Annals of Nuclear Energy 61 (2013) 23–35

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Early phase fuel degradation in Phébus FP: Initiating phenomena of degradation in fuel bundle tests

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ARTICLE INFO

Article history:
Received 30 October 2012
Accepted 31 October 2012
Available online 23 December 2012

Keywords:
Core degradation
Early phase
Severe accidents
Water-cooled reactors
Phébus FP

ABSTRACT

The international Phébus Fission Product Programme investigated key phenomena occurring in light water reactor core meltdown accidents in a series of five in-pile experiments. Four of these tests focused on the degradation of fuel rod bundles, containing a central control rod, and on the resulting release of fission products, structural materials and actinides from the fuel rod bundle, their transport in the reactor coolant system (RCS) and their subsequent behaviour in the containment vessel. Various steam contents were used in the RCS, from highly oxidising conditions (in FPT0 and FPT1) to more reducing ones (in FPT2 and FPT3).

The "early degradation phase" took place at the beginning of the Phébus driver core and fuel bundle heat-up phase, with a quasi-intact fuel bundle geometry. During this phase, the degradation of the control rod and the oxidation runaway due to the fast oxidation of the Zircaloy claddings of the fuel rods, were two major events which took place.

The oxidation runaway locally increased the temperatures much above the temperatures resulting from the Phébus driver core heat transfer to the bundle and yielded a large hydrogen release, which amounted to 70–80% of the whole hydrogen production during the tests. The maximum hydrogen flow rates increased with increasing steam flow rates injected at the fuel bundle inlet.

The failure mechanisms of silver–indium–cadmium (used in three tests) and boron carbide (used in one test) control rods involve eutectic interactions amongst the components of these control rods. Mechanical deformations of the control rod stainless steel cladding against the Zircaloy control rod guide tube are the main presumed mechanisms for the beginning of these eutectic formations. However, different post-failure scenarios can be postulated for the effect of control rod degradation on fuel bundle degradation for both types of control rods. The exothermic oxidation of the exposed boron carbide pellets led to the release of carbonaceous species (CO, CO_2) as well as of additional hydrogen, but no significant methane release could be detected above the limits of detection.

Overall, the results confirmed existing knowledge concerning early phase degradation phenomenology found in previous integral experiments such as CORA and QUENCH (Karlsruhe Institute of Technology) and Phébus SFD (IRSN Cadarache), and formed a sound basis for analysis of the late phase degradation subsequently observed. Quantitative analysis of boron carbide control rod degradation in FPT3 pointed to a need for improved modelling of chemical reactions involving this material, particularly its oxidation in steam; this has been studied in the BECARRE experiments conducted by IRSN in the International Source Term Programme, leading to better quantitative understanding and improved modelling in codes such as the European reference severe accident analysis code ASTEC.

1. Introduction

Since the TMI-2 accident in 1979 (Nuclear Technology, 1989) which led to the meltdown of about one half of the reactor core and to limited releases of radioactive substances to the environment, an important international effort has been made on severe accident research, involving integral experiments, separate-effects tests, model development and application of these models in simulation tools. From the beginning, the Phébus FP programme, owing to its integral nature, has been considered as a necessary complement to the qualification, one by one, of physical models

Abbreviations: AgInCd, silver–indium–cadmium; BR3, Belgian Reactor 3; BWR, boiling water reactor; B_4C, boron carbide; FP, fission product; ISP, International Standard Problem; ISTP, International Source Term Programme; KIT, Karlsruhe Institute of Technology; LWR, light water reactor; OECD, Organisation for Economic Cooperation and Development; PWR, pressurised water reactor; RCS, reactor coolant system; SS, stainless steel; VVER, pressurised water reactor of Russian type (Vodo-Vodianoï Energuetitcheski Reaktor).

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http://dx.doi.org/10.1016/j.anucene.2012.10.026

developed using the results of separate-effects experiments, which have the disadvantage of needing hypotheses about the additivity of different effects and do not ensure that important phenomena have not been omitted (Clément and Zeyen, this issue; March et al., this issue).

The Phébus FP programme investigated key phenomena involved in light water reactor (LWR) severe accident sequences through a series of five in-pile integral experiments, including one test in debris bed geometry, FPT4, which will not be described here, and four tests performed in a fuel rod bundle configuration with irradiated UO_2 fuel (of moderate burn-up, lower than 40 GWd/tU), see Table 1. The test sequences involved heating of the bundle through a succession of power ramps and plateaus, leading to an oxidation runaway, further ramps and plateaus leading to fuel melting and relocation, with the degradation phase being terminated by reactor shutdown about 5 h after the beginning of the heating phase. These sequences led to core degradation far beyond any other integral experiment so far performed, (such as PBF SFD, Phébus-SFD, CORA, FLHT and LOFT-LP-FP-2, see (Haste et al., 1995 and references therein)).

The facility provided prototypic reactor conditions which allowed the study of basic phenomena governing core degradation up to the late phase (melt pool formation), and going through hydrogen production, fission product (FP) release and transport, circuit and containment phenomena, and iodine chemistry.

