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ANALYSIS OF THE QUENCH-14 BUNDLE TEST WITH M5® CLADDING

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ABSTRACT

The QUENCH experimental programme at Forschungszentrum Karlsruhe (FZK) investigates phenomena associated with reflood of a degrading core under postulated severe accident conditions, but where the geometry is still mainly rod-like and degradation is still at an early phase. The QUENCH test bundle is electrically heated and consists of 21 fuel rod simulators with a total length of approximately 2.5 m. The cladding and grid spacers are identical to those used in Pressurized Water Reactors (PWR) whereas the fuel is represented by ZrO_2 pellets.

Experiment QUENCH-14 was successfully performed at FZK in July 2008 and is the first in this programme where Zr-Nb alloy M5® is used as the fuel rod simulator cladding. QUENCH-14 was otherwise essentially the same as experiment QUENCH-06, which was the subject of the CSNI ISP-45 exercise. It is also the first of three experiments in the QUENCH-ACM series, recently launched to examine the effect of advanced cladding materials on oxidation and quenching under otherwise similar conditions.

Pre- and post-test analyses were performed at PSI using a local version of SCDAP/RELAP5 and MELCOR 1.8.6, using input models which had already been benchmarked against QUENCH-06 data. Preliminary pre-test calculations with both codes and alternative correlations for the oxidation kinetics indicated that the planned test protocol would achieve the desired objective of exhibiting whatever effects might arise from the change in cladding-material in the course of a transient similar to QUENCH-06. Several correlations were implemented in the models, namely Cathcart-Pawel, Urbanic-Heidrick, Leistikow-Schanz and Prater-Courtright for Zircaloy-4 (Zry-4), and additionally a new candidate correlation for M5® based on recent separate-effects tests performed at FZK on M5® cladding samples. Analyses of the QUENCH-14 data demonstrate strengths and limitations of the various models. Some tentative recommendations are made concerning choice of correlation and effect of cladding material.

1. INTRODUCTION

The QUENCH programme is being performed at the Forschungszentrum Karlsruhe/Germany (FZK) to investigate the effectiveness of water injection as a means of reflooding and quenching a core, following a beyond-design-basis accident with temperatures above 2000 K and possibly some early phase degradation. Among the topics of concern is the hydrogen generation due to contact between the overheated cladding and the flowing steam. Fourteen experiments have been carried out under a range of flooding/cooling conditions and bundle configurations, thus creating a strong database for model development and code improvement in the field of severe accident simulation [1]. One of the ultimate goals of QUENCH is to identify the limits (temperature, injection rate etc.) for which successful reflood and quench can be achieved.

Almost all the experiments to date were performed with Zry-4 as the cladding material. Other cladding materials based on zirconium-niobium alloys are being increasingly adopted for PWR fuel, by virtue of their improved resistance to corrosion during operation, for example M5® by AREVA and Zirlo® by Westinghouse. In contrast to the extensive database available for Zry-4 oxidation, data for the more recently adopted cladding materials are comparatively scarce. For that reason FZK has recently launched the QUENCH-ACM series [2] in order to investigate the impact of alternative claddings on high-temperature reflood and quench. In parallel FZK is also performing separate-effects experiments, Steinbrueck [3] and Grosse [4], to provide more detailed data on the alternative claddings. The latest experiment, QUENCH-14, is the first in this series and used M5® as the cladding material. The experiments are being performed under essentially the same conditions in order to best meet this objective. The reference case for the series is experiment QUENCH-06 which was subject of the CSNI International Standard Problem No. 45 [5] and has been extensively reviewed and analysed.

2. SUMMARY OF QUENCH FACILITY AND TEST CONDUCT

The main component of the QUENCH facility is the bundle, which typically comprises 21 fuel rod simulators about 2.5 m long, of which 20 are heated over a length of 1024 mm by 6 mm diameter tungsten heaters in the rod centres, surrounded by annular ZrO_2 pellets to simulate the UO_2 fuel. The geometry and most other bundle components are prototypical for Western-type PWRs (M5® cladding and Zry-4 grid spacers were used in QUENCH-14). The central rod is unheated and is used for instrumentation or to simulate a control rod. The heated rods are filled with helium at about 0.22 MPa to allow rod failure detection by the mass spectrometer. The pressure in the test section is around 0.2 MPa. Four corner rods (three of which were Zry-4 and one was E110 in QUENCH-14) are installed to mount additional thermocouples. Two of these rods can be withdrawn during the test to determine the axial oxidation profile at critical phases, while the others are examined after the test. The bundle is surrounded by a Zircaloy shroud to provide encasement, a 37 mm thick ZrO_2 fibre insulation, and a double-walled stainless steel cooling jacket within which a flow of argon is maintained to remove excess heat. The whole set-up is enclosed in a steel containment. The facility bundle cross-section are shown schematically in Figures 1a and 1b.

