Core reflooding:
Synthesis of the QUENCH program and its impact on code modelling

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ABSTRACT

The paper gives an overview on the status of the QUENCH program at FZK, including complementary bundle experiments and separate-effects tests, and in the second part, a discussion of the status of the main severe accident code systems used in Europe. The main objective of the program is to deliver experimental and analytical data to support development and validation quench and related models as used in code systems.

So far, ten QUENCH bundle tests have been performed. The main parameters of these experiments were: degree of pre-oxidation, initial quench temperature, reflood medium (water or steam) and flooding rate, influence of B_4C absorber, steam starvation and air ingress. In four tests reflood of the bundle caused a temporary temperature excursion connected with the release of a significant amount of hydrogen, typically two orders of magnitude greater than in those "successful" quench tests in which cool-down was immediately achieved. Strong and global formation, relocation, and oxidation of melt were observed in all tests with escalation. The temperature boundary between rapid cooldown and temperature escalation was typically 2100-2200 K in the "normal" quench tests, i.e. tests without absorber and/or steam starvation. These factors were found to lead to escalation at lower temperatures.

All phenomena occurring in the bundle tests have been additionally investigated in parametric and more systematic separate-effects tests.

Seven SFD code systems are discussed with respect to the phenomena relevant to reflood scenarios: reflood progression, oxidation of zirconium alloy cladding materials, boron carbide absorber rods and melts, and the oxidation of Zircaloy cladding in air containing atmospheres. The codes are generally able to describe the reflood scenario satisfactorily as long as the bundle has an intact geometry. Recently, progress has been made regarding the modelling of B_4C absorber oxidation, whereas the treatment of the oxidation of relocating/relocated melts as well as the oxidation in atmospheres containing air is under development or foreseen in the future for the most codes.

A. INTRODUCTION

The most important accident management measure to terminate a severe accident transient in a Light Water Reactor (LWR) is the injection of water to cool the uncovered

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degraded core. Analysis of the TMI-2 accident [1] and results of various integral in-pile and out-of-pile experiments (CORA [2], LOFT [3], PHEBUS [4], PBF [5]) have shown that before the water succeeds in cooling the fuel pins there could be an enhanced oxidation of the Zircaloy cladding and other core components that in turn causes a sharp increase in temperature, hydrogen production and fission product release.

The QUENCH programme at Forschungszentrum Karlsruhe (FZK) investigates hydrogen generation, material behaviour and bundle degradation during reflood. Integral bundle experiments are supported by separate-effects tests (SET) and code analyses. The programme is providing experimental and analytical data for the development of quench and related models and for the validation of SFD code systems.

The most recent experiments investigated B_4C control rod behaviour and air ingress. These topics are the subject of the SARNET WP9 EARLY phase core degradation which aims to characterise the starting conditions for later phases.

The paper will summarise the essential experimental results and then discuss in detail the status of modelling in the relevant codes (ASTEC, ATHLET/CD, ICARE/CATHARE, MAAP4, MELCOR, SCDAP/RELAP5, SVECHA/QUENCH) with respect to reflood, B_4C behaviour and air ingress, with emphasis on recent improvements and remaining weaknesses.

A complementary paper on degraded core reflood has been published very recently focussed on consequence evaluation based on available data including QUENCH [6].

B. QUENCH BUNDLE TESTS

The QUENCH program at Forschungszentrum Karlsruhe was initiated in 1996 as the successor of the CORA program in which materials interactions under the conditions of a hypothetical severe nuclear accident were investigated. Some of the CORA experiments were terminated by reflooding the bundle with water and it was shown that quenching may lead to temperature escalations associated with high hydrogen production rates [7]. The mechanisms for the escalations were not clear at that time, and the gas analysis systems used with the CORA facility were only of a limited capability. So the QUENCH program was launched with special emphasis on the quantitative determination of the hydrogen source term.

B1. QUENCH facility and test conduct

The main component of the out-of-pile QUENCH test facility [8] is the test section with the test bundle. The bundle is made up of 21 fuel rod simulators approximately 2.5 m long, of which 20 fuel are heated over a length of 1024 mm. Heating is electric by 6 mm diameter tungsten heaters installed in the rod centre and surrounded by annular ZrO_2 pellets to simulate fuel pellets. The bundle geometry and most other bundle components (Zry-4 cladding, grid spacers) used are prototypical for Western type PWRs and are furthermore very similar to the in-pile PHEBUS bundle [4].

The central rod is unheated and is used for instrumentation or as absorber rod. The heated rods are filled with argon-krypton or helium at a pressure of approx. 0.22 MPa to allow for test rod failure detection by the mass spectrometer. The system pressure in the test section is around 0.2 MPa.

Four Zircaloy corner rods are installed in the bundle to improve the thermal hydraulic conditions. They are also used for additional thermocouple instrumentation and/or can be withdrawn from the bundle during the test to check the amount of oxidation during phases of special interest. The test bundle is surrounded by a shroud of Zircaloy, a 37 mm thick ZrO_2 fiber insulation, and a double-walled cooling jacket of stainless steel. 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.

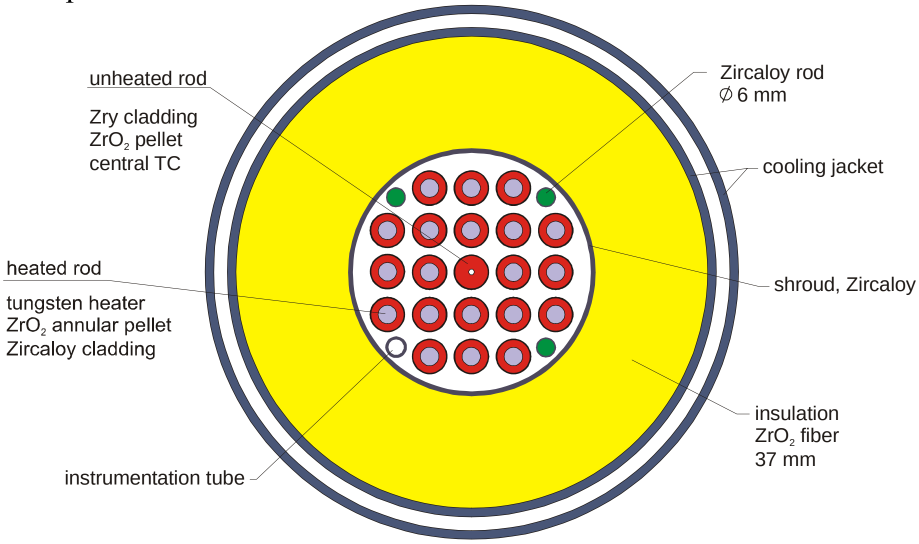

Fig.1: Cross section of the QUENCH bundle

For temperature measurements the test bundle, shroud, and cooling jacket are extensively equipped with thermocouples at different elevations and orientations. Additionally, the test section is provided with various pressure gauges, flow meters, and level detectors. Hydrogen and other gases are analyzed by a state-of-the-art mass spectrometer Balzers GAM300 located 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) is additionally applicable in conditions where no other gases than Ar, H_2 and H_2O are present.

In general, a QUENCH experiment consists of the following test phases: Heatup, pre-oxidation (optional), transient, and quenching/cooldown*. The last phase is accomplished by injecting water or saturated steam at the bottom of the test section. Until the initiation of cooling 3 g/s of superheated steam and 3 g/s of argon as carrier gas enter the test bundle at the bottom and exit at the top together with the gases that are produced in the reactions of zirconium, and where applicable, boron carbide and stainless steel with steam. In the transient phase the test bundle is heated with an initial heating rate of ~0.3 K/s.

As a consequence of the temperature increase the test bundle experiences a temperature excursion due to the exothermal zirconium-steam reaction. This temperature excursion usually begins at the 850-950 mm level leading to the maximum bundle temperature of well above 2000 K and an increased hydrogen generation. The flooding phase is initiated by turning off the flow of 3 g/s superheated steam and injecting water or saturated (cold) steam at flow rates of 40-50 g/s of water and 50 or 15 g/s of steam, respectively. Cool-down in steam is applied because of the better defined boundary conditions for code validation compared to reflood tests with water. At cool-down/flooding initiation the bundle power continues rising or is kept at its maximum for ~20 s.

B2. QUENCH test matrix

So far (as at July 2005) ten bundle tests have been conducted in the QUENCH facility (Table 1). The first six tests were concentrated on the hydrogen source term during reflood of

* Usually the terms "quenching" or "flooding" are used for water tests, and "cool-down" for steam tests. In this report, the terms are used synonymously, unless it is explicitly stated.

the bundle under various boundary conditions; experiments QUENCH-07/08/09 were aimed at the investigation of the influence of B_4C absorber on bundle degradation and gas release; and the topic of QUENCH-10 was air ingress.

Tests QUENCH-01/02/03/06/10 were terminated by flooding with water from the bottom with flooding rates of 40-50 g/s corresponding to about 1.5 cm/s water rising velocity without evaporation. The other tests were stopped by cool-down in saturated steam with 50 g/s (or 15 g/s in QUENCH-07/08) injection rate. Initial heat-up rates by electric power in the transient phases were 0.3-0.5 K/s in all tests, before the additional chemical power due to the reaction between zircaloy and steam caused heat-up rates up to 20 K/s.

During tests QUENCH-01/05/06 a special pre-oxidation phase at temperatures 1400-1500 K was run before the final transient and quench to simulate the higher degree of oxidation in a later phase of the severe accident scenario. The bundles during tests QUENCH-02/03/04 were less oxidised, here the oxide scale thicknesses were only determined by the heat-up history under oxidising conditions. In the B_4C tests QUENCH-07 (with B_4C CR) and QUENCH-08 (reference test without B_4C CR) the bundles were kept at approx. 1723 K for 15 min to allow for interaction of B_4C and relocation of absorber melts under stationary conditions. The special feature of the second experiment with B_4C control rod QUENCH-09 was an 11 min steam starvation phase at about 2073 K with reduced steam injection (0.4 instead of 3.4 g/s) before cool-down.

