STATUS OF FACILITIES AND EXPERIENCE FOR IRRADIATION OF LWR AND V/HTR FUEL IN THE HFR PETTEN

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The present paper describes the 45 MW High Flux Reactor (HFR) which is located in Petten, The Netherlands. This paper focuses on selected technical aspects of this reactor and on nuclear fuel irradiation experiments. These fuel experiments are mainly experiments on Light Water Reactor (LWR) and Very/High Temperature Reactor (V/HTR) fuels, but also on Fast Reactor (FR) fuels, transmutation fuels and Material Test Reactor (MTR) fuels.

KEYWORDS : High Flux Reactor, Fuel Testing, HTR, LWR, FR, Transmutation, Ramp Test

1. INTRODUCTION

The High Flux Reactor (HFR) in Petten is owned by the European Commission's Joint Research Centre (JRC) in Petten, The Netherlands. The research reactor has a thermal power of 45 MW. The reactor operation, maintenance and commercial exploitation are performed by NRG, who has recently also become the license holder.

The HFR is crucial for some activities of NRG and offers many possibilities for research, training, industrial applications and gaining expertise in nuclear technology. At the Petten site, a well-equipped Hot Cell Laboratory for post-irradiation examinations, and a Mo-99 production facility are available. NRG (Nuclear Research and consultancy Group) is the main nuclear research institute in The Netherlands. Besides a wide range of activities related to the HFR, it performs all kinds of services, such a radiation protection, computational analyses and risk assessments. The present paper describes the facilities, which are available at the HFR for the various types of fuel. The present paper focuses on (V)HTR and LWR fuel testing.

2. THE HIGH FLUX REACTOR

2.1 The Irradiation Facility

The HFR is a 45MW tank-in-pool type reactor. The reactor tank is part of the closed primary coolant circuit and is immersed into a water filled pool. The core lattice is a 9x9 array containing 33 fuel assemblies, 6 control elements, 17 experimental positions and 23 reflector elements. The useful height of the core is 600 mm. With the control elements inserted from below the tank, the top lid provides easy access for the in-vessel irradiation positions. In addition, there is the Pool Side Facility (PSF). This PSF is used for materials and fuel irradiation experiments and for the production of radioisotopes. Larger objects such as e.g. graphite blocks can as well be tested (maximum width typically 65mm).

A horizontal cross section of the core is shown in Figure 1. At the left side of the figure, the Pool Side Facility is shown in which experiments can be moved to and from the core. Three out of the four sides of the core are surrounded by beryllium reflector elements. The sections marked by circles are the experiment positions. The hatched sections mark the locations of the fuel elements.

The HFR is operated at full power (45 MW) during 290 days per year. This is done according to a strictly planned schedule. The high number of full power days allows achieving a high fuel burn-up in a relatively short period. The HFR has 17 in-core irradiation positions. In each irradiation position various types of highly standardized inserts can be placed which allow placing up to four independent experiments in one irradiation position. This system strongly enhances the flexibility in the use of the

