

Progress on B₄C modelling in Severe Accident Codes in the frame of SARNET network of excellence Applications to Phebus and Quench experiments

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Summary

Boron carbide is used in many designs of nuclear power plants like BWR, VVER, some PWR, and EPR as a neutron absorber material. It is important, therefore, to assess its effects on the main core degradation phenomena, as well as the gas release, and the impact on the fission products behaviour during severe accidents. This paper is focused on the progress on the B₄C control rod modelling in Severe Accident codes (SA), like ATHLET-CD, ICARE2, ASTEC MELCOR and MAAP, performed in the frame of the Network of Excellence SARNET during the five year activity of the Work Package 9.2, following on from the previous European Union 5th Framework COLOSS project.

Starting from basic modelling derived from available tests reported in literature, large improvements of the correlation for B₄C oxidation were gained from analytical experiments performed at FzK (Germany) and IRSN (France), mainly at higher temperature.

The modelling has been applied to the analysis of experiments involving a B₄C control rod in a small fuel rod assembly, such as Phebus FPT3 in pile experiment, as well as out of pile experiments Quench 07 and 09, aimed at studying the course of severe accidents. Regarding the hydrogen generation, the results given by different code simulations are consistent with the experimental values. Concerning the control rod, SA codes such as ICARE2 and ATHLET-CD, using suitable modelling for B₄C oxidation, predicted rather well the total carbon release. The results of the MELCOR code using at the beginning of the project a B₄C oxidation model designed for use in BWR control blades have been largely improved using the most recently released version 1.8.6, which includes a model extended for PWR B₄C control rods.

There are still some difficulties to reproduce the final degradation of the bundle. Effects of spreading molten materials of the control rods towards fuel rods of the bundle are suspected, meaning that the main effect of the B₄C control rod on the bundle behaviour is connected with B₄C-SS eutectics formation and liquid B₄C-SS-Zry relocation. These phenomena are not accounted for in the SA codes. The need for further code developments of the early phase of core degradation is recognized for the absorber rod material behaviour. The BECARRE experiments, in the framework of the International Source Term Program should help provide in-depth understanding of phenomena and improve the modelling.

A. INTRODUCTION

Boron carbide (B₄C) is used as absorber material in Western (BWRs, some PWRs, EPR) and Russian (VVER) nuclear power plants. During a hypothetical severe accident B₄C material from the control rod can react with steam in the reactor core and produce additional source of hydrogen besides Zircaloy oxidation. Furthermore, gaseous carbon and boron containing species are formed, which may affect the fission product chemistry in the containment.

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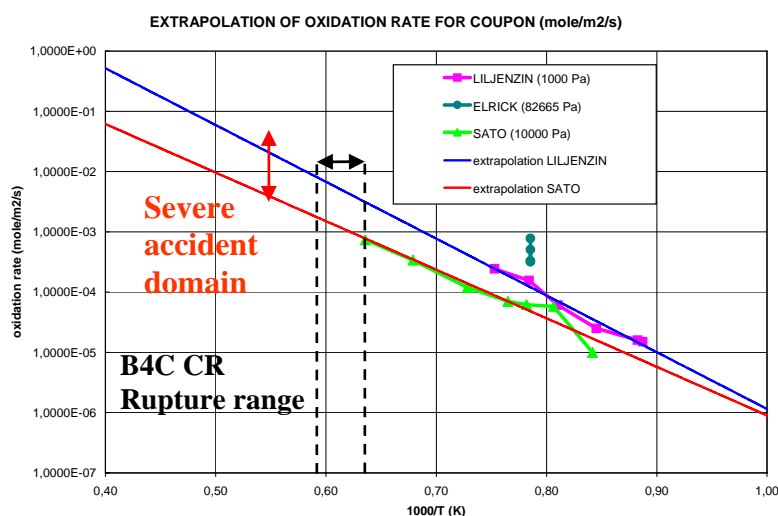
Before the COLOSS and the following SARNET projects, experimental database on the phenomenon was very limited especially at high temperatures ($T \geq 1273$ K). Only a few data sets were available on the oxidation kinetics of boron carbide, most of them have been obtained at temperatures less than 1273K (Litz, 1963 [1] for powders); Elrick et al., 1987 [2]; Liljenzin et al., 1990 [3] and up to temperatures of 1573 K for published results on the oxidation of hot-pressed B₄C pellets Sato et al. (1988 [4]). Temperatures interesting severe Accident transients regarding B₄C oxidation were above 1600-1800 K (Fig. 1) after the failure of the stainless steel control rod tube and the Zircaloy guide tube.

To get complementary data, a program [5] in the VERDI furnace, has been initiated by the IRSN in the framework of the COLOSS project under the EU 5th Framework Programme on Nuclear Fission Safety (contract number FIKS-CT-1999-00002). This issue was not selected in EURSAFE, but the conclusions of the COLOSS project and the foreseen interpretation of Phebus FPT3 test showed needs of improvements of understanding and modelling of B₄C impact on core degradation. This program as BECARRE (part I) continued in the frame of the International Source Term programme jointly carried out by IRSN, CEA and EDF, with European and US-NRC contributions. Other tests were performed by FzK (Germany) in the BÖX [6] and TG [7] facility in parallel to the Bundle-Quench Program within the COLOSS project (2000-2003) [8].

The sections below are focused on the progress on the B₄C control rod modelling in Severe Accident codes, like ATHLET-CD, ICARE2, ASTEC, MELCOR and MAAP performed in the frame of the Network of Excellence SARNET during the five year (2004-2008) activity of the Work Package 9.2 and their applications to Quench and Phebus experiments.