Table 1: QUENCH test matrix with most important boundary conditions

Test Date	**Medium**	**Central rod**	**Pre-ox.**	**Flooding rate, g/s**	**Initial temp. at quench, K**	**Max. oxide after pre-ox., µm**	**Remarks**
QUENCH-01 *Feb 26, 98*	water	unh. instr.	yes	52	1800	312	EC COBE
QUENCH-02 *Jul 07, 98*	water	unh. instr.	no	47	2480	(120)*	EC COBE
QUENCH-03 *Jan 20, 99*	water	unh. instr.	no	40	2450	(110)*	
QUENCH-04 ***Jul 30, 99***	steam	unh. instr.	no	50	2160	82	
QUENCH-05 ***Mar 29, 00***	steam	unh. instr.	yes	48	2020	160	
QUENCH-06 ***Dec 13, 00***	water	unh. instr.	yes	42	2100	207	OECD ISP-45
QUENCH-07 ***Jul 25, 01***	steam	B_4C CR	yes	15	2100	230	EC COLOSS
QUENCH-08 ***Jul 24, 03***	steam	unh. instr.	yes	15	2115	274	QU-07 ref. test without B_4C
QUENCH-09 ***Jul 03, 02***	steam	B_4C CR	yes	49	2200	(360)*	EC COLOSS, steam starvation
QUENCH-10 ***Jul 21, 04***	water	unh. instr.	yes	50	2180	514	EC LACOMERA Air ingress

** estimated from hydrogen release before quench*

After extensive pre-test calculations the air ingress experiment QUENCH-10 was run with an almost two hours lasting pre-oxidation phase at maximum temperatures in the bundle of 1700 K resulting in a maximum oxide scale thickness of 500 µm. To achieve an adequate duration of the air ingress phase, the bundle was then cooled to a temperature of 1180 K by decreasing the electrical power input. For air ingress the steam flow of 3 g/s was replaced by 1 g/s of air. The test was terminated by quenching the bundle with a flow of 50 g/s of water.

B3. Essential results of the bundle experiments

It is not yet possible to draw final conclusions from the ten QUENCH tests performed so far; however, they give important information on the main achievements of the program thus to identify further experimental needs.

In general, the zirconium oxidation, and thus the hydrogen generation, is driven by the temperature evolution, determined by the electric power input and the heat losses. Starting at about 1300 K the chemical power of the exothermal Zr oxidation comes into play and causes an enhanced heat-up. During the quench phase, the cold water/steam on the one hand acts as a coolant (this is the intended effect) but on the other hand it increases the potential for high chemical energy release by acting as a strong oxidant at these high temperatures. The balance between heat generation and its removal following initiation of reflood is the decisive criterion for successful cool-down of the bundle or temperature escalation. So, all of the factors affecting coolability and oxidation kinetics may have an influence on the final result.

QUENCH-01 – QUENCH-06 [9-13]

The first six tests in the series were "pure" quench tests, i.e. geared to the investigation of the hydrogen source term without absorber rod or atmospheres different from steam. Table 2 shows that two of these tests, namely QUENCH-02 and QUENCH-03, revealed a temperature escalation. In both experiments the initial temperature was the highest, clearly above the melting temperature of Zircaloy; the degree of pre-oxidation was low and only determined by the oxidation during heat-up of the bundle. The rapid and extensive formation of hydrogen during the quench phases was probably caused by the oxidation of zircaloy melts [14].

In the other experiments where the bundle temperatures at beginning of reflood were between 1800 and 2150 K, successful cooldown occurred at the beginning of the quench phase. Only relatively small and short peaks in temperature were observed before cool-down accompanied by only 2-4 g of hydrogen. Cooling of the bundle typically proceeds in two stages: a moderate cooling (steam cooling or film boiling) is followed by a period of pronounced cooling, characterised by transition and to nucleate boiling.

Two mechanisms originally thought to loom large during quenching turned out to be only minor effects. The oxidation of cracks formed during cool-down was detected, but finally only a very few grams of hydrogen are additionally released due to crack oxidation. The absorption of hydrogen by the remaining metal phase was analysed to be between 0.1 and 5 g per bundle and thus also seems to play only a minor role. Nevertheless, one should have these mechanisms in mind, because they may be important locally and/or temporally.

QUENCH-07 – QUENCH-09 [15-17]

These three tests were dedicated to the investigation of the influence of boron carbide on degradation of the bundle and gas release. A B_4C absorber rod (very similar to the one in the Phebus FPT-3 test and to those used in French 1300 MW PWRs) was installed in the central position of the bundles QUENCH-07 and QUENCH-09 (see Fig.2); QUENCH-08 was run as reference test to QUENCH-07 without absorber rod. A special feature of QUENCH-09 was an 11 min lasting steam starvation period at high temperatures (2073 K) before reflood. Steam starvation causes the degradation of the oxide scale [18] and thus may be an major factor promoting temperature excursions.

B_4C absorber material in the central rod reacts with stainless steel and zircaloy and forms eutectic melts, i.e. melts that are formed far below the melting point of metallic zircaloy

(~2030 K), and the oxidation of boron/carbon/zirconium-containing melt can lead to increased amounts of hydrogen and to production of CO, CO_2, and CH_4, compared to a bundle without such a control rod.

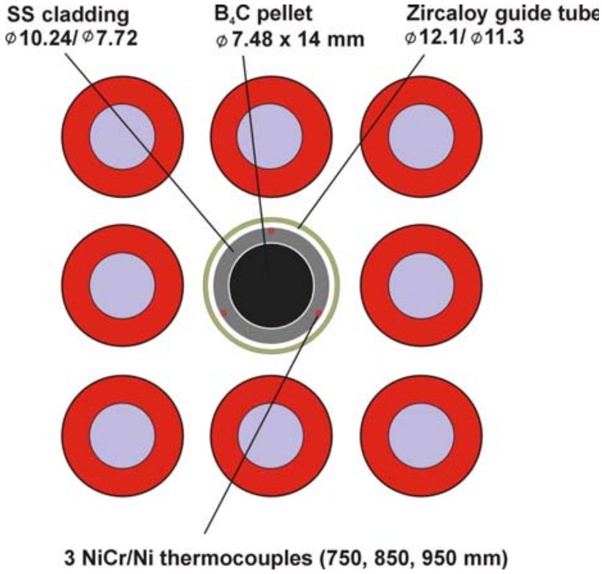

Fig.2: Central part of the bundles QUENCH-07 and QUENCH-09 with B_4C control rod

Although the degree of pre-oxidation in these tests was relatively high (see hydrogen release before reflood, Table 2, which gives an integral figure of pre-oxidation) and the initial temperatures in the quench phase were relatively low, all three experiments revealed temperature and hydrogen escalation during the quench phase. A moderate excursion was seen in QUENCH-08 (without B_4C); here the main difference to the tests QUENCH-01/04/05/06 was the significantly lower steam flow rate (15 instead of 40-50 g/s) during the quench phase. More than three times more hydrogen was released in the similar experiment QUENCH-07 with B_4C control rod. And again a more than three times larger hydrogen production during reflood was observed in QUENCH-09 with absorber rod and steam starvation phase. The main products of the B_4C oxidation were H_2, CO, CO_2, and boric acids, whereas methane, which is of special interest for fission product release, was only released in negligible amounts. However, methane formation via secondary reactions at cooler circuit positions cannot generally ruled out.

The degradation of the bundles with B_4C control rod was much stronger than without B_4C as can be seen in Fig.3. Though these three tests were not completely identical in all other respects, the results give a clear indication for the influence of B_4C and steam starvation on bundle degradation and gas release.

QUENCH-10 [19]

The latest bundle experiment performed in the series so far was an air ingress test. The main objective of this test was to examine the oxidation and nitride formation of Zircaloy during air ingress, before flooding the bundle with water.

The bundle was pre-oxidised in steam at 1620-1690 K to get a maximum oxide thickness of approx. 500 µm, then temporarily cooled down to 1190 K in order to achieve a reasonable long duration of the subsequent air ingress phase. At the onset of the air ingress phase the change in flow from steam to air had the immediate effect of reducing the heat transfer from the bundle, so that the temperatures began to rise. The temperature increase was intensified by moderate raising the electrical power and increasing release of chemical power due to the strongly exothermic reaction between zircaloy and air. Oxygen starvation, i.e. the complete consumption of O_2 at elevations below the top of the bundle, and partial consumption of nitrogen was observed towards the end of the air ingress phase (Fig.4). Reflood of the bundle with 50 g/s water lead to an only very moderate release of hydrogen (~5 g).

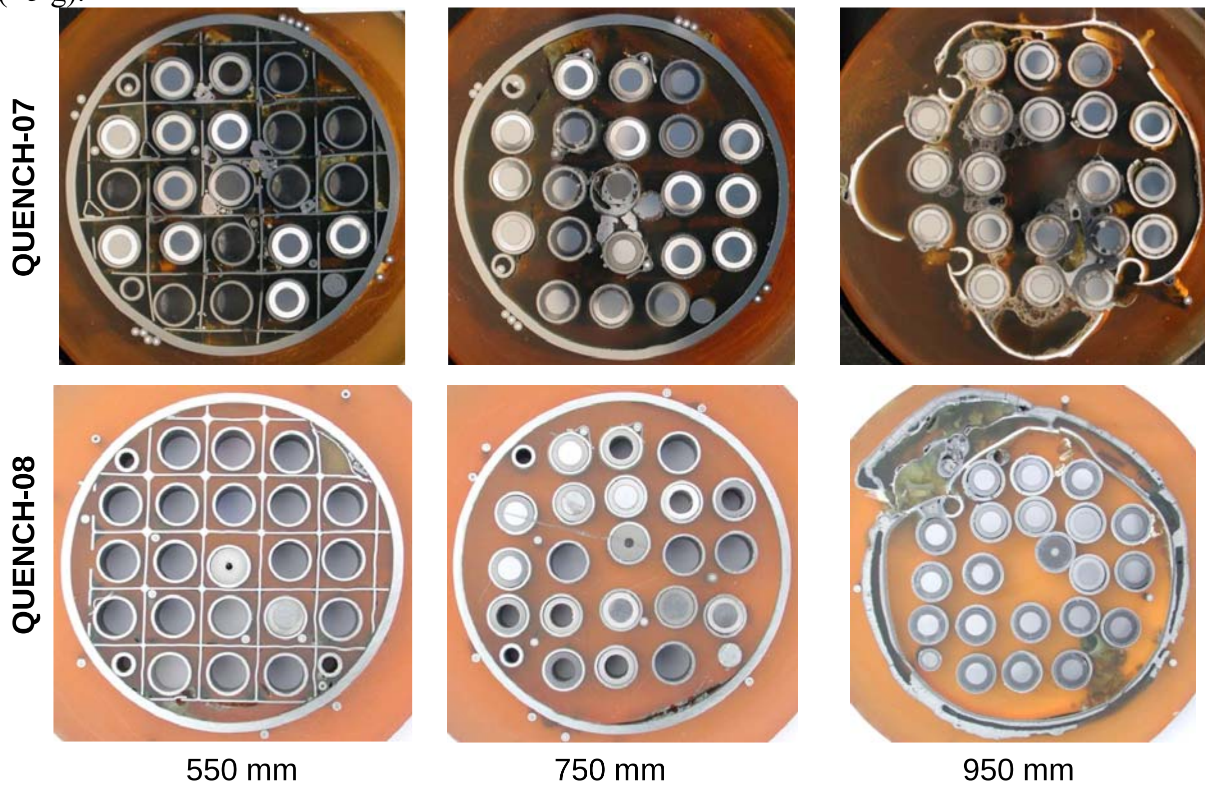

Fig.3: Post-test cross sections of tests QU-07 with absorber rod (top) and QU-08 without absorber rod (bottom)

