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TESTING OF FBR FUEL AND CORE STRUCTURAL MATERIALS IN A MATERIALS TESTING REACTOR

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ABSTRACT

The irradiation programme on testing of FBR fuel and core structural materials will continue over the next years in the High Flux Reactor, HFR, at Petten, the Netherlands. The series of experiments are sponsored by the Kernforschungszentrum Karlsruhe (KfK) in support of the European Fast Reactor (EFR) programme. Additional experiments, sponsored by the Institute for Transuranium Elements (TUI) at Karlsruhe, are designed to study advanced nitride fuel behaviour. Although the HFR is a thermal reactor, fast reactor conditions can be simulated by suitable design of the irradiation devices; for example, the in-pile carriers for fuel irradiation are provided with cadmium screens in order to cut off the thermal neutrons. The fuel pins and the core structural material samples are immersed in sodium and encapsulated in double-containment sealed tubes, and placed in individually cooled experimental carriers, for placement in the reactor. Fuel irradiation conditions that can be simulated include start-up behaviour, power cycling and ramping, transient or steady-state overpower up to fuel melting and loss-of-flow. Pre-irradiated high burn-up fuel pins, having achieved end-of-life conditions in the European fast reactors PHENIX and PFR are also tested. Irradiation of core structural material samples, in sodium up to temperatures of ~823 K, for investigation of tensile and fatigue behaviour are continuing with martensitic steel and AISI 316L. The paper here gives a description of the typical features of an irradiation device, its instrumentation, some of the available ancillary equipment, developments and some results of the experiments.

INTRODUCTION

Since the late 1970s, over 60 FBR fuel pins have been experimentally tested at the High Flux Reactor (HFR) Petten, Netherlands. The HFR, owned and managed by the Commission of the European Communities, is a 45 MW material testing reactor, cooled and moderated by light water /1/. The standard core configuration of the reactor allows up to 17 free positions into which experimental facilities may be placed for irradiation. Depending on the position in the core, a variety of nuclear conditions can be attained. The reactor is also equipped, outside the vessel, with two poolside facilities (PSF) designed to allow for fuel pin power transient tests to be performed, whilst maintaining the reactor power constant. By suitable design of the experimental facilities, fast reactor conditions can be sufficiently achieved and operating conditions, such as start-up and shut-down behaviour, power cycling and ramping, fuel melting, transient over-power and loss-of-flow, can be readily simulated. The extensive FBR programme at Petten /2/ studies the performance of both fuel pins and core structural material. The fuel pin experiments are primarily sponsored by the Kernforschungszentrum Karlsruhe, KfK, previously in support of the development of the demonstration fast breeder reactors SNR-300 and SNR-II, but lately for the European Fast Reactor, EFR, programme /3/. FBR fuel irradiation experiments in the HFR can readily achieve irradiation conditions that simulate transients up to 160% over nominal power, at transient rates up to 5% per second, combined with the possibility to change simultaneously the fuel cladding temperature during the transient. The duration of an experiment varies between a few hours to 2-3 years. With these capabilities, certain features can be measured that are not possible in actual demonstration reactors. These include measurements of the axial increase in the fuel stack and cladding during a transient, measuring the diametral clad displacement at intermittent periods, performing power-to-melt experiments, and utilizing such non-destructive techniques as noise analysis, neutron radiography and gamma spectrometry (scanning) to assess the overall fuel behaviour. From the range of experiments already performed and completed, a wealth of data has been generated on fuel material behaviour under many different operating conditions. The information is used by fuel modellers at KfK and Siemens to help in predicting very accurately fuel behaviour under many envisaged scenarios. In addition, models are being developed to predict power-to-melt conditions (from 16 fuel experiments), cladding diametral displacement (from a recently completed three-year programme) and core reactivity effects due to axial displacement of fuel during a transient (from an on-going series of 5 fuel pin experiments in which the fuel and cladding axial displacement are directly measured). From the range of experiments performed so far, apart from three of the fuel pin irradiations, all used fresh fuel. The said three fuel pins, from a batch of six, were pre-irradiated in the KNK-II reactor at Karlsruhe. Encapsulation of these pre-irradiated fuel pins at Petten is made possible in the specially designed hot cell, called EUROS /4/. The present trend for FBR experiments at the HFR is towards fuel pin behaviour and performance at high burn-up. For this reason, and under the guidance of the EFR working groups, future irradiation experiments will be directed towards pre-irradiated high burn-up fuel. In summer 1993, fuel pins irradiated up to 10% burn-up in the Phenix FBR in France, will be tested at the HFR Petten. Some of the experiments performed already on fresh fuel will be essentially repeated using pre-irradiated fuel. Irradiation of core structural material samples, in the temperature range 523-823 K for investigation of tensile and fatigue behaviour are continuing with martensitic steel and AISI 316L. This report describes the current programme and trends, a typical FBR irradiation device, the instrumentation used, the available ancillary equipment for post-irradiation work and some experiment results.

