

CORE LOSS DURING A SEVERE ACCIDENT (COLOSS)

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SUMMARY

The COLOSS project was a 3-year shared-cost action which started in February 2000. The work-programme performed by 19 partners was shaped around complementary activities aimed at improving severe accident (SA) codes. Unresolved risk-relevant issues regarding H₂ production, melt generation and the source term were studied, through a large number of experiments such as a) dissolution of fresh and high burn-up UO₂ and MOX by Zircaloy, b) simultaneous dissolution of UO₂ and ZrO₂, c) oxidation of U-O-Zr mixtures, d) degradation-oxidation of B₄C control rods. Corresponding models were developed in SA computer codes which were then used to apply results in plant calculations and evaluate their consequences on key SA sequences in different plants involving B₄C control rods and on the TMI-2 accident.

Significant results have been produced from separate-effects, semi-global and large-scale tests on COLOSS topics. Related models were successfully implemented in some SA codes. Break-throughs were achieved on some issues for which more data are needed for consolidation of the modelling in particular on burn-up effects on UO₂ and MOX dissolution and oxidation of U-O-Zr and B₄C-metal mixtures. The plant calculation activity enabled an overall assessment of codes focusing on topics studied in the project. Main results and recommendations for future R&D activities are summarized in this paper.

A. INTRODUCTION

The project provided a contribution to resolve the following key safety-related issues:

- 1) What is the impact of UO₂ and ZrO₂ dissolution on the loss of rod geometry and how can the burn-up affect the dissolution of UO₂ and MOX?
- 2) How does the oxidation of U-O-Zr mixtures contribute to the large H₂ production during early core heat-up and during the reflow of degraded cores?
- 3) What is the effect of B₄C on core degradation and melt progression?
- 4) Can the oxidation of B₄C material affect the chemistry of volatile fission products (FP)?

The general objective was to provide sufficient knowledge from experiments to develop models and improve SA codes to be able to address these issues in safety calculations.

B. WORK PROGRAMME

The work plan involved experiments, model development and SA plant calculations.

- 1) Separate-effects tests (SET) to provide understanding of the following phenomena:
 - Dissolution of high burn-up UO_2 and MOX by molten Zircaloy (Zy)
 - Simultaneous dissolution of UO_2 and ZrO_2 by molten Zy for PWR and VVER rods,
 - Oxidation of B_4C and degradation-oxidation of prototypic B_4C control rods (B_4C -CR),
 - Oxidation of U-O-Zr mixtures and related H_2 production.
- 2) One CODEX and two QUENCH large-scale experiments with VVER and PWR bundles involving a central B_4C -CR to provide a database for code validation.
- 3) Model development and implementation in SA codes used in the EU for safety studies.
- 4) Plant calculations of various key SA sequences. Table 1 summarizes this activity.

Table 1: Plant calculation activity in COLOSS

Plant designs	SA codes	Partners	SA sequences
PWR 1300	ASTEC-MAAP4	IRSN/EDF	“H2 sequence” (*)
PWR 900	ASTEC	IRSN	Same “H2 sequence”
BWR	MELCOR	PSI	Station Blackout (SBO)
VVER-1000	ICARE/CATHARE	KI/LTKK	Large break / SBO
EPR	MAAP4-MELCOR-SCDAP/R5	Fra-SAS/GmbH/FZK	SBO
TMI-2	ASTEC-S/R5-ICARE/C.-MAAP4	IRSN/ENEA/ENEA/EDF	

(*) Total loss of feedwater to the steam generator without safety injections

C. MAIN ACHIEVEMENTS

Main achievements are summarized below. More details can be found in reference [1].

C.1 Separate-effect tests on oxidation of U-Zr-O and Zr-O mixtures (UJP Praha, FZK)

The UJP Praha tests required the construction of a new resistance furnace with on-line H_2 measurements. Various solid U-O-Zr alloys with different compositions were studied up to 1670 K focusing on 65U-30Zr-5O and 5U-90Zr-5O wt% alloys. Main results are:

- Faster oxidation kinetics of U-O-Zr alloys compared to the Zr1%Nb alloy,
- Larger oxidation rates than for Zr especially with O content >2 wt% and U content >15 wt%. Some U-rich alloys were found pyrophoric and disintegrate during oxidation at 970 K,
- Oxide spalling and sample cracking are responsible for the enhanced H_2 release.

While results are consistent with the Prater parabolic law at 1670 K, they show significantly higher kinetics than the extrapolation of this law to lower temperatures. This is a breakthrough in explaining one contribution to the H_2 peak during quenching. Results have to be consolidated and extended for non-isothermal and reflood conditions.