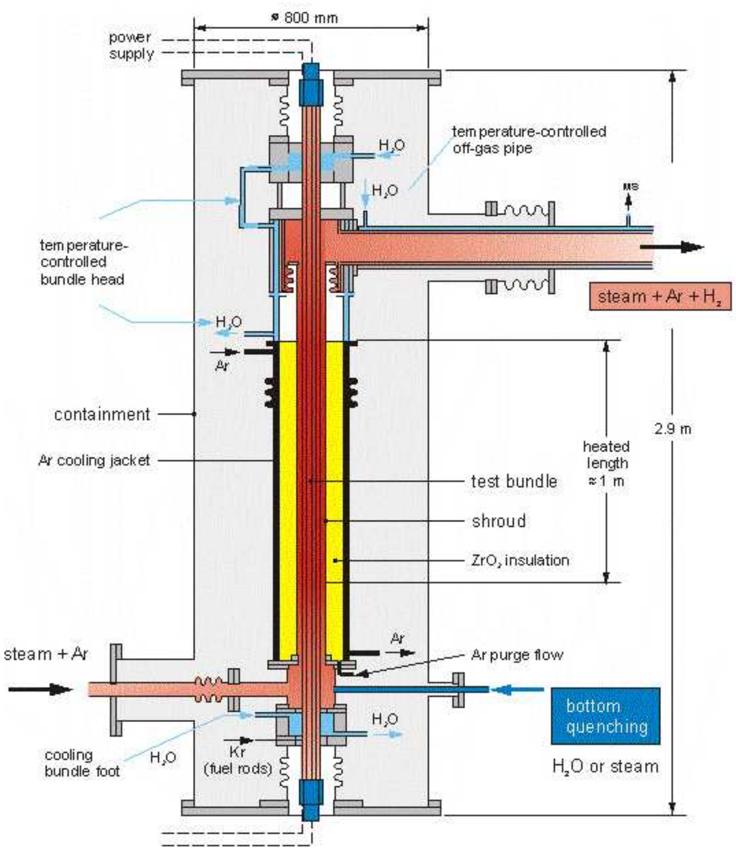

Figure 1a: Schematic of QUENCH facility

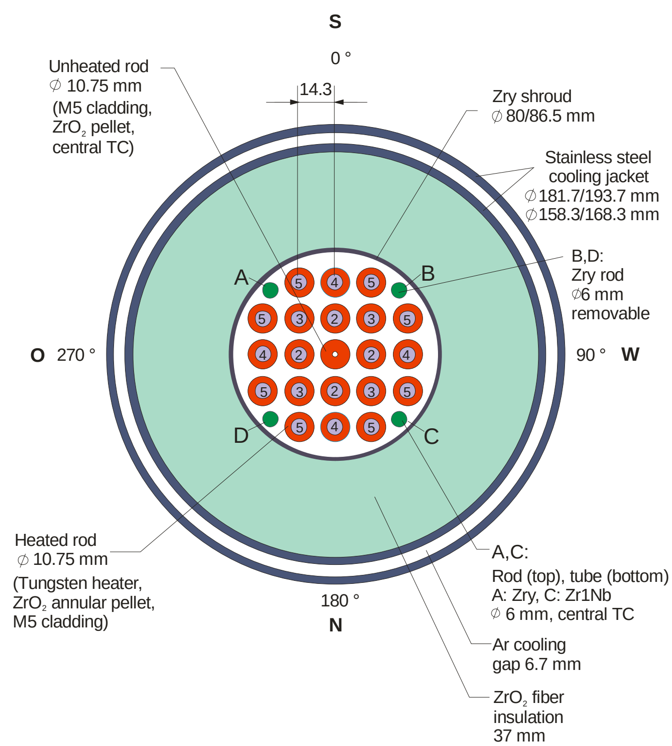

Figure 1b: Cross section of QUENCH-14 bundle

The test bundle, shroud, and cooling jacket are extensively equipped with thermocouples at different elevations and orientations. The test section incorporates pressure gauges, flow meters, and a water level detector. Hydrogen and other gases are analyzed by a mass spectrometer at the off-gas pipe about 2.7 m behind the test section. A redundant hydrogen detection system, based on heat conductivity measurement of binary Ar-H_2 mixtures (Caldos), provides independent data on hydrogen concentration.