IRRADIATION DEVICES & INSTRUMENTATION

A typical experiment basically consists of the test sample, fuel pin or structural material, immersed in liquid metal (Na or NaK), surrounded by a molybdenum shroud for the placement of thermocouples and flux detectors, and then sealed and contained in double, stainless steel containment tubes. The experiment is cooled by water, forced convection, outside of the secondary containment. The experiments are placed in either one-, two- or three-channelled carriers for irradiation. Specially shaped neutron absorbers are designed to compensate the asymmetry in the flux distribution across the fuel due to any neighbouring experiments. The gap between the primary and secondary containments is filled with a mixture of helium/neon/nitrogen. The size of the gap and the mixture of the gases is predetermined by thermal analyses to give the desired fuel cladding or material sample temperatures. The temperature can be adjusted at any time during operation, by changing the composition of the gas mixture. From heat balance equations the increase in the coolant temperature, for a given coolant flow rate, determines the fuel pin power. All the instrumentation, standard and specialised, is connected to the general data acquisition and monitoring system, DACOS /5/. In addition to the in-core positions, the reactor is equipped with a pool-side facility, PSF, outside the reactor vessel wall, see Fig.1. In Fig.1, a cross-section of the reactor set-up is shown indicating a typical PSF and in-core experiment, when positioned for irradiation. The in-core fuel experiments are irradiated under a Cd screen to cut-off the low energy thermal neutrons. In-core experiments are cooled by the reactor primary coolant system, while the PSF experiments are individually cooled at controllable coolant flow rates. The PSF is designed to allow for power transients to be performed without any change in reactor power being necessary. Here most of the FBR transient experiments are carried out. Transient rates up to few % per seconds can be readily achieved /6-7/. The rig standard instrumentation includes: shroud thermocouples, Cr/Al or W/Re, to measure cladding temperatures; calibrated water thermocouples, Cr/Al, to measure inlet and outlet water temperatures; precision differential pressure transducers or flow meters to measure the water flow; Co self-powered neutron detectors to measure on-line the neutron fluence rate; and flux detectors to measure, out-of-pile, the integrated neutron fluences. Besides the general instrumentation, each rig can carry specialised instrumentation, specially designed to comply to the aim of the specific experiment. All the instrumentation, standard and specialised, is connected to the general data acquisition and monitoring system, DACOS. These data, plus general reactor data, are scanned and stored at variable frequencies: from 0.1 to 10 Hz.