The objectives of this paper are to summarise the main experimental outcomes of the fuel rod bundle test series concerning the initial degradation phase in the bundle, called the "early degradation phase". These experimental outcomes are based on the Final Reports of the Phébus tests, and emphasis is put on the experimental data themselves rather than on detailed interpretation of the results. A review of the main experimental results follows directly without emphasis on the description of the facility and of the bundles. Such aspects are described further in (March et al., this issue).

The Phébus FP tests were amongst the few severe accident experiments carried out with irradiated fuel. The effect of the burn-up on the degradation of AgInCd or B_4C control rods should be very limited and will not be discussed in this paper. The melting temperature of irradiated fuel could however be dependant on burn-up, but this concerns more the late phase of fuel degradation in Phébus, as discussed in (Barrachin et al., this issue).

2. Summary of experiments

2.1. Bundle test objectives

The general objectives of the Phébus tests may be stated separately for the fuel degradation, the fission products behaviour in the experimental circuit and in the containment. For the fuel degradation, the two objectives concerning the four tests performed in a fuel rod bundle configuration (FPT0, FPT1, FPT2 and FPT3) were:

- To reach an instantaneous molten fuel mass of about 2 kg (out of 10 kg) in the bundle except for FPT3 where the target instantaneous molten fuel mass was limited to 1 kg.
- To study significant fuel degradation by reaching the liquefaction temperature of the fuel to produce fuel-molten cladding interaction, representative control rod failure and large releases of volatile FPs (about 80%) in a low-pressure and oxidising carrier gas (for FPT0 and FPT1) or in a temporarily-reducing carrier gas (for FPT2 and FPT3). For FPT2, boric acid was added to the injected steam and for FPT3, the effect of B_4C absorber material was studied instead of that of AgInCd.

2.2. Phébus test overview

The first test, FPT0, was carried out in December 1993 (test scenario displayed in Fig. 1). The test bundle contained 20 fresh UO_2 PWR fuel rods and one silver–indium–cadmium absorber control rod (Hanniet-Girault and Repetto, 1999), (Clement et al., 2003). Molten material movements were initially detected in the bundle for fuel temperatures close to 2300–2400 °C and leading at the end of the degradation phase to about 50% of the total fuel mass being liquefied (or degraded), inducing a large release (>80%) of the most volatile fission products.

FPT1 was the second experiment of the Phébus FP Programme. It was performed in July 1996 under similar experimental conditions as in FPT0 (see Fig. 1), but using irradiated fuel from the BR3 reactor. The FPT1 test bundle included eighteen UO_2 PWR fuel rods previously irradiated to a mean burn-up of 23.4 GWd/tU, two instrumented fresh UO_2 fuel rods and one silver–indium–cadmium absorber rod (Jacquemain et al., 2000). Concerning the bundle degradation, the relatively low "relocation temperature" of the fuel rods, estimated in the range 2100–2200 °C, was an important result that confirmed results of the FPT0 experiment. This test also showed that degraded material accumulated on the Zircaloy-4 spacer grids placed at 240 mm and 760 mm, as well as showing the influence of the grid failure upon the melt progression at the bottom of the bundle.

The next experiment was FPT2, performed in October 2000 (Grégoire et al., 2008) according to the scenario displayed in Fig. 1. The fuel bundle configuration was similar to that of the previous test, FPT1, but with BR3 fuel irradiated up to a mean burn-up of 31.8 GWd/tU. The test conditions were also very similar to conditions of the previous FP tests, except for the steam flow rate which remained constant at a low value of 0.5 g s^{-1} during the heat-up phase, thus allowing the study of the effects of reducing conditions during the degradation phase. Concerning the bundle degradation, local relocations began with even lower fuel temperatures than in FPT0 and FPT1 at about 2000 °C, and the degradation objectives were reached with a mass excess in the molten pool zone of about 2.9 kg.

The last experiment FPT3 was performed in November 2004 with BR3 fuel irradiated to 24.5 GWd/tU (Payot et al., 2011). It completed the FPT0, FPT1 and FPT2 test series, with steam-poor flow conditions, similar to the previous FPT2 test, but with a boron carbide control rod used as absorber. The FPT3 test was conducted according to the scenario displayed in Fig. 1 and it provided unique data on the oxidation and degradation effects of the B_4C control rod during the bundle degradation. Again, the relatively low liquefaction and relocation temperatures (2200–2300 °C) of the fuel rods

Table 1
Phébus-FP test matrix – degradation aspects.

Test	Type of fuel	Circuit aspects
FPT-0	Fresh fuel, 9 days pre irradiation, 1 Ag–In–Cd rod	Melt progression and FP release in steam-rich environment
FPT-1	BR3 fuel ≈ 23.4 GWd/tU, 1 Ag–In–Cd rod, re-irradiation	As FPT-0, steam-rich conditions, with irradiated fuel
FPT-2	As FPT-1, 1 Ag–In–Cd rod, but with fuel ≈ 31.8 GWd/tU, re-irradiation	As FPT-1, but steam-poor conditions, with irradiated fuel
FPT-3	As FPT-1 with B4C instead of Ag–In–Cd, fuel 24.5 GWd/tU, re-irradiation	As FPT-2