The QUENCH-14 experiment conduct closely followed QUENCH-06 and comprised four phases as indicated in

Figure 2: initial heat-up, pre-oxidation, transient, and quenching. During heat-up the bundle reached a temperature of about 1500 K at the hottest elevations, 950 mm from the bottom of the heated section, and where significant cladding oxidation occurred. The temperatures were then controlled at a roughly constant level for a period of ca. 6000 s to achieve the desired state of oxidation. A first corner rod was withdrawn near the end of this phase. The transient phase was initiated by an increase in electrical heating and was accompanied by increased hydrogen generation and associated heating. This continued for 1200 s until the reflood temperature criterion of 2050 K was reached at 7213 s. Shortly before then a second corner rod was withdrawn. During the bulk of the test, a flow of 3 g/s steam and 3 g/s Ar as carrier gas for H_2 measurement was maintained. During the last phase, water was injected at the bottom of the test section at a rate of 41 g/s, and power was reduced to simulate typical decay heat level.

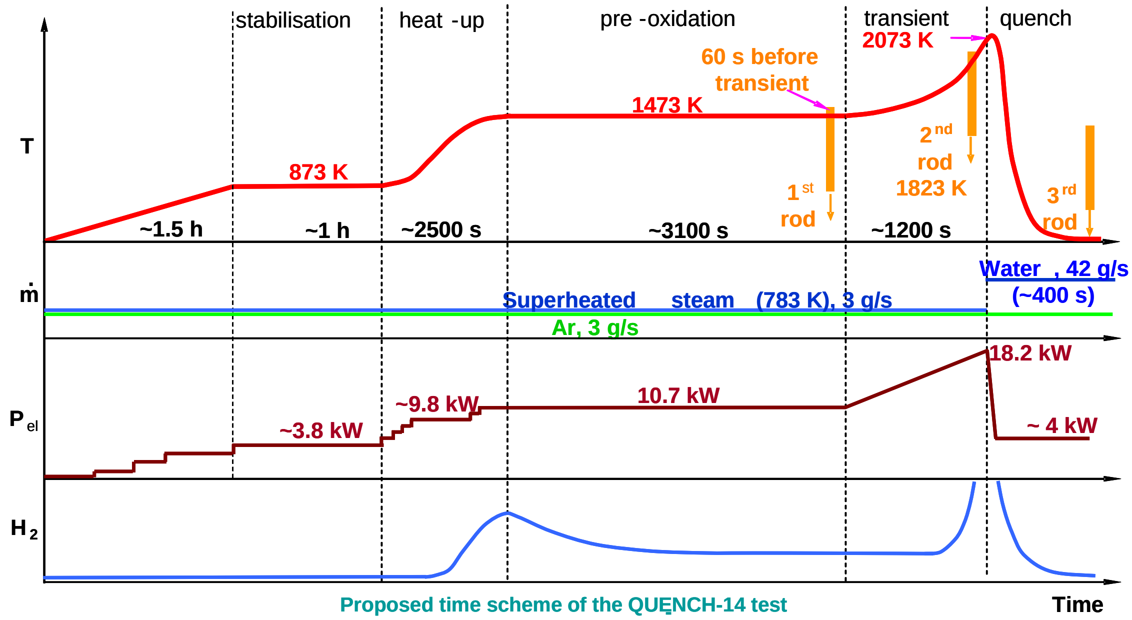

Figure 2: Outline of QUENCH-14 test conduct

Following reflood initiation a moderate temperature excursion was observed, reaching a peak of 2308 K measured on the shroud, shortly after the quench initiation. The thermal response was similar to QUENCH-06, in which reflood was initiated at 7180 s, and a peak temperature of 2242 K was measured shortly after. Hydrogen production was 35 g in the pre-oxidation and transient phases of QUENCH-14 and ca. 5 g in the quench phase, respectively, which was similar to the corresponding amounts generated in QUENCH-06, 32 g and 4 g. The remaining two corner rods were withdrawn after the test, again to check total oxide formation and hydrogen absorption. The conduct and results of QUENCH-14 are described in more detail by Stuckert [6] in a companion to this paper.

3. ANALYSES OF QUENCH-14

3.1 Analytical Tools Used

MELCOR [7] is the primary system-level code used by PSI for nuclear plant safety analysis. The recently released version 1.8.6 is being assessed in readiness for application. The simplified treatment of physical processes by many of the MELCOR models, makes it necessary to perform back-to-back comparison with empirical data and other code systems. For example, a partial two-fluid formulation in which the phases are essentially separated is used to model the two-phase thermal-hydraulics. SCDAP/RELAP5 [8] uses a full two-fluid treatment together with a more complete treatment of the early-phase core degradation processes than MELCOR; it has been widely used in planning and post-test analyses of the QUENCH experiments, and the models are extensively benchmarked [9], [10], [11]. For the present analyses, MELCOR 1.8.6 and SCDAP/RELAP5 were used in tandem, with the latter used as the lead tool. A variant of SCDAP/RELAP5/MOD3.2 is used here, which includes dedicated models for QUENCH developed by Hering [12]. Extensions to the MELCOR code to enable QUENCH simulation were developed by Cole [13]. Previous MELCOR analyses of QUENCH performed at PSI have been carried out using version 1.8.5 [14].