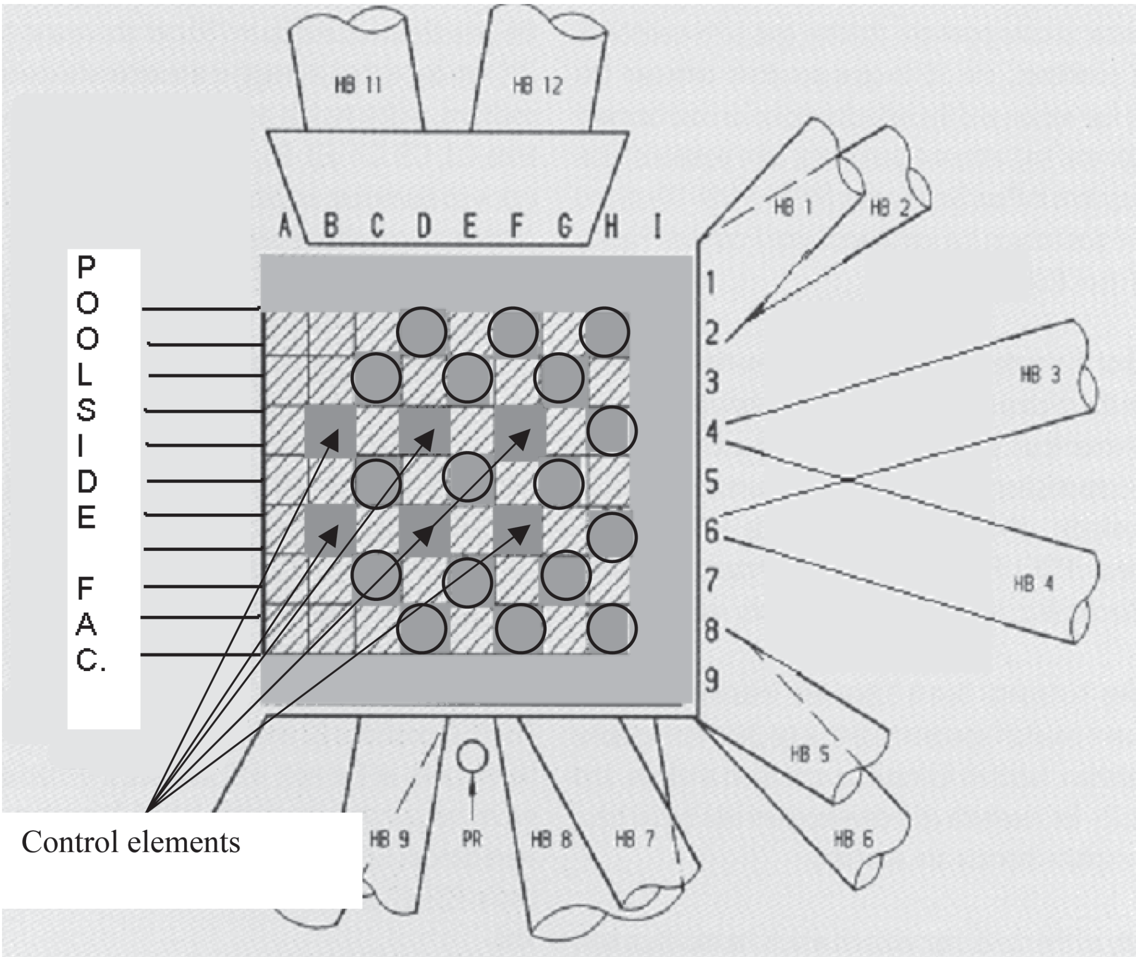

Fig. 1. Horizontal Cross Section of the HFR. The Locations of the Twelve Beam Tubes are Shown (HB1-HB12)

HFR. The large range in neutron flux conditions within the in-core positions makes the HFR a versatile tool for irradiation studies.Initially, the HFR was primarily used for material and fuel research. Past research mainly focussed on the resistance of materials to irradiation with neutrons and on the fuel behaviour during irradiation. Especially materials for fusion and fission reactors were evaluated and tested to demonstrate (or not) the feasibility and to enhance the reliability of components.

In addition to this traditional research many projects not related to energy were initiated in the more recent years:

- Isotope production for medical applications; some 60% of European demand for medical isotopes is supplied by the nuclear facilities in Petten;
- Isotope production for industrial applications (e.g. Ir-192 gamma sources);
- Neutron Transmutation Doping (NTD) of silicon ingots;
- Characterization of materials with neutronographic and activation analyses;
- Product improvement with gamma irradiation;
- The use of neutrons for the irradiation of tumours (mainly brain-tumours), called Neutron Capture Therapy (NCT).

2.2 Auxiliary Equipment

In the HFR and the Hot Cell Laboratory in Petten, a large range of examination equipment is available. Neutron radiography of fuel-irradiation experiments is a powerful tool that can be used to study the fuel structure during interruptions of the irradiation. An example of a fuel segment, which has been studied with neutron radiography is shown in Figure 2. The figure shows two hafnium pellets that can be seen as black squares at either end of the fuel stack. In the middle ten fuel pellets can be seen. Between the fuel pellets and the hafnium pellets, $MgAl_2O_4$ ceramic pellets are located which cannot be detected by neutron radiography.

