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HFR-EU1bis Design and Safety Report

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HFR-EU1bis: Irradiation of High Temperature Reactor Fuel Pebbles at VHTR Conditions in the HFR Petten

Project n° 337.2

Design and Safety Report

rev. C

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Abstract

This document describes the design and safety assessment of the HFR-EU1bis irradiation experiment for testing spherical High Temperature Reactor (HTR) fuel pebbles with TRISO coated particles (UO_2 fuel kernel with successive isotropic layers of porous carbon, dense carbon, dense silicon carbide and dense carbon) for their potential for high temperature performance and high burn up. The irradiation will be performed in the HFR Petten for a period of up to 14 cycles in core position G3 with the option to stop earlier.

Five fuel pebbles from German AVR production (GLE-4 type) will be tested in a sample holder that is loaded in a REFA-170 rig, surrounded by a strongly moderating filler element. The sample holder and the REFA-containment will be connected to independent circuits for process control, in particular for manual temperature control and batch wise surveillance of fission gas release from the fuel elements. In normal condition, the gas in the 1st and 2nd containment will be stagnant. Only for the batchwise fission gas release measurement the sample holder containment will be vented, collecting the purge gas in a shielded tank and analyzing the gas off-line with a gamma spectrometer.

The characteristic irradiation parameters are constant central fuel temperatures of approx. 1250°C, a target burn-up of 16-19% FIMA in the two central pebbles, and a maximum neutron fluence of approx. $5\text{-}7.3 \times 10^{25}$ m^{-2} (E>0.1 MeV).

This document is in agreement with the Terms of Reference for the HFR Safety Committee (HSC) Appendix 2 of 21 October 2002 [22], and the revision of “DSR description of instrumentation” of 4 November 2003 [23].

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1 Introduction

The HFR-EU1bis irradiation experiment in the HFR Petten was proposed by JRC-IE in summer 2002 to the European High Temperature Reactor Technology Network HTR-TN and to the coordinator of the FP5 project HTR-F to provide high burn-up HTR fuel pebbles for KÜFA testing at JRC-ITU. KÜFA tests are isothermal ramp tests to investigate the capability of fission product retention of highly irradiated fuel elements beyond 1600°C under simulated accident conditions of modular HTRs. During an HTR-F WP2 meeting on 3 November 2003 and following an initiative by JRC-IE, it was decided to increase the central fuel temperature of the pebbles up to 1250°C while the extremely high burn-up test was reserved for another planned irradiation test, HFR-EU1. Compared to HFR-EU1, this irradiation is simplified (batchwise instead of continuous fission gas release analysis) and accelerated (higher neutron flux and fission power, thus burn-up). This had become useful because the assembly of the HFR-EU1 rig had accumulated considerable delay thus slowing down the KÜFA tests of this fuel at high burn-up. Additionally, HFR-EU1bis provided some flexibility to adapt the irradiation conditions (fuel temperature and burn-up) to Generation IV (VHTR) relevant conditions. The irradiation will be performed for a period of 11-14 cycles in core position G3 (Figure 1).

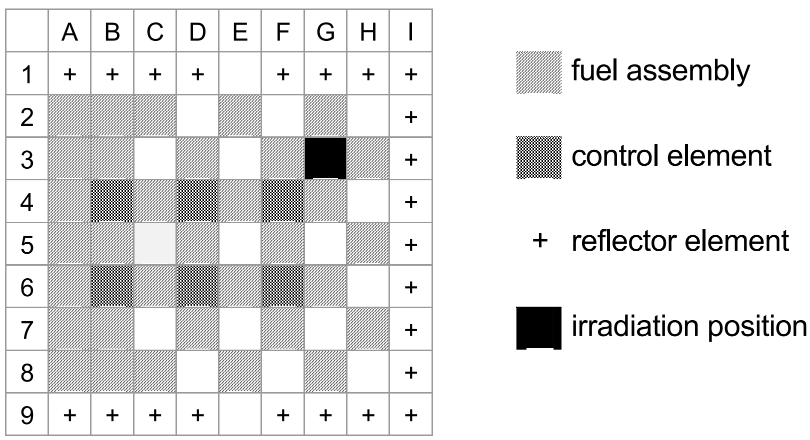

Figure 1: Standard HFR core configuration showing HFR-EU1bis in core position G3

Although the costs for manufacturing are entirely covered by JRC-IE, HFR-EU1bis is followed up by HTR-TN and was technically integrated in the HTR-F/F1 projects [1], [2]. A consortium of 7 partners is participating in the HFR-F and HTR-F1 projects, CEA (coordinator), Framatome-ANP, NRG, FZJ, JRC-ITU, JRC-IE and BNFL. The HTR-F project was approved under the reference FIKI-CT-2000-00099, and HTR-F1 under reference FIKS-CT-2001-00150 [3].

For the HTR-F and HTR-F1 projects, the global objective is focused on the innovation potential of past and current HTR fuel technology based on the TRISO coated fuel particle design. The project is structured into four work packages:

- **WP1:** The objective is to gather in a common database the available experience gained from various types of fuels tested in the past in European reactors.
- **WP 2:** The objective is to perform in-pile and out-of-pile tests to qualify the fuel particle behavior under irradiation. Irradiation and PIE of HFR-EU1 are managed within this work package.

- **WP 3:** The objective is to model the different phenomena occurring in the fuel under irradiation in order to understand and predict the irradiation behavior,
- **WP 4:** The objective is to restore the fabrication capability in Europe with the challenge to reach a very high quality level.

The experiments HFR-EU1 and HFR-EU1bis share the objective of exploring the potential for high performance and high burn-up of the existing fuel pebbles for application to the conceptual Generation IV Very High Temperature Reactor (VHTR) [4]. During extensive irradiation tests at and above nominal 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 [5], [7]. Irradiating this fuel under defined conditions to extremely high burn-ups and testing it afterwards in thermal ramp tests to simulate cooling accidents will provide a better understanding of the fission product release and failure mechanisms should coating failure occur.

The fuel to be irradiated comes as pebbles of 60 mm diameter with LEU-TRISO coated particles of former German production, type AVR GLE-4.

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

- increased central fuel temperature of up to 1250°C compared to 1100°C for the GLE-4 pebbles in HFR-EU1;
- irradiation to a burn-up of 16 - 19% FIMA;
- evaluation of fuel performance at high burn-up to explore the limits of the existing coated particles that had originally been designed and licensed only for the operating conditions of the HTR-Module, i.e. 80 MWd/kg burn-up;
- confirmation of low failure rates of coated particles 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 ^{110m}Ag, for evaluating the suitability of this fuel for gas-cooled reactors with direct (no secondary circuit) Brayton cycle for power conversion (risk of silver plate-out on the gas turbine creating radioactive hot spots and maintenance problems);
- post-irradiation verification of fission product retention by out-of-pile heating tests beyond 1600°C;

The design of HFR-EU1bis is based on previous experience of HTR fuel irradiations within the European Union, namely "HFR-P4", "HFR-K5", "HFR-K6" and "SiC Balls" [11], [12], [14]. The five pebbles will be tested in the "Full Size HTR Fuel Element Rig". A schematic drawing is shown in Figure 2. The sample holder (1st containment) is located at the maximum axial flux in a REFA-170 rig, which forms the 2nd containment. The temperature of the fuel surface can be controlled by adjusting the He/Ne mixture in both the 1st and 2nd containment. This temperature adjustment is required to compensate for changes of time and fluence dependent operating parameters such as fission power depletion (burn-up), dimensional changes of specimen assembly (graphite shrinkage, typical turn-around dose $10\text{-}15\times10^{21}$ n cm^{-2}, typical shrinkage at turn-around approx. –2% at 470-500°C), changes in thermal conductivity and thermal expansion, changes in nuclear characteristics from cycle to cycle and movement of control rods of the reactor. The predicted useful range of temperature change by these gas changes is approx. 120 K [17].

The 1st and 2nd containment remain normally closed (stagnant gas). They can be purged to modify the He/Ne gas mixtures for temperature adjustment and for taking gas samples. (Both 1st and 2nd containments will be used for temperature control.) In this case, the gas from the 1st containment will be cleaned by routing it through activated charcoal filters that are built into the rig. In addition, the 1st containment can be vented batchwisely in e.g. weekly intervals into a sampling container to quantify the release of volatile fission products, mainly long-lived Kr and Xe gases. For this measurement, the filters can be bypassed.

The changing position of the axial neutron flux buckling due to the axial movement of the HFR control rods can be compensated by a remotely operated vertical displacement unit (VDU, maximum stroke 50 mm, irradiation starting at lowest possible VDU position) and enables additional temperature adjustment. To accelerate the burn-up, yet without exceeding the allowable power density in the fuel, the neutron spectrum is strongly moderated using a custom filler element with a large water fraction in the in-core position G3. Cycle-by-cycle turning of the experiment by 180º reduces radial gradients in neutron fluence and burn-up across the pebbles. The nominal duration of the irradiation will be 14 HFR cycles. The project partners could decide an earlier stop should temperature control by the gas mixture technique provide no sufficient reserves to maintain the target temperature.