The SCDAP/RELAP5 input model is unchanged from analyses of the previous QUENCH experiments. The model comprises a single radial and sixteen axial hydraulic nodes for the test section with ten nodes for the 1 m tungsten heated length, and extends to include the upper region and offgas pipe. The cooling jackets are represented by separate hydraulic systems and containment is represented as a boundary condition. Although the number of axial nodes comparable with many plant models, the node length is shorter, as dictated by the need to resolve the steep temperature profile in QUENCH. The MELCOR 1.8.6 input was adapted from the 1.8.5 model by means of the supplied converter followed by some manual modification to achieve compatibility of the lower volume with the input specification of the 1.8.6 version. A simpler hydraulic noding is used with MELCOR than with SCDAP/RELAP5, with just four axial nodes for the tungsten heated length but with ten core component nodes to resolve the axial profile. The comparative levels of detail reflect customary practice in many applications.

A point about QUENCH is the significant fraction of total electrical power that is dissipated by the electrical resistance of the external circuitry and its contact with the copper electrodes. This is represented (with all codes) by a user-chosen constant. Since the resistance is not known and can vary from test to test, perhaps also during a test, sensitivity studies were performed also with respect to its value.

It is known that the hydrogen generation and likelihood of an excursion during reflood can depend strongly on the choice of oxidation correlation. The Urbanic-Heidrick (UH) model [15] is default in MELCOR; however, several alternatives were used, including a recent provisional correlation for M5® by Grosse [4] (which we refer to as GM5) to characterise better the oxidation in QUENCH-14 and to assess any potential sensitivity.

SCDAP/RELAP5 uses the pairing of Cathcart-Pawel (CP) [16] and UH correlations for oxidation in the temperature regimes below 1853 K (low/intermediate) and above 1873 K (high), with linear interpolation in between. The combination is part of the MATPRO material property library [8] (volume 4). Since model changes cannot be made via input, local code versions were developed with the Leistikow (L)/Prater-Courtright (PC) correlation [17] and with the GM5/UH pair of correlations applied in the low/intermediate (T < 1853 K) and high (T > 1873 K) regimes respectively. It is noted that the L/PC model [17] yields similar kinetics to CP/PC. The GM5 correlation was obtained from data in the range 1073 - 1673 K and formulated as two branches, with a "step" at 1323 K which is approximately the transition temperature between the monoclinic and tetragonal phases of the oxide, as shown in Figure 3. Similarly reduced kinetics were also observed at the lower temperature in experiments with Zry-4, Duplex and E-110. The Grosse data do not extend into the high temperature regime above 1853 K. In the SCDAP implementation both branches were implemented and the correlation merged with MATPRO (i.e. UH) at the higher temperature. A variant of MATPRO was also implemented with the Zry-4 low temperature branch from [4] replacing CP at T < 1300 K.

MELCOR allows just two branches to be input, so it was not possible to fully represent all three regimes: GM5(low), GM5(high), and T > 1853K. Therefore the model was applied in two different ways: (i) the two branches of the GM5 model with smoothing between 1300 and 1350 K; (ii) the upper branch at T < 1800 K and either PC or UH at T > 1900 K (with interpolation in between) in attempt to cover the full range of temperatures. Case (i) covers the entire period of pre-oxidation and in particular the slower oxidation rate at T < 1300, while case (ii) captures the faster kinetics at T > 1800 K but not the slower oxidation at lower temperatures.

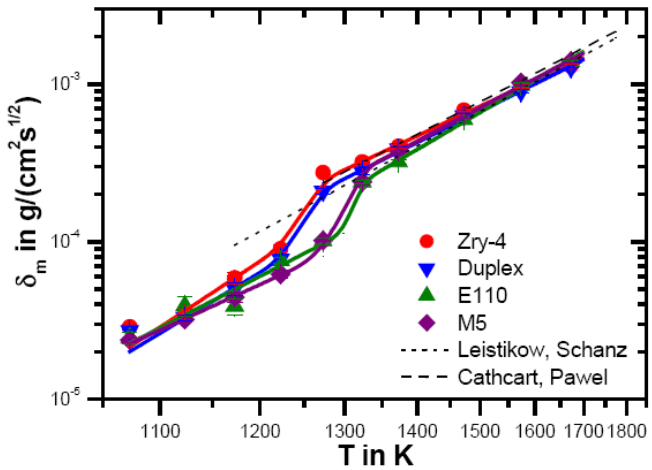

Figure 3: Mass gain measurements for different cladding materials (from Grosse [4])

The present analysis is the first application of the MELCOR 1.8.6 code version to QUENCH. An input model was developed by converting the MELCOR 1.8.5 QUENCH model according to the version 1.8.6 input specifications and benchmarked against the QUENCH-06 data. Good agreement was obtained for the important signatures without significant changes to the input, as shown figure 4. Different choices of oxidation correlation were used, showing only a mild dependence of the thermal response. The same input model was then used in the planning analysis for QUENCH-14, with nominal boundary conditions as indicated in figure 2.

