Objectives

A severe accident (SA), which can arise on a nuclear reactor in case of safety systems failure, could develop via core heat-up in steam, components interaction phenomena, loss of core integrity, melt relocation and corium melt pool formation, if other counteraction measures were not successful. Core degradation and liquefaction are the source of risk from gas and fission products (FP) releases and corium formation initiates core melting scenarios. Consequently, the mechanisms and their interaction require detailed analysis and quantification. Powerful computer codes are used for safety studies to evaluate these effects and improve the accident management and hence reduce the overall risk of radioactive contamination.

The aim of the project was to improve the knowledge on key core degradation phenomena affecting the corium formation, and thus the gas and FP release, based on new experiments that enable SA code developments and/or improvements. Main topics studied were a) dissolution by molten Zircaloy (Zr) of fresh and irradiated UO_2 and MOX fuel (high burn-up), b) simultaneous dissolution of UO_2 and ZrO_2 in rod geometry, c) oxidation of liquid and solid U-O-Zr mixtures, d) oxidation of B_4C material, and e) degradation-oxidation of B_4C control rods (CR). Both PWR and VVER UO_2 and B_4C materials were investigated.

Three kinds of activities were performed: 1) experiments at different scales including global tests with fuel rod bundles, 2) modelling for SA codes and 3) plant calculations of significant severe accident sequences on various plant designs: PWR, BWR, VVER-1000, EPR and the TMI-2 accident.

Core Loss during a Severe Accident (COLOSS)

Challenges to be met

The main challenge addressed was the in-depth analysis of experimental results produced and the development of models for SA codes. The priority was put on the application of results in codes and on the implications of results on the safety viewpoint. Efforts were focussed on the following risk-relevant topics:

- Effects of B_4C, a neutron absorbing material used in high power nuclear reactors, were poorly understood, and models were either missing or inadequate. The main concern was to identify the gas production (H_2, CO, CO_2, CH_4, B-compounds) from B_4C oxidation suspected to affect the chemistry and transport of volatile FP out of the core, in particular that of iodine which represents the main radiological risk in the short-term of SA situations.

- Fuel dissolution responsible for liquefaction of the fuel ~1000 K below UO_2 melting point (~3100 K), was characterized by large uncertainties on the effect of burn-up and no data were available on MOX dissolution. Effects on the corium formation and final fuel rod liquefaction and collapse were not correctly understood.

- Metal-rich U-O-Zr mixtures oxidise in steam during relocation and freezing at lower core zones. This is a key source of H_2 during core degradation and particularly during reflooding. The corresponding modelling is either missing or inadequate. The main concern was the high H_2 production rates which can reduce the efficiency of H_2 mitigation measures in the containment or even determine a H_2 explosion risk.

Achievements

- Main B_4C oxidation issues have been resolved. The large database produced showed that B_4C oxidation is strongly dependent on thermal-hydraulic conditions. Productions of limited H_2, CO, CO_2, very low CH_4 and large amounts of aerosol were found (Fig. 1). The CO and CO_2 production is sufficient to affect the volatile FP chemistry in the circuit, in particular the iodine and caesium speciation. Models for B_4C-CR were developed and validated. These outcomes are of particular interest for the preparation of the Phébus FPT3 test dealing more specifically with B_4C effects on FPs.

- Data obtained on oxidation of U-O-Zr molten and solid mixtures showed faster kinetics than for pure Zr. This confirms that Zr-rich metallic mixtures (including B4C-rich metallic mixtures) are a significant source of rapid H_2 production during core degradation and, mainly, during core reflooding. This is a key insight for the H_2-peak production modelling during reflooding. Preliminary models were developed with enhanced oxidation kinetics and H_2 release rates.

- A significant database was produced on the burn-up effect on UO_2 dissolution and, for the first time, on MOX fuel dissolution, showing enhanced kinetics and greater apparent dissolution and fuel decohesion than for fresh fuel. Complementary results were produced on simultaneous UO_2 and ZrO_2 dissolution. Models taking into account burn-up effect and improved fuel rod liquefaction were developed.

- PWR and VVER UO_2 and B_4C materials were found to have similar behaviour.

