Code Assessment Program for MELCOR1.8.6

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Duration of project	March 21, 2006 to February 21, 2009 (3 years)

ABSTRACT

The MELCOR code developed at Sandia National Laboratories for the USNRC is established in Switzerland as the preferred code for analysis of severe accident transients in light water reactors, from initiating event through to potential release of fission products to the environment. One area of international concern is that of air ingress, either into the reactor core or to spent fuel in a storage pool or transport cask. This can lead to accelerated fuel degradation and enhanced release of fission products, especially the highly radiotoxic ruthenium. Assessment has shown that existing oxidation models do not fully represent all the relevant physical processes, and cannot be guaranteed always to be conservative. So, an improved stand-alone model for Zircaloy-4 oxidation in air has been formulated at PSI, on the basis of FZ Karlsruhe separate-effects experiments, and is reaching the end of its developmental assessment phase. This model captures the essential features of initial parabolic (protective) kinetics, the transition to linear (breakaway) kinetics as the protective effect of the initially formed oxide is progressively lost, and the linear kinetics themselves. The next steps are assessment of the model against independent separate-effects and integral data, and implementation into MELCOR. Extension of the model to advanced cladding materials such as Zirlo™ and M5® cladding could form part of a follow-on contract, as could widening the range to encompass conditions in postulated spent fuel pond accidents, with lower temperatures and possibly flow rates. Such extension would aid use of the code in PSA level 2 applications to this kind of event.

Das MELCOR-Programm, entwickelt von den Sandia National Laboratorys für die USNRC, ist in der Schweiz als das bevorzugte Programm für die Analyse von schweren Unfällen vom einleitenden Ereignis bis zur Freisetzung von Spaltprodukten in die Umgebung anerkannt. Ein Gebiet von internationalem Interesse ist das Thema des Lufteinbruchs entweder in den Reaktorkern während der Spätphase eines schweren Unfalles im Normalbetrieb, in den Reaktordruckbehälter während der Wartungsphase bei geöffnetem Druckbehälterdeckel, bei den abgebrannten Brennelementen im Speicherbecken oder im Transportbehälter. Dieser Lufteinbruch kann zu einer beschleunigten Kernzerstörung und einer erhöhten Freisetzung von Spaltprodukten führen, speziell von stark radiotoxischem Ruthenium. Verifizierungen von Programm-Modellen zur Oxidation von Zirkaloy haben gezeigt, dass der momentane Stand der Programme nicht alle relevanten physikalischen Prozesse zur Zufriedenheit beschreibt und deshalb die Konservativität der Ergebnisse nicht unter allen Umständen garantiert werden kann. Am PSI wurde deshalb ein Modell entwickelt, welches die Oxidation von Zirkaloy-4 an Luft beschreibt, basierend auf Experimenten des FZ Karlsruhe. Dieses Modell befindet sich in der abschliessenden Verifizierungsphase. Das Modell beinhaltet die wichtigen Gesichtspunkte der anfänglich parabolischen Reaktionskinetik (Schutz durch Oxidschicht), den Übergang zur linearen Kinetik (Bruch der Oxidschicht) bis hin zur linearen Kinetik nach dem Verlust der schützenden Oxidschicht. Die nächsten Schritte sind die Verifizierung des Modells mit Daten aus Seperat Effekt Tests und integralen Experimenten sowie der Einbau in das Programm MELCOR. Erweiterung des Modells zur Berücksichtigung von neu entwickelten Hüllrohr-Materialien wie Zirlo™ und M5® könnten in einen späteren Kontrakt einfliessen. Auch die Erweiterung des Modells auf die Bedingungen eines Unfalls im Speicherbecken mit niedrigeren Temperaturen und niedrigeren Flussraten kann später vorgenommen werden. Diese Erweiterungen würden das Programm MELCOR für PSA Level 2 Studien für diese Art der Unfälle ertüchtigen.

Project Goals

The safety impacts of air ingress on nuclear fuel elements at high temperature have been studied for many years, in situations such as those in-vessel following hot-leg failure in a PWR severe accident with subsequent failure of the reactor pressure vessel (RPV) lower head [1], in-vessel in shutdown conditions with the lower head removed [1] and with loss of residual heat removal, and in spent fuel ponds after accidental loss of coolant water [2], [3], [4]. The presence of air can lead to accelerated oxidation of the Zircaloy cladding compared with that in steam, owing to the faster kinetics, while the 85% higher heat of reaction drives this process further. Air ingress is typically associated with poor heat transfer; the combined effect of these factors can give rise to an in creased rate of core degradation. Furthermore, the exposure of uranium dioxide to air at elevated temperatures can lead to increased release of some fission products, notably the highly-radiotoxic ruthenium [5], [6]. The situation is kept under continual review, with experimental and modelling studies performed, notably within the European Union 6th Framework SARNET project [7], [8] in which PSI participated until its end in September 2008, and the ongoing International Source Term Programme (ISTP) [9], [10], in which PSI also takes part.

