EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-F

High-Temperature Reactor Fuel Technology

CONTRACT N°
FIKI-CT-2000-00099

Test Specification for the Irradiation Experiment HFR-EU1

R. CONRAD (JRC/IAM)
K. BAKKER (NRG)
K. VERFONDERN (FZJ)
H. NABIELEK (FZJ)

Dissemination level : RE
Document Number: HTR-F-01/07-D-2.1.1
Revision 4
Deliverable Number: 6

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1. Context

To demonstrate the suitability of coated particles (CP) and fuel elements (FE) for future HTGR designs, irradiation tests are required. The main goals of irradiation tests are:

- the demonstration of coated particle integrity and fission product retention,
- the provision of irradiated material for accident condition heating tests,
- the generation of information for future improvement of the CP design.

An extensive program has been conducted in Germany 1980 – 1994 with LEU UO_2 fuel of 10 % enrichment for HHT and PNP projects as well as for the HTR-Module concept of SIEMENS/ABB. The coated fuel particles were designed for 10 % FIMA and 1000 °C operating temperature as the most important irradiation related parameters. In the licensing procedure for the HTR-Module, the maximum burnup has been limited to about 80.000 MWd/t (8.6 % FIMA), although these particles have survived 14 % FIMA at extreme high neutron fluence in perfect condition in various earlier tests in HFR-Petten, AVR and DIDO, Jülich. There are good chances that these particles survive even higher burnups than 14 % FIMA and will allow an increase in the licensable values.

The new European HTGR fuel program that is conducted within the project n° FIKI-CT-2000-00099, “HTR-F”, of the 5th Framework Program of the European Union, is based on previous experience and plans to explore the potential for high-performance, high-burnup fuel. If coating failure occurs, it will provide a better understanding of the failure mechanisms.

The HFR-EU1 irradiation experiment will be carried out at the High Flux Reactor (HFR) Petten in close cooperation between FZJ, NRG and JRC Petten. Post-irradiation examinations (PIE) will be performed both at NRG Petten and at ITU Karlsruhe. Accident simulation tests will be done at ITU Karlsruhe.

In addition, two concurrent irradiation tests are planned at HFR Petten to support on-going R&D on HTGR fuels: (a) Two spherical fuel elements that were fabricated by INET for the HTR-10 test reactor, will be included in the HFR-EU1 test. The test specifications are described in this paper. (b) US fuel compacts that contain German reference coated particles (batch: EUO 2358-2365) and that were manufactured at General Atomics (GA) will be tested in a separate irradiation experiment, code-named HFR-EU2. The test specifications of HFR-EU2 are being prepared at present.

2. Objectives

The main objective of the HFR-EU1 irradiation test of the German GLE-4 fuel elements is the demonstration of the feasibility of high burnup for the existing German high-quality fuel. It will include in particular:

- the irradiation to the 200 GWd/t range to be reached within 2 years;
- the evaluation of fuel performance at such ultra-high burnup to explore the real limits of the existing CP that have formerly only been designed for operational conditions of the HTR-Module;
- the extension of the existing data base for the EOL metallic fission product release, particularly the silver isotope Ag-110m for an improved assessment of the particle choice for the gas turbine HTGR concept;
- the post-irradiation demonstration of fission product retention beyond 1600 °C are the main subjects of investigation.

The main objective of the irradiation of the INET fuel elements in the HFR-EU1 test is the demonstration of the feasibility of high burnup beyond 100 GWd/t, in particular:

- the irradiation up to the 160 GWd/t burnup range, to be reached within 2 years;
- the evaluation of fuel performance at such ultra-high burnup to explore the real limits of the coated particle system that have been designed for operational conditions of the HTR-10;
- the post-irradiation demonstration of fission product retention beyond 1600 °C are the main subjects of investigation.

3. Description of Samples

Three spherical fuel elements of German production with 60 mm outer diameter, type AVR GLE-4 (AVR reload 21-2) will be irradiated in one of the two independent capsules of the HFR-EU1 test. The enrichment in U-235 is 16.7 %. The characteristic fuel data are listed in Table I. The spherical fuel elements will be irradiated under well-controlled irradiation conditions and will be subjected to an extensive post-irradiation program. During the AVR reactor operation, GLE-4 fuel elements have reached a calculated average burnup of 8.6 % FIMA with a maximum burnup of approx. 21 % FIMA. Since no peculiarities in the gas release measurements have been observed, a high potential of LEU-TRISO particles to withstand consistently extreme high fuel burn-up can be expected.