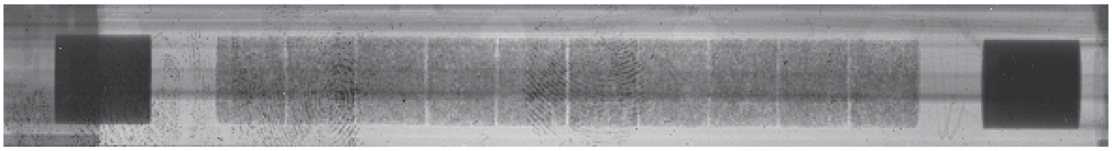

Fig. 2. Section of a neutron radiograph made of a fuel rodlet consisting of a ceramics inert matrix containing fissile (Pu) particles [1]. The separate pellets can be detected and it can be detected that they show proper behaviour.

3. LWR FUEL TESTING

3.1 LWR Fuel Ramp Testing

Light Water Reactor fuels can be irradiated both at base-irradiation conditions and ramp testing conditions. Ramp testing of PWR fuels is done in the so-called BWFC facility. This facility is applied for the irradiation testing of single LWR fuel rods under typical LWR conditions. Considerable experience has been gathered with this facility, during several hundreds of transients and performance tests using pre-irradiated segmented fuel rods from commercial power reactors or re-fabricated fuel rods. The fuel rod is contained in a pressurized capsule. The outside of the pressurized capsule is cooled by pool water of the HFR. In the capsule support thermocouples and a water flow meter are used to determine the instant fuel rod power.

The BWFC facility is placed in the Pool Side Facility of the HFR. The power of the fuel can be varied in a continuous manner by changing the distance between the fuel rodlet and the reactor core. The fact that the facility is placed in the PSF enables changing the power very rapidly and independently of the reactor power. This also allows to “freeze” a fuel rodlet directly after detection of the failure of the capsule by fast withdrawal of the facility away from the reactor core. The maximum allowed linear power in the facility is 700 W/cm.

The pressurized primary water system is conceived as a miniature loop enabling monitoring during the irradiation of cladding failures by means of activity monitors. Cobalt self-powered neutron detectors are provided for supplementary supervision of transient conditions.

3.2 LWR Fuel Base-Irradiation

LWR fuel base-irradiation can be done in various manners in the HFR. The most common is placing the fuel in a double stainless steel-contained sodium bath containing stagnant sodium. By controlling the heat transfer between the sodium and the cooling water of the reactor, the temperature of the fuel cladding can be adjusted to LWR values (300-350 °C). The sodium temperature is measured by thermocouples that are located directly in the stagnant sodium close to the fuel cladding. The fuel rodlets can be equipped with pressure transducers (to evaluate the release of fission gases) and with central thermocouples.

The advantage of this technique is that an LWR relevant cladding temperature can be achieved without handling high-pressure coolant water. This technique does, however, not cause an LWR typical pressure on the outside of the fuel cladding; hence it is not fully representative for LWR conditions.

4. V/HTR FUEL TESTING

4.1 Background

Fuel and fuel element structures of an HTR fuel element (typically spherical pebbles or cylindrical compacts) are the first barriers against fission product release. The assessment of fission product retention under normal and off-normal operating conditions is therefore the primary goal of HTR fuel irradiation experiments. Starting from screening tests of experimental coated fuel embedded in coupons or compacts, large irradiation programs in the 1980’s and 1990’s concentrated on performance testing of reference coated fuel particles and reference fuel elements. In particular, the UO_2 Low Enriched Uranium (LEU) fuel cycle for the German concepts HTR-MODUL and HTR-500, as well as the LEU fissile/ThO_2 fertile fuel system for former US HTGRs have extensively been investigated at the HFR. These programs on HTR fuel testing were terminated in 1994. More details can be found in [2].

Around the year 2000 the European interest in the HTR concept revived, which did amongst others lead to the start of European projects on HTR fuel research (HTR-F/F1) [3,4]. Within these projects, two HTR fuel irradiation tests will be performed in the HFR, codenamed HFR-EU1 and HFR-EU1bis. A consortium of 7 partners is participating in these projects that are co-financed by the European Commission: CEA (coordinator), Framatome-ANP, NRG, FZJ, JRC-ITU, JRC-IE and BNFL.

For these projects, the global objective focuses on the innovation potential of past and current HTR fuel technology based on the German TRISO coated fuel particle design.