B. PROGRESS IN B₄C MODELLING DURING THE COLOSS AND SARNET PROJECTS

The need for B₄C modelling in ICARE2 raised in the frame of the preparation of the Phebus FPT3 experiment in 1999. At that time, as introduced before, the only available data were those of Elrick, Liljenzin and Sato, for temperature below 1573K. The extrapolation of those oxidation rates at higher temperature was found to introduce too large uncertainties up to factors of 8 to 10 (figure 1). So, additional experiments were launched by IRSN and FzK. Nevertheless, it was decided to start modelling activity for ICARE2. At that time (in 2000 for the first Phebus FPT3 test protocol), the Liljenzin correlation (table 1 –line 1) was chosen.



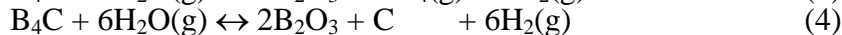
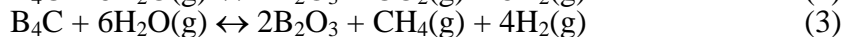
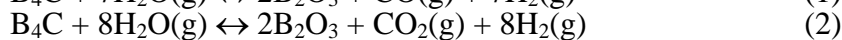
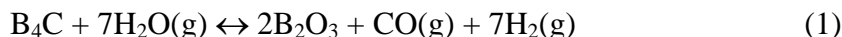
Analysing those available results (Fig. 1) in more details, it was shown a dependence of the kinetics as function of partial steam and total pressure. A simplified model was developed in ICARE2 code in 2001 ([9]), following an Arrhenius form with the below formula for the kinetic:

$$k = k_0 e^{\frac{-E_a}{RT}} P_{H_2O}^\alpha P_{Tot}^\beta$$

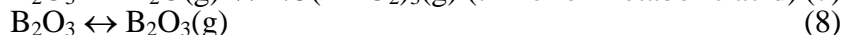
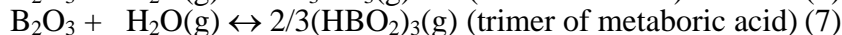
Figure 1: B₄C Oxidation kinetics (mole/m2/s) available before 1990

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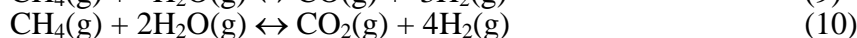
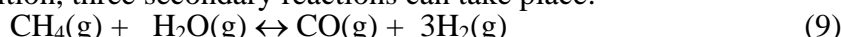
The various chemical reactions involved in the B₄C oxidation by steam are described by the following reactions:



The resulting boric oxide can react with steam to form boric acid or it can be vaporized:



In addition, three secondary reactions can take place:



The oxidation of a solid B₄C pellet results in the formation of liquid boron oxide (B₂O₃), of gaseous carbon species and hydrogen. At high temperatures, the liquid boron oxide directly evaporates or reacts with steam to form volatile boric acids. The kinetics depend on the B₂O₃ behaviour, but considering the temperature range which corresponds to accidental conditions including B₄C oxidation, a linear kinetics assumption, consistent with experimental results, has been retained (meaning a null or a constant thickness of the B₂O₃ liquid film).

In this simple modelling, the code user must decide upon the amount of H₂O consumed and of H₂ released to oxidize one mole of B₄C. Based on thermodynamics equilibrium calculations, a set of most probable equations has been retained leading to the following results ([9]): the oxidation of one mole of B₄C consumes 10 moles of H₂O and releases 8 moles of H₂ (reactions taking into account B₄C oxidation and B₂O₃ consumption).

The heat released by the oxidation reaction is constant versus the temperature depending on whether or not the consumption of B₂O₃ is taken into account. Up to 1327°C, the used value is 800 kJ/mole of oxidized B₄C; beyond 1327°C, the heat is lowered to 100 kJ/mole of oxidized B₄C, mainly to take into account the formation of metaboric acid.

This preliminary modelling (with parameters given in table 1 –line 4) was used to perform FPT3 pre-calculations in 2002. The correlation has been improved by IRSN in 2004 by taking into account new results coming from VERDI [5] and BOX [10] experiments. This new kinetic (table 1 – line 5) has been used to analyze Quench 07-09 experiments and in the preliminary Phebus FPT-3 post test calculations (cf section §D).

In the same way, FzK and GRS for ATHLET-CD developed other kinetics (table 1 – lines 6, 7 and 8). Analysing all the results coming only from FzK [11] (T<1673K), Veshchunov et al. ([12]) have developed specific modelling where the kinetics depends on temperature, linked to physical understanding of the chemical process. Below 1373K, the kinetics are mainly governed by the formation of boric acids from the B₂O₃ reaction with steam (eq. 5 to 7), and above 1373K, the kinetic are governed by direct evaporation of B₂O₃ (eq. 8). This modelling following the same parameters (table 1 – line 11) as proposed by IRSN in 2002, has been published in 2007 [13].

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	T(K)	k_0 (molB ₄ C/m ² /s)	Ea (10 ⁵ J/mol)	α	β
Liljenzin		$3.29 \cdot 10^{+3}$	1.81	0	0
Litz		$5.29 \cdot 10^{-9}$	0.46	0	0
Sato		$1.03 \cdot 10^{+2}$	1.54	0	0
IRSN (2002)		34.17	1.6334	1.18	-0.78
IRSN (2004)		263.32	1.8587	1.18	-0.75
BOX data (FzK 6979)		$6.81 \cdot 10^{+3}$	1.887	0	0
VERDI data (GRS)		$1.143 \cdot 10^{+3}$	1.503	0	0
VERDI BOX data (GRS)	< 1800	$1.143 \cdot 10^{+3}$	1.503	0	0
	> 1800	$1.471 \cdot 10^{+6}$	2.586	0	0
FzK BOX data *		$1.471 \cdot 10^{+6}$	2.586	0	0
FzK BOX/TG data *		$1.250 \cdot 10^{+6}$	2.650	0	0
Veshchunov (2005)	< 1373	$2.5 \cdot 10^{-7}$	0.216	1	0
	> 1373	$6.0 \cdot 10^{+5}$	3.829	1	0
IRSN (2006)	< 1400	$4.33 \cdot 10^{-6}$	0.25	1	-0.25
	> 1400	3.64	1.775	1	-0.25