Two spherical fuel elements of INET production with 60 mm outer diameter will be irradiated in the second independent capsule of the HFR-EU1 test. The enrichment in U-235 is 17.08 %. The characteristic fuel data are listed Table II. The spherical fuel elements will be irradiated under well-controlled irradiation conditions and will be subjected to an extensive post-irradiation program.

Table I: Characteristic data of AVR GLE-4 spherical fuel elements with LEU TRISO UO_2 fuel particles as loading for the experiment HFR-EU1

Coated Particle	
Particle batch	HT 354-383
Kernel composition	UO_2
Kernel diameter [µm]	501
Enrichment [U-235 wt.%]	16.76 and 16.67, respectively
Coating thicknesses [µm]:	
buffer	92
inner PyC	38
SiC	33
outer PyC	41
Fuel Element	
Heavy metal loading [g/FE]	6.0
U-235 contents [g/FE]	1.00 ± 1 %
Number of cp per FE	9560
Volume packing fraction [%]	6.2
Defective SiC layers [U/U_{tot}]	$7.8*10^{-6}$
Matrix graphite grade	A3-3
Matrix density [kg/m³]	1750
Temperature at final heat treatment [°C]	1900

Table II: Characteristic data of INET spherical fuel elements with LEU TRISO UO_2 fuel particles as loading for the experiment HFR-EU1

Coated Particle	
Particle batch	V000802
Kernel composition	UO_2
Kernel diameter [µm]	490.3
Enrichment [U-235 wt.%]	17.08 %
Coating thicknesses [µm]:	
buffer	97.7
inner PyC	42.0
SiC	37.8
outer PyC	40.8
Fuel Element	
Heavy metal loading [g/FE]	5.02
U-235 contents [g/FE]	0.858
Number of cp per FE	8500
Volume packing fraction [%]	5.0
Defective SiC layers [U/U_{tot}]	$2.3x10^{-7}$
Matrix graphite grade	A3-3
Matrix density [kg/m³]	1760

4. Irradiation Device

4.1 Irradiation Facility

The irradiation experiment will be performed in the High Flux Reactor (HFR) Petten. The nominal reactor power is 45 MW. Its core lattice includes 33 fuel assemblies and 19 experimental in-core positions. Irradiation devices can be positioned in central and peripheral core positions. The HFR is operated during 11 to 12 cycles per year. The cycle duration is 24.7 days.

Excellent results have been obtained in the past from extensive HTGR fuel irradiation testing in the HFR Petten under various conditions comprising both spherical fuel elements and a large variety of compacts and loose coated particles. The experience in the past resulted in optimized design and instrumentation of the irradiation facilities and irradiation under well-controlled conditions.

The proposed irradiation facility of the HFR-EU1 test for testing spherical fuel elements simultaneously in two independent capsules aims at a reliable design "fit-for-use". The fuel elements are doubly contained in a sample holder, which is inserted into a rig, code-named REFA-172. This REFA-172 rig is a standard facility that can repeatable be used. The GLE-4 and the INET fuel elements are located in two separate capsules, one superimposed on the other, Figure 1. Each capsule has its own instrumentation for process control. The GLE-4 samples are positioned at the maximum flux in the lower capsule. The containments that enclose the fuel elements will be continuously purged with high-purity helium for fission gas release measurements. Each capsule has its own purge gas circuit. The second containment that is formed by the thimble of the REFA-172 rig is used for temperature adjustment by means of gas mixture technique. The out-of-pile consoles, code-named Sweep Loops, allow the continuous and independent surveillance of all in-pile containment, Fig. 2.

The fuel elements are closely packed in order to obtain quasi-identical and high nuclear quantities, especially for the German GLE-4 fuel elements. The ratio between minimum and maximum burnup for the three GLE-4 FE's is only 0.85. The two INET FE's receive a burnup of 15 to 30% less than the highest loaded GLE-4 FE. A drawback of the design with more than one FE in one capsule is the fact that the fission product release measurements are overall figures and cannot be traced back to a specific fuel sphere. The ideal solution in terms of fission product measurements would be a design with separate capsules for each fuel element, however, on the expense of a burnup value below 100 GWd/t for the outer fuel elements.

4.2 Irradiation

The irradiation will be performed in a peripheral in-core position of the HFR (see Figure 3). The required burnup level can be reached after approx. 2 calendar years or about 22 irradiation cycles.