2 Experimental Requirements

The objective of the HFR-EU1bis test is to irradiate 5 HTR fuel pebbles at increased temperature up to high burn-ups that are beyond the characteristics of current HTR reactor designs with pebble bed cores, e.g. HTR-Module, HTR-10 and PMBR. This should demonstrate that pebble bed HTRs are capable of meeting VHTR requirements in terms of sustainability (further increased power conversion efficiency, better use of fuel) and thus reduced waste production. The end-of-irradiation neutron fluence in the HFR shall not exceed the projected value that correlates with nominal burn-up. The central temperature of all pebbles should be as close as possible at approximately 1250°C and kept constant during the entire irradiation, with the exception of HFR downtime and power transients. This is the expected maximum central fuel temperature of a pebble bed VHTR with a coolant outlet temperature of 1000°C. This temperature cannot be directly measured with a thermocouple because drilling of a hole for the thermocouple would damage several particles. Therefore, and accepting the uncertainty in thermal conductivity data for the calculation of the order of 10%, the irradiation shall be conducted by controlling the surface temperature of the pebbles such that the central temperature will remain as constant as possible. Due to power depletion with burn-up, the surface temperature will have to be raised during the experiment. The calculated data for power, surface and central temperature per pebble and per cycle are shown in Table 1. This table was not prepared for safety purposes but to assess the feasibility of the high burnup/high temperature test. It can be seen that temperature control always requires pure Ne in the 1st containment while the Ne fraction in the 2nd containment will need to be gradually increased. Pure N_2 in the 1st containment is required only for cycles 13 and 14 to maintain the nominal fuel temperatures. The change in axial flux buckling of the HFR core shall be compensated by the vertical displacement unit VDU.

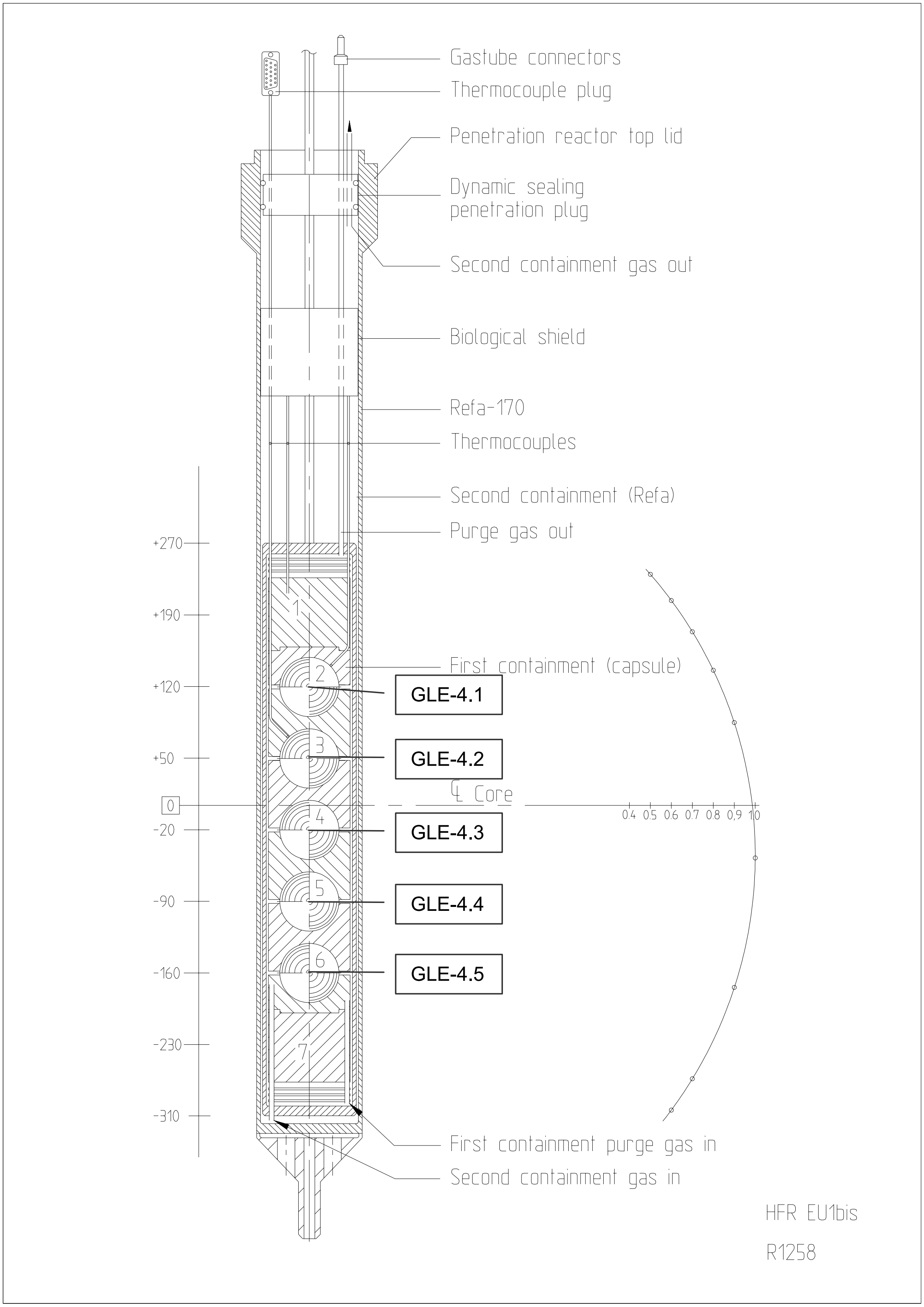

Figure 2: Conceptual sketch of HFR-EU1bis

	Pebble Power (fission power + gamma heating) [W]					Surface Temperature [°C]					Central Temperature [°C]					1st Cont. Gas Mix [%]		2nd Cont. Gas Mix [%]	
Cycle	GLE-4.1	GLE-4.2	GLE-4.3	GLE-4.4	GLE-4.5	GLE-4.1	GLE-4.2	GLE-4.3	GLE-4.4	GLE-4.5	GLE-4.1	GLE-4.2	GLE-4.3	GLE-4.4	GLE-4.5	He	Ne	He	Ne
	axial position with respect to center line at 0 [mm]																		
	110	40	-30	-100	-170														
1	3318	3975	4305	4117	3783	1014	1016	1009	1015	1006	1216	1244	1250	1247	1227	0	100	96	4
2	3142	3762	4073	3893	3579	1026	1031	1024	1030	1020	1215	1244	1251	1248	1227	0	100	79	21
3	2990	3578	3872	3700	3401	1036	1044	1038	1043	1032	1215	1245	1252	1249	1228	0	100	65	35
4	2839	3396	3673	3508	3226	1042	1052	1047	1052	1040	1211	1242	1249	1246	1224	0	100	54	46
5	2708	3237	3499	3341	3073	1053	1065	1062	1066	1052	1211	1244	1252	1249	1226	0	100	43	57
6	2576	3078	3326	3174	2920	1058	1074	1072	1075	1060	1208	1242	1251	1248	1224	0	100	34	66
7	2462	2940	3175	3029	2787	1065	1083	1082	1086	1069	1207	1243	1252	1249	1224	0	100	26	74
8	2352	2808	3030	2890	2659	1067	1087	1088	1091	1073	1202	1238	1248	1245	1220	0	100	20	80
9	2256	2691	2903	2767	2547	1076	1099	1101	1103	1083	1203	1242	1253	1250	1223	0	100	13	87
10	2164	2580	2781	2650	2440	1079	1104	1108	1109	1088	1199	1240	1252	1248	1220	0	100	8	92
11	2085	2484	2677	2550	2348	1084	1112	1117	1118	1095	1199	1242	1254	1250	1221	0	100	3	97
12	2006	2389	2573	2450	2257	1082	1110	1115	1117	1097	1192	1234	1252	1248	1217	0	100	0	100
13	1945	2315	2492	2372	2185	1092	1123	1129	1130	1105	1197	1242	1255	1252	1221	**0***	**0***	0	100
14	1883	2241	2411	2294	2114	1083	1112	1119	1119	1096	1183	1226	1240	1236	1207	**0***	**0***	0	100

Table 1: Predicted power and temperature evolution per pebble and required gas mixture per cycle;
*: cycles 13 and 14 require pure N_2 in 1st containment

Temperature transients other than those imposed by cycle start-ups and shut-downs should be avoided during the irradiation. The maximum fission power of a single coated particle should be kept below 340 mW. This value had been tested previously in the HFR-K5/K6 irradiation without particle damage [24]. Temperatures shall be continuously monitored, and fluence detectors shall be installed to quantify the neutron fluence after irradiation. For comparison, the irradiation targets of HFR-EU1bis and HFR-EU1 are listed and compared in Table 2. Table 3 contains a comparison with the irradiation parameters of the latest HFR test (HFR-K6) with fuel pebbles and with characteristic data of current HTR reactor designs with pebble bed cores.

The target burn-up for the highest loaded pebble shall be 16-19% FIMA depending on whether the irradiation temperature can be maintained. The fast neutron fluence of the highest loaded pebble shall not significantly exceed the value of $5\text{-}7.3\times10^{25}$ m^{-2} (E>0.1 MeV). The predicted irradiation characteristics for each of the five pebbles of the HFR-EU1bis test are listed in Table 4.

The water vapor concentration in the 1st containment from outgassing of the graphite shall be reduced by flushing with pure He in the beginning of the first cycle with the filters bypassed to avoid their saturation.

Continuous fission gas release measurement is not a prime objective of HFR-EU1bis. The release of gaseous fission products shall be monitored by occasionally (typically once per week) analyzing gas samples from the 1st containment off-line by gamma spectrometry for Kr and Xe isotopes. Thanks to the sensitivity of this method, the failure of a single particle out of 50000 can be detected, corresponding to a fractional release of 2×10^{-5}.

The pebbles can be irradiated in the HFR under well-controlled conditions. During the AVR reactor operation, GLE-4 fuel elements had reached a calculated average burn-up of 8.6% FIMA with maximum burn-ups of approximately 21% FIMA. Since no peculiarities in the gas release measurements have been observed, LEU-TRISO particles are expected to survive even higher burn-ups [5], [6], [7].

