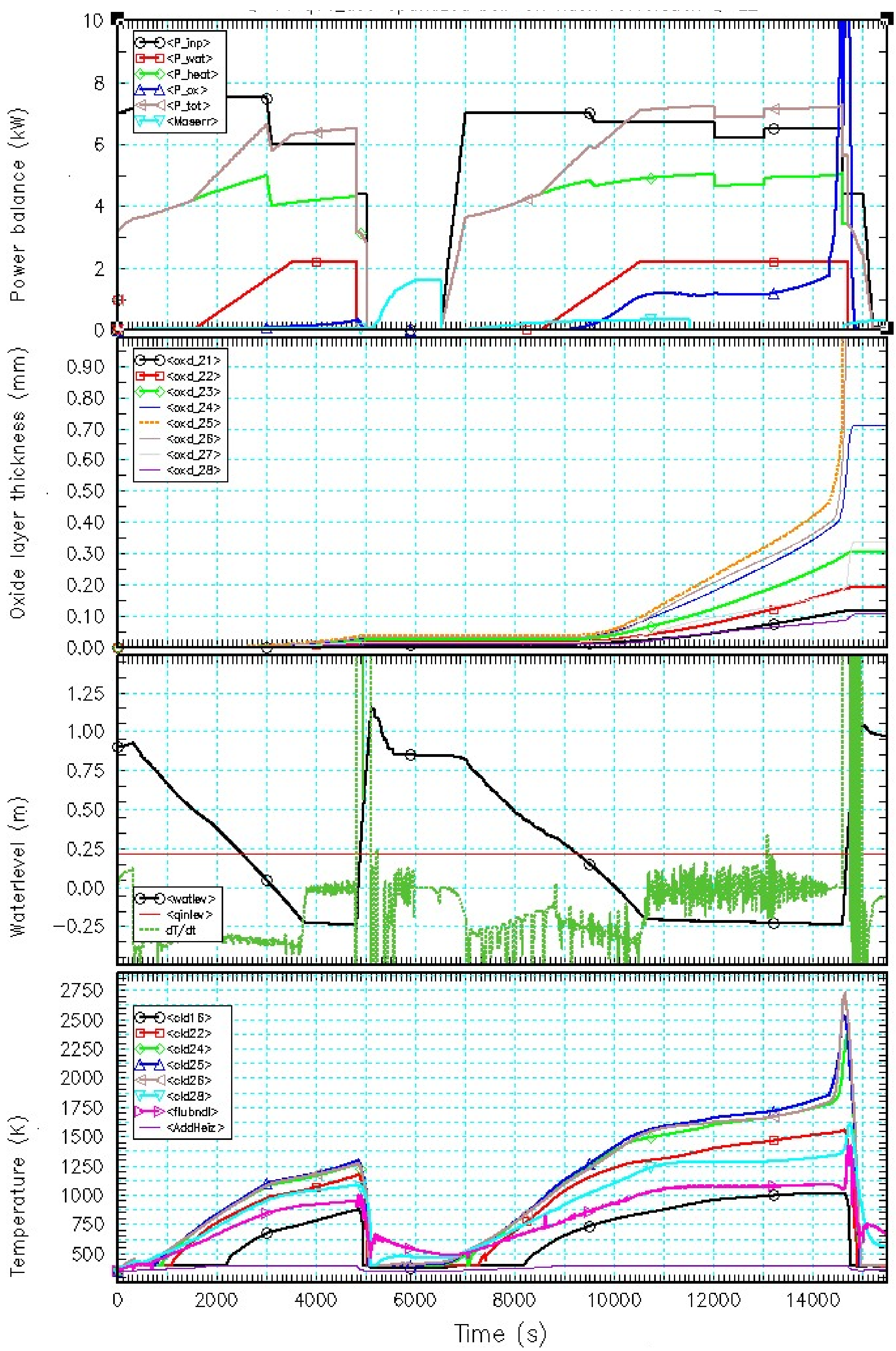

Fig. 5-9 Complete sequence of Q11v3 and Q11 calculated with S/R5
Top: Power, oxide layer thickness, steam flow rate at bundle exit, collapsed water level, and heater rod temperature