FZK tests on dissolution of ZrO_2 crucibles by molten Zr showed that in the long term, this interaction is similar to the oxidation of Zr-O melts observed in QUENCH bundle tests. Tests at 2370 and 2470 K with annealing times up to 290 min enabled the identification of melt oxidation processes with quite linear kinetics and formation of solid ZrO_2 precipitates.

C.2 Fuel dissolution tests (RIAR, JRC/IE, AEKI, JRC/ITU)

Three complementary experimental programmes were devoted to fuel rod dissolution: RIAR's *separate-effects tests* (SETs) to study the simultaneous dissolution of UO_2 and ZrO_2 by molten Zr using crucibles, AEKI's *semi-global* tests to study the same topic using

prototypic fuel rods and ITU's SETs to study the burn-up effect on UO₂ and MOX dissolution.

RIAR tests were characterized by a UO₂ crucible, a central ZrO₂ rod and Zr in-between. Performed to consolidate previous CIT results [2], they showed also a large dissolution of the ZrO₂ rod. Results enabled the validation of the SVECHA fuel rod dissolution model.

AEKI semi-global tests with prototypic VVER and PWR fresh fuel rods were performed to validate the dissolution model derived from crucible tests to rod geometry. Main results are:

- Differences on fuel dissolution phenomenology at the *rod scale* due to additional coupled phenomena compared with crucible tests, in particular concerning the UO₂-cladding gap effect and the inner melt relocation to lower positions into the space between pellets.
- Local effects with non-uniform axial and radial UO₂ and ZrO₂ dissolution due to stronger dissolution in zones with smaller UO₂-cladding gap width.
- Complete dissolution of ZrO₂ in some tests with a thin initial oxide layer.
- Some cladding failure due to radial cracking or total dissolution of the outer ZrO₂ layer.
- No significant difference between PWR and VVER rods.

These data enabled the fuel rod models of SVECHA and ICARE/C codes to be checked.

JRC/ITU tests were aimed at comparing dissolution of fresh and irradiated UO₂ and MOX using thin clad fuel samples. A new furnace was constructed to work in a hot cell. In spite of difficulties, tests were successfully done by heating simultaneously a fresh and an irradiated sample of either UO₂ or MOX located in two Y₂O₃ crucibles, one placed top of the other. Post-test analysis enabled the dissolution to be quantified. Main results are:

- More rapid and extended dissolution of irradiated MOX compared with fresh UO₂ with quite total dissolution of irradiated fuel at 2270 K in less than 60 min.
- Evidence of large fragmentation-decohesion of irradiated fuel not observed for fresh fuel.
- Fission products cause bubbling of the melt and improve the melt-fuel contact.
- Final tests with irradiated MOX (44 GWd/tU) and UO₂ (90 GWd/tU) showed a wide scattering of results. Additional data are needed for quantification of the kinetics.

C.3 Separate-effect tests on B₄C (IRSN and FZK)

Two complementary programmes on B₄C oxidation and B₄C-CR degradation were performed at IRSN using the VERDI furnace and at FZK using various set-ups 1) a thermo-balance suitable for on-line measuring of kinetics, 2) a new BOX rig with a mass spectrometer to measure the gases resulting from B₄C and B₄C-steel-Zr oxidation and 3) the QUENCH rig to study the degradation of short B₄C-CR. Different temperatures, flow rate and steam partial pressure conditions were studied. A large database was produced, key results being:

- The understanding of B₄C oxidation has been considerably improved. It is mainly determined by formation and evaporation of a liquid B₂O₃ layer that acts as a diffusion barrier. Two regimes were found: 1) at lower temperatures the B₂O₃ layer growth results in initial parabolic oxidation kinetics 2) at higher temperatures (T>1400 K), the B₂O₃ evaporation and reaction with steam result in linear oxidation kinetics. For both regimes, the kinetics is influenced by the steam partial pressure and flow rate. The porosity of the B₄C specimens has only an initial influence on the oxidation kinetics. Very low amounts of CH₄ were measured.
- The degradation of a B₄C-CR is strongly dependent on the external ZrO₂ scale thickness of the guide tube that acts as a crucible for the inner B₄C-rich melt and prevents the melt from early release. Its failure triggers large oxidation of both the absorber melt and remaining B₄C

pellets. The oxidation of B₄C-steel-Zr melts was found to be more violent than that of the pure components. Additional data are needed for quantification.

C.4 Large-scale tests with a fuel rod bundle and a central B₄C-CR (FZK and AEKI)

Three bundle tests QUENCH-07 (Q-07), QUENCH-09 (Q-09) and CODEX-B₄C were performed with a central B₄C-CR. The first two tests representative of a PWR design were performed in oxidizing and steam-starvation conditions respectively. The latter, with a VVER-1000 design, was performed in mainly oxidizing conditions. Main results are:

- The B₄C-CR failed above 1500 K and more than 40% of B₄C was oxidized.
- The B₄C effect on core degradation was limited due to the rapid axial B₄C-melt relocation.
- Main gases produced are H₂, CO, CO₂ and gaseous B-species. CH₄ was negligible.
- A very high release of aerosols, mainly B-compounds, was measured in the CODEX test.
- The B₄C-CR behaviour was found to depend significantly on the oxygen potential.