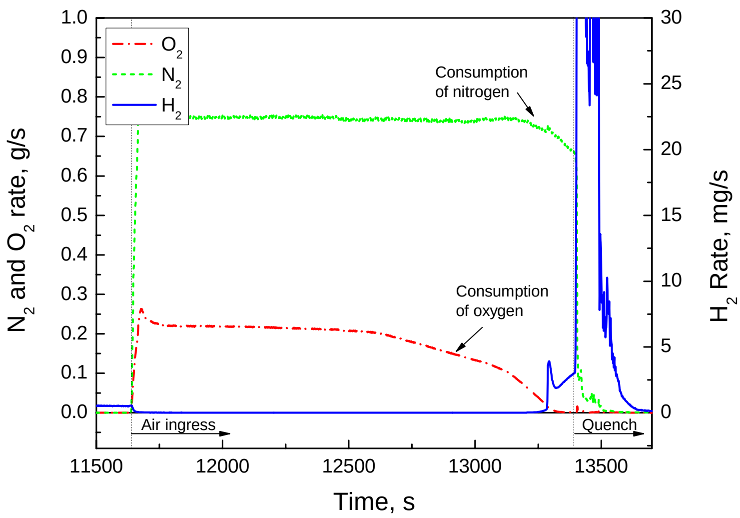

Fig.4: Mass spectrometer measurements of H_2, N_2, and O_2 during the air ingress and quenching phase of QUENCH-10. A small amount of H_2 (note: scale is mg/s!) was released when O_2 is almost completely consumed, at the end of air ingress

The post-test inspection revealed an extremely oxidised and degraded bundle with strong relocation of cladding debris never seen before in any other QUENCH test, but no melt formation in the bundle. Nitride phases were (locally) detected over almost the whole bundle, causing enhanced degradation and loss of the protective effect of the oxide scale.

Table 2: Essential results of QUENCH bundle tests 01-10

Test	Max. temp., K	Max. oxide, µm	Melt formation?	H_2 release before quench, g	H_2 release during quench, g	absorbed H, g
QUENCH-01	1810	580	no	36	3	1
QUENCH-02	>2500	complete	yes	20	140	5
QUENCH-03	>2500	complete	yes	18	120	Not evaluated
QUENCH-04	2300	170	no	10	2	0.1
QUENCH-05	2300	400	no	25	2	0.3
QUENCH-06	2300	600	no	32	4	2
QUENCH-07	>2400	complete	yes	66	120	3
QUENCH-08	2280	complete	no	46	38	2
QUENCH-09	>2400	complete	yes	60	400	Not evaluated
QUENCH-10	2280	complete	no	47	5	Not yet eval.

C. SEPARATE-EFFECTS TESTS

Many separate-effects tests (SET) have been conducted at FZK and elsewhere to support the bundle tests and to deliver data for model development and validation. A detailed description of these experiments is outside the scope of this paper, so only some selected results of actual interest and corresponding references shall be mentioned here.

C1. B_4C control rod degradation and oxidation

Within the EC COLOSS program [21] extensive test series on 1) the oxidation of pure B_4C [22-25], 2) the degradation of B_4C control rods, 3) the oxidation of B_4C/SS/Zry absorber melts, and 4) the liquefaction of stainless steel (SS) by B_4C [26] were performed.

Unlike e.g. the oxidation of zircaloy, the oxidation of boron carbide turned out to be strongly dependent on the thermo-hydraulic boundary conditions, especially on steam partial pressure and gas flow rates. This necessitates a coupling of thermo-hydraulics and chemistry in modelling the oxidation of boron carbide in the SFD code systems. Methane (CH_4), which is of interest due to its potential to form volatile organic iodine compounds, is only produced in negligible amounts also in the SETs under the conditions thought to be relevant during severe accidents.

The degradation of control rods, consisting of boron carbide pellets, surrounded by stainless steel cladding inside a Zircaloy-4 guide tube, rapidly starts at temperature above ~1520 K by the formation of complex eutectic melts inside the gap between the B_4C pellet and the external oxide scale formed at the guide tube surface (Fig.5). After failure of the oxide shell at approx. 1720 K the oxidation of the molten B_4C/SS/Zry takes place very rapidly leading to the formation of CO, CO_2, boric acids and additional hydrogen. Again, almost no methane was detected during these tests. Finally, it was shown that 1 g of boron carbide is able to liquefy 100 g of steel 200 K below its melting temperature.

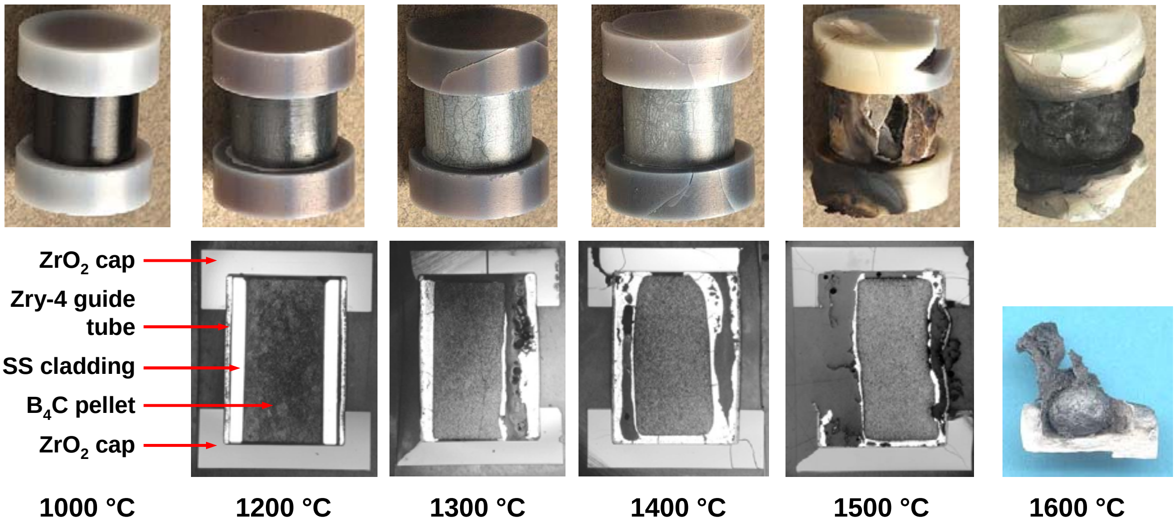

Fig.5: Post-test appearance and axial cross section of B_4C/SS/Zry specimens after 1 hour isothermal tests at temperatures between 1000 and 1600 °C

C2. Air ingress

More recently, the more prototypic oxidation of Zircaloy first pre-oxidised in steam in air as well as the oxidation of zircaloy in mixed air-steam atmospheres has been investigated [19]. It was shown that air significantly influences degradation of the cladding. In mixed air-steam atmospheres the destructive effect of air increases with air concentration and temperature. An oxide scale once formed under steam atmosphere seems to be stable in air as long as no defects (e.g. due to breakaway) occur. However, the oxide is severely attacked by pure nitrogen simulating oxygen starvation conditions (like in QUENCH-10).

C3. Steam starvation

Steam starvation conditions on fuel rod surfaces are possible during a severe accident due to dry-out of the reactor core and blockage formation and complete consumption of the steam in the lower parts of the core. Under these conditions the oxide layer of the cladding will be reduced by the underlying metallic.

The reduction kinetics of the oxide layer during a steam starvation phase was investigated in SETs. A homogeneous formation of α-Zr(O) precipitations inside the oxide layer and the formation of an α-Zr(O) scale on the cladding outer surface were detected in addition to a reduction of the oxide layer thickness.

D. APPLICATION OF SFD CODES ON QUENCH. STATUS OF MODELLING

Generally, integral experiments such as CORA, QUENCH, and PHEBUS are used to validate severe accident codes, which are designed for plant analyses. In the following the status of the main SFD codes used world-wide with respect to reflood and quench related phenomena is summarised. The codes are discussed in alphabetical order. Table 4 at the end of this chapter gives a compact overview on the various code systems.

D1. ASTEC

The integral code ASTEC (Accident Source Term Evaluation Code) is being developed by IRSN (Institut de Radioprotection et de Sûreté Nucléaire), France, and GRS (Gesellschaft für Anlagen- und Reaktorsicherheit), Germany, since 1994. The aim is the creation of a fast running integral code which allows the calculation of the entire sequence of a severe accident in a LWR from the initiating event up to the release of fission products into the environment, covering all important in-vessel and ex-vessel phenomena. The main fields of application of this code are PSA level 2 studies, accident sequence evaluation, uncertainty analysis, and support to experiments. The code validation was initiated under the EVITA Programme of the 5th European FP and is still ongoing in SARNET (6th European FP).

The severe core damage module DIVA [27] of ASTEC V1, was derived from the detailed severe core damage code ICARE2, is validated using QUENCH experiments. Some ICARE2 models have been simplified to meet computation speed criteria, but all significant models are available to simulate adequately the core degradation phase.

Validation started with the draft reflood model of version V1.02 with open calculation of the ISP-45 (QUENCH-06) Benchmark [28]. The present version ASTEC V1.2 is used as a fast tool for QUENCH pre-test and post-test calculations.