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 - 19**	≤ 20	≤ 17
Surface temp. [ºC]	**1000-1050 at BOI, raising to maintain central temperature constant at 1250**	950	950
Fluence [$m^{-2}s^{-1}$] E > 0.1 MeV	**approx. 5-7.3×10^{25}**	< 6.0×10^{25}	< 5.3×10^{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 - daily quantitatively	- continuous qualitatively - daily quantitatively
Purge gas impurities	**batch wise surveillance**	≤ 10 ppm after first irradiation cycle, continuous surveillance of up- and downstream of purge gas	≤ 10 ppm after first irradiation cycle, continuous surveillance of up- and downstream of purge gas

Table 2: Experimental requirements for HFR-EU1bis compared to HFR-EU1

Parameter	HTR-Module	HFR-K6	**HFR-EU1bis GLE-4**	HFR-EU1 GLE-4	HFR-EU1 INET	HTR-10	PBMR
Fuel	UO_2, LEU-TRISO coated particles						
Target burn-up [% FIMA]	9.8	9.7	**16-19**	21	16.6	8.6	9.8
Target fluence [10^{25} m^{-2}] (E>0.1 MeV)	2.4	4.8	**< 7.3**	6	5.3		2.4
Max. temp. [°C] gas outlet	750					700/900	900
Max. temp. [°C] fuel surface	926	800(1)	**1050(4)**	950	900	831	1000
Max. temp. [°C] fuel center	1130	1000(1) 1200(2)	**1250**	1100	1000	864	1100
Maximum fission power per pebble [kW]	1.6	1.5(3) - 2.7(3)	**3.4**	2.3	2	0.52	3.4/4.5(5)
Max. fission power per particle [mW]	150	250	**340**	250	250	< 250	250/300(5)
Irradiation time [efpd]		634	**300 - 350**	550 - 600	550 - 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) To be increased in order to keep the central temperature constant

(5) Equilibrium core / first core

Table 3: Irradiation targets of HFR-EU1bis and HFR-EU1 in comparison to operating conditions of reference test HFR-K6 and current designs of pebble bed HTRs

Fuel element type	AVR GLE-4 (9560 particles per pebble)				
Id n°	GLE-4.1 (top)	GLE-4.2	GLE-4.3	GLE-4.4	GLE4.5 (bottom)
Pebble temp. [°C]					
- surface BOI	1014 (975-1079)	1017 (972-1077)	1009 (968-1059)	1015 (971-1073)	1006 (969-1075)
- central BOI	1216	1244	1250	1247	1227
- surface EOI	1083 (1052-1137)	1112 (1083-1147)	1119 (1090-1153)	1119 (1090-1152)	1096 (1068-1149)
- central EOI	1183	1226	1240	1236	1207
BOL power per pebble [W]					
- fission power	2452	2936	3237	3114	2853
- gamma heating	866	1012	1068	1002	930
BOL fission power per particle [mW]	256	310	339	326	298
EOL power per pebble [W]					
- fission power	1017	1229	1343	1292	1183
- gamma heating	866	1012	1068	1002	930
EOL fission power per particle [mW]	106	128	140	135	124
Burnup [% FIMA]	14.4	17.4	19.0	18.3	16.4
Fast fluence [m^{-2}] (E>0.1 MeV)	5.92×10^{25}	6.91×10^{25}	7.30×10^{25}	6.85×10^{25}	6.36×10^{25}

Table 4: Predicted irradiation characteristics of pebbles in HFR-EU1bis; BOI = cycle 1, EOI = cycle 14

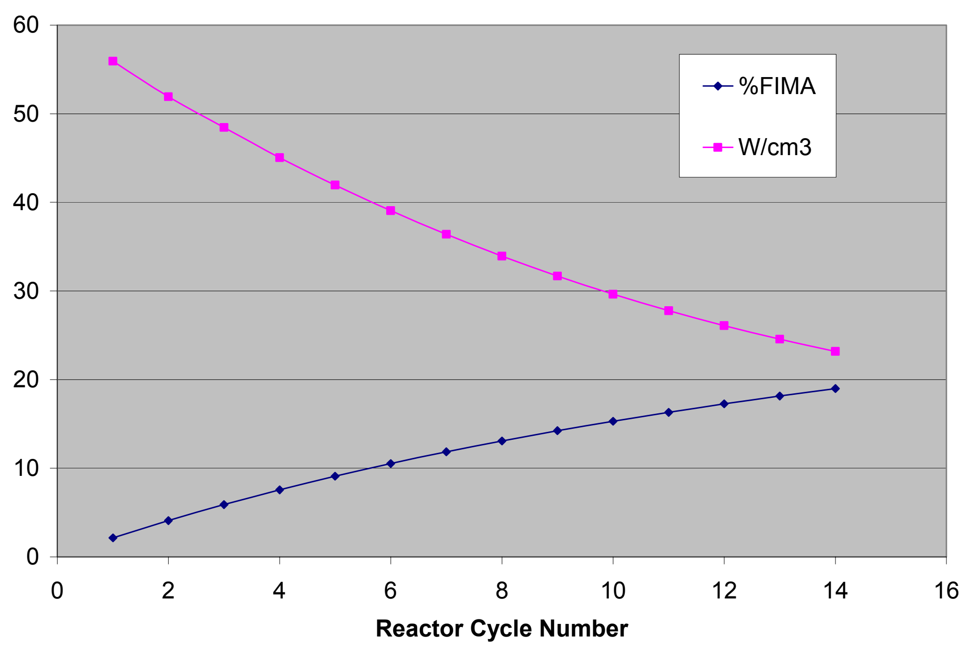

Figure 3: Power density (fission + gamma power) and burn up evolution with irradiation for pebble in maximum flux position (GLE-4.3)

Thermal calculations had shown that, except when using N_2 in the gas gaps, the minimum pebble power density to maintain the central temperature at 1250°C would be 27.5 W/cm^3 [17]. From the power depletion plotted in Figure 3 it can be deduced that this minimum pebble power is reached after 11 cycles. The corresponding maximum burn-up is 16.3% FIMA. Considering the uncertainties in the power predictions and thermal calculations, the irradiation shall be pursued up to 14 cycles with N_2 in both containments if with He/Ne mixtures the temperature control margin should prove insufficient to maintain the target temperature.

3 Irradiation Target

The irradiation specimens are 5 HTR pebbles and 6 mini samples containing 10 particles each.

The 6 mini samples consist of Nb tubes ∅1.6/1.2 mm × 25 mm. These are filled with graphite powder and 10 HTR fuel particles each. They are inserted in the thickest areas of the graphite half shells (cf. drawing GCO 66866 C).

The pebbles have an outer diameter of 60 mm and are of German production, type AVR GLE-4 (AVR reload 21-2). They were manufactured by HOBEG [7]. The characteristic fuel data are listed in Table 5 and Table 6.

		External pebble diameters in 3 orientations [mm]		
Sample ID as delivered	Pebble Number	0° N N - S	N 0° 0 - 180°	N 90° 90 - 270°
4/23	GLE-4.1	59.95	59.96	59.95
5/23	GLE-4.2	59.92	59.90	59.93
9/23	GLE-4.3	59.92	59.90	59.90
12/23	GLE-4.4	59.93	59.93	59.92
13/23	GLE-4.5	60.03	60.04	60.02

Table 5: Diameters of selected pebbles for HFR-EU1bis

The HTR fuel pebbles consist of a molded carbonaceous matrix of 60 mm diameter that contains the 9560 coated particles in an inner zone of ~47 mm diameter and with a fuel free shell of >5 mm thickness. The coated particles consist of a central LEU UO_2 fuel kernel and a TRISO coating: from the inside to the outside, the UO_2 kernel is coated by low density pyrocarbon “PyC” (buffer), by high density PyC, by high density SiC and a final high density PyC layer.

The North poles of the pebbles were arbitrarily marked on the axis of the traces from lathing. The equator is marked at one arbitrary point with ‘O’ corresponding to 0° and with 'X' corresponding to 90°. The 0° equatorial position will be positioned in the capsule such that it shows in direction North with respect to the HFR core during the first cycle. The pebbles will be loaded into the capsules such that the North pole is on the top.

FZJ had shipped a total of 23 pebbles to JRC-IE in numbered aluminum cans. To make a choice of these pebbles for HFR-EU1 and HFR-EU1bis, the initial criteria were sphericity and surface state. The selected pebbles for HFR-EU1bis are: batch BP-002100, samples 4/23, 5/23, 9/23, 12/23 and 13/23.

These pebbles underwent a precise measurement of their characteristic dimensions (Table 5), and X-rays of the pole and equator plane were taken to verify the homogeneity of the particle distribution and the thickness of the fuel free zone (cf. example Figure 4). This was to ensure that the blind holes of the thermocouples for measuring the temperatures in the fuel free zone (pebbles 1 and 5 only) do not penetrate into the fuel zone where they may damage fuel particles. The blind holes are 1.2 mm in diameter and 4 mm deep (Figure 5) from the surface to the tip of the drill. From the X-rays it was deduced that the fuel free zone is thick enough in all cases to accommodate these blind holes. The fuel particle distribution is sufficiently homogeneous.