The experiments HFR-EU1 (planned to start in 2006) and HFR-EU1bis (completed in 2005) share the objective of exploring the potential for high performance and high burn-up of the existing fuel pebbles for application in a pebble bed VHTR. During extensive irradiation tests at

Table 1. Experimental Requirements for HFR-EU1bis Compared to HFR-EU1

Parameters	HFR-EU1bis(GLE-4 pebbles)	HFR-EU1(GLE-4 pebbles)	HFR-EU1(INET pebbles)
n° of pebbles	5	3	2
particles/pebble	9560	9560	8500
Burnup[% FIMA]	16	$\leq$ 20	$\leq$ 17
Surface temp [ºC]	1000-1050 at BOI, raised to maintain central temperature constant at 1250	950	950
Fluence [m^{-2}] E > 0.1 MeV	approx. 5×10^{25}	$< 6.0 \times 10^{25}$	$< 5.3 \times 10^{25}$
Fission power[W]	< 3400 W/pebble < 340 mW/particle	< 2300 W/pebble < 241 mW/particle	< 1750 W/pebble < 206 mW/ particle
Fission gas release measurements	batch wise quantitatively	- continuous qualitatively - continuous quantitatively for one isotope (NaI detector) - daily quantitatively	- continuous qualitatively - daily quantitatively
Purge gas impurities	batch wise surveillance	$\leq$ 10 ppm after first irradiation cycle, continuous surveillance of up- and downstream of purge gas	$\leq$ 10 ppm after first irradiation cycle, continuous surveillance of up- and downstream of purge gas

and above nominal reference power plant conditions in the 1980's and 1990's, not a single coated particle of German 'near-to-production' fuel elements with LEU-TRISO coated particles failed in the sense of irreversibly increased fission gas release rate [2,5]. Irradiating this fuel under defined conditions to extremely high burn-ups and testing it afterwards in heating tests to simulate reactor core heatup accident scenarios will provide a better understanding of the fission product release and failure mechanisms, should coating failure occur.

HFR-EU1 is a combined irradiation of three German-made HTR fuel pebbles and two Chinese (INET made) pebbles. An overview of the experimental requirements for this irradiation is given in Table 1, while further information on HFR-EU1bis is provided in the next section.

4.2 HFR-EU1bis Irradiation Conditions

The main objective of HFR-EU1bis is the demonstration of the feasibility of low particle failure rates at very high temperature and burn-up for the existing German fuel. It includes in particular:

- Increased central fuel temperature up to 1250°C compared to 1000-1200°C in earlier tests;
- Irradiation to a burn-up of nominally 16% FIMA to explore the limits of the existing fuel that had originally been designed and licensed only for the operating conditions of the HTR-Modul, i.e. a burn-up of approximately 9% FIMA;
- Confirmation of low particle failure due to temperature, burn-up and neutron fluence;
- Confirmation of low 'free uranium' contamination of the fresh fuel pebble;
- Extension of the existing data base for metallic fission product release, particularly Ag-110m, for evaluating the suitability of this fuel for HTRs with direct Brayton cycle for power conversion;
- Post-irradiation verification of fission product retention by out-of-pile heating tests in the KÜFA facility beyond 1600°C. The KÜFA facility is an out-of-pile heating facility operated at the European Commission's Institute for Transuranium Elements JRC-ITU in Karlsruhe, Germany.

The fuel specimens are five HTR pebbles and six mini samples containing ten particles each. The six mini samples consist of Nb tubes ϕ 1.6/1.2 mm $\times$ 25 mm. The pebbles have an outer diameter of 60 mm.

4.3 HFR-EU1bis Sample Holder Design

The sample holder comprises three main sections, i.e. lower, middle and upper section. A schematic overview of the sample holder is shown in Figure 3. The three sections are tightly fixed together with bars. The sample holder can freely expand towards the lower end. The middle section consists of a shielding plug, dust filters in all capillary tubes and activated charcoal filters. The upper section of the sample holder consists of the penetration plug with the dynamic O-ring sealing and the connectors for the thermocouples, connectors for the gas lines and the carrier bar of the sample holder.

The lower in-pile section comprises the graphite structure with its five pebbles and the mini samples. The pebbles and the graphite half shells are enclosed in an AISI 321 stainless steel capsule. At either end, 3 mm thick axially centred Mo discs act as heat shields for thermal insulation. The upper heat shield set is elastically fixed in order to accommodate differential thermal expansion.