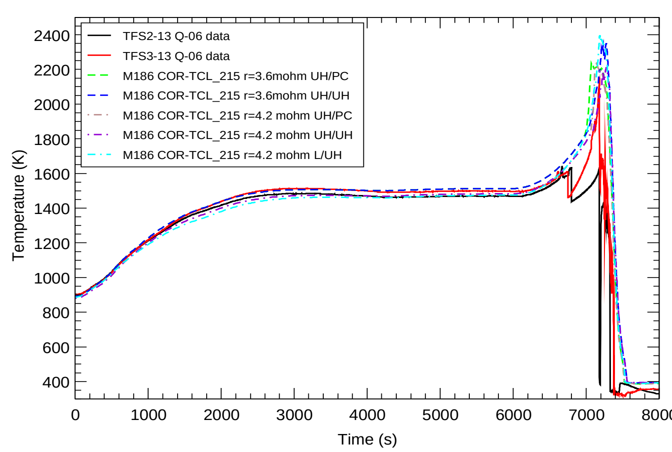

Figure 4: MELCOR 1.8.6 calculation of QUENCH-06 bundle temperature at 950 mm, with alternative oxidation models

3.2 Pre-test analyses

The primary goal of the pre-test calculations was to support the experiment conduct, in particular to indicate if uncertainties in the facility characteristics might cause unexpected departure from the target transient. Secondary goals were to provide additional code validation by means of totally blind simulation and to prepare for post-test analyses.

Figure 5 shows the predicted heater rod cladding temperature history at the 950 mm elevation calculated by MELCOR, with the two variants of the GM5 model described above. The choice had only a minimal effect on the temperature at this location, but the low branch of the correlation gave noticeably reduced overall hydrogen generation during the pre-oxidation phase, as is seen from Figure 6.

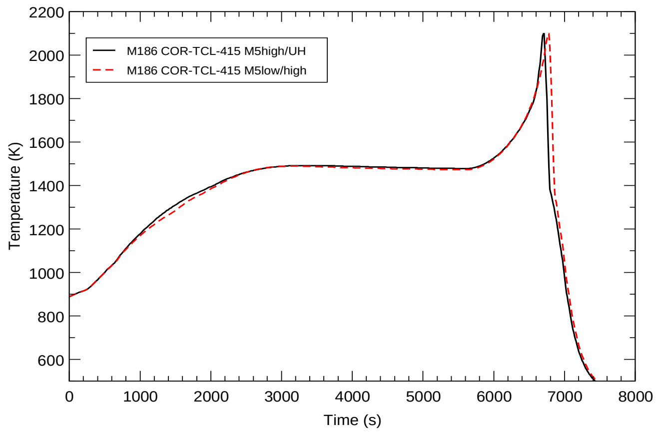

Figure 5: MELCOR 1.8.6 prediction of QUENCH-14 bundle temperature at 950 mm, with alternative forms of GM5

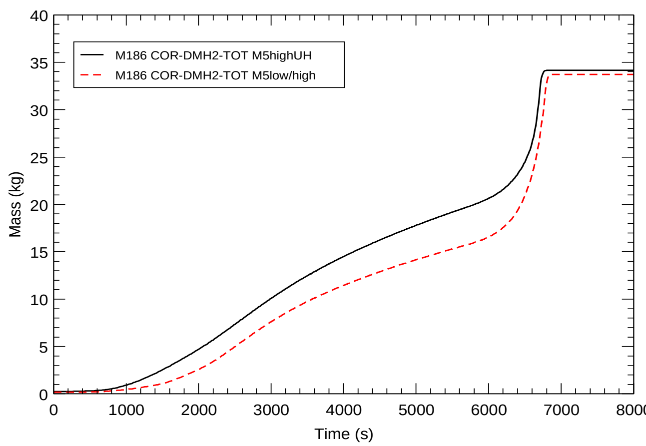

Figure 6: MELCOR 1.8.6 prediction of QUENCH-14 total hydrogen generation, with alternative forms of GM5

Figures 7 and 8 show corresponding results obtained using SCDAP/RELAP5, again with the nominal boundary conditions. Four different oxidation models were used: CP/UH (i.e. MATPRO), CP/PC, GM5 and the MATPRO variant in which reduced kinetics was applied at T < 1300 K. There is no significant effect on the temperature until the high temperature phase shortly before reflood, when the PC correlation predicted a sharp but short-lived excursion which is reflected by the hydrogen generation. The GM5 and MATPRO variant correlations gave almost the same hydrogen generation, and less than the standard MATPRO, consistent with the observation from the MELCOR calculations.