During heat-up and transient phase of ISP-45, the measured (symbols) bundle temperatures at three elevations (150mm, 550mm, 950mm) are predicted rather well by both code versions (numbers) as can be seen in Fig. 6. During reflood phase, however, the draft reflood model of ASTEC V1.02, which calculated too fast a cool down, while the standard heat transfer package from DIVA is much closer to the experiment. Neither code version tracks sufficiently the measured reflood curves, even if the experimental uncertainties are taken into account.

The validation is continuing with ASTEC V1.2 on code to data comparison using several QUENCH experiments and on comparison with other codes.

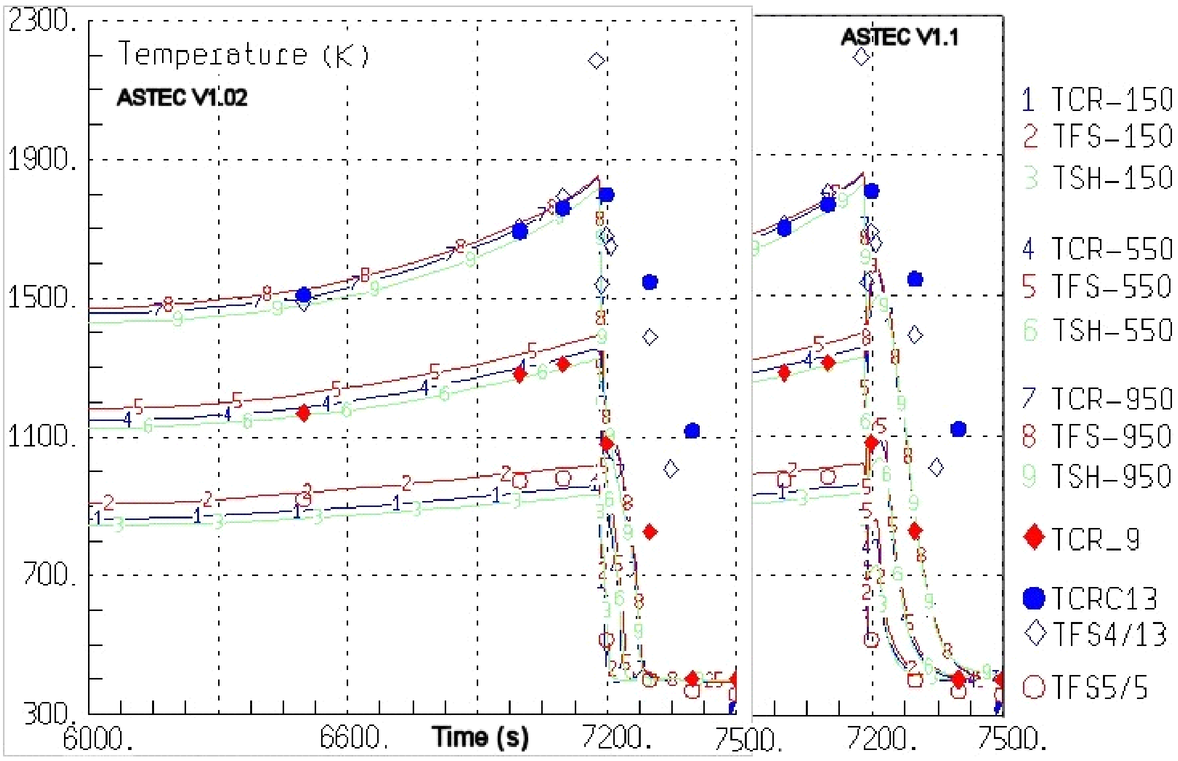

Fig. 6: QUENCH-06, comparison of ASTEC V1.02 (left) and ASTEC V1.1 (right)

D2. ATHLET/CD

ATHLET-CD has been used successfully by GRS and RUB-LEE to analyse the QUENCH experiments. Features of the test-train configuration, notably the Zircaloy shroud and electrical heater elements, require modelling treatments that differ somewhat from those used in typical plant models. However, the code is sufficiently flexible to represent the essential features of the QUENCH facility.

RUB-LEE validated the code against the QUENCH tests Q-03 to Q-06 [29]. In all calculations the recommended or default options have been used, thus the oxidation was calculated with Cathcart correlation at low temperature (T < 1853 K) and Urbanic-Heidrick in the high temperature region. To simulate the quench process, a quench front propagation model is used. This model has been widely validated by means of thermal-hydraulic tests for design based accidents. As long as the structure is not severely damaged, the model allows the simulation of beyond design accidents, too. The reproduction of the thermal behaviour in the heated region for both, rod and shroud temperatures, is satisfactory to all four calculated tests. The calculated hydrogen production is in good agreement for all tests, where the bundle was not severely damaged before the reflood (Q-06 in Fig. 7). Even the simulation of Q-03 shows fair agreement with the results of the hydrogen production before the beginning of reflood (Fig. 7). But during the quench phase, where a severe damage occurred especially of the shroud, the calculated H_2 generation is significantly underestimated. This will be investigated in detail in the ongoing follow-up project BMWA 150 1305.

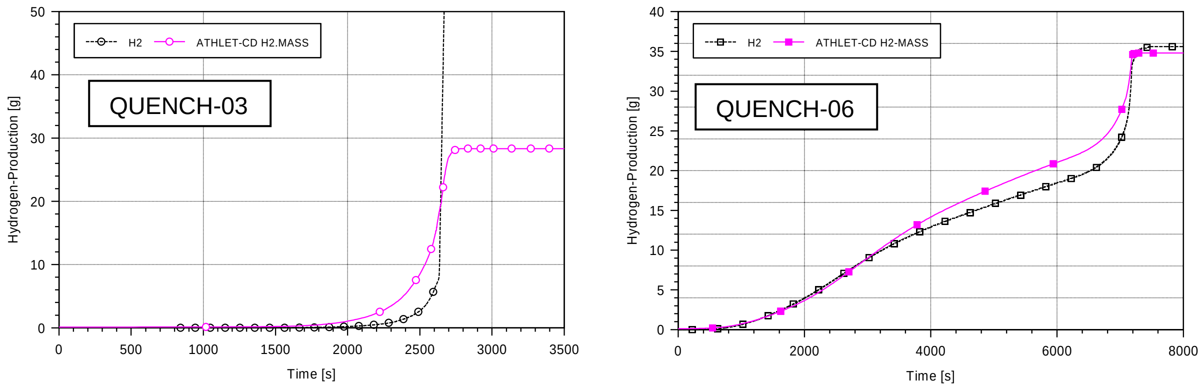

Fig. 7: Hydrogen Generation during QUENCH-03 and -06

GRS validated the code against the two QUENCH test Q-07 and Q-08 [30]. The post-test calculations with ATHLET-CD were performed using the same input data, except for the value of the external rod resistance. For the analyses of the zirconium oxidation the correlations of Cathcart (T < 1773 K) and Prater/Courtright (T > 1773 K) were used. A new model to calculate the interaction between the B_4C pellet and the stainless steel clad of the control rod was implemented into the code. With the clad failure the oxidation of the B_4C is initiated. The B_4C-SS interaction is calculated by using the correlation of Nagase. Additionally, the oxidation is also considered for dissolved B_4C. The duration of the preoxidation period of the experiment Q-08 was slightly longer than the one in Q-07. Therefore, the initiating of the cool down period started 120 s later. The power input was slightly different in the experiments yielding in higher bundle temperatures in Q-07. An important result of this comparison is that the calculated and measured masses of hydrogen generated only from the B_4C oxidation agree well. If the experimental hydrogen generation associated with only those components whose oxidation is modelled by the code is considered , then the mass of hydrogen generated in Q-07 is only about 25 % higher than the calculation, whereas in Q-08 the calculated and test data are almost equal (Fig. 8). The calculated total hydrogen mass in Q-07 is ~40 % higher than in Q-08. To investigate the contribution of B_4C to the hydrogen generation, a second calculation of Q-07 without consideration of the B_4C oxidation shows that its direct effect on temperatures and hydrogen generation is not very high. Consequently, the main difference between the two tests might be related to the higher temperatures in Q-07 resulting from the unintended but different experimental conditions. On the other hand, the melting due to the interaction of absorber material with the fuel rods is not modelled by the code, which underestimates the effect of B_4C on melt formation.

The test QUENCH-10 is used for the development of the model for the oxidation of Zr under the presence of an air and steam mixture. Two options are being tested; the Powers correlation and a correlation derived from the Codex AI tests. The two correlations are leading to very different results in O_2 consumption and thermal behaviour. The preliminary observation is that the Powers correlation underestimates the reaction while the Codex correlation overestimates it. The model is still under development, more reliable results will be available soon.

D3. ICARE/CATHARE

The ICARE/CATHARE modelling involves one-dimensional two-phase thermal-hydraulics (gaseous flow, composed of steam and argon as carrier gas, is injected at the inlet), absorption of radiation in steam, oxidation of materials containing zircaloy, iron and B_4C, interactions involving either fuel rod or control rod materials, conduction in radial and axial direction and radiative transfer. The cladding embrittlement is triggered by a user criterion, according ZrO_2 layer thickness and clad temperature. The ICARE/CATHARE nodalization is a two dimensional representation of the QUENCH bundle. The central rod (unheated or B_4C control rod), the inner and outer rings of heated rods are modelled separately. The shroud (composed of Zircaloy liner, Zirconia fibers and stainless steel cooling jacket) as well as the various grids and corner rods are simulated, too.

Tests QUENCH-01/03 to -09 were simulated successfully with the ICARE/CATHARE code [31-34].The available correlations for Zircaloy oxidation have recently been carefully evaluated by Schanz [35] who recommended the best-fitted correlation based on experimental data. Unfortunately, this correlation, when combined with losses of integrity criteria, leads to large overestimation of the hydrogen generation. Therefore the correlations used for the Zircaloy oxidation in ICARE/CATHARE are Cathcart-Pawel up to 1853 K and Urbanic-Heidrick beyond. These choices are also suitable to simulate the Phebus FP integral experiments. The change of kinetic rate around 1853 K results from the appearance of the cubic ZrO_2 phase in equilibrium with the tetragonal ZrO_2 phase. The enhancement of the kinetic rate is thus explained by the higher diffusion coefficient of oxygen in the cubic phase than in the tetragonal one. This set of oxidation correlations leads to a good agreement between measured and simulated masses of hydrogen released (Fig. 9, Table 3) and temperatures in the whole bundle prior the quenching phase, including the temperature plateaus caused by the steam-starved conditions in QUENCH-09 [34]. Comparison of measured and simulated temperatures after the quenching phase is more difficult due to degradation of non-prototypic components and to destruction of thermocouples in the hot region. However, the ICARE/CATHARE code seems to over-estimate the temperatures in the hot region during the quenching phase. Results of simulations have shown that the degradation and the oxidation excursion are highly sensitive to the prevailing thermo-hydraulic conditions around the regime of rapid kinetics and to the losses of integrity of the cladding.