Coated Particle	
Particle batch	HT 354-383
Kernel composition	UO_2
Kernel diameter [μm]	501
Enrichment [U-235 wt.%]	16.75
Thickness of coatings [μm]: buffer inner PyC SiC outer PyC	 92 38 33 41
Particle diameter [μm]	909
Pebble	
Heavy metal loading [g/pebble]	6.0
U-235 content [g/pebble]	1.00 ± 1 %
Number of coated particles per pebble	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 6: Nominal characteristic data of AVR GLE-4 pebbles

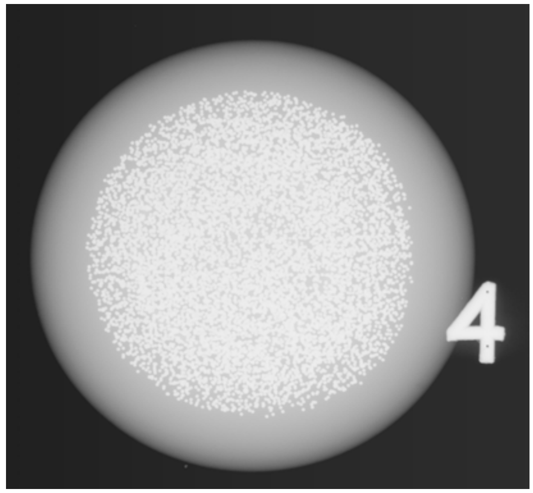

Figure 4: X-ray of pebble 4/23 N up, 0° front (not to scale)

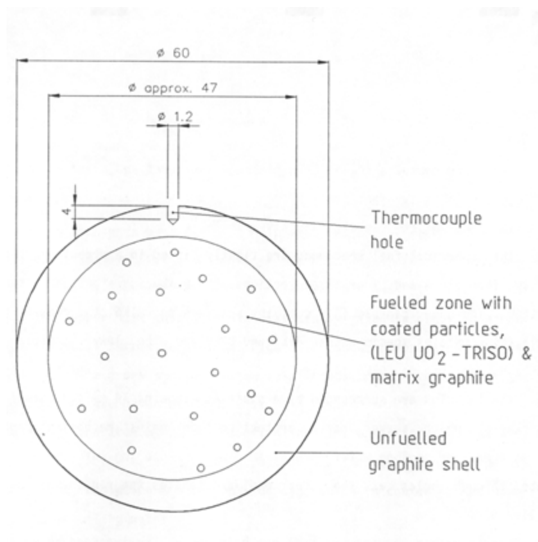

Figure 5: Pebble cross section with blind hole for thermocouple

Each pebble is enclosed by two cylindrical graphite half-shells whose inner hemispherical dimensions are exactly machined to the corresponding hemisphere of the pebble with the objective of reaching a thermal contact better than 80% of the surface. This required precise 3-d mapping of the pebbles with laser metrology. The half-shells are made of commercial isotropic graphite, type R 6650 by SGL Carbon [9].

The graphite of the fuel pebbles and of the half shells must be expected to shrink during the irradiation, the turn-around point, where this shrinkage is reversed to swelling, will not be reached in this experiment (typical turn-around dose $10\text{-}15\times10^{21}$ n cm^{-2}, typical shrinkage at turn-around –2% at 470-500°C). Shrinkage of the graphite would lead to slightly increased gas gaps in the 1st containment, which is expected to somewhat self compensate the effect of fission power depletion on fuel temperature, thus contributing to maintain the high central fuel temperature with increasing burn-up. To account for uncertainties in the irradiation behavior of the graphite, the gas mixture adjustment in the 2nd containment is sufficient.

4 Irradiation Facility

The High Flux Reactor (HFR) Petten is a multi-purpose material test reactor of the tank-in-pool type, it is light water-cooled and moderated, and it is operated at 45 MW at a prescribed schedule of 11-12 cycles per year, each consisting of about 25 operating days and 3 shut-down days. The reactor provides a variety of irradiation possibilities in the reactor core, in the reflector region, as well as in the so-called poolside facility outside the reactor vessel. Twelve horizontal beam tubes are installed for research with neutrons [14].

The irradiation of the HFR-EU1bis experiment will be carried out with an irradiation facility that is based on the design of the rig for the experiment "SiC Ball" [15] (irradiation of SiC coated 60 mm graphite spheres, project number 247) for the in-pile section and on the PSF glove box system, an out-of-pile instrumentation and operating system for the irradiation of fuel samples. The sample holder is inserted into a standard REFA-170 rig. The upper part of the sample holder is extended with solenoid valves in the up- and downstream gas lines of the 1st containment. Differing from the standard is the use of a moderating filler element.

4.1 In-core section

The in-core section holding the fuel pebbles consists of four elements:

- the sample holder, which comprises one capsule, forming the 1st containment;
- the REFA-170 rig containing the sample holder and representing the 2nd containment thimble;
- the moderating filler element, filling the core position and accommodating the cylindrical rig;
- the rig head, representing the transition between in-pile section and out-of-pile installation and carrying all instrumentation leads and gas tubes.

The sample holder accommodates the capsule acting as the 1st containment for the fuel pebbles. The HFR-EU1bis sample holder is loaded into the thimble of a REFA-170 rig, which forms the second controlled containment for the pebbles. This REFA-170 rig is a standard facility that can be re-used. HFR-EU1bis will use a strongly moderating filler element (code E-816, drawing RH-M-U76 A), which accommodates the REFA rig with the sample holder in the core position. This filler element, bore diameter 72.2 mm, is made of aluminum and, by milling out the corners to a rectangular section, provides a larger water fraction to enhance the thermal part of the neutron spectrum in the capsule, thus accelerating the burn-up and reducing the EOI fast neutron fluence.

4.1.1 Sample holder

The sample holder consists of three main sections, i.e. lower, middle and upper section. The three sections are tightly fixed together with bars. When loaded in the REFA-170 rig, the sample holder is suspended at a snap coupling of the vertical displacement unit VDU that is located in the rig head. The sample holder can freely expand towards the lower end.

Lower in-pile section: This 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 ∅69.4-69.5×630 mm. At either end, 3 mm thick axially centered Mo discs act as heat shields for thermal insulation. The upper heat shield set is elastically fixed in order to accommodate differential thermal expansion.

The dimensions of the graphite half shells and graphite end plugs are given in Table 7 from the bottom to the top.

item no (cf. GCO-66866 C)	description	external diameter [mm]	length [mm]	corresponding drawing no.
12	bottom plug	65.63 – 67.07 cf. Table 8	55	66871
13	½ shell		49.5	66872
14	2 ½ shells		69	66873
15	2 ½ shells		69	66874
16	2 ½ shells		69	66875
17	2 ½ shells		69	66876
18	½ shell		50.5	66877
19	top plug		74	66878

Table 7: Dimensions of the graphite half shells and end plugs

axial position low [mm]	axial position high [mm]	half shell outer diameter [mm]	cold gas gap [μm]
-269.0	-214.0	66.24	780
-214.0	-134.0	66.24	780
-134.0	-64.0	67.05	375
-64.0	+6.0	67.07	365
+6.0	+76.0	67.01	395
+76.0	+156.0	65.63	1085
+156.0	+231.0	65.63	1085

Table 8: Dimensions of the cold gas gap between graphite half shells and capsule tube [17] positioned with respect to core centerline

The instrumentation leads and gas tubes penetrate the sample holder cap from the top. These penetrations are sealed by means of high-temperature brazing. The thick cap on the bottom (cf. general assembly drawing GCO 66866 C) absorbs a significant amount of gamma power and thus requires additional heat removal to keep temperatures and thermal stresses in the capsule wall and welds at low levels. This is achieved by an aluminum disc inside the capsule between the Mo disc and the caps. Three steel rodlets transmit the weight of the capsule from the Mo disc onto the aluminum disc and thus press the aluminum disc against the cap surface. This distributes evenly the heat generated in the caps to the capsule walls. On the top of the capsule there is no risk of excessive thermal stress, essentially because the gamma heating is lower and the cap is thinner.

The instrumentation of the capsule consists of 24 thermocouples (TC), 2 fluence detectors (FD) and 1 gamma scan wire (GSW). The TCs for measuring the surface temperatures are positioned laterally in the pebble surface (fuel free zone). Additionally, the extremities of the top and bottom pebbles are instrumented with 2 TCs each, situated approximately on the vertical axis. FDs and GSW are positioned such that they enable a 3-d fluence mapping after irradiation.

A drawback of the design with more than one pebble per capsule is that the fission product release measurements are cumulative figures for all pebbles and can only be traced back to a possibly failed pebble during PIE. The ideal solution in terms of fission product release measurements would be a design with separate capsules for each fuel element, however, as this is space consuming, this would cause a significant burn-up loss for the outer pebbles and would cause high costs for gas analysis panels.

All gas gaps between graphite shells and 1st containment tube and 1st and 2nd containment tubes are sized 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 down-stream primary water coolant. Homogeneous fuel element surface temperatures are achieved by stepped gas gaps between graphite half shells and capsule wall. These gas gaps are achieved by stepped outer diameters of the graphite half shells.

Middle section: This section consists of the shielding plug, dust filters in all capillary tubes and activated charcoal filters. The design of the shielding plug is in accordance with the standard design for sample holders [12]. One filter with activated charcoal is fitted in the down-stream line of the 2nd containment. The charcoal filter for the 2nd containment, which has a reaction length of 800 mm and a diameter of 8 mm, is filled with ~40 cm^3 activated charcoal. The function of this filter is to adsorb any radioactive gases, which might be released into the 2nd containment. Two gas volumes equip the normal downstream gas tube of the capsule (1st containment). These are two volumes of 725 cm^3 each (in other rigs used as delay volumes) and are filled with activated charcoal filters. They can be bypassed for gas sampling. In purge mode (e.g. for gas mixture adjustment), the gas flows from the 1st containment through the activated charcoal filter. The purge gas flow can be directed by means of a set of solenoid valves in the rig head; either from (a) fast, (b) through the filter volume or (c) stop flow.

Upper section: The upper section of the sample holder consists of the penetration plug with the dynamic O-ring sealing of the REFA thimble and the connectors for the thermocouples, snap-tight connectors for the gas lines and the carrier bar of the sample holder with a snap connector for the coupling with the VDU in the rig head, as well as three solenoid valves. The entire sample holder is suspended on this snap connector. The dynamic sealing grants the leak tightness of the REFA thimble during VDU displacement of the sample holder. The maximum VDU stroke is 50 mm. This value is smaller as usual (150 mm) because an unmodified rig head will be used to save time. As a consequence, the magnetic valves were not mounted in the rig head but on the sample holder thus reducing the VDU stroke.