Those cases which included PC were the most conservative of the options used. It was concluded that the planned test conduct would achieve the target conditions during the main part of the experiment transient and would reveal whether the switch from Zry-4 to M5® would promote a more significant excursion during reflood than was observed in QUENCH-06. Although previously untried in QUENCH simulation the GM5/UH correlation was considered as best estimate from the point of view of expected behaviour. Sensitivity calculations using both codes showed that the results are not greatly affected by moderate changes to external resistance and electrical power.

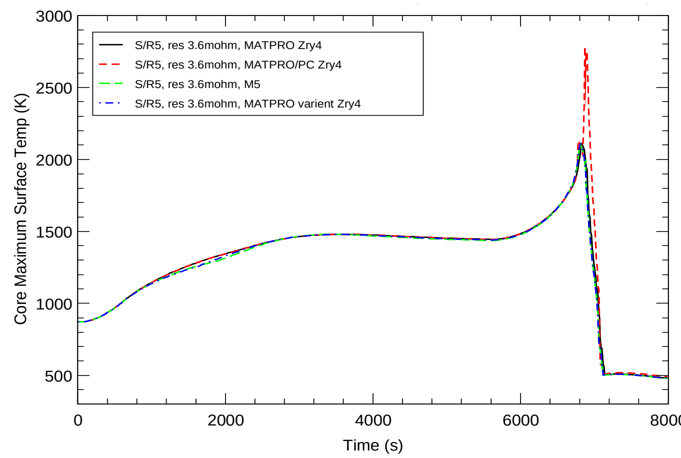

Figure 7: SCDAP/RELAP5 prediction of QUENCH-14 bundle temperature at 950 mm, with alternative oxidation models

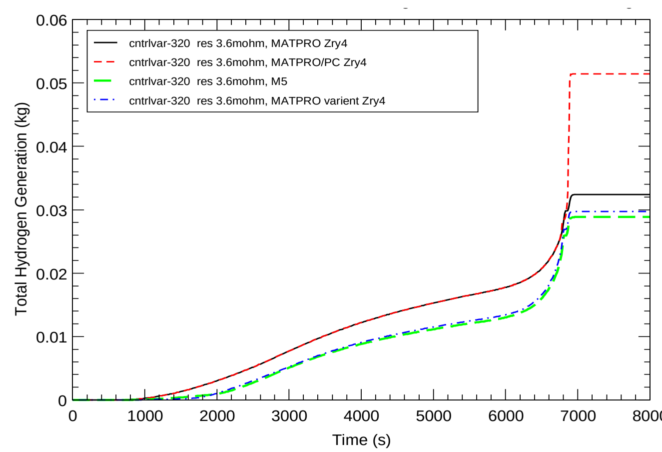

Figure 8: SCDAP/RELAP5 prediction of QUENCH-14 total hydrogen generation, with alternative oxidation models

3.3 Post-test analyses

Post-test calculations were performed with MELCOR 1.8.6 and SCDAP/RELAP5, using the same input models as the pre-test analyses. The experimental boundary conditions for electrical power and inlet flows were used in the base case calculation, imposed as functions of time except that reflood initiation was specified according to the same maximum temperature condition as in the experiment. This was done to provide conditions at the start of reflood as close as possible to the experiment.

In QUENCH-14 the highest temperature was measured on the shroud, and reflood was initiated at 7213 s at which time the temperature at the 950 mm elevation was 2120 K. Since the shroud thermocouples are the most reliable, that location was used for the comparison. Figures 9 and 10 compare the measured temperatures and hydrogen generation with MELCOR using three applications of GM5: low/high, GM5(high)/UH and GM5(high)/PC. In each case the injection was initiated when the peak temperature of 2120 K was reached, which occurred at 7230 (within a few seconds), i.e. only very slightly later than in the experiment.

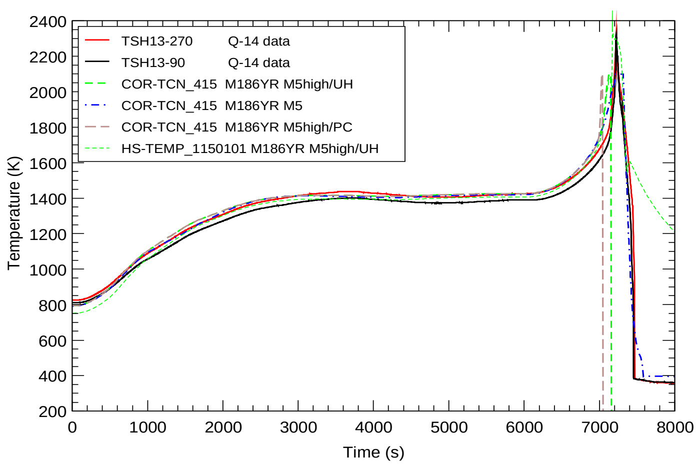

Figure 9: MELCOR 1.8.6 calculation of QUENCH-14 shroud temperature at 950 mm, with alternative forms of GM5