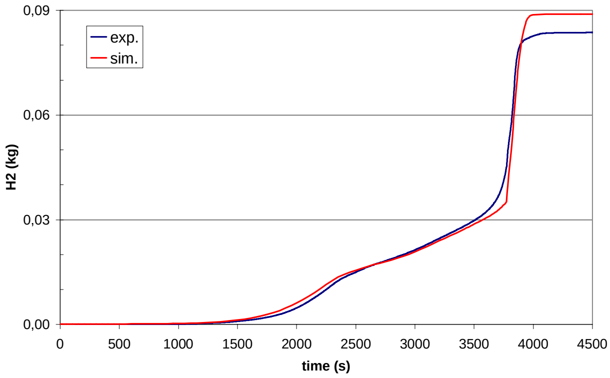

Fig.9: Mass of hydrogen released during QUENCH-08

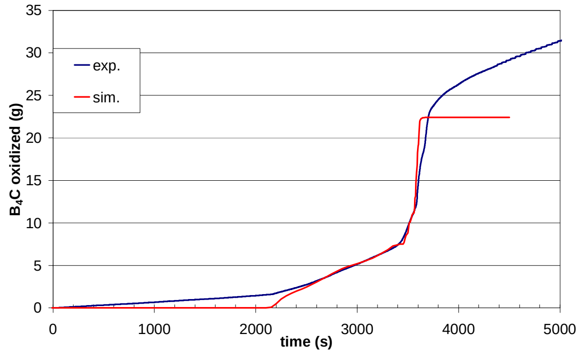

Fig.10: Mass of B_4C oxidized during QUENCH-07

ICARE/CATHARE takes into account the oxidation of relocated molten material and debris once this material is motionless but not during its candling. The bundle states obtained at the end of the simulations present the same features (degradation of the rods, location of relocated mixtures…) as those determined by the post-test examinations [15, 16].

A recent improvement in the model for B_4C oxidation is inclusion of a solid/solid SS/ B_4C interaction occurs above 1073 K, leading to a liquefaction of the reaction zone for temperature above 1500 K. The SS is totally liquefied between 1500 and 1800 K depending on the temperature transient and on the SS/B_4C ratio in the liquid phase (4 to 15%). The liquid resulting from the aforementioned process interacts with and triggers a breach in the Zircaloy guide tube (assumed to be instantaneous in ICARE/CATHARE because of the very fast kinetics of this interaction). This event permits the flow down of the SS-B-C mixture and the oxidation of the remaining B_4C exposed to the steam. The correlation for the B_4C oxidation kinetics has been extended to wider ranges of temperature and steam partial pressure (last results of VERDI experiments). The B_4C oxidation kinetics rate has been obtained for severe accident conditions (above 1500K) where linear oxidation kinetics are applicable and where the governing chemical reaction scheme may be simplified [34].

Table 3: Comparison of hydrogen masses produced per component during QUENCH-09 experiment.

Components	Experiment [20]	Simulation	Relative error
Zry Cladding	132 g	112 g	~15 %
Grid Spacer	13 g	8 g	~37 %
B4C+SS+Zry	10+7+2 g	8.5+1+3.2 g	~33 %

As very few results on B_4C oxidation in mixtures are available, it has been assumed that the oxidation kinetics for mixtures is the same as for solid material. However, experimental tests are foreseen in the frame of the Source Term Program in order to evaluate more precisely the B_4C oxidation kinetics in mixtures.

Comparisons of QUENCH-07/09 simulations with experimental results indicate that rather good agreement can be obtained for the total oxidation and the hydrogen released by B_4C oxidation (Fig. 10, Table 3). Gaseous measurements of CO/CO_2 and CH_4 in QUENCH-07 provide an opportunity to assess this B_4C oxidation modelling and the computation of the B_4C off-gas composition from the coupling between ICARE/CATHARE and the GEMINI2 code, taking into account gaseous convective transports.

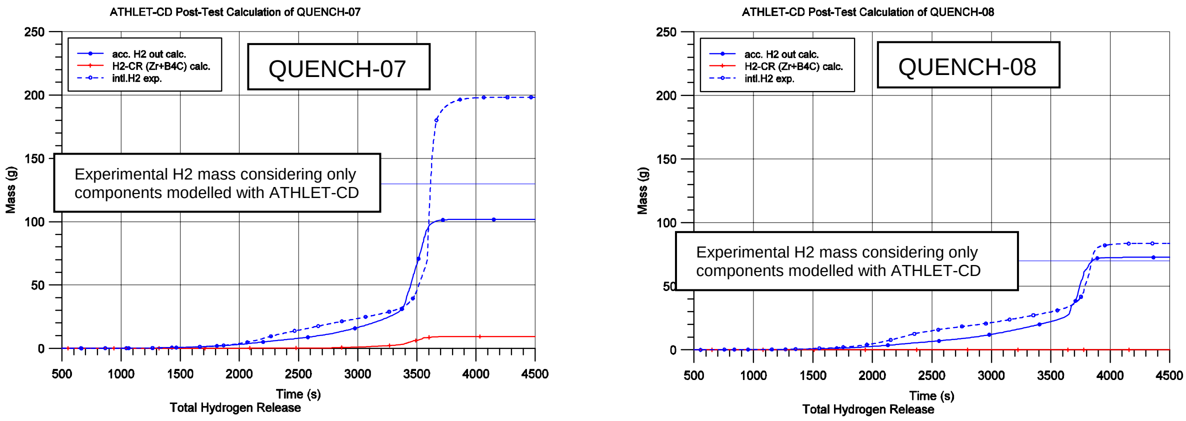

Fig. 8: Hydrogen Generation during QUENCH-07 and -08

Currently there is no model for dissolution of fuel rod materials by B/C/SS mixtures and hence propagation of the interaction zone through the bundle [17] is not captured. To achieve improved understanding of these phenomena and to interpret the FPT-3 Phebus FP test, experimental tests are also foreseen at IRSN (BECARRE program).

The modelling of the oxidation of Zircaloy by air is presently studied at FZK (BOX, QUENCH-SR, and TG tests) and at IRSN (separate-effect tests in the MOZART program). A preliminary model has been implemented in the ICARE/CATHARE code [36] and is currently under improvement. This model has already been used for the calculation of the CODEX AIT 1 experiment and, in a near future the QUENCH-10 test will be calculated using the ICARE/CATHARE code.

D4. MAAP4

EDF uses the MAAP (Modular Accident Analysis Program) code for severe accident analyses. The code is designed to describe the overall reactor coolant system and containment thermal-hydraulic response and core damage progression. Because of the structure of MAAP4, it is possible for the user to adapt and run the code to model experiments for validation and benchmarking purposes. However it still requires a few modifications in the code to model specific geometry and physical phenomena and to define initial and boundary conditions. These modifications are specific to the EDF version (MAAP4.04d) of the code MAAP4.

The standard MAAP4 version uses the Baker-Just correlation as the default oxidation model at high temperature range (beyond 1850 K). The Baker-Just correlation is considered to be too conservative for best estimate calculations. Consequently, EDF decided to allow the user to choose among other correlations that are recognized in the scientific community: the Urbanic and the Prater correlations. The QUENCH-06 modelling with MAAP4.04d shows that the Baker-Just correlation over-predicts hydrogen generation (Fig. 11). The Urbanic correlation slightly under-predicts hydrogen production compared to the experimental data, but the values given by this correlation are closer to the experimental values. The results obtained with the Prater correlation do not give realistic predictions. This points out the lack of a model for the steam diffusion through the hydrogen boundary layer in MAAP4 EDF version.

An independent module was also added in MAAP4 EDF current version to allow the calculation of the thickness of the different cladding layers, β-Zr, α-Zr(O), and ZrO_2. It allows a more detailed approach regarding the cladding behaviour during core temperature escalation, so the code can be coupled with a finite element code in order to study physical phenomena like clad fissuring and shattering [37]. The validation of this model was based upon post-mortem metallographic analysis of the QUENCH-01 and QUENCH-04 test (Fig. 12).

A generic model for U-Zr-O melt oxidation was also developed. This model is based on two criteria, the occurrence of U-Zr-O melt inside the rod and the cladding failure [38]. This model was tested for the oxidation of Zr-O melt on QUENCH-07 and -09 calculations. The use of this model in the calculations gives for QUENCH-07: 15% of hydrogen more than for the reference case with B_4C oxidation (Fig. 14). This is because this new model oxidizes the Zr-O melt which pouring outside the oxide shell.

In the standard MAAP4 version the flow patterns used to model the quench propagation do not take into account the two phase flow region. To make more accurate calculation a two phase flow model was developed. This model is based on the distribution of the void fraction in the core. The main objective was to estimate closely the temperature gradient at the quench front. The hypothesis made was that the quench front is located in the middle of the temperature drop [39]. With the two-phase flow model, the quench front has a clear influence on the cladding temperature profile (Fig. 16). Without this model, the influence of reflooding on cladding temperature is non-existent (Fig. 15).