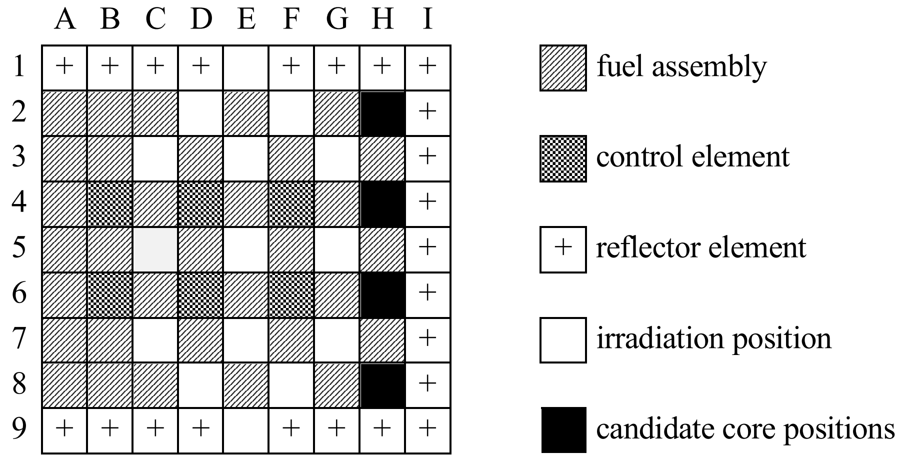

Figure 3: Standard core configuration of the HFR Petten, showing the candidate in-core positions for HFR-EU1 in black

Tailoring of the neutron spectrum to realize the required burnup / fluence correlation is feasible by the use of a variety of in-core positions and dedicated filler elements. Temperature adjustment is realized by purging the outer rig containment with an adjustable helium/neon gas mixture. A vertical displacement unit allows a further adjustment of fluence / burnup and temperature. The in-pile section can be turned cycle-wise to realize a homogeneous azimuth fluence distribution in the large specimens.
First nuclear calculations have shown that selecting core position H 2 in connection with a moderating filler element, thus more thermalised neutron spectrum can reduce the fast neutron fluence.

The inner containments of the rig will continuously be purged with high-purity helium to monitor the downstream of the first containment on fission gas release from the test fuel by means of adequate radioactivity detectors (as, e.g., Geiger-Müller and NaI counters). Furthermore, provisions will be made for an intermittent quantitative gas sampling for the analysis of medium- and long-lived gaseous fission products of krypton and xenon. The scientific instrumentation consists of thermocouples, gamma scan wires, SPN (Self-Powered Neutrons) detectors and neutron dosimeters.

5. Irradiation Testing

The irradiation rig of the HFR-EU1 experiment will consist of two separated, fully instrumented and monitored capsules for individual control of fission gas release. For both capsules, an integral temperature control will be made by means of He/Ne gas mixtures in the outer containment (REFA-172) and by vertical movement of the sample holder in the REFA channel. Capsule design shall ensure that the total amount of solid fission product released from the fuel elements can be measured easily during PIE (leach from steel capsule surfaces). Thermal shields shall be arranged such that heat flow is predominantly in radial direction. Thermocouples will be placed around the surfaces of the fuel elements to provide an extensive temperature mapping as input for detailed calculation of the spatial temperature field inside the fuel elements.

The required irradiation parameters go far beyond the current HTGR designs, e.g., HTR-Module and HTR-10. The HFR-EU1 test shall be conducted such that the central temperatures of GLE-4 fuel specimens are held constant at about 1100°C. The central fuel temperature of the INET FE's will be held constant at about 1000°C. This will require a gradual increase of the surface temperature to compensate for the reduction of the temperature gradient with increasing burnup. The procedure involves for the accompanying calculation inherent uncertainties such as power profile and material properties as a function of temperature and fluence. Temperature transients should not be performed during the irradiation. The fission power per particle should remain below 250 mW.

The irradiation shall be conducted until a maximum burnup of approximately 21 % FIMA in the highest loaded GLE-4 fuel element is achieved, whereby the highest loaded INET fuel element shall have about 16.6 % FIMA. The fast neutron fluence of the highest loaded fuel element shall not exceed $6x10^{25}$ m^{-2} (E>0.1 MeV), if irradiation takes place in position H 2 with a moderating fuel element.

Below 18 % FIMA of the highest loaded GLE-4 fuel element, the irradiation shall be discontinued at the end of the actual cycle if a significant enhanced ^{85m}Kr release is observed as a result of massive failure of coated particles. Beyond 18 % FIMA, however, the irradiation test shall be continued, until the final burnup of 21 % FIMA in the highest loaded GLE-4 FE is reached, irrespective of a potentially massive failure of coated particles late in the test. The occurrence of particle failure should initiate an assessment of the consequences of later PIE heating tests of this fuel for the KüFA facility. The irradiation duration for the two INET fuel elements shall follow the scheme of GLE-4 FE's.