* for B₂O₃ reduction

Table 1: Coefficient for the B₄C oxidation kinetics

Remark : those correlations are not available for high pressure transient

The table 2 summarizes all the data, which were used by IRSN, including the last results obtained in the BECARRE (part I) experiments [14] to build a best estimate correlation for the B₄C oxidation kinetic in 2006 and recently published [15].

Experiments	Liljenzin, Litz, Sato	BOX FzK [11]	VERDI [14]
	1963-1990	2000-2003	2001-2005
Number of tests used for modelling	21	~40 (29 used for IRSN modelling)	69 tests
Pellets	Pellets and powders	Framatome, Codex, ESK	Framatome
Type of measurement	Mass balance	H ₂ release	Mass balance
P _{tot} (atm)	$10^{-2} - 1$	1	1
P _{steam} (atm)	$10^{-2} - 10^{-1}$	0.43 - 0.07(8) - 0.6(1)	0.2 - 0.4 - 0.8 0.9
Temperature (K)	1127-1573	1073-1673	1473-2073
Q _{tot} (g/min)			2.5 - 10
Velocity (m/s)			1 - 5

Table 2 : Synthesis of experiments related to B₄C oxidation

The main point of the model concerns the building of the reaction kinetics, which has been done with a large set of available experiments dedicated to the measurement of B₄C oxidation kinetics. This set is composed of about 120 tests, including tests performed by Liljenzin, Sato, tests realised at FzK in the BOX facility for the temperature range between 1073 and 1673K and 69 tests realised in the VERDI furnace at IRSN, for a temperature range extending the previous one to the domain to 1473-2073K. The main conclusions derived from the analysis of these experiments, are that the reaction kinetics can be described in the form of an Arrhenius law, the main relevant parameters being the temperature, the steam partial pressure, and the total pressure as proposed earlier (table 1 – line 12).

Figure 2 illustrates the kinetics calculated with this correlation as function of oxidation rate for experiments, plotted in $\ln(k)$. The whole set of points staying close to the bisecting line supported the validity of the correlation along the various test conditions. The tests issued from the VERDI experiment (red points) represent the conditions of high kinetics, and are grouped toward the upper right extremity.

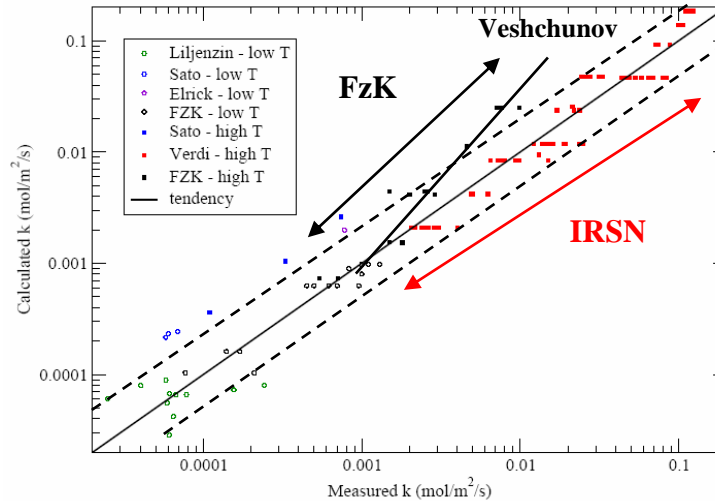


Figure 2: Oxidation kinetics law in ICARE2 code versus experiments

The higher kinetics given by the Veshchunov correlation at high temperature, which did not take into account the VERDI results, could explain the discrepancy (factor of 2 on the Activation Energy E_a – table 1).

C. SUMMARY DESCRIPTION OF THE SEVERE ACCIDENT CODE

C.1 ICARE/CATHARE code

The ICARE2 V3mod1.4 code is the stand-alone core degradation module of the ICARE/CATHARE V1 code system developed by IRSN, devoted to the Nuclear Power Plant calculations under severe accident conditions with an extensible validation campaign ([16]). We only describe, here after, models dealing with B_4C control rod degradation.

a) Chemical interaction B_4C/SS : in “ideal” conditions (inert atmosphere and “ideal” contact), a 1 mm thick wall of an as-received SS tube can be converted by B_4C at 1250°C into a liquid phase within ~100 s. These results were calculated by empirical correlations, obtained by Hoffman and Uetsuka in experiments with crucible (see Belovsky et al, 1997 [17]). Later, Belovsky developed a B_4C/SS chemical interaction model for ICARE2, based on separate effects tests (SET). He showed that the parabolic correlations are applicable to the real geometry of control rod segments and to transient conditions as well. Modifications were performed on the original model; the main conclusions were the following:

1. the parabolic correlations of Uetsuka for B_4C -pellets were added,
2. the B_4C/SS interaction begins at 800°C; the transition temperature to the accelerated kinetics is set to 1210°C and the reaction rate is increased above this temperature,
3. because ~6 wt% of carbon was detected in the reaction zone, the B_4C fraction in the B_4C/SS mixture simulating the reaction zone was increased from 5.5 wt% to 9 wt%.

b) Chemical interaction $B_4C/SS/Zircaloy-4$: in ICARE2 there is a module which calculates the liquefaction of Zircaloy by solid stainless steel. It is however not used in the calculation, mainly because the contact between the steel cladding and the guide tube is never met, not allowing the interaction to begin. Because of the lack of modelling of chemical interaction $B_4C/SS/Zry-4$, it is therefore usual, in standard ICARE2 simulations, to assume that the control rod failure is issued from an instantaneous Zircaloy dissolution by the molten

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B₄C/SS mixture. Usually, the melting temperature of the stainless steel (~1450°C) is selected as key-event to trigger the rupture of the control rod.