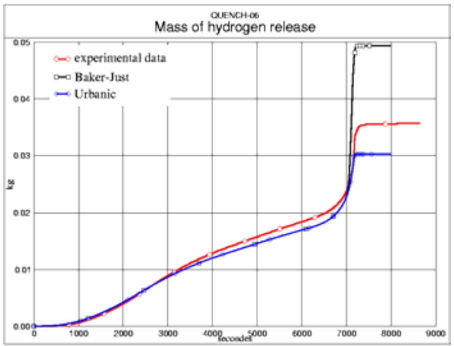

Figure 11 : Zircaloy oxidation – QUENCH-06

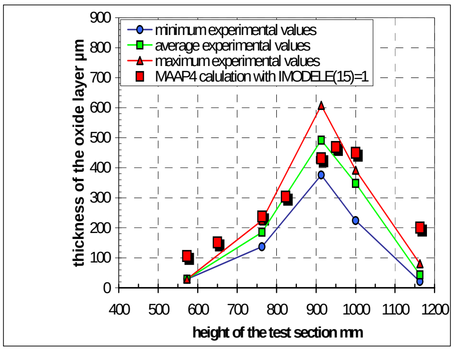

Figure 12 : Oxide layer thickness – QUENCH-01

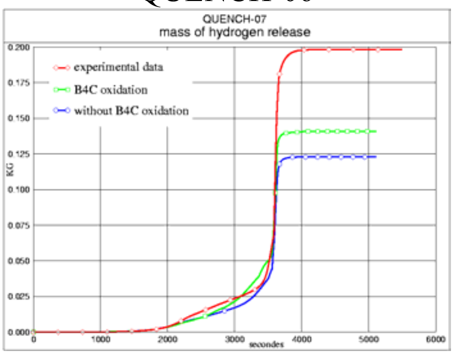

Figure 13 : B_4C oxidation – QUENCH-07

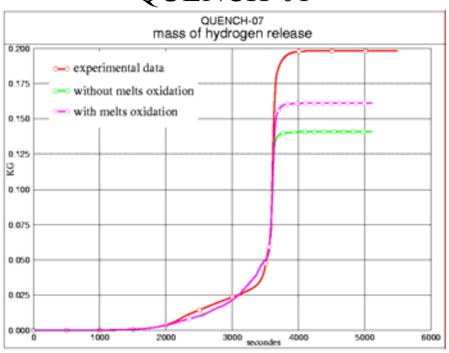

Figure 14 : Melts oxidation – QUENCH-07

In MAAP4 EDF current version, an effort has been devoted to the modelling of a B_4C oxidation and degradation model. First, the model developed takes into account the relocation and the thermal effect of the B_4C. Secondly, a set of three B_4C oxidation correlations produced within the COLOSS project on the basis of experimental programs made at FZK and IRSN, was introduced in MAAP4 EDF version. The modelling of QUENCH-07 and -09 experiments with MAAP4 EDF current version allows to determine which correlation best captures the influence of B_4C oxidation on the hydrogen production (Fig. 13) [38]. Finally, these correlations were linked with thermal-chemical equilibrium for non-condensable gaseous species such as H_2, CO, CO_2 and CH_4. Although this model for the production of non-condensable gases gives good results for hydrogen production, it under-estimates the production of CO, CO_2 and CH_4 (although negligible).

The QUENCH tests have proved useful for improving the modelling of the physical phenomena occurring at the quench time in EDF SA code.

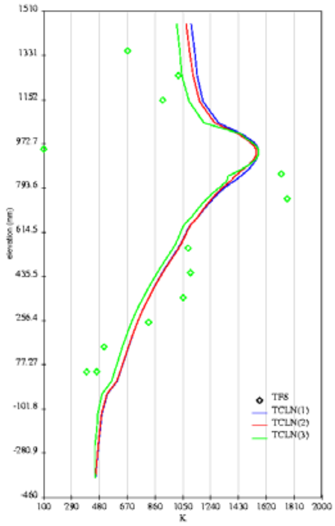

Figure 15 : clad temperature profile without two phase flow model - QUENCH-06 (7200 s)

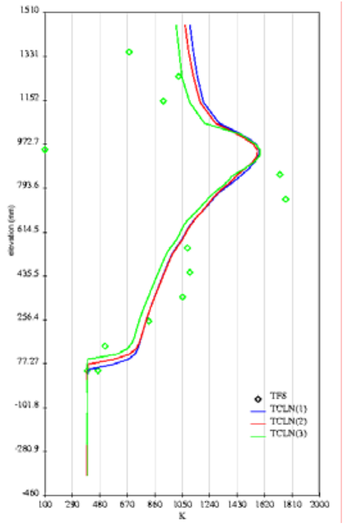

Figure 16 : clad temperature profile with two-phase flow model - QUENCH-06 (7200 s)

D5. MELCOR

MELCOR has been used successfully by a number of organisations including SNL, NRI Rez and PSI, to analyse the QUENCH experiments. Features of the test-train configuration, notably the Zircaloy shroud and electrical heater elements, require modelling and noding treatments that differ somewhat from those used in typical plant models. However, MELCOR is sufficiently flexible to represent the essential features of the QUENCH facility.

The Urbanic-Heidrick correlation is used as the default oxidation model at all temperatures. Although widely used in severe accident analyses, the correlation has been questioned at temperatures below the phase transition of ZrO_2 [40] (ca. 1850 K), and tends to overestimate the hydrogen generation rate. The controlled temperature plateau in the QUENCH experiments provides a good opportunity to assess the oxidation models, of which the Leistikow correlation leads to improved agreement for the hydrogen generation at temperatures below 1800 K (Fig. 17). Assessment of the oxidation models against QUENCH data at higher temperatures is more difficult because of the transient behaviour and the occurrence of degradation which can extend to non-prototypic components. Although MELCOR does not fully take into account the oxidation of relocating molten material or of debris, the Urbanic-Heidrick model performs adequately during the transient phase prior to degradation.

Reflood quench is represented in recent versions of MELCOR by a semi-empirical model for quench front propagation which has performed successfully in simulations where the bundle was not significantly damaged prior to reflood, for example QUENCH-06 (Fig. 18). In such cases there was only modest oxidation during the reflood and this is reflected also in the MELCOR simulations. Quenching of a degraded bundle was observed to provoke significant oxidation excursion, whether this was affected by water reflooding or by steam cooling. Generally MELCOR was then unable to reproduce accurately the excursion, typically underestimating the oxidation for the reasons indicated above.

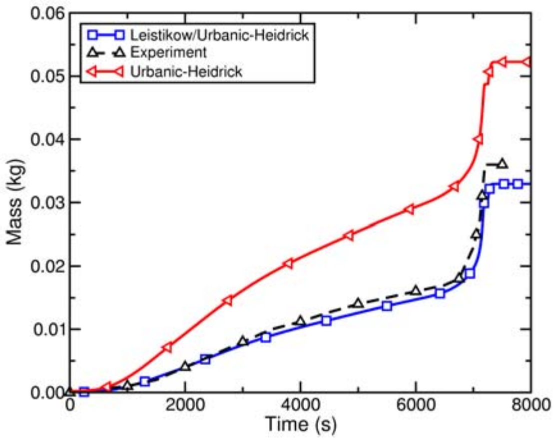

Fig. 17: Hydrogen generation during QUENCH-06

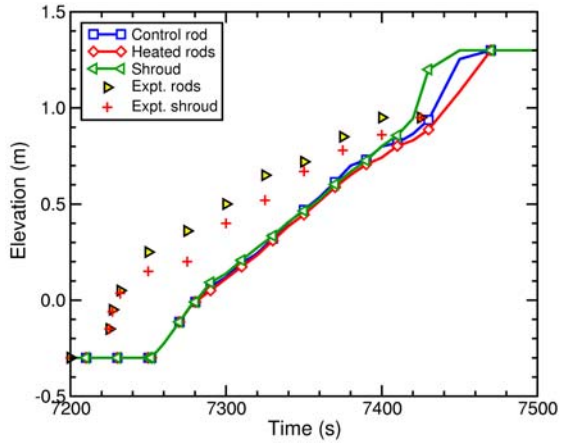

Fig. 18: Quench progression during QUENCH-06

The models for oxidation and degradation of B_4C are designed for the BWR control blade and channel box configuration, and do not readily apply to PWR control rods. Eutectic reactions between the materials and oxidation are included. The model assumes a small fraction (2 percent) of the B_4C is released to the fluid and oxidises rapidly according to simple zero-order kinetics, followed by liquefaction and relocation of the unoxidised materials. The models are subject to rate coefficients and limit values which can be modified via input. Analyses indicate that fairly good agreement can be obtained for the total oxidation and extent of degradation during QUENCH-07 and -09, with a suitable choice of input. In particular the restriction on the oxidisable fraction of B_4C should be removed. However, the rate of oxidation is overstated (Fig. 19) and should be reduced by about two orders of magnitude for PWR control rod simulations. The model does not attempt to represent the oxidation process, and should be regarded as essentially parametric.

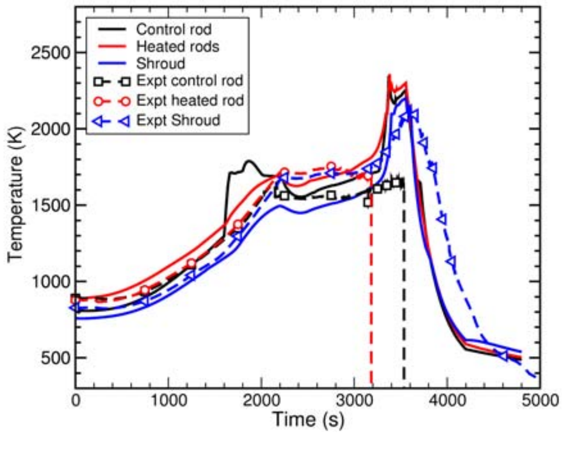

Fig. 19: Temperatures at top of bundle during QUENCH-07

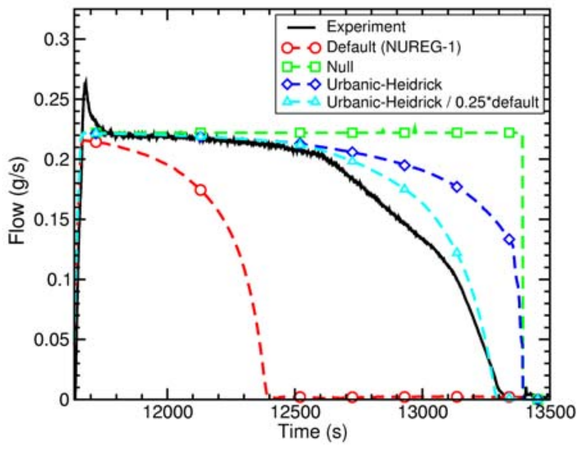

Fig. 20: Oxygen exit flow from bundle during QUENCH-10 air ingress phase

The kinetics of air oxidation are faster than steam because the nitrogen reduces the oxide's resistance to oxygen diffusion and this is reflected in the MELCOR model which had previously given good agreement for air oxidation of the mildly pre-oxidised Zircaloy cladding in CODEX AIT-1 [41]. The model also gave a sharp increase in the oxidation rate soon after the start of air ingress during QUENCH-10. By contrast the experiment showed a more gradual increase from the steam kinetics and a slower transition to complete oxygen consumption. A composite model which attempted, purely for the purpose of interpreting the QUENCH-10 behaviour, to represent a gradual and partial transition from steam to air kinetics, showed quite good agreement for the oxygen uptake and temperature escalation (Fig. 20). It appears that the extensive oxide layer formed by pre-oxidation in steam initially limited the kinetics of air oxidation, and this effect gradually reduced. The limitations in the air oxidation model are being addressed through experimental efforts by FZK and modelling by PSI. MELCOR does not contain a model for the nitriding observed in QUENCH-10.