Most components of the sample holder are made of stainless steel AISI 316L except the capsule tube (AISI 321) and the Mo discs for the sample support, the Mo heat shields and the Al disc for heat dissipation. Welds are of the TIG type. Thermocouples and gas tubes are brazed into the caps of the capsules by means of high-temperature brazing. The overall mass of the sample holder is approx. 15 kg.

Item	Outer diameter	Inner diameter	Thickness	Cold Gas Gap
REFA-170	72.0 mm	70.0 mm	1.00 mm	
Capsule wall non-fuel area -310 – -220	69.5 mm	67.8 mm	0.85 mm	250 μm
Capsule wall fuel area -220 – 170	69.4 mm	67.8 mm	0.80 mm	300 μm
Capsule wall non-fuel area 170 – 320	69.5 mm	67.8 mm	0.85 mm	250 μm

Table 9: Capsule dimensions of HFR-EU1bis

4.1.2 Rig Head and Connection Boxes

Instrumentation leads and gas tubes, which are required to monitor and control the process parameters, have to be guided safely between the in-pile sample holder and the out-of-pile instrumentation consoles and gas panels. The following constraints have to be respected:

- they must be protected, especially in the reactor pool and reactor building;
- in particular the gas tubes have to be enclosed in a second controlled containment;
- provision for easy loading of sample holder and handling in the pool;
- the ALARA principle.

The leads for thermocouples, VDU and solenoid valves together with the gas tubes are bundled in a flexible hose which is guided through the pool and across the pool wall to the central connection box at the third floor South side belonging to the PSF gas box 8. The rig head contains two main cables with Cu leads for 48 thermocouples. One cable will be used for 24 thermocouples, some leads of the other cable will pilot the three solenoid valves (24 VDC). The gas tubes are guided to the connection box of the PSF installation.

The major connection box is the so-called rig head that is located on top of the REFA rig. It allows loading and connection of dedicated sample holders. It contains all instrumentation leads and gas tubes and their appropriate connectors for thermocouples, solenoid valves and gas tubes. In addition, the rig head contains the vertical displacement unit, VDU.

A special REFA head (identification N-R1-04-CA) will be used. It is equipped with:

- 2 cables with 25 copper extension cables for thermocouple wires (the 3 solenoid valves are connected via extension cable 2)

- 1 cable (5 leads) for vertical displacement unit VDU
- 5 gas lines for pressurization of rig head and connection box with N_2
- 8 gas lines (in/out 1st containment, in/out 2nd containment)

Snap-tight couplings that close on both the male and female side when disconnected are used for all gas tube connections. The remotely operated vertical displacement unit is fully accommodated in the rig head. The overall length of the rig head is approx. 1150 mm. The cover of the rig head is sealed by two O-rings and held in position by a bayonet lock and bolts at the upper end. The rig head features a large snap-tight coupling in order to enable effective sweeping of the rig head prior to opening. The flexible hoses are long enough to allow access of the REFA rig with loaded and connected sample holder to any reactor position, to the neutron radiography camera and to the storage facility at the pool wall.

Provision is made for turning the rig after each cycle with respect to the previous position. This will be formalized through the monthly core planning meetings.

4.2 External Installations

4.2.1 Cooling System

This section is not relevant because of use of primary reactor coolant.

4.2.2 Gas Supply and Circulation System

The HFR-EU1bis irradiation will be operated and controlled by a modified panel in glove box 8 of the Pool Side Facility (PSF) gas boxes located on the 2nd floor, which also enables gas sampling in the 1st containment. This panel allows independent gas adjustment and sweeping of either containment by separate circuits and manual gas composition changes for temperature control. The corresponding connection box for the gas circuits is located on the HFR 3rd floor. After the passage through the rig, the gas lines return into the connection box, where possible gas leakage there is monitored by a GM counter and from where the gas is routed back to the PSF gas station, where also gas samples can be taken for analysis. From the PSF gas station, the gas flows to a decay tank, and then to the HFR off-gas system.

In normal operation, all gases are stagnant. Check valves in up- and down-stream gas lines avoid back flow. Back-diffusion of possibly released radioactive gases from the 1st or 2nd containment into the gas supply system is excluded due to the high density of the concerned isotopes (mainly Kr and Xe) while I isotopes (melting point 113.7°C, boiling point 184.4°C) will plate out on the cold gas lines within the rig itself. This was confirmed in several previous irradiations (project numbers J 96, E 91, D 138.1, R 137).

An additionally built rack contains the control buttons for all solenoid valves, the PAU units for the pressure transducers, the read-out for the mass flow controller and the wiring for safety-related interlocks. The read-out of the GM1 counter is situated in a separate rack opposite the PSF gas box.

The data acquisition is performed by the DACOS system. A DACOS terminal next to the PSF gas boxes will be used.

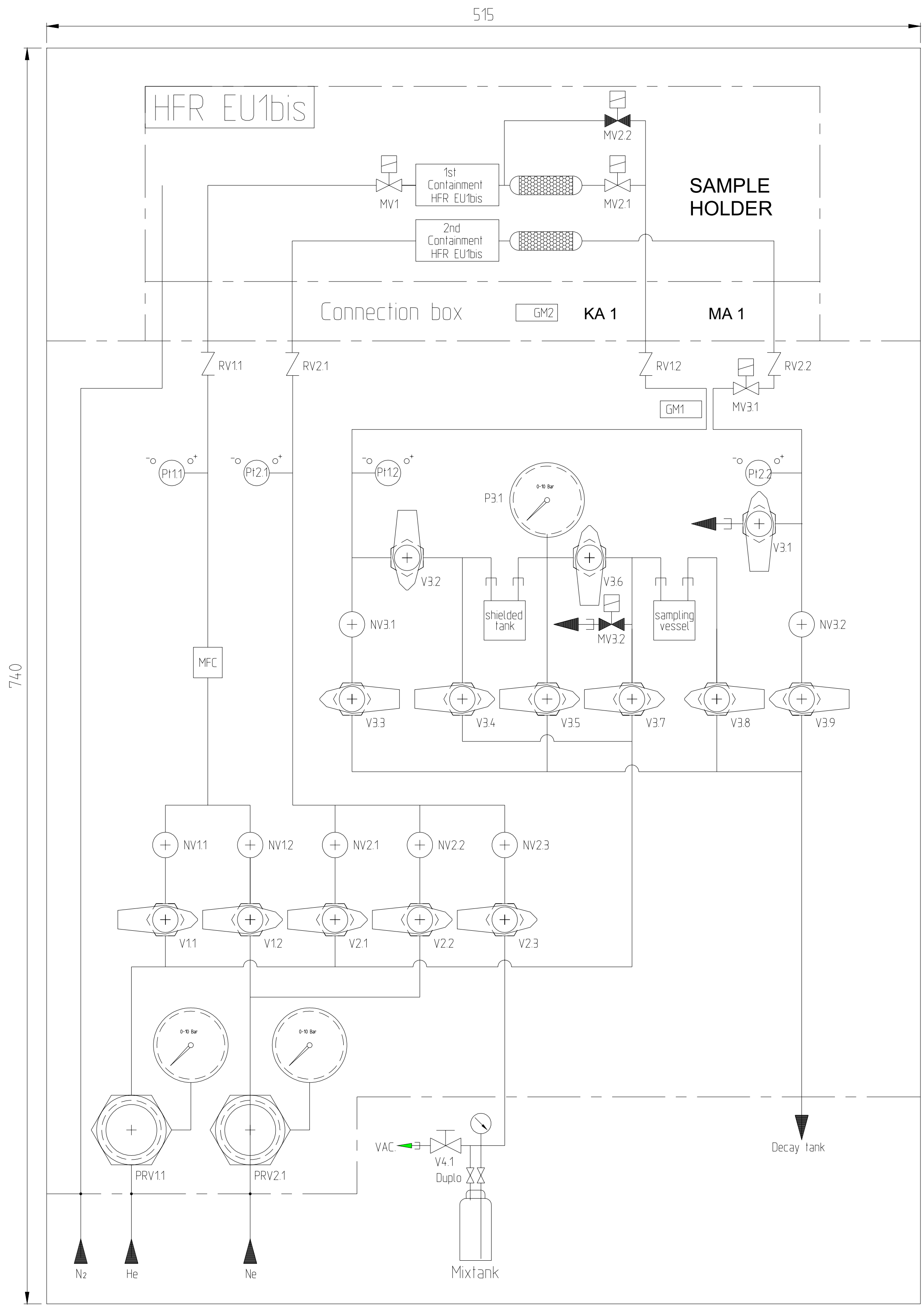

Figure 6: HFR-EU1bis gas routing scheme

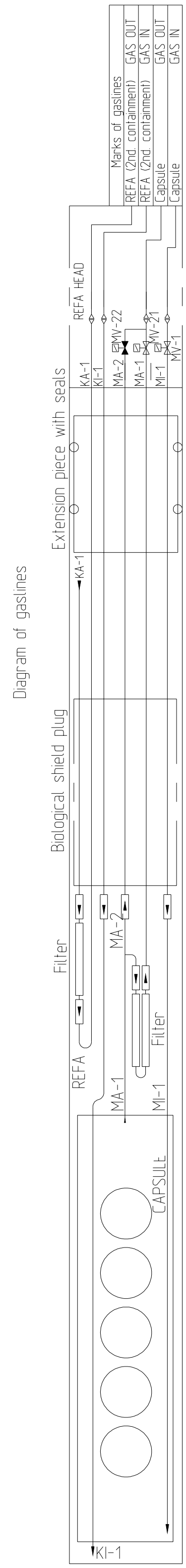

Figure 7: Gas routing and valves in rig

4.3 Instrumentation

4.3.1 General

The instrumentation of the HFR-EU1bis experiment consists of 24 thermocouples (TC), 3 neutron fluence detectors (FD), and 1 gamma-scan wire (GSW). Specifications of thermocouples and extension cables are provided in Table 10. Numbering starts from top and North.