In the experiments made by Hoffman and Uetsuka, under similar “ideal” conditions, a 0.5 mm thick zircaloy-4 wall can be consumed by steel at 1200°C within ~10 s. This illustrates the hypothesis of quasi instantaneous Zircaloy dissolution by the molten B₄C/SS mixture, as compared to the timing of the B₄C/SS interaction. However, in the more appropriate geometry of control rod segments, it was shown by Belovsky in 2000 that an important parameter influencing the specimen behavior was the degree of oxidation of the Zircaloy-4 guide tube, meaning the thickness of the zirconia scale. One possibility to take into account this experimental observation in the modelling was the following recommendation, for ICARE2 users, to set the integrity criteria of the guide tube in such a way that its failure happened between ~1300°C and ~1450°C (1723K). These facts were confirmed by the Separate Effects Tests made at FzK ([18]), which showed the importance of the outer ZrO₂ oxide scale preventing melt relocation. Concerning the embrittlement criteria of the guide tube, the option usually selected is based on the dislocation of the steel cladding. This dislocation can happen upon melting, but also on the disappearance of the initial solid zircaloy, when all the cladding has been transformed into B₄C/SS mixture.

So, the failure of the control rod is foreseen for 2 criteria:

1. When the SS cladding is totally dissolved by the B₄C (B₄C/SS interaction) or
2. when guide tube temperature > 1450°C (1723K)

After the failure of the B₄C control rod, B₄C oxidation can start. The kinetics used in ICARE/CATHARE code is well described in the section B.

The ICARE2 provides the amount of H₂ released and the amount of B₄C consumed due to the boron carbide oxidation. The formation of various carbonaceous species is not taken into account.

C.2 ATHLET-CD code

The severe accident code system ATHLET-CD (Analysis of Thermal-Hydraulics of LEaks and Transients with Core Degradation) is under development by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) in Germany for the simulation of design basis and – in cooperation with the Institut für Kernenergetik und Energiesysteme (IKE) at the University of Stuttgart– beyond design basis accidents with core degradation in LWR ([19]).

The ATHLET code is divided into five modules reflecting the main physical processes to be simulated. In the TFD module the thermo-fluid-dynamic network is defined, which mainly allows to evaluate the transient thermal-hydraulic behaviour of the system under specified transient boundary conditions. The TFD module has two different fluid-dynamic equation systems, the five-equation and the six-equation model. The simulation of heat transfer and heat conduction in structures is performed within the basic module HECU. The heat conduction objects are coupled to the thermo-fluid objects (TFO) of the TFD module. The neutron kinetics module NEUKIN simulates the nuclear heat generation.

The CD part of ATHLET-CD mainly deals with the early and the late phase core degradation in severe accidents. Four modules are available to simulate the most important phenomena.

Numerous correlations for B₄C oxidation have been implemented in ATHLET-CD code from different authors (Fig. 3), in particular those coming from VERDI and BOX experiments (table 1 – line 3 and 4). In addition, the B₂O₃ reduction is taking into account in the modelling using specific correlations coming from BOX and TG data (table 1 – lines 9 and 10). The correlation usually used in simulations are R1(7) for B₄C oxidation and R2(2) for the B₂O₃ reduction.

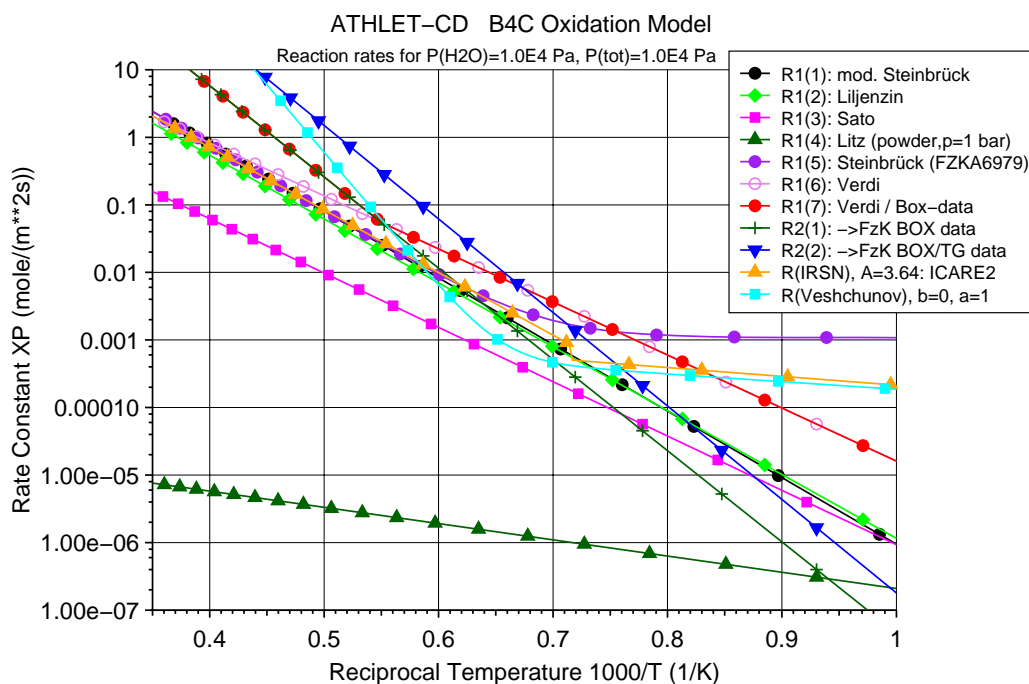


Figure 3: Oxidation kinetics law in ATHLET-CD code (different options)

C.3 MELCOR code

MELCOR ([19]) is designed to simulate all phases of a plant severe accident, the relevant plant phenomena and components. The objective is to concentrate on the major characteristics and parameters important for plant safety rather than to capture the processes in detail. MELCOR comprises, typically, simple empirical correlations or parametric statements, and is normally used conjunction with coarse-mesh input models.