The MELCOR code is the major tool in use in Switzerland for analysis of severe accidents in light water reactors, from initiating events through to potential release of radionuclide fission products to the environment. Version 1.8.5 [11] is still the main production code, while version 1.8.6 [12] is under assessment and development at PSI. MELCOR is supported by SCDAP-based codes (SCDAP/RELAP5/MOD3.2 [13] and SCDAPSIM/MOD3.4 [14]), for more detailed analysis of thermal hydraulics in the vessel and primary circuit, and treatment of core degradation phenomena. The modelling of air ingress in MELCOR is not sufficient to capture all aspects of the associated phenomena; in particular the accelerated oxidation of the Zircaloy cladding that can occur under air conditions. Therefore, the current three-year project aims finally to develop and validate an improved Zircaloy/air oxidation model for the code. In the first year, relevant data were collected and reviewed, while in the second year the review was updated, the status of modelling in other codes was assessed, and an outline of the proposed model has been formulated. In the third year, detailed model development and testing has taken place, coupled with continual review of experimental data and modelling/code assessment activities elsewhere. The end result will lead to improved predictability of core degradation and fission product release under air ingress conditions, for Zircaloy-clad fuel in light water reactors.

Work Carried Out and Results Obtained

This section is divided into two parts; the first reviews the state of knowledge concerning boundary conditions, experimental results, and air oxidation models in other codes, concentrating on new material in the year since the previous progress report [15]. The second describes development of a new model by PSI that is consistent with the requirements of MELCOR, including model description, development, results of preliminary assessment, and current status. An indication is given of further work that could be carried out including assessment against independent separate-effects data and integral data, and a possible generalisation of the model to advanced cladding materials such as Zirlo^{TM} and M5^{TM}, that commonly feature in current new build.

Review of state of knowledge

This section describes advances in the state of knowledge since the previous progress report.

Boundary Conditions

The boundary conditions for the experimental and modelling work, derived from new plant studies and review of earlier work, were summarised in a paper to the ERMSAR2007 meeting, which has since been published in the open literature [16]; this represents the final status of this topic. Within the SARNET project, which finished in September 2008, there has been considerable progress both experimentally and theoretically in understanding the release from the fuel and transport in the circuit of ruthenium under conditions relevant to air ingress accidents, as summarised in a paper to ERMSAR2008 [17]. It has been demonstrated that conditions favourable to ruthenium release in-core can be experienced in air ingress events, that the ruthenium can be transported in the circuit to the containment, and that volatile ruthenium species can persist in the containment for long enough to be released to the environment in the event of containment failure. Models have been improved or newly developed for these processes, centred on the ASTEC code [18], and this work is expected to come to final fruition in a follow-up project SARNET2, for which a start is envisaged early in 2009, for a proposed 4 years.

Experimental Activities

The last formal review of activities in the experimental area, as presented in ERMSAR2007 [19], was summarised in last year's progress report. Since then, there has been a period of consolidation, with work at the various institutes concerned being summarised and published. The new developments are listed below; a new experimental focus has been on the oxidation of advanced cladding alloys such as Duplex-D4 (Areva), Zirlo™ (Westinghouse) and M5® (Areva), as well as on the Russian Zr1%Nb binary alloy E110, in comparison with Zircaloy-4. It is noteworthy that investigation of the advanced cladding materials under reflooding conditions in an integral geometry has started in the QUENCH programme [20], with one test, QUENCH-14 [21], already performed using Zirlo™, two more are planned using M5® and Duplex material respectively. PSI is assisting with calculational support [22].

Forschungszentrum Karlsruhe tests, Germany

FZK have investigated in detail the oxidation behaviour of the advanced cladding alloys mentioned above, in steam, oxygen and air, in comparison with the extensive database publically available for Zircaloy-4. The most recent results in steam were presented at the last QUENCH Workshop [23], following publication of the results of the tests in oxygen [24], while an overall picture was given at the TOPSAFE2008 meeting [25]. The oxidation of Zr alloys with only slightly different composition (see Table 1) is quite complex with strong differences up to 1000 °C, with less but sometimes significant differences at higher temperatures. A summary of results is presented in Figure 1.