Large differences were found between Q-07 and Q-09 tests. After CR rupture, a continuous B₄C oxidation was observed in oxidizing conditions of Q-07 while it was negligible during the steam-starvation conditions of Q-09. The final cooling phase showed oxidation escalation of both Zr and B₄C, limited in CODEX test due to a small steam flow (0.5 g/s), significant in Q-07 test with high steam flow (15 g/s) and very large in Q-09 test with an even higher steam flow (50 g/s). In the latter test, the escalation was also enhanced by the previous steam-starvation conditions known to favour the re-dissolution of the protective ZrO₂ layers. The understanding of differences between the two QUENCH tests needs more investigation.

The three integral tests with B₄C gave, for the first time, an experimental database on the on-line B₄C-reaction gas production. Results are important for the future Phébus FPT3 test dealing with B₄C effects including those on FPs. Results were extensively used for the validation of codes such as ICARE/C, ATHLET-CD, MELCOR, MAAP4 and SCDAP/R5.

C.5 Modelling activities (IRSN, ENEA, FZK, IBRAE, JRC/IE, EDF, IKE and RUB)

Fuel dissolution (IBRAE, IRSN). The previous model of simultaneous UO₂ and ZrO₂ dissolution developed in the CIT project [2] was improved and validated against RIAR tests. It was implemented in the mechanistic SVECHA code and used to prepare and analyse the AEKI fuel rod dissolution tests. The model is suitable to be implemented in ICARE/C code.

The burn-up effect observed in JRC/ITU tests on fuel dissolution was taken into account by a parametric model. Faster kinetics for irradiated fuel is simulated by a higher “effective” temperature of interaction. The temperature shift depends on type of fuel, temperature and burn-up. This preliminary model needs more results and validation.

Oxidation of Zr-O and U-Zr-O mixtures (JRC/IE, IBRAE, IRSN and RUB). The IBRAE modelling of *molten mixtures* was based on post-test examinations of relocated melts in CORA and QUENCH bundle tests as well as FZK tests on long-term dissolution of ZrO₂ crucibles by molten Zr. It predicts a continuous oxidation/precipitation process in the saturated melts and a much faster oxidation and H₂ generation rate than with the standard parabolic oxidation laws. A similar model was developed in ICARE/C by IRSN. Modelling of *solid U-O-Zr mixtures* (T < 1670 K) was based on the enhanced kinetics measured in the UJP tests. These data were tabulated in ICARE/C taking into account the O and U wt% studied.

B₄C-CR degradation and oxidation (IRSN, ENEA, FZK, IKE, EDF). Models were developed in ICARE/C, ASTEC, ATHLET-CD and MAAP4 using the large B₄C database produced. The B₄C models which take into account H₂, CO, CO₂, CH₄ production were validated on bundle tests with B₄C-CR. Oxidation of B₄C-steel-Zr mixtures is not taken into account and there is no gas chemistry model to evaluate correctly B₄C-reaction gases behaviour from the core up to the primary circuit in order to evaluate effects on FP chemistry.

C.6 Plant calculations and safety implications

The Plant Analysis Group was composed of 11 partners and ran three integral codes ASTEC, MELCOR and MAAP4 and two mechanistic codes ICARE/C and SCDAP/R5 on key SA sequences. The final calculations were run with improved codes during the project.

Assessment of SA codes on H₂ production, B₄C effects and corium formation

Plant calculations, code-benchmarks and sensitivity studies on key parameters of the core degradation (Zr and B₄C oxidation laws and B₄C-CR and UO₂ rod degradation criteria) enabled the identification of abilities and deficiencies of codes and needs for improvements.

H₂ production: Sensitivity studies on early degradation models showed more significant effects on *H₂ rate* during early core heat-up or during quenching than on *total* production found to be in the 20-35% range depending on the SA sequence. The H₂ rate during melt relocation is certainly underestimated due to the lack of correct melt oxidation models.

Oxidation of mixtures: This is a key weakness of SA codes resulting in underestimation of the H₂ rate. Modelling is either missing or inadequate. Convincing results could be obtained using a melt oxidation model coupled with a 2D corium relocation model. This approach needs also to take account of steam supply considering 2D thermal-hydraulic effects.

B₄C oxidation: Effect on core degradation were calculated as limited, H₂ from B₄C is often less than 10% of total H₂ and very little CH₄ is produced. More important for FP chemistry is the CO and CO₂ release. The rapid oxidation of B₄C-melts is not yet modelled.