This instrumentation is completed out-of-pile by pressure transducers for the 1st and 2nd containment, a manometer for the rig head containment and by Geiger-Müller counters, one in the connection box and one in the gas panel to monitor the gas activity.

The FDs are described in section 4.3.6. The positions of all detectors in the rig are given in drawing GCO-66866 C. The orientation of the FD with respect to the core orientation is defined and marked. The FDs are positioned between pebbles in the graphite half shells. They provide the accumulated neutron fluence at the position of the detector after irradiation. All FDs are positioned at the North side. Since the experiment will be turned after each cycle by 180° in order to smoothen the azimuthal fluence profile, the FDs will only be positioned at the North side. Former experiments have shown that this is an adequate instrumentation for fluence measurements.

In addition, a GSW (stainless steel wire, diameter 1 mm, length 615 mm) runs internally on the North side along almost the whole capsule. By gamma scanning after irradiation it provides the relative axial and azimuthal thermal and fast neutron fluence distribution. In addition, neutron fluences can be derived from the results of the GSW measurements. Small pieces of < 1 g, cut from such a wire, are included in each FD.

The thermocouples (type N) are positioned in the surface of the pebbles and between pebbles in the graphite half shells. The pebbles 1 and 5 are equipped with TCs in the fuel free zone at the North and South pole, respectively. Four TCs are used in the upper and lower graphite cylinders to evaluate the thermal insulation technique and 16 TCs measure the surface temperature of the pebbles. This enables a good mapping of the temperature profile and provides input for the verification of the thermal computations. This design has successfully been applied in previous HTR fuel irradiations [11].

instrument	inside capsule
Thermocouples	total 24 2 on vertical axis of top pebble (North pole) 2 on vertical axis of bottom pebble (South pole) 1 in center of Al disc (bottom cap) nature of wires: Nicrosil / Nisil, type N sheath material: Inconel 600 outer ∅1.05 mm insulator: MgO length: 5 m type: 2 LMI 10/5m/Ti/MgO/X-ray (Sodern)
Thermocouple extension cables	nature of wires: Cu/Cu length: 12 m
Fluence Detectors	3, North
Gamma Scan Wire	1, North stainless steel, ∅1×615 mm

Table 10: Overview of instrumentation of HFR-EU1bis

4.3.2 Process Instrumentation

The process instrumentation measures the sample temperatures and enables their adjustment. It is completed by pressure measurements for the three containments.

Sample #	TC #
1 Graphite	1, 2, 3
2 (pebble 1)	4, 5, 6
Intermediate Graphite	7, 8
3 (pebble 2)	9
Intermediate Graphite	10, 11
4 (pebble 3)	12, 13
Intermediate Graphite	14, 15
5 (pebble 4)	16
Intermediate Graphite	17, 18
6 (pebble 5)	19, 20, 21
7 Graphite	22, 23
Aluminum Block	24

Table 11: Thermocouple positions in the sample holder

During the irradiation, the surface temperatures of the samples will have to be raised according to Table 1. This will be done by using suitable gases or gas mixtures in the 1st and 2nd containment prepared in the PSF panel. Once the desired temperatures are reached and stable, the pressures will be adjusted, the gas flow will be stopped and the containments will be isolated.

The process data is recorded by a data logger of the central HFR computer data acquisition system DACOS. Values are scanned with 10-second intervals and stored on mass storage. A software package reduces the data volume: The 10-seconds data is reduced after one hour to 2-minutes data. The 2-minutes data is reduced after 24 hours to 10-minutes data. The 10-minutes data is used for off-line data evaluation. Optionally, the 10-seconds data and the 2-minutes data can be stored. This option is used during transients such as start-up and shutdown.

4.3.3 Operational Instrumentation

The experiment makes use of the PSF glove box 8, the related connection box and a special rack for instrumentation, valve switches, alarms etc. The commissioning report is detailed in [21]. Two existing GM counter read-outs opposite the PSF gas boxes and a DACOS terminal complete the installation. The instrumentation in these elements is as follows (cf. Figure 6):

1. **PSF Glove Box 8:**
   The PSF glove box 8 provides the required gas mixtures for the 1st and 2nd containment and receives the gas back from these containments. It also enables the pressurization of the rig head with N_2. The pressure of the containments will be monitored by one standard membrane manometer with low and high alarm contacts for the rig head containment and by 4 up- and downstream pressure transducers for the 1st and 2nd containments. These pressure transducers are connected to PAU units that allow adjustable thresholds for upper and lower alarm. Pressures of these containments can thus be recorded by DACOS for continuous monitoring and enable the verification of the integrity of the containments. The gas panel also contains a mass flow controller for the 1st containment, a Geiger-Müller counter GM1 for monitoring the activity in the 1st and 2nd containment and in the glove box, and a membrane manometer in the sampling string of the downstream gas lines.

2. **Connection Box:**
   The connection box for the PSF glove box 8 is used. It is be equipped with a Geiger-Müller counter GM2 to monitor radioactivity leakage and to indicate the arrival of active gas in the PSF glove box.

3. **Instrumentation Rack:**
   The instrumentation rack is a 19-inch rack positioned next to the PSF glove box 8. It contains the following elements:
   - 4 pressure alarm units for the 4 pressure transducers
   - Read-out for the mass flow controller
   - Switches for all magnetic valves (3 on top of the sample holder and 2 in the gas panel) with LEDs (red = closed, green = open) on the gas panel itself
   - Power supply and transformer 220 V AC ➔ 24 V DC for operation of valves etc.
   - A relay system to trigger interlocks and alarms

- Override buttons for all interlocks together and individually
- Flashlight and buzzer for alarm indications
- LED tester
- Alarm tester, acknowledgement, reset, on/off

The three magnetic valves in the rig head are designated MV1, MV21 and MV22. MV 22 is a normally (de-energized) closed valve and MV1 and MV21 are normally open valves. In standard mode, the capsule is purged via MV1 (upstream) and MV21 (downstream). When purged, the downstream gas must pass a filter, filled with activated charcoal. MV22 is only opened in gas sampling mode, MV21 is then closed. The magnetic valve to the vacuum pump MV32 is a normally closed valve. The magnetic valve in the downstream string of the 2nd containment MV31 is a normally open valve. An interlock will trigger the closure of the downstream magnetic valves of the 1st and 2nd containment (MV21, MV22 and MV31) when opening MV32 to avoid undesired depressurization of the containments.

The read-out for the GM1 counter is situated in a rack opposite the PSF gas panels and provides its alarm signal to the PLC. The read-out for GM2 is situated next to the connection box.

For the adjustment of the VDU, a portable control unit is used and disconnected during operation.

4. **A DACOS terminal** is positioned next to the PSF gas box 8 to provide feed back of the manual actions in the gas box. DACOS is used for data logging and data storage of experimental data such as temperatures and pressures. Audible alarms are released in case of transgression of lower or upper operating limits of temperature and pressure settings. The operating limits are defined in the graphic file of DACOS.

4.3.4 Scientific Instrumentation

The scientific instrumentation comprises the temperature readings and the gas analyses data. As shown in Figure 6, the gas analysis is performed by regular sampling in the PSF gas panel while bypassing the 1st containment filters. This gas will then be further analyzed by mass spectrometry in the radiation protection laboratory.

A possible method of gas sampling from the 1st containment is as follows:

- Evacuate decay tank
- Override pressure alarm of 1st containment
- Close MV1 and MV21
- Open MV22, gas of 1st containment will be sucked into the decay tank, volume >1000 cm^3
- Purge 1st containment by opening MV1 until 2 bar is achieved
- Close MV1 and MV22
- Evacuate sampling container, approx. 100 cm^3 volume

- Connect decay tank and gas sampling container and take gas sample by pressure equalization
- Disconnect sampling container, remove it through the gas box port and perform measurement with multi-channel analyzer for quantitative determination of Kr and Xe isotopes
- Adjust correct pressure in 1st containment, close all valves and adjust required conditions

Another method would be to take a direct sample from the 1st or 2nd containment gas as follows:

- purge containment through the built-in filter with a known mass flow
- bypass built-in filter and monitor GM counter reading until stable
- evacuate sampling container
- open valve to sampling container until pressure is same as in containment
- close valves and resume normal operation

4.3.5 Safety Instrumentation

4.3.5.1 General

Radiation control is part of the PSF facility. A Geiger-Müller counter monitors the downstream effluents and the gas activity in the PSF glove box. In normal operation and only in purge mode, the radioactivity release is expected to be very low due to the passage of the purge gas for 1st and 2nd containment through activated charcoal filters. Only for quantitative measurement of the fission gas release, the filter for the 1st containment will be bypassed (MV21 closed, MV22 opened) and gas samples can be taken at the PSF facility. The transgression of radioactivity thresholds in the downstream effluent lines triggers DACOS alarms.

The operating parameters of the HFR-EU1bis experiment with respect to power, temperature, mechanical stresses and reactivity are modest, cf. chapter 5. Therefore, no interlock with reactor operation is provided. Relevant experiment and process data, i.e. temperatures of the graphite and fuel surface and the pressure of the 1st, 2nd and rig head containment are recorded by DACOS.

High and low alarm thresholds are defined for containment pressures, temperatures and activity of the personnel area. In addition, operating limits are defined for all process parameters that are recorded by DACOS. These limits will be defined in the manual. Transgression of alarm thresholds and operating limits triggers an audible and visible alarm at the PSF installation, in DACOS, and in the reactor control room. Alarms will be followed by manual action of the shift personnel. If the temperatures are too high, the Ne fraction in the 1st and/or 2nd containment will be reduced, if the temperatures are too low, the Ne fraction will be increased. Sudden temperature increase (max. possible <1550°C central fuel temperature, max. possible 435°C capsule temperature) of the specimens due to faulty gas mixture at BOI has no influence on the capsule containment (cf. Table 20). Action is restricted and not urgent, i.e. manual closure of Ne supply line.