The kinetics are mainly determined by the oxide scale (breakaway, crystallographic phase, degree of substoichiometry etc.). The review paper concentrates on behaviour in steam, while noting previous conclusions concerning air; the strong importance of the breakaway effect, the significant effect of nitrogen on clad oxidation and degradation under severe accident conditions

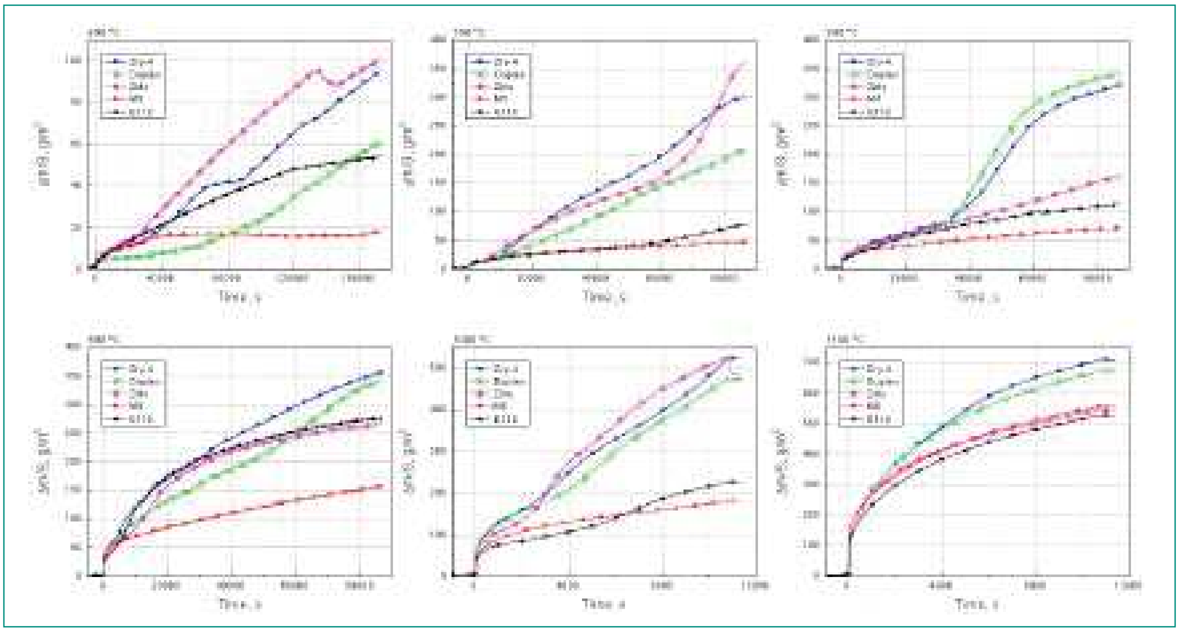

Fig. 1: *FZK experimental data on comparative oxidation of Zr-alloys in steam [23].*

Alloy	Sn	Nb	Fe	Cr	O
E110	<0.04	1.00	<0.01	<0.003	0.05
D4	0.59	0.0001	0.5	0.20	0.14
M5	<0.03	1.00	0.34	0.04	0.14
Zry-4	1.50	0.0001	0.21	0.10	0.14

Table 1: *Chemical composition of Zr-based cladding alloys, (Zr-balance) [25].*

(though oxide formation is thermodynamically favoured), stated to be due to the role of nitride phases that are formed under oxygen starvation conditions. The linear time dependence is associated with the formation of a very porous oxide scale mixed with zirconium nitride formed at positions where (local) oxygen starvation occurs and sub-stoichiometric oxides are formed.

IRSN MOZART tests, Cadarache, France

The current campaign of separate-effects tests in MOZART is essentially complete, with the final activity being an account of the comparative behaviour of Zircaloy-4 and M5® oxidation in air [26]. Oxidation in air for the two alloys was studied thermogravimetrically in the temperature range 600 – 1200 °C for as-received material and with material pre-oxidised at 500 °C to simulate in-reactor corrosion. The importance of the breakaway effect is highlighted, and the scale thickness at breakaway has been determined in isothermal conditions as a function of temperature. Acceleration of oxidation after breakaway is seen particularly at 800 °C and above. The role of nitride formation is also emphasised, along with the formation of highly-cracked, porous non-protective oxide. Nitriding can even be favoured by pre-oxidation. The data were obtained in high air flow conditions; the authors note that in oxygen-starved conditions, such as may occur in some accident situations, degradation may be even faster because of earlier initiation of nitriding. Therefore, new experiments involving nitrogen-rich atmospheres and air and steam atmospheres are recommended, with tests under temperature transient conditions also.

PARAMETER tests, Luch, Russia

The PARAMETER facility [27] operated under the auspices of the International Science and Technology Centre (ISTC) incorporates a 19-rod electrically-heated bundle of VVER-1000 dimensions, materials (cladding E110, Zr1%Nb) and geometry. The overall capability is similar to that of QUENCH [20], but with top as well as bottom flooding, while the rods have a heated length of 1.275 m compared with 1 m in QUENCH. Three tests have been carried out with one more planned; the fourth, SF4, scheduled for 2009, is planned as an air ingress experiment similar to QUENCH-10 [28], with pre-oxidation in steam at 1200-1300 °C to an extent to be decided, followed by cooling to 900 °C, then an air ingress phase with maximum temperatures envisaged of 1800 °C, with bottom reflooding (previously envisaged top reflooding). The detailed test conditions are being determined by a cooperative series of pre-test calculations, which PSI leads (firstly under the auspices of SARNET, this is expected to continue formally in SARNET2). This experiment will enable models for air oxidation for the E110 cladding to be assessed under integral conditions.