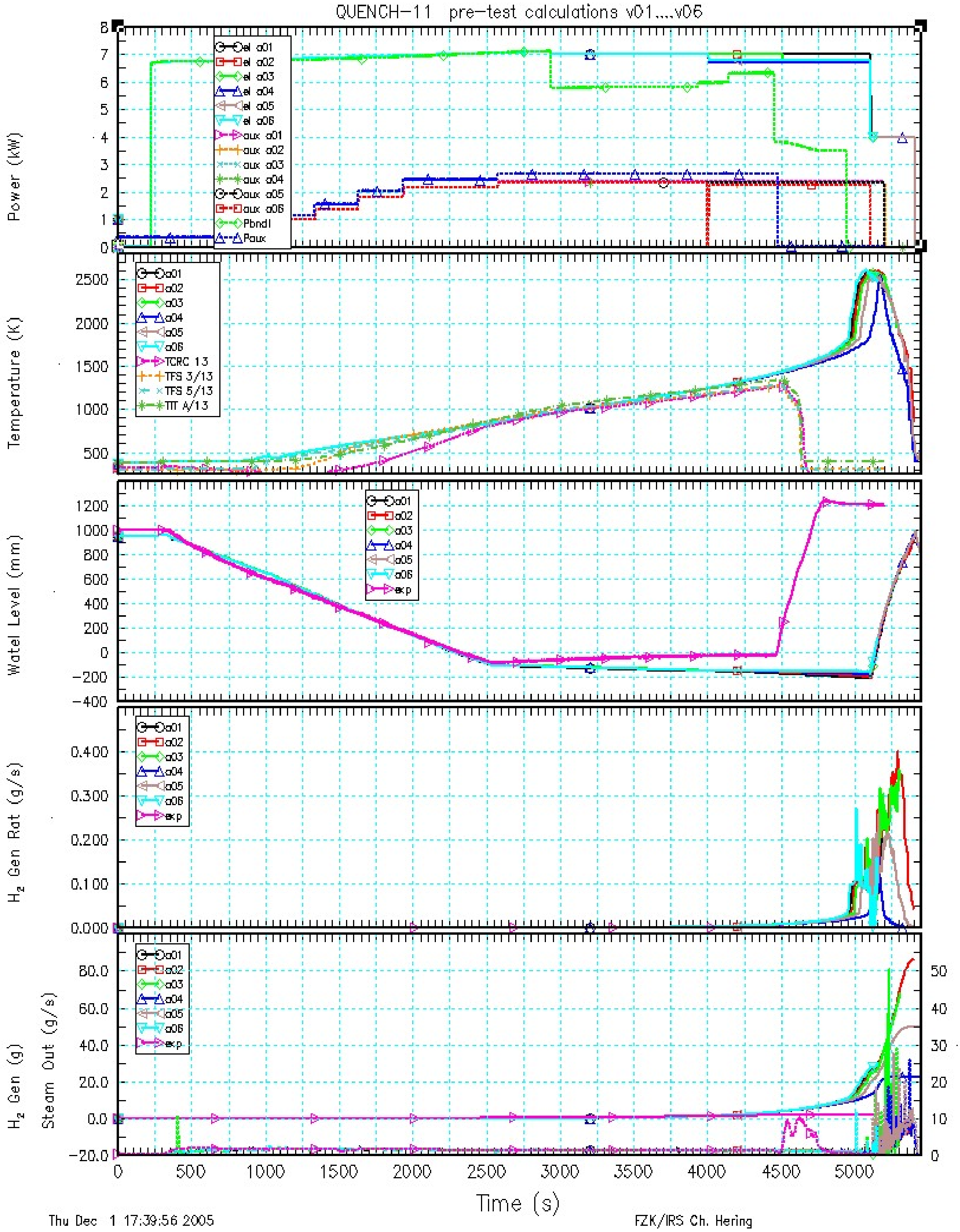

Fig. 5-10 Comparison of the QUENCH-11 pre-test calculations with S/R5

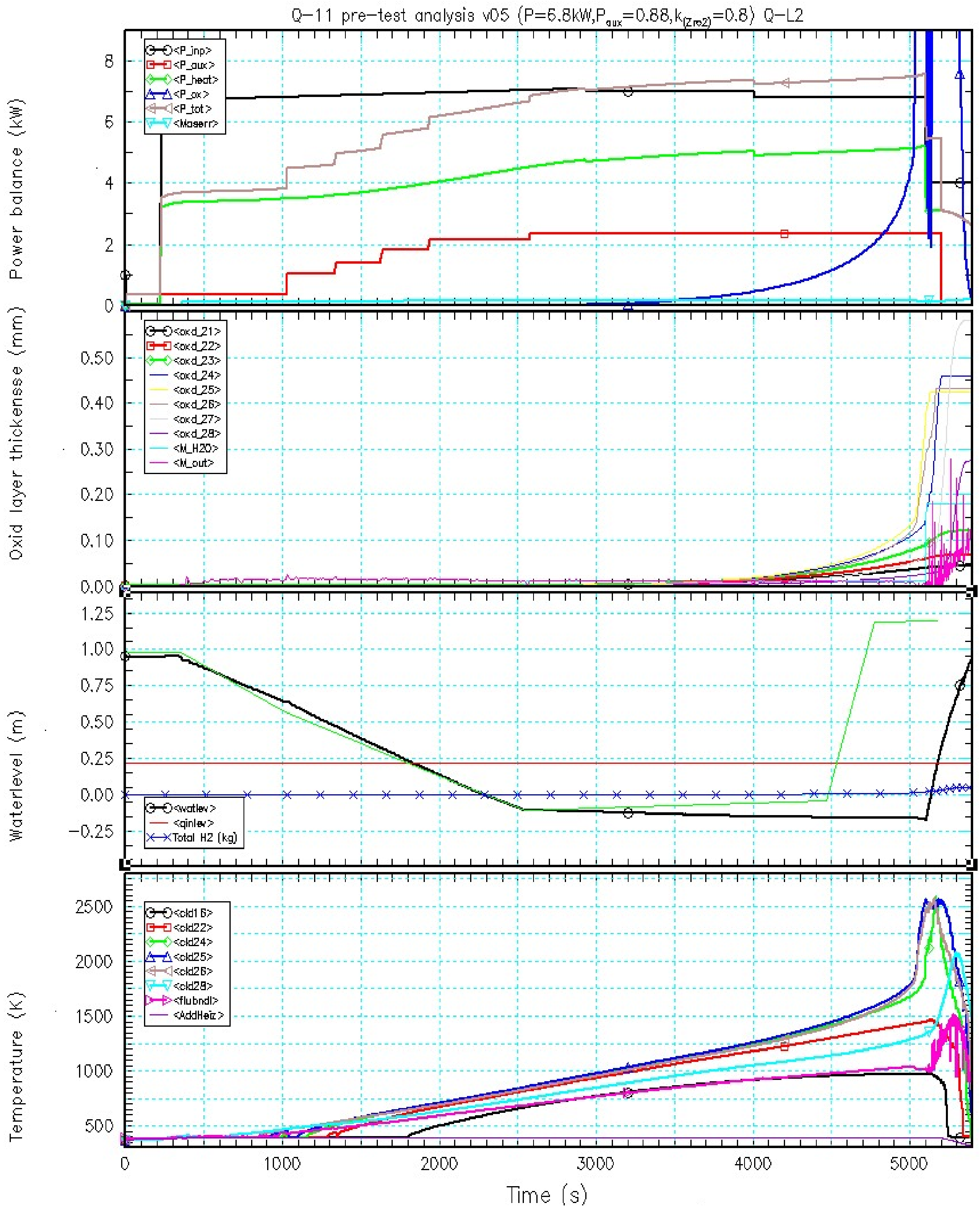

Fig. 5-11 Proposed scenario for QUENCH-11 (v05)

test section follows to start the pre-test simulation of the main test with realistic temperatures and water level. It is only afterwards that the pre-test calculation for the main test starts. The two first phases of the simulation last to a time of about 6600 s, as can be seen in Fig. 5-9. The code calculates a maximum oxide scale of about 50 µm, a value that is not too far from the measured value of about 30 µm. As can be seen in Fig. 5-9, the influence of this pre-oxidation is small compared to the other uncertainties and can therefore be neglected.

5.3.3 Proposed Scenario

Fig. 5-10 gives an overview of the six QUENCH-11 pre-test calculations; the data of the pre-test Q11v3 are added for comparison. As can be seen in the temperature plot of Fig. 5-10, QUENCH-11 follows the Q11v3 until bundle power reduction at 2930 s.

Based on the various pre-test calculations and their analyses, the calculation, shown in Fig. 5-11, was considered the most reasonable scenario for the test QUENCH-11. The case is characterized by an early (4000 s) power reduction of bundle power at 4000 s from 7.0 kW to 6.8 kW.