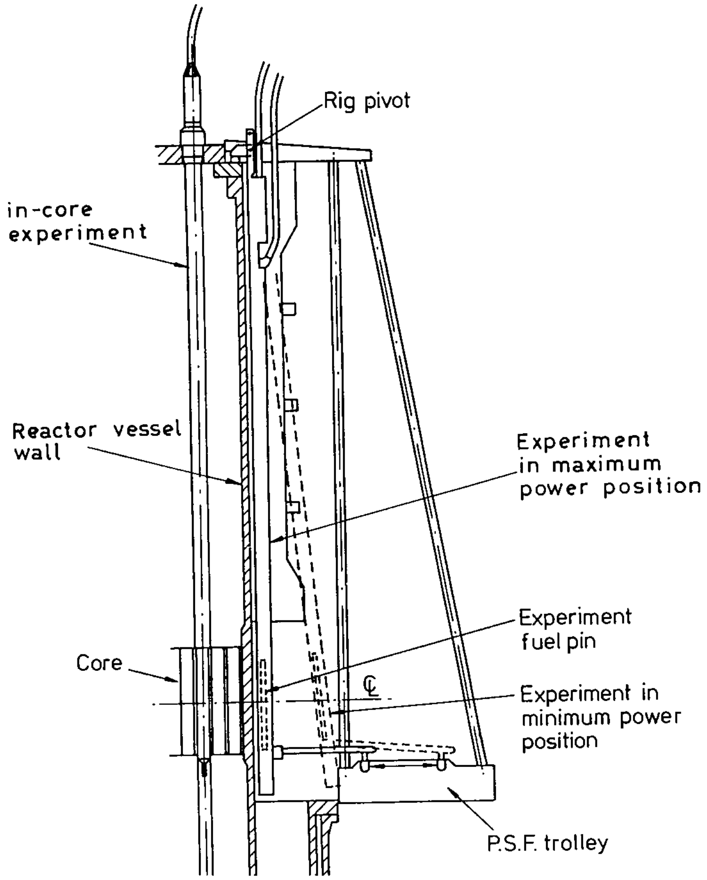

Figure 1 - Vertical cross-section through reactor vessel, indicating in-core and PSF experiments in position

TRANSIENT TESTS WITH PRE-IRRADIATED FBR FUEL

The transient testing of FBR irradiated high burn-up fuel pins implies some additional problems when compared with similar experiments with fresh fuel. Firstly, the dimensions of actual FBR pins have pre-fixed dimensions, being normally much longer than the fresh pins specifically designed for testing. The handling of such pins in all phases can only be done in sealed, shielded containers, able to accept longer pins. The irradiation carrier must also be capable of accepting such long and different pins. Cleansing and surface decontamination of the pins have to be performed, and carried out in a hot cell. Finally, the encapsulation and sodium-filling must also be performed in a specially equipped hot cell for the task; i.e. a sodium-filling station, remote controlled welding and helium leak test equipment. The pin and capsule handling is performed at Petten by means of two, internally shielded transport containers: ILONKA and EUROS-container. The ILONKA container is a dry shielded container, whilst the EUROS-container is able to go under water to unload the capsules in the HFR pool. Both containers are equipped with a SYNTACS loading port. The PSF irradiation carrier, see also Fig.1, can accept different capsules up to a length of 2.2 m. The pin cleansing and surface de-contamination can be performed in the ECN hot cells. The cleansed and de-contaminated pins are encapsulated and sodium-filled in the specially designed, JRC hot cell EUROS /4/, EUropean Remote encapsulation Operating System. The cell is alpha-tight and equipped with sodium filling, welding and helium leak testing installations. It is also provided with a SYNTACS load port.

For the high burn-up pre-irradiated fuel pins, the presence of poisons severely restricts the achievable fissile power. The poisons are fission products, mainly Sm, that have a very large thermal cross-section. In an FBR neutron spectrum, they are not burned effectively and accumulate in such a high quantity as to depress strongly the thermal neutron fluence rate. Hence the maximum achievable linear fissile power in the pool side facility of the reactor is severly reduced /7/. However, this is solved by pre-conditioning of the fuel pins. In this phase, the fuel is kept at constant power, for a known, calculated time, in order to burn most of the poisons. Constant fuel power is obtained by gradually withdrawing the capsule on the PSF as the poison concentration decreases. The poison pre-burning time is in the range of a few HFR cycles, which are 25 days each. After this time, the poisons have almost reached an equilibrium value and the pins are ready for a power increase and ramping.

POWER-TO-MELT EXPERIMENTS

The determination of rod powers leading to fuel melting is the objective of the POTOM experimental series. At present, a total of 9 fuel pins have been irradiated and 3 are currently in irradiation in the HFR; 6 more fuel pins are planned to be tested in 1994. The temperature of fuel melting depends on the plutonium content, hence three concentrations of Pu are used: 15%, 20% and 30%. The POTOM test matrix is summarized in Table 1. The previously performed POTOM tests irradiated fuel pins at low linear fissile power for a time duration ranging from 1 hour to 4 days. After this irradiation period, the pins were brought and maintained, for a few minutes, at the target high power for melting. The tests with the remaining fuel pins will be similar but at different accumulated burn-up stages, implying much longer, low fissile linear power irradiation times: up to 192 days. From the post-irradiation, gamma scanning measurements, it is possible to obtain the actual, axial shape of the fissile power along the fuel axis. It is then possible to attribute the local power to identified regions where melting occurs. The available results, evaluated by KfK Karlsruhe /8/, are shown in Fig. 2.