In Table III, the irradiation targets of HFR-EU1 are compared with those of the latest HFR test (K6) and characteristic data of some HTGR designs. The predicted irradiation characteristics of the FE's of the HFR-EU1 test are listed in Table IV.

Table III: Irradiation targets of HFR-EU1 in comparison to respective operating conditions of reference test HFR-K6 and various HTGR designs

Parameter	**HTR-Module**	**HFR-K6**	**HFR-EU1 GLE-4**	**HFR-EU1 INET**	**HTR-10**	**GT-MHR**	**PBMR**
Fuel	UO_2 LEU-TRISO	UO_2 LEU-TRISO	UO_2 LEU-TRISO	UO_2 LEU-TRISO	UO_2 LEU-TRISO	PuO_{2-x} (UO_2) TRISO	UO_2 LEU-TRISO
Max. Burnup [% FIMA]	9.8	9.7	21	16.6	8.6	85 (20)	9.8
Max. Fluence [10^{25} m^{-2}] (E>0.1 MeV)	2.4	4.8	6	5.1		7.5-8.3 (7.5-8.3)	2.4
Max. Temperatures:							
Gas outlet [°C]	750	-	-	-	700/900	850	900
Fuel surface [°C]	926		> 800$^{(4)}$	>800	831		1000
Fuel center [°C]	1130	800$^{(1)}$ 1000$^{(1)}$ 1200$^{(2)}$	1100	1000	864	1350 (1250)	1100
Maximum fission power per FE [kW]	1.6	1.5$^{(3)}$ - 2.7$^{(3)}$	2.3	2	0.52		3.4/4.5$^{(6)}$
Maximum fission power per particle [mW]	150	250	<250	<250	<250	30$^{(5)}$ (< 400)	250/300$^{(6)}$
Irradiation time [efpd]		634	560 - 600	560 - 600	1116		900
Simulation of number of passes	17	17	-	-	-	-	10

(1) 1/3 and 2/3 temperature of cycle,
simulation of one full pass of FE in the HTR-Module core
(2) Simulation of operational temperature transient of 5 hours at beginning, half and end-of irradiation
(3) Maximum power at beginning of irradiation
(4) Increases in order to keep the central temperature constant
(5) Average value
(6) Equilibrium core / first core

Table IV: Predicted irradiation characteristics of fuel elements of HFR-EU1 test

Fuel element type	GLE-4			INET	
Id n°	1	2	3	I-1	I-2
Temperature central of FE [°C]	1100	1100	1100	1000	1000
Fission power per FE [W]	2300	2150	1950	1750	1450
Fission power per particle [mW]	240	220	200	200	170
Burnup [GWd/t]	200	190	170	155	125
Fast fluence [m^{-2}] (E>0.1 MeV)	$6x10^{25}$	$5.7x10^{25}$	$5.1x10^{25}$	$5.1x10^{25}$	$4.2x10^{25}$
Axial position with respect to centre-line core [mm]	Centre-line core	-70	-140	+150	+220

6. Pre- and Post-Irradiation Examination

The focus will be laid upon the PIE experimental program. It includes:

- Dimensions and weights (before/after) measurements
- Burnup measurements
- Distribution of fission products in FE and CP
- Determination of (free) heavy metals (mass spectrometry, burn-leach)
- Ceramography
- Heating tests
- Fission product transient release (Kr-85, Cs-137, Ag-110m, Sr-90)
- sphere disintegration (fission product distribution within FE)
- Ceramography

This program has to be defined in more detail. The executing laboratories have to be identified for the course of the program.

The tasks at FZ Jülich shall include the following items:

- Specification of irradiation parameters in close cooperation with the project partners
- Specification of material properties of samples
- Pre-test measurements of fuel and graphite samples
- Delivery of samples (and graphite raw materials)
- Transport of unirradiated fuel spheres to Petten
- Irradiation proposal
- Project management

The tasks at JRC Petten and NRG shall include the following items:

- Irradiation proposal
- Project management of HFR activities
- Nuclear and thermal hydraulic design of the irradiation test
- Design and safety report
- Design, fabrication, and assembly of entire irradiation facility
- Instrumentation of sample holder
- X-ray photographs of fuel specimens and sample holder prior to irradiation
- Neutron radiographs prior, during and after irradiation
- Operation of Sweep Loops
- Data acquisition and evaluation
- Irradiation progress reports after every operating cycle
- Recovery of samples
- Burnup measurements by γ-spectrometry (for short-lived isotope analysis)
- Leaching of steel / graphite capsules (for short-lived isotope analysis)
- Measuring release of solid fission products into graphite parts
- Transport of irradiated material to ITU
- Electrolytical deconsolidation of highest-burnup sphere (FZJ/Harwell method)
- Neutron dosimetry report
- Final irradiation report, including evaluation of irradiation and PIE data