There was remarkably little difference between the calculated temperature histories and also the peak (the structure is assumed to collapse upon melting and no longer participates in the oxidation). Comparison is shown also with the calculated temperature of the ZrO_2 insulation, which shows a continuing increase. The first option gave the best agreement for hydrogen generation, while the other options gave (similar) moderate overestimates, with GM5(high)/PC showing a faster generation rate during the high temperature phase. Despite the difference between the GM5, UH and PC correlations at temperatures above 1850 K, the calculated hydrogen masses generated during the high temperature phase were similar, since the MELCOR model terminates the oxidation locally at ca. 2050 K, when the metallic cladding melts and relocates downward.

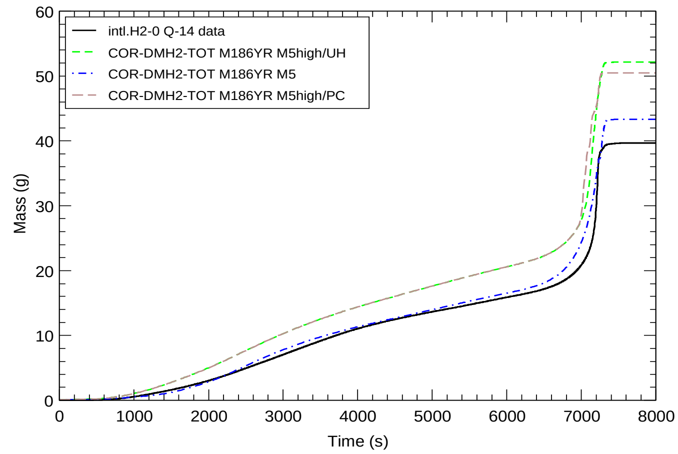

Figure 10: MELCOR 1.8.6 calculation of QUENCH-14 total hydrogen generation, with alternative forms of GM5

Comparisons of the same measured temperatures with SCDAP/RELAP5 are shown in Figure 11. As in the pre-test analyses, alternative oxidation correlations were used, namely GM5(low/high)/UH (indicated as M5sm on the figure), already identified as the best estimate case, and L/PC (indicated as LPCsm). The best estimate case, using GM5(low/high)/UH, generally followed the data closely. Remarkably, and perhaps rather fortuitously, the temperature of 2120 K at which reflood was initiated was reached at the same time in the calculations as in the experiment. Again, there was no strong sensitivity to choice of oxidation model until temperatures exceeded 1800 K, since GM5(high) and L kinetics are similar. However, above 1800 K the PC correlation calculated a strong escalation with the result that the reflood criterion was reached about 50 s earlier.. Unlike MELCOR, SCDAP/RELAP5 calculates continued oxidation until temperatures well above the metallic melting point.

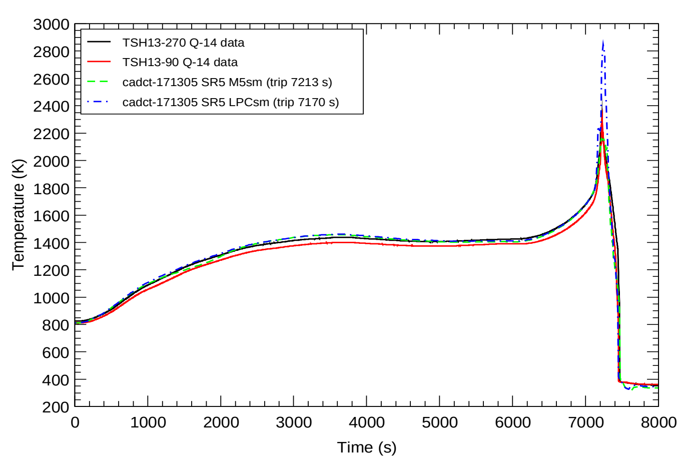

Figure 11: SCDAP/RELAP5 calculation of QUENCH-14 shroud temperature at 950 mm, with alternative oxidation models

The effect can be seen more clearly in Figure 12 which concentrates on the transient and reflood phases, when GM5/UH gave remarkably close agreement with the data. The strong excursion using L/PC was still calculated even though the reflood initiation time brought forward to 7170 s, corresponding to the same temperature of 2120 K as applied in the experiment. A further sensitivity studies on time of reflood initiation did not affect the results. As can be seen from Figure 13, GM5/UH also gave the best agreement for hydrogen generation.