The thermal-hydraulic module is pivotal within the code, and is the most intimately linked to the other modules. In particular, it furnishes the thermal and fluid conditions for all of the process and component models: degradation, fission-product transport, corium-concrete interaction, etc. In the spirit of the coarse-nodding approach, fairly large regions are often represented by just one hydraulic cell. Each cell normally comprises two regions: a pool, which may be a single-phase liquid or a two-phase bubble-rise region, and an atmosphere which may contain liquid water in the form of fog. The cells are connected by flow paths where the flows of the pool and atmosphere are separately calculated by means of a simplified, one-dimensional treatment of momentum balance. Heat conducting structures provide the physical and thermal boundaries for the hydraulic system; these can ablate or undergo failure through thermo-mechanical loads.

The core models follow the heat-up, oxidation, fuel dissolution, bulk melting and relocation. The core components include fuel rods, absorber rods, cladding, non-supporting structures such as guide tubes, and supporting structures. Heat generation in the core is by a combination of fission, decay and oxidation. Melting occurs at the melting point of the pure material, or due to eutectic interactions between metallic (e.g. steel and Zr) and between metallic and oxide (e.g. Zr and UO₂, Zr and ZrO₂). The fuel rods are considered to be locally reduced to debris, once intact geometry is lost; this according to a temperature criterion (2500 K according to the analyses of the Phebus PF experiments, 2800 K for UO₂-ZrO₂ or when melting occurs 3113 K). Both liquid and solid debris can relocate downwards or radially, provided there is space for them to occupy. Material relocates to the lower head when the supporting structures fail, according to an empirical correlation or parametric criterion.

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The treatment B₄C oxidation in MELCOR 1.8.5 is based on an old model developed for BWR control blades. It assumes very rapid, linear kinetics on the assumption that the B₄C is in the form of powder and only a small fraction would be released to the coolant channel steam following breach of the stainless steel (SS) rod cladding and the Zircaloy blade. The remainder of the B₄C is presumed to form a eutectic melt with the SS and relocate. The model in version 1.8.6 has been extended to enable PWR control rods to be represented and is less restrictive concerning criteria for enabling oxidation, but the treatment of oxidation is largely unchanged. The code includes built-in parameter values for the parameters that determine oxidation but all of these values can be modified by user input.

MELCOR 1.8.5 and 1.8.6 adopt different treatments of the material interaction. Version 1.8.5 uses a kinetic model to calculate the eutectic reaction between B₄C, SS and Zircaloy and hence the breach which releases the B₄C. In version 1.8.5 the reaction can occur provided (i) a certain fraction (default 10%) of the SS has melted and relocated away, (ii) the temperature exceeds some threshold temperature (default 1500 K), and (iii) less than a maximum fraction (default 2%) has oxidized. These values should be modified for PWR control rods so there is no restriction on the maximum oxidisable fraction. Version 1.8.6 does not model the eutectic interaction; instead the effective melting temperature of the B₄C can be input (default 1700K). Otherwise the 1.8.6 version adopts essentially the same model as 1.8.5 for the BWR control blade. It also includes a PWR model in which oxidation is initiated according to a temperature criterion (default 1500 K) to represent control rod breach. This is assumed to apply regardless of SS melting and there is no restriction on the amount of B₄C that may oxidize. A present limitation is that oxidation of melted B₄C (in 1.8.6) or (B₄C/SS in 1.8.5) mixtures is not represented, so it is likely that the B₄C oxidation will be underestimated by version 1.8.5 and by 1.8.6 unless the eutectic reaction is suppressed by a high temperature values for the melting. This limitation is being addressed by SNL. The kinetic model in both 1.8.5 and 1.8.6 (BWR and PWR) is as follows:

$$d(M/M_0)/dt = 166216.7 \exp(-188299.5/RT) \quad T > 1500 \text{ K},$$

provided no overriding restrictions apply. M is the current mass of B₄C and M₀ is the initial value and T is the temperature. It is noted that no dependence on flow rate of steam partial pressure is considered, provided it is not steam starved.

Two options exist for the reaction scheme. The “simple model” considers formation of B₂O₃ and partitioning between CO, CO₂ and CH₄ formation as given by equations 1 to 3 of section §B. An “advanced model” option considers thermodynamic equilibrium between these products and HBO₂, H₃B₃O₆, BOH, BH₃, B₂H₆, O, B and C. However, the advanced model appears to offer no advantage despite the added complexity.

Overall, the 1.8.6 treatment is simpler but more flexible and differentiates between the BWR and PWR configuration. However, the kinetics is more appropriate to powdered B₄C than pellets, while the lack of model for melted B₄C or B₄C/SS mixture restricts its applicability to PWR rods. Reducing the kinetic coefficient may provide a more realistic oxidation rate but what is needed is for the model take account of the comparatively recent IRSN and FzK data for oxidation of B₄C pellets.