D6. SCDAP/RELAP5 and SCDAPSIM

Versions of SCDAP/RELAP5 have been used extensively in the planning support and analyses of the QUENCH experiments. Extensions to the core components model package in SCDAP were made by FZK to enable the heater rods to be represented and to address axial boundaries for the heater rods correctly.

Elsewhere the code contains all the features needed to simulate the test train and facility, including the outer cooling loops, and these features are incorporated into the QUENCH input model developed by FZK. SCDAP/RELAP5 is no longer being supported by the USNRC, while SCDAPSIM does not at present include the extensions needed to represent the QUENCH facility. S/R5irs is routinely used to pre-calculate QUENCH tests.

Zircaloy oxidation is modelled by Cathcart-Pawel and Urbanic-Heidrick correlations at temperatures below and above 1850 K, respectively. A feature of the model is the very sharp increase in kinetic rate at the transition temperature, and this reflects the escalation frequently observed in QUENCH experiments when maximum temperatures exceed ca. 1800 K. Despite the inclusion of treatment of debris oxidation in the current version (MOD 3.2), which is dependent on the Zr concentration in the debris, the code does not fully take account of the increasing oxidation rate following the onset of metallic melting, so that the reflood excursion observed in several tests is generally not reproduced.

SCDAP includes an oxide shattering option which provides a means of simulating the enhanced oxidation when molten metallic is exposed to flowing steam. Although it does not capture the processes which actually occurred, the calculated hydrogen mass comes closer to the measured one during the cooldown phase of QUENCH-07.

SCDAP/RELAP5 contains a mechanistic treatment of quench progression, based on the two-phase flow and heat transfer package of RELAP5 combined with calculation of the axial conduction of heat from the hot unquenched cladding to the quenched zone. The process coupling involved in this approach presents a technical challenge, as evidenced by the scatter in calculations for QUENCH-06 (ISP-45) [28]. However, it avoids the need to tune the quench model parameters. No automatic mesh refinement is included like in RELAP5 or TRACE, so that the mesh size should not exceed 0.05m. To allow this, the mesh limitation of the code was extended.

The modelling approach and code structure of SCDAP/RELAP5 would provide a platform for a mechanistic treatment of B_4C control rod degradation and oxidation. Although SCDAP includes the same model as MELCOR for the BWR B_4C control rod, blade and channel box configuration, it cannot be adapted for PWR control rods. Analyses of QUENCH-07 and -09 cannot take account of the B_4C control rod. SCDAP does not contain a model for oxidation in air, but is to be developed at PSI, using data from FZK SET and QUENCH-10, for inclusion in SCDAP/RELAP5 and SCDAPSIM.

As an example for SCDAP/RELAP5 calculations, results are given for Q-06 as a function of time (Fig. 21) and as axial profiles at the time, when corner rod B was withdrawn to determine the oxide scale profile at that time (Fig. 22). All calculated results (solid lines) agree quite well with experimental data (dashed lines or symbols). Temperature is somewhat lower at the start of the quench phase so that cumulated hydrogen production in that phase is somewhat underestimated. Calculated axial profile of linear electrical power demonstrates the necessity to include the positive temperature feedback for power release in electrical heaters.

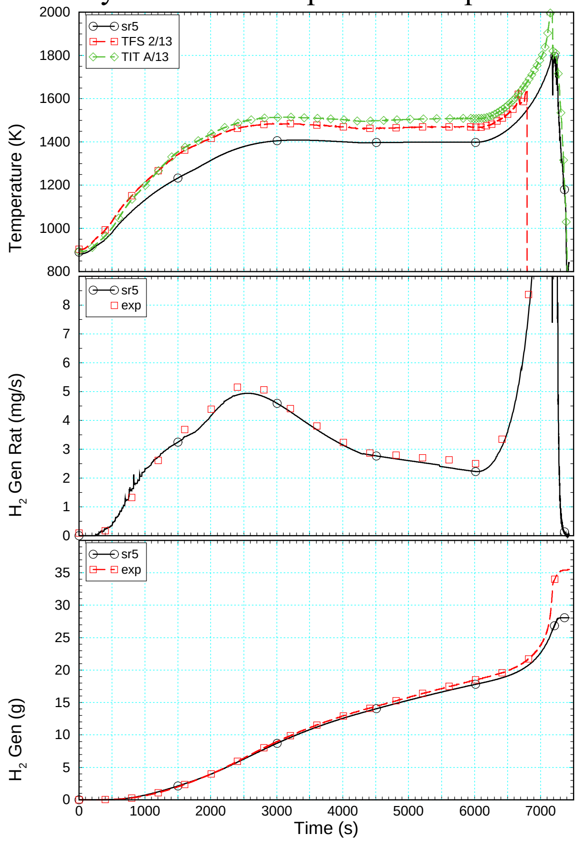

Fig. 21: Temperature, hydrogen production rate and cumulated hydrogen mass for Q-06

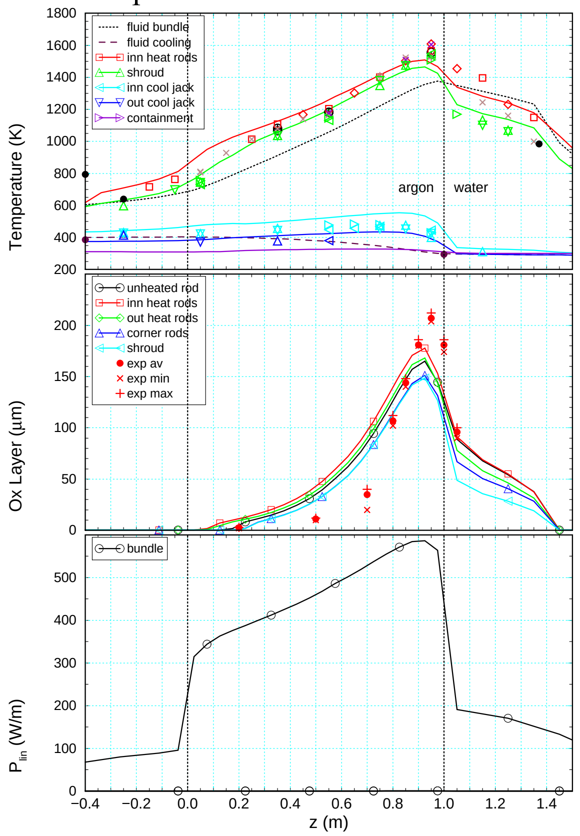

Fig. 22: Axial profiles of temperatures, oxide scales and linear rod power for Q-06

D7. SVECHA/QUENCH

The computer code SVECHA/QUENCH (S/Q) was developed in the Nuclear Safety Institute (IBRAE) of Russian Academy of Sciences, initially for the detailed modelling of reflooding phenomena observed in the FZK (Germany) single-rod QUENCH-SR rig tests, in close cooperation with German experimentalists [42-44]. Within the framework of the S/Q code the main physical phenomena occurring during degradation of fuel rods are considered: cladding oxidation, cladding mechanical deformation, hydrogen uptake and release, heat conduction inside the fuel rod, and heat and mass exchange in the surrounding two-phase media. For the adequate description of the profound mutual influence of the above phenomena the self-consistent coupling of the Oxidation, Mechanical Deformation, Hydrogen Absorption, Heat Conduction and Thermal-Hydraulic models in the SVECHA/QUENCH code was performed.

The cladding oxidation module is based on a mechanistic treatment of the oxygen diffusion problem in the multilayered structure of oxidized cladding, simulates oxidation kinetics up to the metal Zr melting with consideration of mechanical effects and temperature gradients and cladding hydrogen absorption and release [42, 43]. A thorough analysis of available oxidation tests data on Zr oxidation kinetics with respect to their reliability, statistical methods of evaluation of the data sets and the formulation and solution of the coupled diffusion problem, allowed the best determination of the oxygen diffusion coefficients in α-Zr, β-Zr and ZrO_2 phases. The model was successfully validated against various transient oxidation tests.

For temperatures above the metallic Zr melting point, a new mechanism of melt oxidation in steam was developed based on the FZK separate-effect tests evaluation [45]. The new model developed in the framework of the COLOSS Project was tightly coupled with the dissolution model that simulates kinetics of simultaneous dissolution of ZrO_2 and UO_2 [46], and allows interpretation of the melt physico-chemical interactions in the QUENCH bundle tests.

The deformation module simulates deformation and failure of the fuel rod multilayered cladding with consideration of oxidation influence on cladding mechanical properties [42, 43]. In particular, a new mechanistic failure criterion for oxidized cladding was developed on the base of the FZK separate-effect tests [47] and used for interpretation of fuel rods degradation in the bundle tests.

On the basis of detailed systematic study of various physico-chemical processes of B_4C oxidation at high temperatures performed in the FZK BOX Rig, a new model for the B_4C oxidation kinetics was developed [48]. The model self-consistently considers chemical interactions and mass transfer of various species in the multi-component interaction system (solid and liquid interaction layers, gas mixture and their interfaces), and is thoroughly verified against the FZK BOX Rig tests. The model was implemented in the SVECHA/QUENCH code and applied to simulation of the FZK bundle test QUENCH-07 with the central absorber B_4C rod.