Model development and assessment in other codes

The status of model development was recently summarised in a paper to ERMSAR2008 [29]. The codes differ in the level of detail, corresponding with their overall philosophy. All the codes consider breakaway effects.

ATHLET-CD

As summarised in [29], the ATHLET-CD code [30] includes a selection of eight empirical correlations to simulate parabolic kinetics; at a user-defined oxide thickness (default 0.25 mm) a transfer to linear kinetics is made, by disregarding any further increase in oxide mass in the rate equation. In a steam-air mixture, reaction of Zircaloy with oxygen is preferred. Steam starvation is treated by a correlational approach. The model was assessed against QUENCH-10 and CODEX-AIT data as summarised in [15]. The treatment has since been enhanced [31] at Ruhr-University Bochum by inclusion of a nitriding model based on FZK separate-effects data [32], considering both parabolic and linear regimes. There has been some success in reproducing the observed trends, while the need for improvements is recognised, with further analysis of the processes occurring in the oxide layer. This development continues, with assessment against QUENCH-10 [28] and the AEKI experiment CODEX-AIT1 [33] foreseen; testing against QUENCH-10 is reported in [29].

ICARE/CATHARE

This code [34] is the most detailed of those considered here, and the treatment of air oxidation (first described in [35], since updated) reflects this, at least as concerns the modelling of breakaway. A selection of parabolic correlations is available, as for the other two codes considered here. Oxygen starvation, formation of nitride in the case of total oxygen starvation, and simulation of breakaway effects are considered. The breakaway modelling notes that conclusion from MOZART that the transition occurs for a critical value of weight gain that is strongly temperature dependent; it is supported by the assumption that it is linked to the transformation from monoclinic to tetragonal zirconia. A hyperbolic correla-

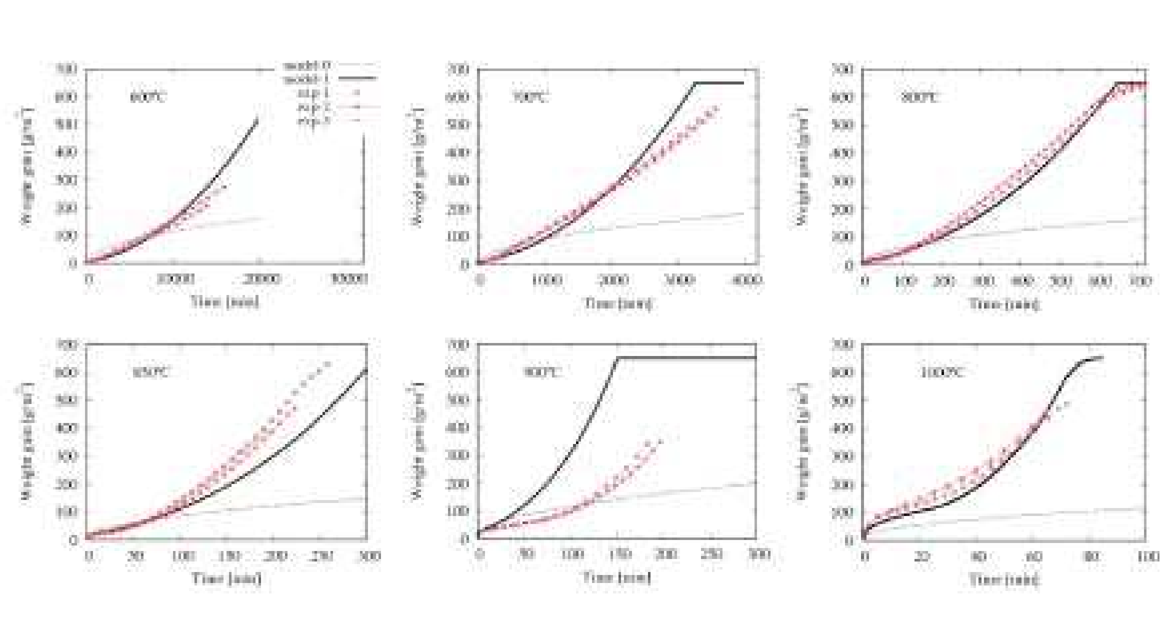

Fig. 2: *Comparison of ICARE/CATHARE calculations with MOZART data [29] (model-0 refers to original model with only parabolic kinetics, model-1 refers to the improved model that takes into account breakaway, exp-1,-2-3, refer to experimental data).*

tion is used for the transition model, fitted to MOZART data. After the transition, a linear kinetics correlation is applied. The model shows good agreement with MOZART data, see Figure 2, at 600-700, 800-850, and 1000 °C, while under-estimating the time to reach complete oxidation at 900 °C, due to the transition being calculated too early compared with the data; after that the oxidation rates were comparable.