The following measures are taken to safely operate the experiment that contains nuclear fuel:

- There will be no connection of the 1st and 2nd containments to the N_2 supply line in order to prevent excessive target and containment temperatures at BOI in case of faulty operation;
- The downstream gas lines of the 1st and 2nd containment are provided with filters. In case of radioactive gas release, they are delayed sufficiently to allow decay below admissible levels. The filter volumes are filled with activated charcoal.

The minimum required instrumentation to guarantee safe operation of the experiment and to yield sufficient experimental data is:

- Any 3 TCs measuring the surface temperature of the fuel pebbles (numbers in brackets are reserve), for example: TC 4(5, 6), TC 12 (13) and TC 19 (20, 21); they are not interlocked with reactor operation;
- 1 gas pressure indication for the 1st containment,
- 1 gas pressure indication for the 2nd containment,
- 1 gas pressure indication for the rig head containment,
- 1 Geiger-Müller counter in the downstream lines of the connection box,
- 1 Geiger-Müller counter for activity monitoring in the PSF glove box and in the downstream lines of the 1st and 2nd containment during purging and gas sampling.

4.3.5.2 Experiment Interlocks

The following interlocks are installed:

- A high activity alarm in GM1 isolates the 1st containment (closure of MV1, MV21 and MV22). The same will happen for specific HFR alarms, i.e. off-gas pressure and off-gas activity.
- Alarms by the 4 pressure transducers isolate the 1st containment (closure of MV1, MV21 and MV22). This implies that in case of an in-pile leakage, the maximum released purge gas volume is 1300 Ncm^3.
- Opening of MV32 to the vacuum pump will automatically close MV21, MV22 and MV31 to avoid incidental depressurization of the 1st or 2nd containment by possibly wrong handling of the manual valves.

No interference with reactor operation (APD or scram) is required due to moderate operating conditions.

4.3.6 Additional Experimental Instrumentation

For the purpose of neutron dosimetry, 3 standard neutron fluence detector sets (FD) and 1 gamma scan wire (GSW) are located inside the central tube of the sample holder. The FD sets are composed of pieces of Ni-Co, Ti, Fe and Nb. These pieces are encapsulated in a quartz tube and this assembly is again encapsulated in a stainless steel tube of (∅2.0/1.6 mm length 25 mm) [18].

The GSW is made of stainless steel. Its diameter is 1 mm extending over almost the entire length of the capsule. The GSW and detector sets are marked. The neutron detector sets and the GSW will be analyzed after irradiation.

The post-irradiation counting results of FD and GSW will provide the following data:

- thermal neutron fluence,
- fast neutron fluence (e.g. for Ni and for E> 0.1 MeV and E>1 MeV),
- equivalent fission fluence,
- spectrum indices,
- fuel burn-up,
- axial and azimuthal relative and absolute distribution of thermal and fast fluence.

4.4 Utilities

The utilities required for the operation of the HFR-EU1bis experiment are inert gases He, Ne and N_2, supplied by the HFR standard service system. The 1st and 2nd containments will be connected to a PSF glove box for integrity control and temperature adjustment with appropriate He/Ne gas mixtures and gas sampling of the 1st containment. The rig head containment will be pressurized with N_2.

4.4.1 Electrical Power Supply System

Electricity is needed for the operation of the PSF gas panel and the instrumentation rack and is covered by the off-site power supply. Process instrumentation is connected with the uninterrupted power supply.

4.4.2 (Make-Up) Water Supply System

N/A

4.4.3 (Service) Gas Supply Systems

The required gases He, Ne and N_2 are provided by the standard HFR gas supply system.

	1st containment	2nd containment	rig head containment	total flow rate during purging
He [sccm/min]	static	static	--	< 200
Ne [sccm/min]	static	static	--	< 200
N_2 [sccm/min]	--	static	static	< 200
Total [sccm/min]	static	static	static	< 600

Table 12: Gas requirements for HFR-EU1bis

Continuous purging will only be performed during initial start-up for 1-2 days to reduce the water vapor content in the graphite, subsequent start-ups with 1 hour purge. Further batch wise purging is required only for gas sampling and temperature adjustment, thus the total gas consumption and release are low.

4.5 Waste System

The waste system for containment gases and for the glove box is the off-gas system of the HFR. Optionally, radioactive gases can be stored in a shielded decay tank until sufficiently decayed. The tank belongs to the standard PSF service system for experiments. Gases can be released from that tank into the off-gas system in a controlled manner. Gas samples for the determination of the release of fission gases can be taken from that decay tank.

4.5.1 Off-Gas System

The gaseous effluents of all containments are routed to the decay tank, prior to transfer to the HFR off-gas system, which has a capacity of 2×10^3 m^3h^{-1}. The off-gas is guided in large tubes into the manifold of the off-gas system. The specific activity release rate of fission gases into the filter station is under normal operating conditions <10 Bq s^{-1}, thus the release into the off-gas system is <<1 Bq s^{-1}.

4.5.2 Water-Disposal System

N/A

4.6 Shielding

The shielding of the in-core section is composed of a standard shielding plug for sample holders (designed in accordance with the specifications for standard in-core facilities) and of a 4 m high water column above the rig head. This shielding is sufficient to keep the radiation levels induced by this experiment above the pool and in the personnel area during operation and handling < 50 μSv/h.

Shielding of the standard PSF glove boxes is sufficient for the operation of HFR-EU1bis. These boxes are designed for operation of Pu-containing irradiation capsules with much higher fission product content than in HFR-EU1bis. The radiation level in the working area during gas sampling of one capsule is < 50 μSv/h. This was verified during the operation of former experiments [11] and would correspond to a significant Release/Birth fraction of R/B ≈ 0.4 without filter, i.e. 40% of all particles have failed and the gas is released into the containers in the PSF glove box without filtering. In reality, even higher failure rates could be accepted because the gas will be filtered and because the decay tank is shielded.

5 Characteristics

5.1 Nuclear Characteristics

The nuclear analysis was performed by means of the WIMS8 nuclear package, the HFR-TEDDI code and the FISPACT code [16].

The fluence rates are summarized in Table 13. The resulting power evolution per pebble per cycle was already shown in Table 1.

Group	Energy range	Fluence Rate [$cm^{-2}s^{-1}$]
1	1.353 MeV - 19.64 MeV	0.741 E14
2	67.34 keV - 1.353 MeV	1.225 E14
3	0.625 eV - 67.34 keV	1.523 E14
4	0.0001 eV - 0.625 eV	0.979 E14
	E > 1 MeV	0.935 E14
	E > 0.1 MeV	1.857 E14
"2200 ms^{-1}" (Co)		0.854 E14
gamma heating		4.21 W g^{-1}

Table 13: Position-averaged (± 300 mm from core center line) broad group fluence rates and gamma heating

5.2 Thermal Characteristics

The fission and gamma power is dissipated mainly radially by conduction and radiation through the solid material layers and gas gaps. The temperature of the pebbles is controlled by adjusting the gas mixtures in the gas gaps. Thermal analyses have been performed with special emphasis on obtaining constant central pebble temperatures in all pebbles throughout the irradiation. The variable design parameters for a given heavy metal loading of the pebbles are irradiation position, material composition, gas gap dimension, and initial gas mixture.

The parameters to be considered are pebble temperature and temperature gradient, burn-up/fluence correlation, maximum power per particle, and fission power depletion with time. Changes of material properties as a function of neutron fluence and temperature as well as shrinkage phenomena of the graphite were not accounted for as these effects can be compensated with the appropriate gas mixture and are not safety relevant.

The required power per pebble (fission + gamma), central pebble temperature and burn-up/fluence correlation can be achieved in position G3 or equivalent. The general purpose FE-code MARC, version 2003 has been used for the numerical calculations using an axisymmetric model. The model and the used material properties are described in detail in [17]. The power evolution with time together with the axial buckling for neutron flux and gamma heating were used as input. The results of this analysis are in particular the stepped gas gaps between graphite and 1st containment (Table 8) and the stepped gas gap between 1st containment and REFA rig (Table 9).

The temperature control margin for the initial conditions at BOI was determined by adjusting the gas mixture in the outer gas gap between 100% Ne and 100% He. The result is about 1 and 0.75 K/vol% Ne in He for BOI and EOI, respectively. The radial heat flux densities are well below the acceptable limit of the REFA rig (100 W/cm^2) and create no critical thermal conditions. The coolant temperature increase is < 5 K.

The thermo-mechanical stress in the mini-samples was not explicitly calculated as the produced power is only of the order of 10 W.

In conclusion, the temperatures remain significantly below the acceptable limits in all materials under all possible, including erroneous and accidental, operating conditions.