UO₂ dissolution: Large uncertainties were evidenced by large differences between models and results on UO₂ liquefaction. The *burn-up effect* known to enhance significantly UO₂ liquefaction and suspected to favour early rod collapse has to be modelled in SA codes.

Corium behaviour: Large discrepancies were found in the amount of corium produced, in its composition and in the distribution between core, core by-pass and lower head. Corium behaviour is more dependent on the late melt progression modelling than on that of the early degradation. One exception is the *fuel rod collapse criterion*, which controls the corium formation and affects significantly late corium behaviour.

Needs for short-term code improvements are:

- Add gas chemistry models for B₄C oxidation in the core and chemistry and in the circuit,
- Extend the fuel rod dissolution models to the burn-up effect,
- Use more mechanistic modelling for Zr oxidation, clad failure and UO₂ rod collapse,
- Extend melt oxidation models to heat-up and reflooding core conditions,
- Improve core 2D thermal-hydraulic effects and 2D melt progression-oxidation coupling.

Safety implications of results

The *H₂ rate* during early core heat-up or during quenching is at least as important as the *total H₂ production* regarding explosion risk and the efficiency of H₂ mitigation measures in the containment. This rate is certainly underestimated due to code weaknesses on the oxidation of mixtures. Data from COLOSS enabled a break-through for code improvements.

The main risk with *B₄C oxidation* comes from CO and CO₂ gases that can be converted into CH₄ in the cooler zones of the primary circuit during H₂-rich phases. In this case, non-negligible quantities of volatile CH₃I, a key factor of radiological risk, can be formed.

Corium behaviour is affected by large uncertainties in the amount of corium formation and in its oxidation which drive the metallic-oxidic composition and in the final distribution

between the core, the core by-pass and lower head. These factors are important for the risk of steam explosion, the late H₂ release and the final corium retention and vessel failure mode.

D. DISSEMINATION AND EXPLOITATION OF THE RESULTS

The project provided the opportunity to disseminate acquired knowledge and experience on SA among the European Nuclear Energy Community, including two new member states. The code-benchmarking activity has been extended to the EVITA project providing positive feedbacks on the European ASTEC code. Code users involved in the design, in the mitigation measures or in the emergency plans have gained important information about the uncertainties that exist when applying their tools for SA situations. Dissemination of results were met through distribution of improved SA codes. The results were also publicised in the QUENCH workshops at FZ Karlsruhe and in Phébus meetings. B₄C results were of particular interest for the future Phébus FPT3 test. Strong links with some 5th FP projects such as ENTHALPY, EVITA, THENPHEBISP and also with QUENCH and CORPHAD ISTC projects enabled the definition of complementary efforts and improved exploitation of results.

E. CONCLUSIONS

A large experimental database was produced involving key results:

- Main B₄C oxidation issues have been largely resolved. The large database produced from SETs and large scale CODEX and QUENCH bundle tests showed that B₄C oxidation is strongly dependent on thermal-hydraulic conditions. Productions of limited H₂, CO, CO₂, very low CH₄ and large amounts of aerosol were found. The CO and CO₂ production is sufficient to affect the volatile FP chemistry in the circuit, in particular the iodine speciation.
- Data obtained on oxidation of U-O-Zr mixtures showed faster kinetics than for pure Zr. These data confirm that mixtures are a significant source of H₂ production during core degradation and, mainly, during core reflooding. This is a key insight for the modelling the H₂-peak production during reflooding, which is presently inadequate in codes.
- Results on simultaneous UO₂ and ZrO₂ dissolution improved understanding of fuel rod liquefaction, nevertheless more data are needed on the induced clad failure and rod collapse.
- Data were produced on the burn-up effect on UO₂ dissolution and, for the first time, on MOX fuel dissolution, showing enhanced kinetics and greater apparent dissolution than for fresh fuel. Burn-up is a key factor suspected to favour the early fuel rod collapse.

Mechanistic and parametric models were produced on B₄C oxidation, fuel dissolution and mixture oxidation enabling SA codes under development in the EU to be upgraded. This effort was continued after the project to take full account of the findings and focussing more on the coupling between phenomena suspected to be as important as the separate models.

A large series of plant calculations was done, final ones run with codes improved by the project. Sensitivity studies and code-benchmarks enabled code uncertainties to be evaluated on the H₂ production, B₄C-reaction gases and corium behaviour. The implications for safety were identified as well as strengths and weaknesses of SA codes regarding core degradation.

Experimental and modelling results will be consolidated in the future SARNET network (6th FP), in particular on dissolution of irradiated fuel and on oxidation of mixtures during core degradation and reflooding. SA code weaknesses identified in the project will be addressed, the priority being put on the improvement of the European ASTEC code. Further plant applications with sensitivity studies and code benchmarking are strongly recommended.

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