MAAP4

The treatment in MAAP4 [36] follows the code's philosophy of fast-running, simplified modelling in keeping with PSA level 2 studies. Eight parabolic correlations are used, as in ATHLET-CD, with the breakaway being modelled by a parameterised temperature criterion, defined on the phase transformation of zirconia at 1447 K, or by a criterion based on weight gain, specified by IRSN on the basis of MOZART experiments. Linear or parabolic behaviour may be selected for the post-transition behaviour. If both steam and oxygen are present, the oxidation uses the majority component and nitriding is not considered for now (planned later). Testing against QUENCH-10 data is reported in [29] and also at the 2008 QUENCH Workshop [37]. The maximum clad temperatures were undercalculated in the air phase. It was concluded that more needed to be done concerning modelling of the breakaway.

Model development for MELCOR1.8.6

This section describes the work performed on model development and testing during the past year.

Model development and testing strategy

Data are available in summary form in the documents referenced in last year's report [15], or provided by IRSN (MOZART), and in detail by FZK (thermal-balance and BOX rigs). The FZK detailed thermal-balance data [32] are particularly suitable for model development since they comprise temporally resolved evolutions of the mass gain of the samples under a large number of test conditions temperature, oxidising gas flow and composition, in addition to details of the rig operation. The strategy adopted was as follows:

1. construct and code a model along the lines described above, using the detailed thermal-balance data from FZK to determine suitable values for the parameters in the model;
2. perform developmental testing and update the model parameter values as necessary to obtain optimally consistent agreement with the test data;
3. perform verification studies using independent set of experimental data;
4. implement the model in MELCOR, with the assistance of the code's development team at Sandia National laboratories.

Outline description of air oxidation model

The essential features of the model are as described in the previous progress report [15]. Classically, parabolic kinetics represent the protective effect of a growing oxide layer.

The air oxidation model is derived by first rewriting the parabolic kinetic rate as:

$d(M)/dt = K\delta$ (1)

where M is the mass gain by oxidation and it is assumed that the oxide thickness, δ, is bounded by a maximum, δ^* whose value depends primarily on the temperature and the oxidising medium, but also perhaps on the cladding alloy composition and the past oxidation history of the cladding. The model is formulated in such a way to accommodate these dependencies, according to need.

The data also show a pre-transition mode which appears to operate at oxide scales below some critical value. It is conjectured that the oxide scale loses its coherence when this critical value, δ^{cr} say, is reached and becomes progressively degraded until only a thin residual layer of coherent oxide remains, whose thickness is identified as δ^*. An effective value, $\delta^{*,eff}$ say, is applied to represent the progressive degradation of the oxide scale. A strong mechanism for breakaway oxidation in air is the local conversion from oxide to nitride, which is much denser and therefore leaves gaps on the oxide-nitride scale.

Experimental data from numerous sources show that although transition to breakaway oxidation occurs in air at all temperatures, it can also occur in steam in the temperature regime below the monoclinic-tetragonal phase transition, i.e. up to about 1000 °C for Zircaloy-4. Although the physical mechanisms for breakaway may be different, the end effect is qualitatively similar. Separate values of δ^{cr} and δ^* are defined for steam and air. In fact, while data show clearly that the oxidation rates in steam and oxygen are not greatly different; the presence of nitrogen has the major influence in promoting breakaway oxidation. The values of δ^{cr} and δ^* are applied in the absence or presence of nitrogen. Typically, large values of δ^{cr} and δ^* are adopted for steam at temperatures of 1100 °C and above.

A further complication is that pre-oxidation of the cladding in steam can modify the transition to breakaway oxidation when the cladding is exposed to air (or strictly, a nitrogen-bearing mixture). At temperatures above the monoclinic-tetragonal phase transition, pre-oxidation in steam delays or may even prevent transition to breakaway, effectively maintaining a robust scale of protective oxide. At lower temperatures pre-oxidation in steam can delay the breakaway under some conditions, but appears to provide little or no protection against breakaway in other conditions. The reasons for these contrasting trends are not yet fully understood.

Development of the new air oxidation model

The model described above was coded and tested against data from the FZK thermal-balance tests. The tests were conducted under isothermal conditions at 800, 1000, 1200 and 1400 °C and with a variety of gas compositions: air+argon, oxygen+argon, nitrogen+argon, oxygen+argon followed by air+argon. It was necessary to incorporate control logic into the model to accommodate the different compositions and also the change from one composition to another.