The tasks at ITU Karlsruhe include the following items:

- Burnup re-measurements by γ-spectrometry (for longer-lived isotope analysis)
- γ-spectrometric re-measurements of graphite cups (for longer-lived isotope analysis)
- Isothermal heating tests with three spheres at 1600 / 1650 / 1700 / 1750 °C in the KüFA facility according to procedures still to specify
- Solid fission product release + CP measurements

Other tasks at organizations to be determined include, e.g., the following items:

- Parallel control calculations of irradiation results
- Model predictions of CP failure and fission product release during irradiation and accident condition heating tests

The activities of other partners still have to be defined complementarily.

Fig. 1
Schematic drawing of in-pile section of HFR-EU1 test

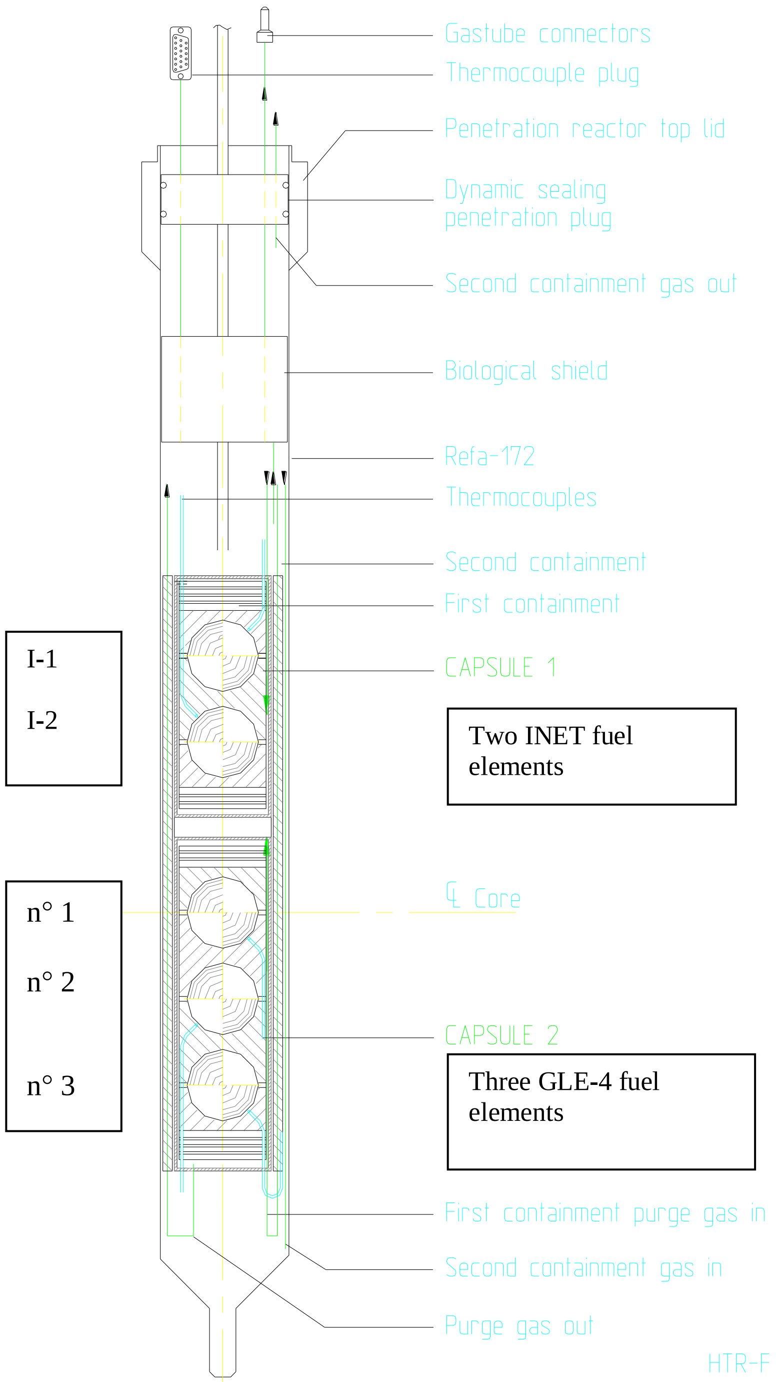

Fig. 2
Schematic drawing of Sweep Loops for HFR-EU1 test