5.4 Pre-Test Calculations with ASTEC

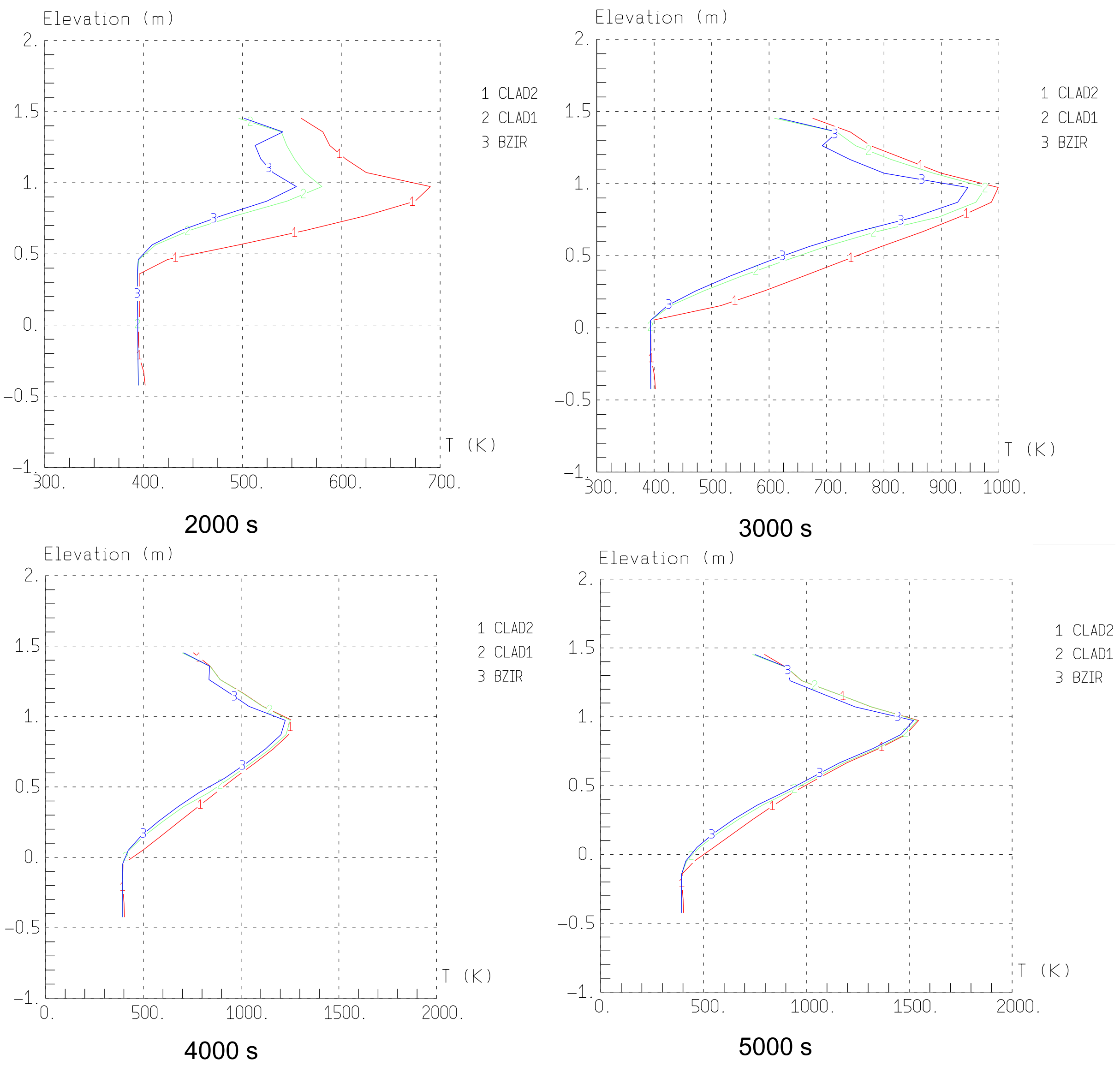

Fig. 5-12 Axial temperature profiles calculated with ASTEC at various times

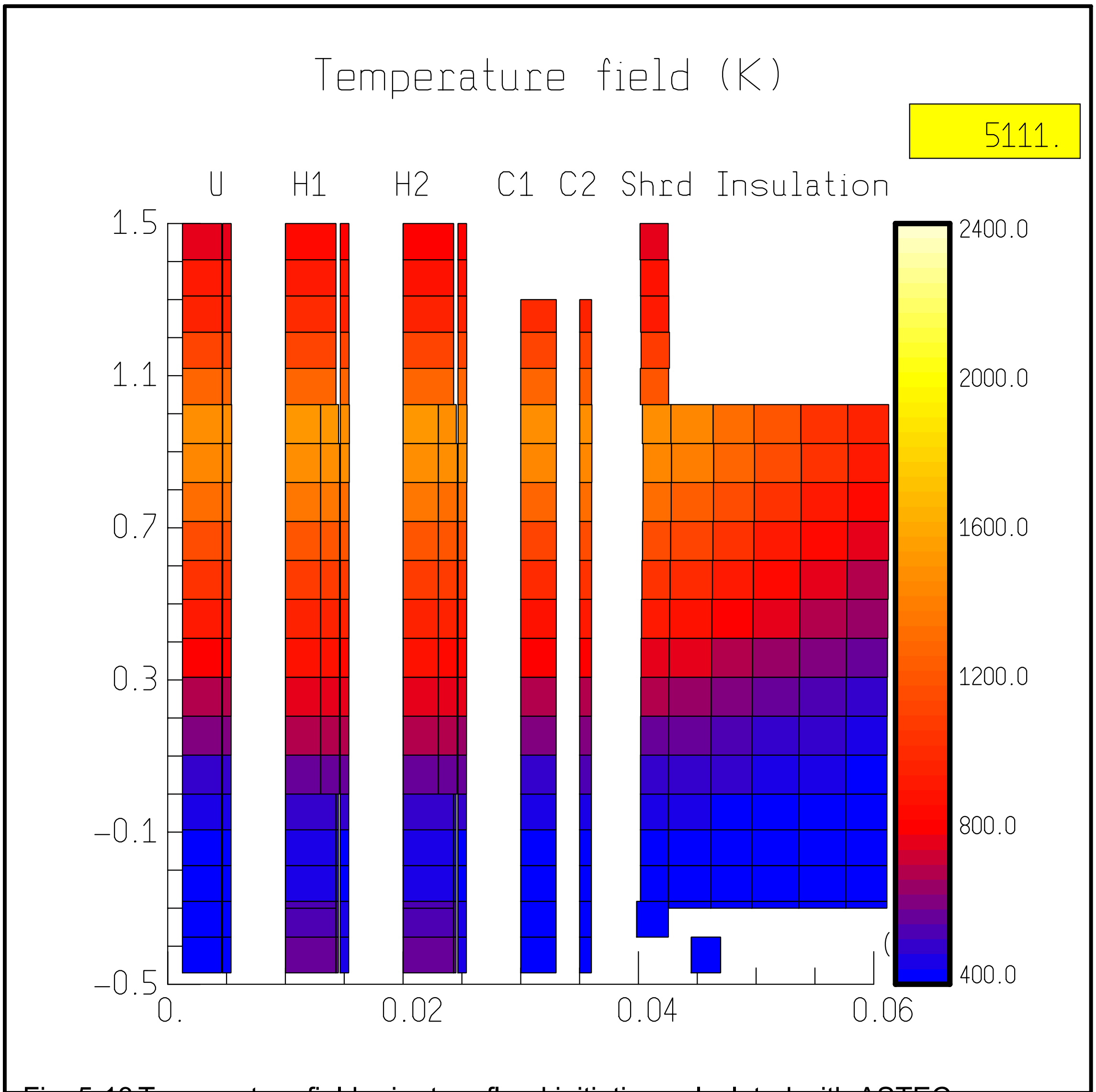

Fig. 5-13 Temperature field prior to reflood initiation calculated with ASTEC

As part of the 6th EU-Framework programme SARNET analytical support is also performed using the French-German integral code ASTEC, especially the DIVA module (section 3.4.1). The input deck was adapted using data from S/R5 calculations to overcome some weaknesses of the facility modelling. The details are given in section 3.4.2.

One feature of the ASTEC programme, the on-line visualization was used to check the influence of parameter optimization easily. In addition, data, which are not extractable easily from the S/R5 database, are visualized by ASTEC.

The temperature field in Fig. 5-13 gives an impression of the bundle state prior to reflood initiation. No temperature escalation due to oxidation has taken place. Centre parts of the shroud insulation are still at low temperatures. The extrapolation of Q11v3 shows still too low temperatures so that the time of reflood initiation should be delayed. Therefore, 5100 s is considered as the earliest time to start the bundle reflood.