The starting point for the air oxidation model is the Hofmann-Uetsuka correlation for oxidation in oxygen, based on the MONA tests at FZK [38]. In fact the oxygen correlation differs only slightly from the Leistikow [39] and Cathcart-Pawel [40] correlations for steam oxidation. The correlation was introduced and compared with the test data at 1000 °C, as shown in Figure 3. Since the correlation was based on those same data the agreement merely confirms that the correlation had been derived and implemented correctly. As might be expected, comparison with the result from a test in air at 1200 °C, Figure 4, shows an underestimate of the total oxidation. However, the discrepancy is much reduced when the air oxidation occurs after a period of pre-oxidation in steam. The Hofmann-Uetsuka parabolic correlation [38] was therefore chosen as the pre-transition from of the air oxidation model. Since oxidation during reactor air-ingress or spent fuel pond accidents are likely to involve exposure to steam alone and steam-air mixtures, standard correlations for steam oxidation (Leistikow [39], Cathcart-Pawel [40] and Urbanic-Heidrick [41]) are included also.

There are three important and specific components of the air oxidation model. (1) Logic is included which dictates that oxidation in oxygen, if present, always takes precedence over steam. (2) Trial values for δ^{cr} and δ^* were specified as functions of temperature for both nitrogen present or absent – these values were refined in the course of the testing. (3) A «breakaway flag» (ibr) was defined to indicate the presence or absence of nitrogen and if the transition to breakaway had occurred. For convenience, we refer to the model as «Hofmann-Birchley» to indicate the original basis for the correlation and the present modifications to take account of breakaway transition. These modifications are applied analogously to both air and steam as oxidising medium.

Results of assessment against isothermal test data

Figure 5 compares calculated results with data from four tests performed at 800 °C in the thermal-balance rig, comprising oxygen alone, air alone and different periods of pre-oxidation in oxygen followed by air. The accelerated oxidation rate due to transition to breakaway is apparent in each case involving air, and with clear establishment of linear kinetics after a delay which depends strongly on the time period of pre-oxidation. There is a slight acceleration of the kinetics in oxygen. The trends and magnitudes are very well captured by the model.

The agreement between model and experiment is not as good at the higher temperatures. Indeed, close inspection of the data reveals a significant scattering and a much less clear trend. The higher temperature oxidation is subject to a number of factors which may enhance or reduce the observed oxidation rate and which effectively introduce «noise» into the results. For example, the oxidation heat is known to increase the temperature locally, above the nominal temperature of the tests. Oxygen starvation can limit the oxidation rate but, in the presence of nitrogen, can also promote nitride formation and hence breakaway. Figure 6 shows comparison between data for air oxidation at 1400 °C and several alternative models. Although the model under present development gives the best agreement for this case, the good agreement does not extend to all of the higher temperature tests.

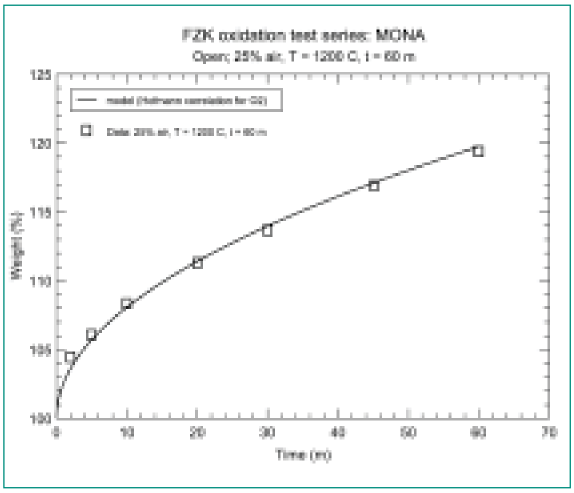

Fig. 3: *Comparison of PSI model with FZK data test in 25% O2/75% Ar mixture at 1000 °C.*

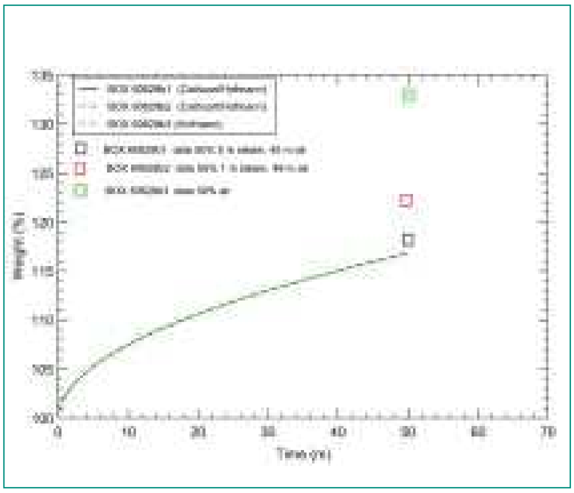

Fig. 4: *Comparison of PSI model with FZK BOX test in air and steam then air at 1200 °C.*