C.4 MAAP code

The MAAP (Modular Accident Analysis Program [21]) code was originally developed in the early 1980's by Fauske & Associates Inc. (FAI) as part of the Industry Degraded Core Rulemaking (IDCOR) program which gathered about sixty American utilities and other organizations. The goal of this program was to address the needs for a reliable tool for performing physical studies, basis for PSA's, both for PWRs and BWRs. Since the dissolution of IDCOR, EPRI is the owner of the MAAP code, with new developments realized by FAI. The current version of the code is MAAP4. The MAAP4 functional modelling is particularly adapted to investigate the impact of operator actions on the progression of sequences. MAAP4 can be used for the following studies: PSA level 2, studies supporting the elaboration of Severe Accidents Management Guidance (SAMG) procedures and the design of mitigation systems. MAAP4 is the code used at EDF for severe accidents modelling. After acquiring the code, EDF has developed its own know-how in developing and validating MAAP4 in

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addition to FAI activity. Since 1996, EDF has pushed this logic of development by carrying out particular versions of MAAP that contain specific contributions.

Initial versions of MAAP4 for PWRs considered only silver-indium-cadmium (SIC) alloy as material for control rods. Some EDF reactors (1300 MWe and N4 series, EPR) use hybrid control rods: the lower part of some control rods is made of Ag-In-Cd alloy, the upper part is made of boron carbide (B_4C). So, for those EDF reactors, B_4C behaviour under severe accident conditions had to be modelled in a MAAP4 specific version. Several phenomena can occur during B_4C degradation:

- Interaction of B_4C with surrounding materials: stainless steel (SS) cladding first, zircaloy guide tube later on. This interaction involves only a fraction of the actual B_4C , since the eutectic B_4C -SS has a limited content in B_4C (supposed 9% in mass).
- Pure B_4C oxidation by steam, releasing gases like H_2 , CO , CO_2 and possibly CH_4 .
- Pure B_4C melting.
- Relocation and oxidation of molten material (mainly the B_4C -SS mixture).

The MAAP4.04 version of the code has included a modelling of the main phenomena (B_4C -SS mixture formation, B_4C oxidation and melting, relocation of molten materials). Developments concerning B_4C -SS oxidation and an improved B_4C oxidation law are in progress for a future version. Concerning B_4C oxidation, three empirical oxidation laws have been implemented in MAAP4.04:

- the MELCOR modelling proposes an Arrhenius temperature dependant law for the ratio "current mass to initial mass" (this MELCOR correlation is based on B_4C powders oxidation use in BWR),
- the "FzK correlation" is based upon the BOX test.
- the "IRSN correlation from ICARE2" comes from a best fit on existing tests and is validated against the BOX and VERDI experiments (cf section §B).

Concerning gases production, the three main possible reactions are given by equations (1) (2) and (3), described in section §B: Chemical constants (from the MELCOR model or from GEMINI/COACH calculations) for these reactions are implemented in MAAP4.04, thus leading to gas production for the different species.

Melting and freezing of the B_4C -SS mixture have been modelled considering liquidus (1500 K) and solidus (1550 K) temperatures. For pure B_4C the melting point is assumed to be 2673 K. Molten materials are added to the liquid phase in each node and relocated with this liquid phase.

New developments in MAAP4

The B_4C oxidation law used in ICARE/CATHARE (see corresponding §B) has been implemented. Oxidation of the B_4C -SS mixture has been modelled according to the indications given in a "Source Term modelling" meeting between IRSN and EDF (17th December 2007), i.e. use of the same correlation for boron oxidation in a liquid mixture as for solid B_4C , adapting the gas release rate to the dominant reaction ($B + 3/2 H_2O \rightarrow 1/2 B_2O_3 + 3/2 H_2$ instead of $B_4C + 8 H_2O \rightarrow 2 B_2O_3 + CO_2 + 8 H_2$). Those results are coming from the recent preliminary IRSN analyses of the BECARRE (part II) experiments related to oxidation of liquid B_4C -SS mixture. This has to be further consolidated for the hydrogen source taking into account the fact that it will correspond to a small fraction to the total H_2 releases.

D. APPLICATION TO PHEBUS AND QUENCH EXPERIMENTS

This section describes the application of B_4C degradation modelling included in the Severe Accident Code to experiments which have been performed in out of pile (Quench) and in-pile, both including a B_4C control rod, namely Quench 07/09 and Phebus FPT3. The results will be focused only on B_4C degradation and the corresponding gas releases.

D1 Quench 07 and 09 experiment

Global bundle Quench tests 07 [22] and 09 [23] were carried out at FzK within the COLOSS project of the EU 5th Framework Program. The bundle of Quench -07 and -09 tests simulates a fuel assembly including pertinent materials for cladding and spacer grids while fuel pellet are simulated by ZrO_2 . The test section consists of 20 fuel rods simulators

(electrically heated) which surround a central rod: either a B₄C control rod in Quench -07 and -09 or an unheated rod in Quench -08 ([24]).

Those experiments have been used to validate ICARE/CATHARE (IRSN [25]) and ATHLET-CD (with contribution of GRS [26] and RUB [27]) and more recently with MAAP4 code (EDF) [28]. Those applications have been performed in the frame of SARNET WP9.2 activities from 2005 to March 2008.

Before the analyses of the B₄C control behaviour, let us have a short look on the thermal results by both the S.A codes. The figure below provides temperature evolution during the transient at two elevations (1150mm and 950mm). Two codes matched well the experimental results (Fig. 4a and 4b).