All gas gaps between graphite shells and 1st containment tube and 1st and 2nd containment tubes have dimensions, such that the gas mixture technique enables obtaining the required temperatures in the pebbles during the entire irradiation. The heat generated by gamma absorption and fission is dissipated mainly radially through the materials by conduction and through the gas gaps by conduction and radiation to the outside containment, which is cooled by the downstream primary water coolant. Axially homogeneous pebble temperatures can be achieved by optimizing the axial width distribution of the gas gaps between graphite half shells and capsule wall. These gas gaps are formed

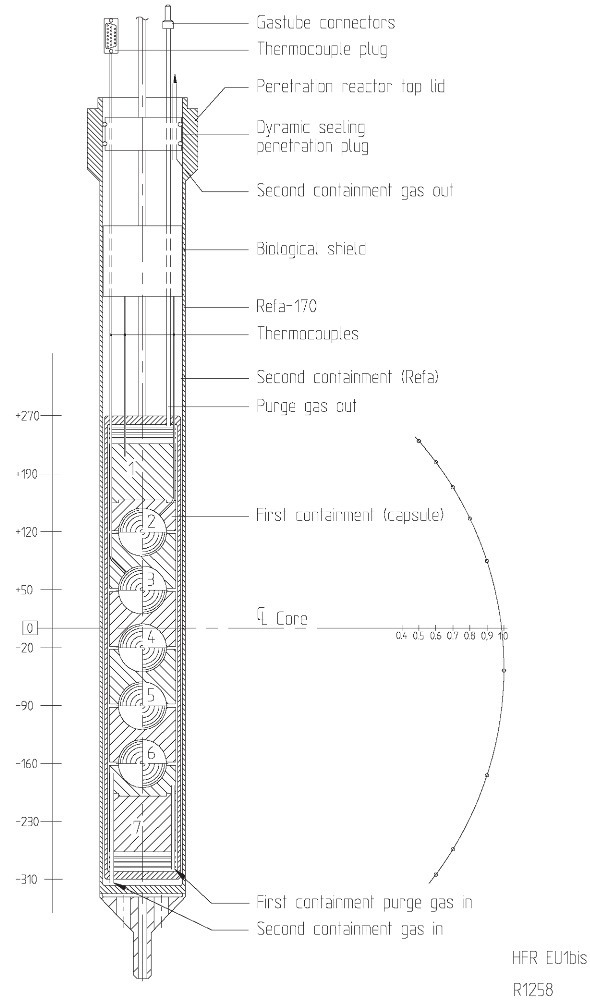

Fig. 3. Conceptual Sketch of HFR-EU1bis In-core Section

by stepped outer diameters of the graphite half shells. Further details on the HFR-EU1bis irradiation can be found in [6].

5. OTHER TYPES OF FUEL TESTING

Besides LWR fuel and (V)HTR fuels also other types of fuels are being tested: Fast Reactor fuels, Material Test Reactor (MTR) fuels and transmutation fuels/targets. Within the FUJI project (a co-operation between JNC, PSI and NRG) various types of fast reactor fuel pins are currently being tested [7].

Research on the transmutation of long-lived radioactive fission products (e.g. I-129 and Tc-99) and of actinides (Pu, Am) has strong political support in the Netherlands. Several types of innovative fuels, such as Inert Matrix Fuels (IMF), have been tested in the HFR [1,8].

The main tests that have been conducted on these innovative fuels are long-term irradiations, with the purpose of:

- Selecting suitable inert matrix materials
- Studying the behaviour of these innovative materials at high actinide burn-ups.

Both NRG and JRC-IE participate in the EFTTRA collaboration [8]. EFTTRA is an acronym for Experimental Feasibility of Targets for TRAnsmutation. Within EFTTRA, several European nuclear research institutes cooperate in developing concepts for the transmutation of long-lived fission products and americium. In the latest EFTTRA irradiation, americium-241, embedded in a spinel inert matrix, was transmuted to an extent of 99.8% [9]!

6. CONCLUSIONS

The HFR is a versatile reactor suitable for many different kinds of fuel irradiation experiments. The present paper gave a short overview of the various types of fuel irradiations that are done in the HFR. At the HFR, a large experience exists with tests of the following types of fuels: LWR, (V)HTR, fast reactor, MTR and transmutation. Significant synergies can be offered with other installations operated by the different companies on the Petten site.

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