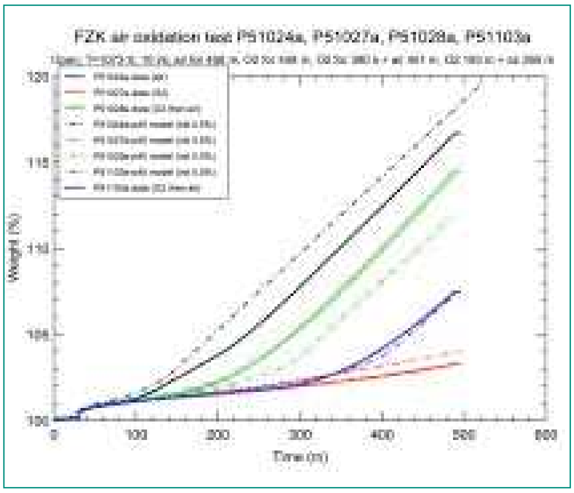

Fig. 5: *Comparison of PSI model with FZK thermal balance tests in O2 and air (T = 800 °C).*

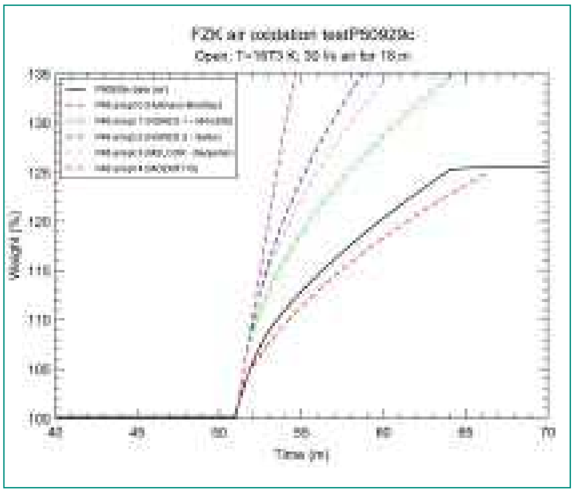

Fig. 6: *Comparison of PSI model with FZK thermal balance tests in O2 and air (T = 800 °C).*

First results of assessment against transient data

The bulk of developmental assessment has been performed using isothermal test data. Oxide formed at temperatures below 1000 °C has a different microstructure from oxide formed above 1000 °C, and might not provide the same protective effect. Transient thermal conditions may therefore be expected to modify the transition to breakaway, although it is not known to what extent or even in which direction. For the present, the (time-varying) values of δ^{cr} and δ^* derived from analyses of isothermal tests are applied. A first scoping calculation has been performed for the conditions of experiment QUENCH-10, with the local temperature history provided as boundary condition. Figure 7 shows the calculated build-up of oxide at the hottest location (950 mm elevation in the bundle), with and without including breakaway compared with the final experimental value obtained from post-test examinations. A qualitative comparison of the oxidation history can be deduced from the shape of the overall bundle oxidation. It should be remembered, however, that the overall bundle oxidation is not in exact proportion to the local oxidation but is only an indication.

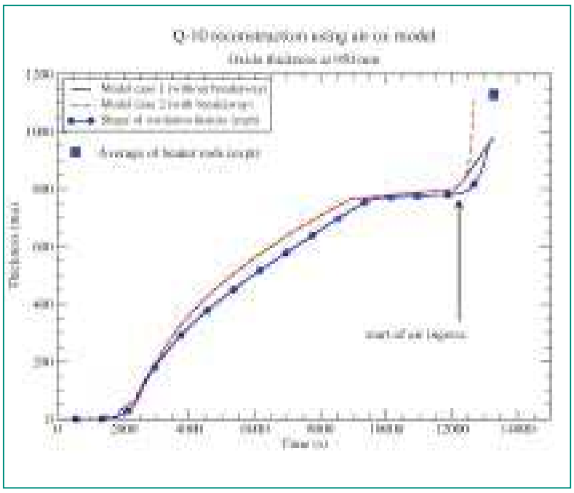

Fig. 7: *Reconstruction of QUENCH-10 oxide layer growth at 950 mm bundle elevation.*

Current status

The developmental testing is near completion. The next step will be to increase confidence in the model by assessment against independent data from other sources, chiefly IRSN MOZART tests. Implementation into MELCOR is planned; this will depend on detailed cooperation with the USNRC and Sandia National Labs. The implementation would be into the latest development version, (the current official release is version 2.1, as version 1.8.6 has been frozen since the present contract started). The model then could be tested against QUENCH-10 for a full assessment of the model in an integral setting, which would give confidence in applying it to reactor transients.