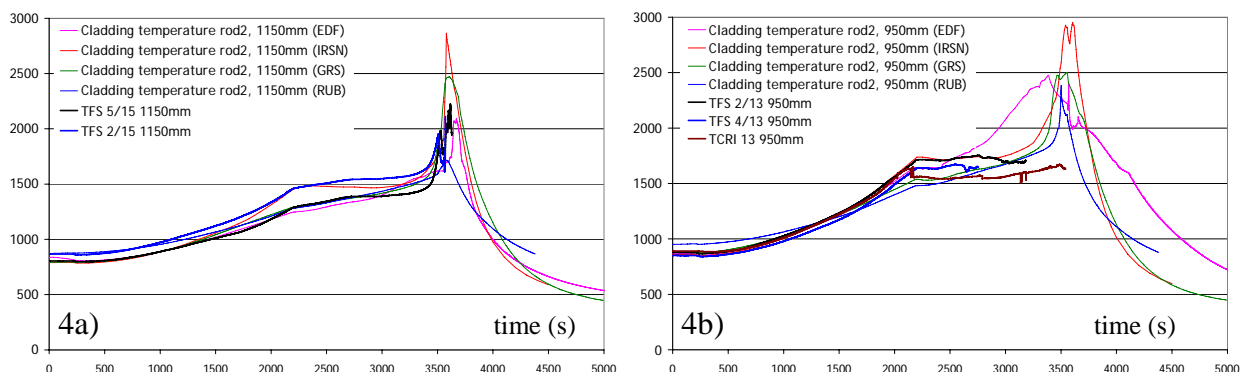


Figure 4: Quench 07 test - temperature evolution (K) for 1150 and 950 mm elevation (ICARE/CATHARE, ATHLET-CD and MAAP4 results)

Regarding the B₄C oxidation, the results have been improved with the ICARE/CATHARE (Fig. 5) code using the new correlation obtained in 2004 compared to that used earlier in the FPT- 3 preparation (correlation IRSN 2002 –see §B): 18.2 to 22.4 grams. The additional amount in the test could be due to B₄C oxidation in mixture form not accounted for by the code.

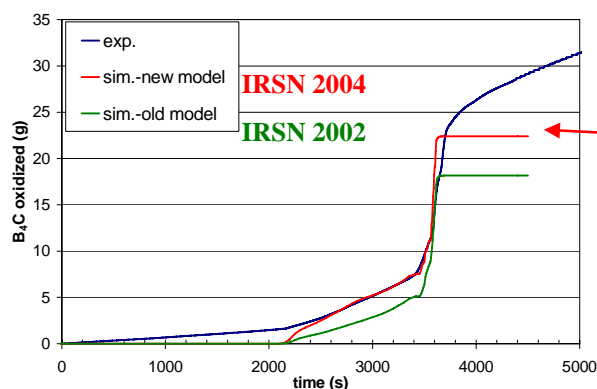


Figure 5 : B₄C oxidation for Quench 07 test with ICARE/CATHARE

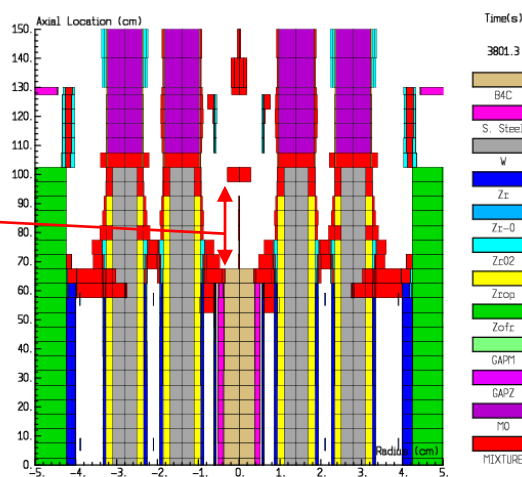


Figure 6 : bundle degradation (I/C)

Figure 6 gives an example of the final configuration of the Quench 07 bundle given by ICARE/CATHARE code. About one third of the B₄C control rod has been degraded (lower amount compared to FPT3 – section §D2).

The H₂ generation (very sensitive to the escalation during the quench phase) has to be improved for some contributions (Fig. 7a), nevertheless, the carbon release obtained for most of the simulations (Fig. 7b) gave satisfactorily results except that of MAAP4. This could be

linked to the B₄C relocation mode probably connected to the higher temperature at the 950mm elevation (Fig. 4b). A specific benchmark (under preparation) will indicate more details on Quench 07 and 09 analyses.

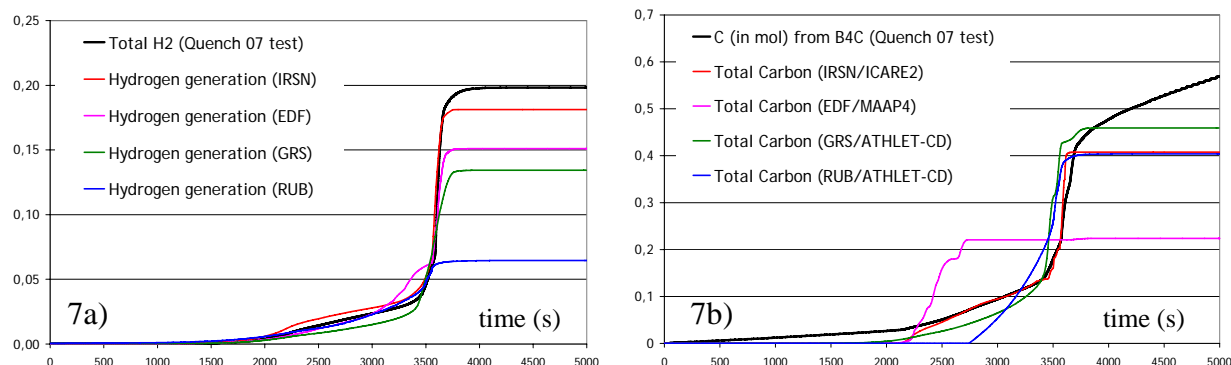
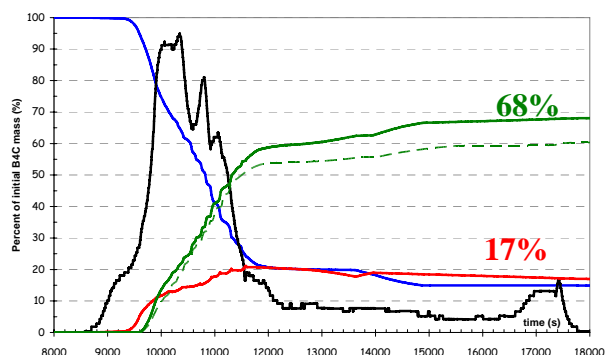