Table 1 - POTOM EXPERIMENT MATRIX

TEST - PIN Number	Pu % - pin design	Pre-irradiation power level - duration	Maximum power
POTOM 1 - pin 1	15% - heterogeneous	480 W cm^{-1} - ~1 hour	830 W cm^{-1}
POTOM 1 - pin 2	20% - heterogeneous	530 W cm^{-1} - ~1 hour	830 W cm^{-1}
POTOM 1 - pin 3	30% - heterogeneous	450 W cm^{-1} - ~1 hour	805 W cm^{-1}
POTOM 2A - pin 4	15% - heterogeneous	480 W cm^{-1} - ~2 days	615 W cm^{-1}
POTOM 2A - pin 5	20% - heterogeneous	510 W cm^{-1} - ~2 days	636 W cm^{-1}
POTOM 2A - pin 6	30% - heterogeneous	500 W cm^{-1} - ~2 days	608 W cm^{-1}
POTOM 2B - pin 7	15% - heterogeneous	440 W cm^{-1} - ~3 days	847 W cm^{-1}
POTOM 2B - pin 8	20% - heterogeneous	480 W cm^{-1} - ~3 days	879 W cm^{-1}
POTOM 2B - pin 9	30% - heterogeneous	490 W cm^{-1} - ~3 days	845 W cm^{-1}
POTOM 3 - pin 10	20% - homogeneous	470 W cm^{-1} - ~4 days	639 W cm^{-1}
POTOM 3 - pin 11	20% - homogeneous	505 W cm^{-1} - ~4 days	676 W cm^{-1} (*)
POTOM 3 - pin 12	20% - homogeneous	430 W cm^{-1} - ~4 days	630 W cm^{-1} (*)
POTOM 3 - pin 13	20% - homogeneous	no pre-irradiation	423 W cm^{-1} (*)
POTOM 4 - pin 14	15% - heterogeneous	450 W cm^{-1} - 96 days (**)	750 W cm^{-1} (**)
POTOM 4 - pin 15	20% - heterogeneous	450 W cm^{-1} - 144 days (**)	750 W cm^{-1} (**)
POTOM 4 - pin 16	30% - heterogeneous	450 W cm^{-1} - 192 days (**)	750 W cm^{-1} (**)