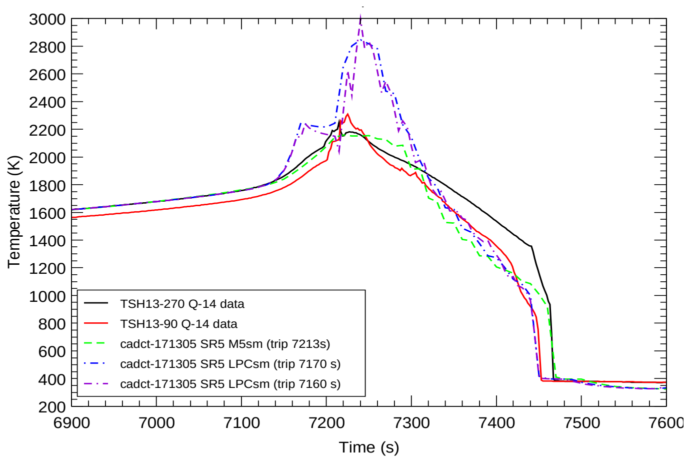

Figure 12: SCDAP/RELAP5 calculation of QUENCH-14 shroud temperature at 950 mm, with alternative oxidation models (reflood)

In summary, the best agreement for the hydrogen generation during the pre-oxidation period was clearly obtained by the GM5(low/high) model, whether used with MELCOR or SCDAP/RELAP5, strongly indicating the effect of slower kinetics in the low temperature regime. Assessment of the models is more complicated during the transient shortly before and just after the start of reflood, because different elevations of the bundle span all three temperature regimes. However, good agreement was obtained during the transient and reflood phases with UH in the high temperature regime. The three regime model of GM5(low/high) and UH provided the best agreement of those used, which was possible to use in a special version of SCDAP/RELAP5. Cases which included PC overestimated both the temperature escalation and hydrogen generation during these phases of the experiment.

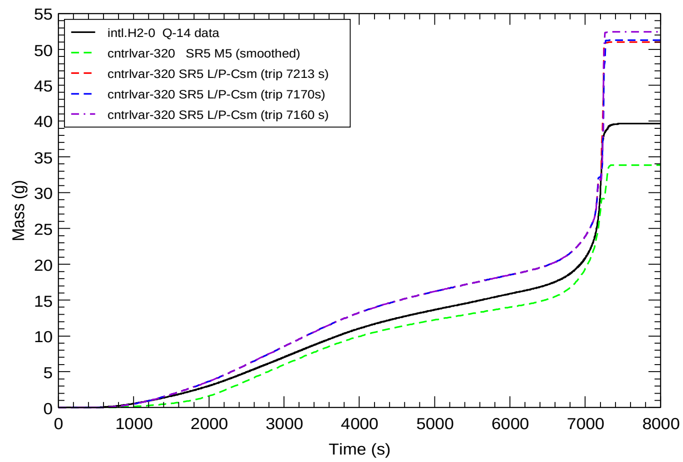

Figure 13: SCDAP/RELAP5 calculation of QUENCH-14 total hydrogen generation, with alternative oxidation models

5. SUMMARY AND CONCLUSIONS

The conduct of QUENCH-14 closely followed QUENCH-06, providing an opportunity to assess oxidation characteristics of M5® in comparison with Zry-4 during the course of a bundle transient spanning a wide temperature range. Immediate consideration of the experimental results suggests at most only a minor difference between the two cladding materials.

This observation is consistent with the fact that the correlation recently obtained by Grosse is similar to the CP correlation which is well established for Zry-4 in the temperature range 1300 – 1800 K.

Input models for MELCOR 1.8.6 and SCDAP/RELAP5 were developed and benchmarked against QUENCH-06 data. A range of oxidation correlations was used in conjunction with both codes, among them the trial correlation for M5® derived by Grosse. The models were used for pre- and post-test analyses.

The post-test analyses confirm the interpretations based on direct comparison between QUENCH-06 and -14. Closer examination reveals that the low temperature branch of the GM5 correlation provides better agreement at temperatures below 1300 K. However, the effect of the low temperature kinetics on the behaviour near the top of the bundle is minor, since the local temperatures were above 1300 K during almost the entire experiment.

The GM5 correlation is highly promising, and continuation of the test programme under a wider range of conditions and for the different cladding materials is most desirable.

Inclusion of a low temperature oxidation model for M5® in the reactor accident analysis codes is strongly recommended, to enable the kinetics to be captured over the whole temperature range of interest. An analogous extension of the MATPRO correlation might be considered for Zry-4 and other claddings, pending further data acquisition and model development.

The above conclusions based on the present work are provisional. QUENCH-14 was the first in the ACM series which is presently ongoing, as are the separate-effects oxidation tests. Further analyses will be performed when the full set of results are available, from which a more complete assessment can be made concerning the effect of different cladding materials on oxidation and quenching.

ACKNOWLEDGMENTS

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