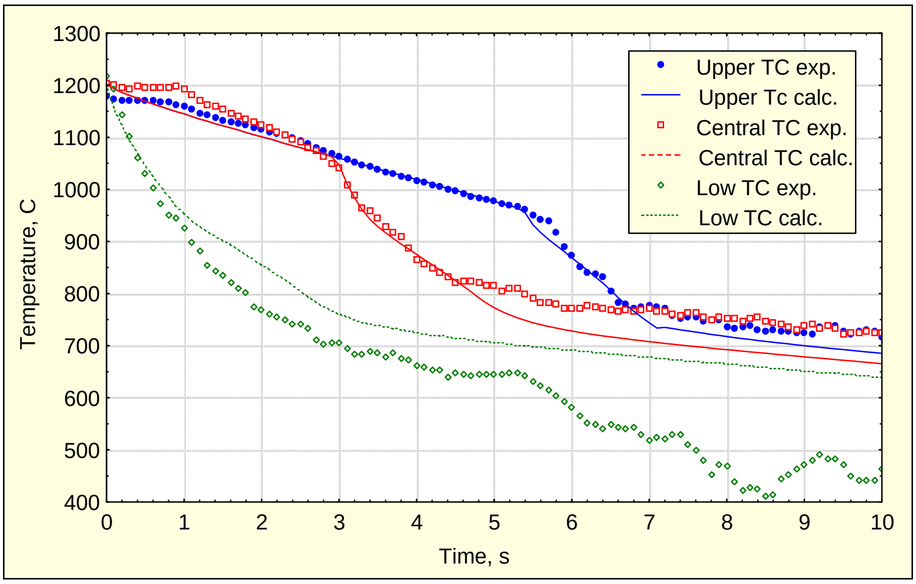

Fig. 23: Simulation of the FZK QUENCH Rig test T2408_1. Temperature evolution of upper, central and lower TCs for the time interval 0 - 10 s.

Code Application to Single-Rod Quenching Tests (QUENCH-SR Rig)

The S/Q code has been verified against the FZK small-scale experimental data [44] (23 tests with water quenching and 6 tests with cooling by steam). The code demonstrated the satisfactory reproduction of the experimentally observed temperature evolution curves in the full range of the single rod experiments conditions (different pre-oxidation and initial temperatures) without tuning and adjusting of the code parameters, Fig. 23.

Code Application to Bundle Tests (QUENCH Facility)

The ‘effective channel’ approach to the QUENCH bundle tests simulation by the S/Q code was developed. This approach assumes the usage of the experimentally measured temperatures of heated rods and shroud for the formulation of the central rod boundary conditions. On the basis of such conditions the S/Q code allows the correct solution of the temperature problem inside the rod, and so allows detailed description of the cladding mechanical deformation, oxidation and hydrogen absorption processes during reflooding, as well as generation of various gaseous components owing to oxidation of B_4C absorber rod in steam (Figs. 24 and 25).

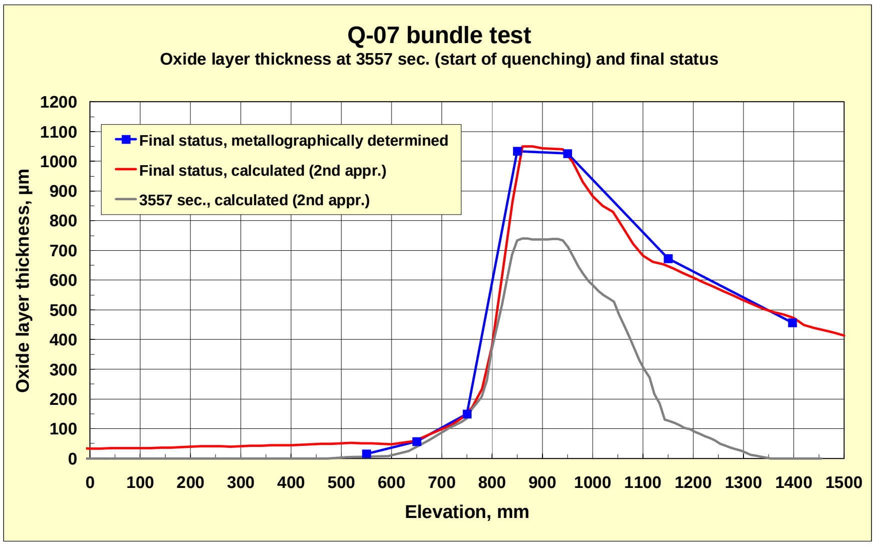

Fig. 24. Measured oxide layer thickness (averaged over the rods, final status), calculated oxide layer thickness of the central rod at 3557 sec. (initiation of cooldown) and calculated oxide layer thickness of the central rod (final status).

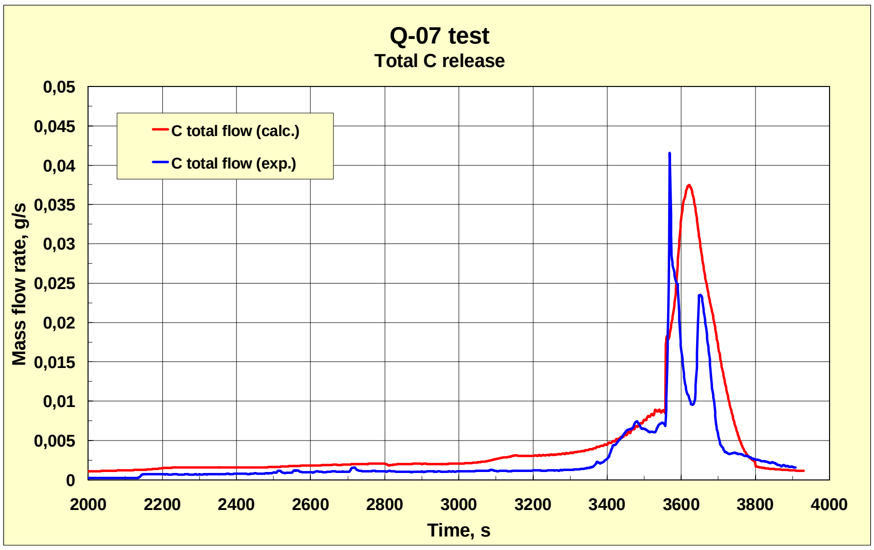

Fig. 25. Experimentally measured and calculated C mass flow rate (in CO_2, CO, CH_4).

E. SUMMARY

An outcome of almost a decade of the QUENCH program has been many advances with respect to the phenomenological understanding, modelling and code development of the reflood process.

The ten QUENCH bundle tests performed so far and an extensive supporting separate-tests effects program provide an extensive experimental data base for model development and code validation. Reflood progression and oxidation of the cladding tubes under highly transient conditions and the corresponding hydrogen source term under various boundary conditions were the topics of the first six bundle tests. It turned out that phenomena like oxide spalling, crack formation and hydrogen absorption by the remaining metal are only of minor effect for the integral hydrogen source term. Temperature escalation was seen during reflood only in tests where quantities of α-Zr(O) bearing melt were exposed to the flowing steam. This was typically the case when temperatures exceeded the melting point of the α-Zr(O), but was also observed when presence of other materials caused melt to form at lower temperatures or when steam starvation had led to erosion of the confining layer of ZrO_2. First SETs on B_4C absorber melt oxidation impressively revealed much faster oxidation kinetics of the melts in comparison to the single solid materials at the same temperatures. QUENCH bundle tests 07-09 confirmed the results of the small scale tests. Another crucial phenomenon is steam starvation which causes thinning and degradation of the protective oxide scale and thus increases the probability for temperature excursions during reflood.

Seven codes were discussed with a wide range of applicability and levels of modelling, starting from a single-rod code with advanced mechanistic modelling to system-level codes able to describe a whole plant with semi-empirical models and parametric correlations. They more or less cover the phenomena relevant to reflood scenarios of actual interest: reflood progression, oxidation of zirconium alloy cladding materials, boron carbide absorber rods and melts as well as the oxidation of Zircaloy cladding in air containing atmospheres.

The codes are generally able to describe the reflood scenario satisfactorily as long as the bundle has an intact geometry. Recently, progress has been made regarding the modelling of B_4C absorber oxidation. The treatment of the oxidation of relocating/relocated melts as well as the oxidation in atmospheres containing air is under development or foreseen in the future for the most codes.

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Table 4: Overview on SFD code systems

		Modelling of				
Code	**Type**	**Reflood**	**B_4C ox./degrad.**	**Melt ox.**	**Air ox.**	**Remarks**
ASTEC	System level (whole plant)	Semi-empirical model for quench progression; beta-status	Correlation, no damage sequence model	Limited user defined	Planned, based on I/C	ASTEC V2.0 will include all ICARE models
ATHLET/CD	Mechanistic system code (vessel and coolant systems)	Semi-empirical model for top and bottom quench front tracking	Model for B_4C control rod, BWR components under development	Model for metallic melt rivulets and crust, model for debris under development	Model for air steam mixture under development (Powers, Codex)	New contract for development until end of 2008
ICARE/ CATHARE	Mechanistic system code (vessel and coolant system)	Based on the CATHARE2 model (convective exchanges enhanced downstream from the Quench front)	Correlation based on separated-effect tests, valid for large ranges (temp., steam partial pressure)	Relocated material oxidation (Zircaloy, B4C).	Parabolic kinetic model,	new version released in April 05
MAAP4	System level (whole plant)	Two phase flow semi-empirical model	Model designed for B_4C control rods	Model for U-Zr-O melts oxidation	No	MAAP5 planned early 2006
MELCOR	System level (whole plant)	Semi-empirical model for quench progression; beta-status	Model designed for BWR control blade; can accommodate B_4C control rod	Limited representation of relocated material oxidation	Parabolic kinetic model	New version imminent (as of 07/2005)
SCDAP/RELAP5 and SCDAPSIM	Mechanistic system code (vessel and coolant systems)	Mechanistic model for quench propagation	Model restricted to BWR control blade	Candled and debris metallic and metallic-ceramic mixtures	Planned for SCDAPSIM	SCDAP/RELAP5 no longer supported
SVECHA/ QUENCH	Detailed mechanistic single-rod code with advanced models	Mechanistic model for quench propagation	Self-consistent consideration of chem. interactions and mass transfer based on SETs, valid for large ranges (T, $p(H_2O)$, flow rate)	Mechanistic model for U-Zr-O melts oxidation based on separate-effect tests and coupled with UO2 dissolution model	Planned	The advanced mechanistic models of the S/Q code are implemented in the system-level code RATEG/SVECHA