(*) re-irradiated for 18 days at ~ 450 W cm^{-1} (**) current planning

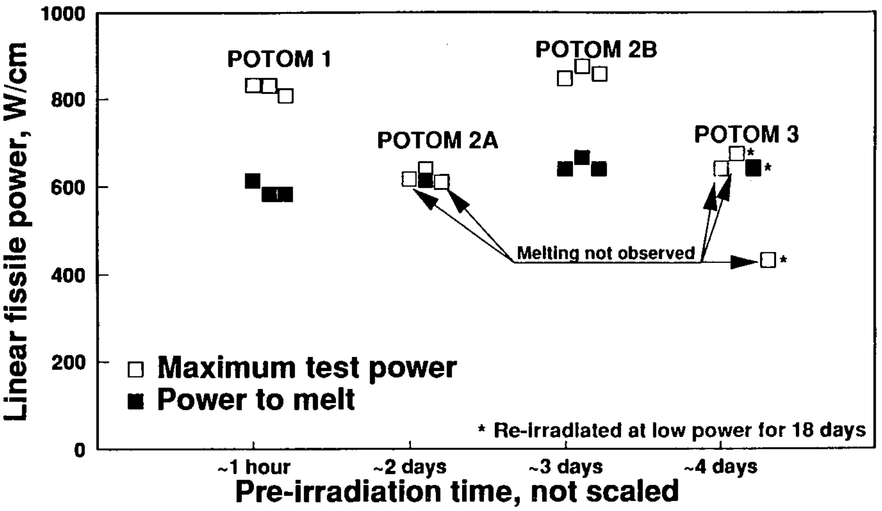

Figure 2 - POTOM RESULTS

IRRADIATION OF STRUCTURAL MATERIALS

The behaviour of structural material properties as a function of damage, dpa, and temperature is carried out in the experimental series SINAS, Steel Irradiation in NAtrium. The objective of the experiment is to compare the crack propagation and fracture toughness properties between unirradiated and irradiated AISI 316 and Martensitic steel specimens. The irradiation temperatures vary between 523 to 823 K, with accumulated displacement damage between 0.5 to 1.0 dpa. Some interesting results were obtained for irradiated steel samples of electron beam welded DIN 1.4914, EBW, at 0.5 dpa and 525 K /9/. A summary of the results is given in the following:

Impact toughness. The brittle-ductile transition temperatures of the plate and EBW's are identical below 270 K. The upper-shelf energies of EBW metal are higher than those of plate.

Tensile testing. There exists a small but significant difference between the 0.2% yield stress, YS, and the ultimate tensile strength, UTS. In Fig. 3, the UTS of irradiated EBW joints and joints in reference condition can be compared. At 0.5 dpa and 525 K, considerable hardening is induced; being typical for ferritic martensitic alloy. The total elongation decreases from 15-20% in reference conditions, to 10-15% for the temperature range of 300-900 K.

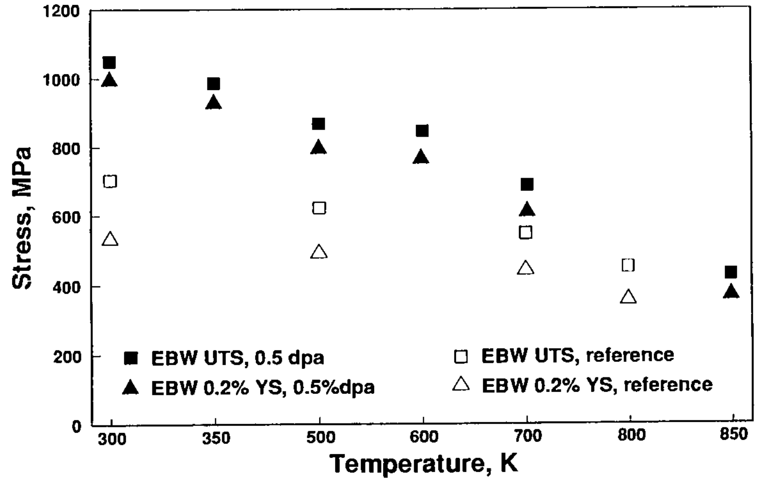

Figure 3 - 0.2% yield stress, YS, and ultimate tensile strength vs. test temperature of EBW

Creep testing. From the preliminary results, it appears that rupture times up to 5000 hours are obtained at 800 K. Reduction of creep strength of 15 MPa are observed for EBW when compared to parent metal; implying rupture time reductions by a factor 3-4 compared with the reference specimen.

CONCLUDING REMARKS

The FBR experimental programme of irradiations at the HFR Petten has performed over 60 irradiations on various FBR fuel pins and several irradiations on structural materials. Although the HFR is a thermal reactor, fast reactor conditions can be simulated by suitable design of the irradiation devices. The different series have studied and have demonstrated that start-up behaviour, power cycling and other conditions, using both fresh and pre-irradiated fuel, can be readily simulated. The irradiation programme on the transient testing of FBR fuel pins will continue over the coming years at Petten. The new challenge is the irradiation of pre-irradiated, high bum-up fuel pins originating from European fast reactors. Prior to irradiation testing, the fuel pins, after having achieved end-of-life conditions in reactors, such as PHENIX and PFR, are decontaminated, encapsulated and the capsule sodium-filled and welded in the dedicated hot cell, EUROS. The cell is designed to allow pre-irradiated fuel pins to be encapsulated in a standard type capsule, by remote control, in a fully-shielded environment. A wide variety of results have been drawn. Only two of the many have been addressed in this paper. In particular, the POTOM series of experiments, have been extensively valuable.

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