- Models produced on B_4C oxidation, fuel dissolution and oxidation of mixtures enabled SA codes under development in the EU to be upgraded. Code improvements are being continued after the project to take full account of these findings.

- A large series of severe accident plant calculations was done using main codes in use in the EU. Final calculations were run with codes improved during the project. This activity is illustrated in Fig. 2 showing the final state of a VVER-1000 loss of coolant accident calculated by the ICARE/CATHARE code. Sensitivity studies and code-benchmarks enabled code weaknesses to be identified and uncertainties on COLOSS issues to be evaluated.

- The implications of results for safety were identified. In particular:
  - Calculations with the ASTEC code confirmed that CO and CO_2 from B_4C can convert in H_2-rich conditions of the circuit into CH_4 which then induces the formation of volatile CH_3I, a key factor for the radiological risk.
  - The burn-up was confirmed as a key factor driving the early fuel rod collapse observed in some conditions 400 K below the UO_2-ZrO_2 liquefaction point ~2870 K.
  - The scatter regarding *total H_2* prediction by codes was estimated to be in the 20-35% range and is probably larger for the high *H_2 rates* during rapid transients.

• Oxidation of melts during core degradation, which appeared to be underestimated, anticipates late corium oxidation and related H_2 evolution, thus reducing the risk ascribed to the late metal-oxide corium bevaviour.

Experimental and modelling results on COLOSS topics should be consolidated in the SARNET network (6th FP), in particular dissolution of irradiated fuel and 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. The follow-up of the plant calculation and benchmarking activity of COLOSS is planned for code assessment and re-evaluation of code uncertainties using upgraded versions.

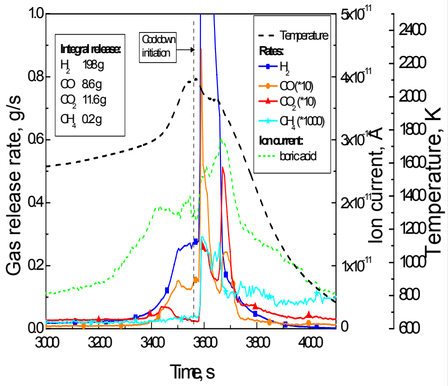

Fig. 1: QUENCH-07 test: B_4C-reaction gases and core temperature

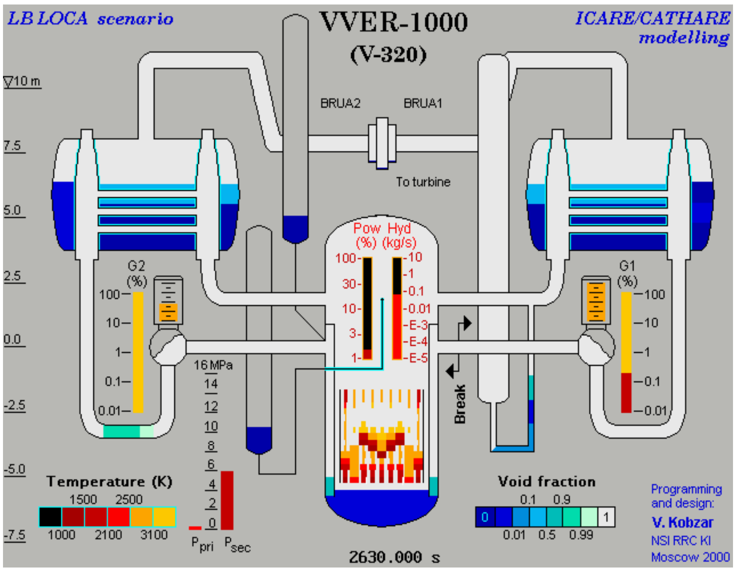

Fig. 2: Final state of a VVER-1000 Large Break depressurisation accident

Partnership

Eighteen partners from 13 EU, 2 NAS and 3 Russian laboratories having an excellent expertise on core degradation under SA conditions were involved in the project, including plant designers, R&D organisations working on nuclear safety, the French Utility and four Universities. Significant progress on knowledge and SA codes improvements was made possible thanks to a close cooperation inside the project between experimentalists and analysts and outside with the EVITA and ENTHALPY 5th FP projects and also with the Phébus FP and QUENCH programmes.

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Core loss during a severe accident **(COLOSS)**

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