Figure 7: Quench 07 test –gas releases – Hydrogen (in kg) and Carbon (in mole) (ICARE/CATHARE, ATHLET-CD and MAAP4 results)

D.2 FPT3 Phebus experiment

The applications of the B₄C degradation model included in S.A to Phebus FPT3 experiment have been already published and presented during the previous ERMSAR conference in 2007 in Karlsruhe ([29]). We just recall the results regarding B₄C and gas releases.



As an example, the results given by ICARE2 (Fig. 8) lead to oxidation of 68% of the initial inventory in solid form whereas 17% was dissolved by S.S and do not participate to the oxidation process. The new IRSN kinetics increased the amount of B₄C oxidation (solid line) and consequently the corresponding gas releases in more agreement [30] to that was measured during the experiment (Fig. 9a). Only 15% of the initial mass is still intact, which is consistent with the experiment.

Figure 8: Phebus FPT3 - B₄C oxidation (ICARE2)

Taking into account the most probable reaction (eq. 1 to 4), one mole of B₄C oxidized should produce one mole of carbon. So, the validation of the modelling has been tested against the total carbon release given by the codes.

To summarize the results on Phebus FPT-3, SA codes such as ICARE/CATHARE and ATHLET-CD, using suitable modelling for B₄C oxidation, predicted that about 70 to 80% of the initial B₄C mass has reacted with the steam leading to carbon release consistent with the experimental results (Fig. 9a.). MELCOR code applies a B₄C oxidation model designed for use in BWR control blades, which is not suitable for PWR B₄C control rods (cf § C3). As can be seen (Fig. 9b), the formation of carbon gases is underestimated by version 1.8.5 and by 1.8.6 when the best estimate B₄C/SS melting temperature of 1700 K is used. Increasing the temperature to 2600 K [30], close to the melting temperature of pure B₄C gives better agreement but at the expense of suppressing the formation of B₄C/SS melt.

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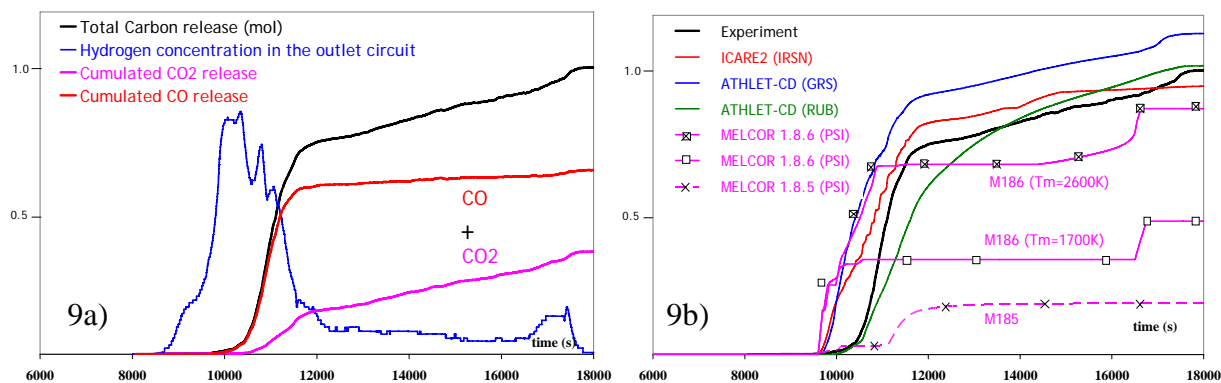


Figure 9: Phebus FPT3 –gas releases CO and CO₂ : total carbon release (in mole) (ICARE/CATHARE, ATHLET-CD and MELCOR results)

E. CONCLUSIONS

The works which have been performed in the SARNET produced significant improvement regarding the control rod behaviour, mainly for the B₄C oxidation process. The Severe Accident Code capabilities to simulate the control rod behaviour in a fuel rod assembly during the course of severe accident transient have been demonstrated, nevertheless, some progress in degradation processes are needed.

There are still some difficulties to reproduce the final degradation of the bundle using codes (which is out of the scope of this paper). The nearly total destruction of the control rod is well reproduced in the calculations. Effects of spreading molten materials of the control rods towards fuel rods of the bundle are suspected, meaning that the main effect of the B₄C control rod on the bundle behaviour could be connected with B₄C-SS eutectics formation and liquid B₄C-SS-Zry relocation. These phenomena are not accounted for in the SA codes up to now. The need for further code developments of the early phase of core degradation is recognized for the absorber rod material behaviour. BECARRE III experiments, foreseen to be conducted in 2009, in the framework of the International Source Term Program ([31]) should help us in the understanding and improving the modelling. Out of the scope of the following SARNET 2, a synthesis of the B₄C aspect is foreseen in 2010 to close this specific issue.

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