5.5 Sensitive Parameters

In standard QUENCH experiments, the most sensitive parameters in decreasing order are the external resistance of the electrical heater rods, the fluid inlet temperature, and the heat conductivity of the fibre insulation material in the shroud.

Depending on the modelling depth of the facility in various codes, the magnitude of the external resistance may vary. Detailed codes such as ASTEC, when DIVA is applied, and S/R5 input decks simulate correctly the whole length of the heater rods, so that the external resistance is restricted to the values of the sliding contacts and the copper wires. Other codes add parts of the electrode zones to the external resistance, which then becomes temperature dependent.

In the boil-off test QUENCH-11, an additional uncertainty is added due to the steam mass flow, which is produced by evaporation in the bundle. It can only be measured by the mass spectrometer or, rather coarsely, by the collapsed water level or the condensate mass. However, a small error of ±1 mm/s gives an error in the steam of about 3 g/s, which is significantly above the desired value of 1 g/s.

5.6 Proposed Test Protocol for QUENCH-11

Based on the data gathered from experimental work and the multitude of pre-test calculations, the following test protocol was determined. Times are derived from pre-test calculations, and stand only for an approximate indication for the test conduct, because it is well known that for one or another reason a test conduct is normally different from pre-test calculations.

Table 5-6 Test protocol for the main test

	Action	Remarks
1	Start of data record with the frequency of 1 Hz	
2	t=219 s Start of bundle heating P=6.7 kW (q11v3)	
3	t ~300 s Start of boil off	
4	t=1026 s Start of auxiliary power transient P=1.14 kW	
5	t=1335 s Increase Aux-Power = 1.56 kW	
6	t=1630 s Increase Aux-Power = 2.05 kW	
7	t=1932 s Increase Aux-Power = 2.45 kW	
8	t=2540 s Start of water feed R001 to compensate evaporation	
9	t=2573 s Increase Aux-Power = 2.66 kW	
10	t=2933 s Reduction of bundle power to 7.0 kW	
11	**t=4000 s Decision criterion** **Determine power reduction if $T_{max} > T_{predict}$**	
12	Check heat-up rate dT/dt < 0.5 K/s and $T_{max} > T_{predict}$	
13	Continue heat-up until : a) t<5100 s and mdot(H_2) > g/s b) t>5100 s and T_{max} > 1800 K	Start: 1. Remove corner rod 2. Start reflood
14	Start quench pump with 17 g/s	= t (quench)
15	Remove bundle power to decay heat level ~ 4 kW	
16	t(quench) + 300 s: stop auxiliary heater and bundle power	
17	t(quench) + 360 s or L501 > 1.2 m: stop quench pump	
18	t(quench) + 370 s or L501 > 1.2 m: stop additional water pump	
19	t(quench) + 600 s and T_{max} > 400 K: remove 2nd corner rod	

6 Summary and Conclusion

QUENCH-11 was the first integral test, where boil-down of a bundle, partially filled with water, was performed. A huge amount of experimental and analytical work was performed to prepare QUENCH-11 and to establish a qualified test protocol. It could only partly be covered by calculations with the well-known severe accident codes ASTEC, MELCOR, SCDAP/RELAP5, SCDAPSIM, and much familiarity with the QUENCH facility was necessary to do that work successfully. The effort was necessary, because the facility was upgraded to a new working field, which was not foreseen in the original design. However, the results indicate that the instrumentation is close to its design capability so that no large safety margin is available. Under such conditions, the preparation of such an integral test requires combined efforts as done here on an international basis.

If the deviations in the starting conditions are taken into account, the results of the pre-test calculations agree generally rather well. The calculations were well suited to identify the needs for hardware changes of the facility and helped to quantify the characteristics of the upgrades. They were also indispensable to quantify the characteristics of the pre-tests that were necessary to check the various new components and to assess the behaviour of the upgraded facility. For analysts, pre-test calculations are a fruitful exercise to assess the capability of their codes, but most of the efforts are dedicated to simulate facility peculiarities or to find work-arounds for code limitations.

With the test protocol for the main test, guidelines for the operator were established that also include proposals to cope with unforeseen events during the test. The onset of reflood was set, when the hydrogen mass flow rate, measured by the mass spectrometer, indicated a temperature excursion in the bundle or when a temperature of 1800 K was exceeded. The latter was expected after 5100 s.

7 Acknowledgment

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