Potential model extensions

The separate-effects tests performed at FZK and IRSN show a dependence on cladding type of oxidation in steam, oxygen and air. There is therefore a need to extend the model to Zirlo^{TM} and M5® cladding, as these are could feature in reload fuel in existing plant, and very likely in new build in Switzerland. Extension to E110 cladding would make use of Russian data feasible, especially from the PARAMETER SF4 experiment that will extend the integral test database. There is also potential application to spent fuel pond accidents, where the air ingress is typically at lower temperatures than the in-vessel case, and where flow conditions will be different (lower flows can lead to more nitriding and earlier breakaway). In addition, more difference amongst cladding types is seen at lower temperatures, as evidenced by the FZK and IRSN data referenced above, and also by the Argonne experiments [42] , which were targeted at spent fuel pond conditions. Such extensions, with implementation into MELCOR, would help assure high quality PSA results and help formulate prevention and mitigation strategies for spent fuel pond events.

National Cooperation

This project does not involve cooperation with other Swiss projects.

International Cooperation

Cooperation with organisations within European countries and Canada generally is performed under the auspices of the SARNET [8], this Network of Excellence under the EU 6th Framework programme finished at the end of September 2008 after 4½ years of operation. A proposal for a 7th Framework follow-on project, SARNET2, has been accepted by the EU and is expected to start early in 2009 for another 4 years. The provisions of SARNET allowed access to the data from the Institute of Nuclear Research Pitesti, Romania (referenced in previous reports), and Forschungszentrum Karlsruhe, Germany. Access to data from the MOZART programme of separate-effects tests at IRSN Cadarache, France, is obtained through PSI membership of the International Source Term Programme (IRSN-PSI contract dated 28.3.2006). Access to the ISTC programme is available by contract between PSI and ISTC on a project-by-project basis. The MELCOR code and early access to the results of USNRC programmes is obtained under the Cooperative Severe Accidents Research Programme Agreement (CSARP) between HSK and USNRC, and close contact is kept with the MELCOR developers at Sandia National Laboratories (SNL) regarding code maintenance, development and use. PSI obtains the SCDAPSIM code, maintenance and user support via a licence agreement with Innovative Software Services (ISS), Idaho Falls, USA. SCDAPSIM is a derivative of SCDAP/RELAP5 formerly supported by the USNRC.

Assessment 2008 and Perspectives for 2009

The project has continued to make good progress, keeping up-to-date with relevant experimental work and modelling developments elsewhere, and taking advantage of the cooperative opportunities offered within SARNET, ISTC, CSARP and elsewhere. A leading position has been secured in defining the conditions for the ISTC PARAMETER SF4 air ingress test with reflooding, aimed at providing additional integral data to help assess air oxidation models; this has involved considerable effort in building up an analysis capability including checking the facility model against the results of earlier experiments in the series. However, interpretation of the results of the separate-effects experiments on which the new PSI model is based, especially concerning the breakaway (including the gradual transition from parabolic to linear kinetics as the protective effect of pre-oxidation is gradually lost, a unique feature of the PSI treatment), has been more difficult than expected. While the qualitative mechanism seems fairly clear, translating this into a reliable quantitative form is harder, particularly as stochastic effects seem to play a part. So, the model has not been fully assessed and therefore not considered ready for implementation yet into a system-level code. This could be done in a follow-on study.

Concerning implementation into MELCOR, USNRC have indicated [43] that MELCOR1.8.6 is frozen, while version 2.1 is the current release; indeed the current development version is stated to be MELCOR3. Implementation of a new PSI model would require active cooperation with the USNRC and Sandia National Laboratories to decide on division of the work, access to such source code as may be appropriate, interfacing with other code modules, testing, documentation, quality assurance and other matters. Thus some negotiation will be needed for implementation to proceed.

Publications

PSI participated in papers to the SARNET ERMSAR-2008 meeting concerning modelling of air oxidation of Zircaloy [29], and also in a more general paper on ruthenium release and transport [16] that drew on the clad oxidation work. A detailed contribution was also made to the SARNET final report on corium matters (November 2008), which is not yet publically available.

Nomenclature

AEKI	Atomergia Kutatotintezet
CSARP	Cooperative Severe Accident Research Programme
EdF	Electricité de France
ERMSAR	European Review Meeting on Severe Accident Research
EU	European Union
FZK	Forschungszentrum Karlsruhe
GRS	Gesellschaft für Anlagen und Reaktorsicherheit
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
ISS	Innovative Software Services
ISTC	International Science and Technology Centre
ISTP	International Source Term Programme
PSI	Paul Scherrer Institute
PWR	Pressurised Water Reactor
SARNET	Severe Accident Research Network
USNRC	United States Nuclear Regulatory Commission
VVER	Vodo-Vodyanoi Energetichesky Reactor (PWR of Russian type)

Acknowledgements

The authors gratefully acknowledge M. Steinbrück of Forschungszentrum Karlsruhe (FZK), Germany; Ch. Duriez and O. Coindreau of the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) Cadarache, France, for providing valuable information on the status of their experimental programmes on air ingress and modelling work, and for giving permission for their illustrations to be used in this report.

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