5.3 Stress Characteristics

According to the Pressure Equipment Directive (PED 97/23/EC) Annex I-Art. 7.1.2 [27] the design has to consider the following stress criteria:

Mechanical:

tube part sample holder	$\sigma_{t,\,max} \leq 0.67\ R_e(T)$
bottom/top part sample holder	$\sigma_{t,\,max} \leq R_e(T)$ or $\sigma_{t,\,max} \leq 0.5\ R_m(T)$ whatever is more stringent

Total (thermal + mechanical):

Note that no total stress criteria are defined yet in the PED rules. Therefore, the total stresses are checked against ASME section III criteria:

tube part sample holder	$\sigma_{th,\,max} + \sigma_{t,\,max} \leq 2\ R_e(T)$
bottom/top part sample holder	$\sigma_{th,\,max} + \sigma_{t,\,max} \leq 2\ R_e(T)$

where:

$\sigma_{t,\,max}$ maximum mechanical stress [MPa]

$\sigma_{th,\,max}$ maximum thermal stress [MPa]

$R_e(T)$ yield stress at temperature T [MPa] for 316 L steel:

$R_e(T) = 270.09 - 0.5702\ T + 9.1162\times10^{-4}\ T^2 - 5.6198\times10^{-7}\ T^3$ [MPa]

for the temperature range $0 \leq T[°C] \leq 800$ [28]

$R_m(T)$ ultimate tensile strength at temperature T [MPa] for 316 L steel:

$R_m(T) = 617.275 - 1.775\ T + 7.0659\times10^{-3}\ T^2 - 1.0769\times10^{-5}\ T^3 + 4.8941\times10^{-9}\ T^4$ [MPa]

for the temperature range $0 \leq T[°C] \leq 800$ [28]

5.3.1 Boundary Conditions and Assumptions

The thermo-mechanical calculations are described in detail in [17] including the assumptions, model and material properties. Stresses were calculated together with the thermal characteristics. The maximum values are generally situated in the containment tube near the bottom plate (cf. general assembly drawing GCO 66866 C) when assuming incomplete contact between Al block and steel. The Al block helps dissipating the gamma heating in the lower end cap to a larger surface and thus reduces thermal stresses. Due to the fact that the Al block was machined to fit and due to the higher thermal expansion of the Al compared to the steel tube, this is a very conservative assumption.

For the graphite of the half shells we have assumed a thermal conductivity of 50 $Wm^{-1}K^{-1}$ and for the graphite of the pebbles 31 $Wm^{-1}K^{-1}$. Considering the uncertainty in the thermal conductivity data for both graphite types of 10% (the conductivity will decrease during irradiation), the effect will be a measurable increase of the pebble and graphite temperature while the temperature of the confinement will not be significantly affected. This effect can be compensated with the gas mixture technique and is actually favorable for maintaining the elevated pebble temperatures.

For the mechanical properties of the AISI 321 steel tube, we have assumed those of AISI 316L.

The maximum mechanical stresses are determined by the maximum pressure difference between sample holder and 2nd containment. This pressure difference cannot exceed 1.0 MPa because it corresponds to the maximum pressure in the HFR gas supply system.

The thermal boundary conditions were chosen for two very conservative cases, one in which the maximum stress occurs in the sample holder tube ([17], Table 15, Case 3), the other where the maximum stress occurs in the bottom part of the sample holder ([17], Table 15, Case 4).

The maximum stresses in the tube occur at BOI when due to an operating error there will be 100% He in the 1st containment and 100% Ne in the 2nd containment.

cause	effect	origin
depressurization of 2nd containment	atmospheric pressure 0.1 MPa abs. in 2nd containment	operating error or valve failure
depressurization of 2nd containment with pure Ne at BOI	pure Ne in 2nd containment	operating error
pressurization of 1st containment	1.1 MPa abs. in 1st containment	failure of pressure reduction valve
pressurization of 1st containment with pure Ne at BOI	pure He in 1st containment	operating error

Table 14: Assumptions for maximum stress analysis in the sample holder tube

The maximum stresses in the bottom part of the sample holder occur when we assume that due to an operating error at BOI, pure Ne will be used in the 1st containment.

cause	effect	origin
depressurization of 2^{nd} containment	atmospheric pressure 0.1 MPa abs. in 2^{nd} containment	operating error or valve failure
depressurization of 2^{nd} containment with pure Ne at BOI	pure Ne in 2^{nd} containment	operating error
pressurization of 1^{st} containment	1.1 MPa abs. in 1^{st} containment	failure of pressure reduction valve
pressurization of 1^{st} containment with pure Ne at BOI	pure Ne in 1^{st} containment	normal operating condition

Table 15: Assumptions for stress analysis in the bottom part of the sample holder

So, conservatively, this stress analysis is performed assuming at least two operating errors and one component failure to occur simultaneously. The temperatures indicated in the tables below are those of the areas showing maximum stress. As enveloping cases we have equally shown the results when assuming that the maximum stress would occur at the same place as the maximum temperature.

The assumptions in Table 15 cause the maximum possible central pebble temperatures, which would then range between 1450 and 1550°C.

5.3.2 Mechanical stresses in sample holder tube

The resulting axial and radial mechanical stresses can be estimated as follows ("ketelformule"):

radial stress: $\sigma_{rad} = \frac{\Delta p \cdot d_i}{2t}$ axial stress: $\sigma_{ax} = \frac{\Delta p \cdot d_i}{4t}$

where:

σ_{rad}	radial stress [MPa]
σ_{ax}	axial stress [MPa]
Δp	pressure difference [MPa]
d_i	inner diameter [m]
t	minimum wall thickness [m]
$\sigma_{t,\,max}$	max (σ_{rad}, σ_{ax})

The resulting maximum mechanical stresses are summarized in Table 16.

Δp [MPa]	d_i [mm]	t [mm]	σ_{rad} [MPa]	σ_{ax} [MPa]	T [°C]	0.67 $R_e(T)$ [MPa]	Safety Factor
1.0	67.8	0.8	42.38	21.19	435	99.36	2.34

Table 16: Mechanical stresses in sample holder tube

5.3.3 Thermal stresses in sample holder tube

The maximum thermal stresses in the sample holder tube were calculated as [17]:

Sample holder tube	
T [°C]	$\sigma_{th,max}$ [MPa]
435	145

Table 17: Maximum thermal stresses in sample holder tube

5.3.4 Total stresses in sample holder tube

The total stresses in the sample holder tube were calculated in the table below:

T [°C]	$\sigma_{th,max}$ [MPa]	$\sigma_{t,max}$ [MPa]	$\sigma_{th,max}$ + $\sigma_{t,max}$ [MPa]	2 $R_e(T)$ [MPa]	Safety Factor
435	145	42	187	296.6	1.59

Table 18: Maximum total stresses in sample holder tube

5.3.5 Mechanical stresses in top and bottom parts of sample holder

The mechanical stresses in the top and bottom parts of the sample holder are calculated using the formulas from [29]. For this calculation we have assumed the following boundary conditions:

- uniform internal gas pressure (maximum gas pressure difference between 1st and 2nd containment)
- fixed edges as given in [29], Fig. 10b in Table 24.

The maximum stresses at the top σ_{top} and bottom σ_{bot} parts are defined by the following equations:

$$\sigma_{top} = \frac{6 \times M_b}{t_{top}^2} \qquad \sigma_{bot} = \frac{6 \times M_b}{t_{bot}^2} \qquad M_b = \frac{p \times d_i^2}{32}$$

with:

σ_{top} maximum stress in top part [MPa]

σ_{bot} maximum stress in bottom part [MPa]

M_b maximum bending moment [N]

t_{top} average thickness of top part [m]

t_{bot} average thickness of bottom part [m]

d_{top} inner diameter top part [m]

d_{bot} inner diameter bottom part [m]

Δp pressure difference [MPa]

	Δp [MPa]	d_i [mm]	M_b [N]	t_i [mm]	σ_i [MPa]	T [°C]	$R_e(T)$ [MPa]	Safety Factor
top	1.0	67.8	143.65	3	95.77	< 300	> 165.9	> 1.7
bottom						320	162.56	1.7
*	*1.0*	*67.8*	*143.65*	*3*	*95.77*	*435*	*148.3*	*1.55*

Table 19: Mechanical stresses in sample holder top/bottom parts
** indicates an enveloping case at the maximum possible temperature*

5.3.6 Thermal stresses in top and bottom part of sample holder

The thermal stresses in the sample holder tube were calculated as:

Bottom part of sample holder	
T [°C]	$\sigma_{th,max}$ [MPa]
320	155

Table 20: Temperatures and thermal stresses in bottom part of sample holder

5.3.7 Total stresses in top and bottom part of sample holder

The total stresses in the 1st containment for these cases are:

T [°C]	$\sigma_{th,max}$ [MPa]	$\sigma_{t,max}$ [MPa]	$\sigma_{th,max} + \sigma_{t,max}$ [MPa]	2 $R_e(T)$ [MPa]	Safety Factor
320	155	95.77	251	325.12	1.3
**435*	*155*	*95.77*	*251*	*296.6*	*1.18*

Table 21: Total stresses in top and bottom part of sample holder
** indicates an enveloping case at the maximum possible temperature*

In conclusion, all capsule parts fulfill the design criteria even under the enveloping assumption that the maximum stresses occur at the same places as the maximum temperatures.

Note that during normal operating conditions, the maximum pressure difference between the inside and the outside of the sample holder is only 2.5 bar with the inside being at lower pressure than the outside which makes the mechanical stress calculations very conservative.

In any case, the worst consequence would only be the failure of the 1st containment, which is analyzed in section 10.1.2.

5.4 Reactivity Characteristics

The reactivity calculations for the HFR-EU1bis experiment were performed to evaluate the maximum reactivity insertion due to complete capsule ejection during reactor operation. The reactivity was calculated by the HFR physics group according to the most recent model [16].

The reactivity effects of the experiment in position G3 with respect to a water hole in the same position were calculated using the standard cores 21051 and 22010. The results are given in Table 22. The negative values of the reactivity increase mean that the core reactivity will *decrease* upon removal of the experiment.

Standard core 21051

	ρ_{plug}	$\rho_{exp.}$	Meas. $\rho_{water} - \rho_{plug}$	$\rho_{plug} - \rho_{exp.}$	$\rho_{water} - \rho_{exp.}$	Reactivity change [pcm]
INI	0.07425	0.07281	-0.00100	-0.00036	-0.00136	-136
EQ	0.04631	0.04673	-0.00100	-0.00042	-0.00142	-142
BU	0.03055	0.03094	-0.00100	-0.00039	-0.00139	-139

Standard core 22010

	ρ_{plug}	$\rho_{exp.}$	Meas. $\rho_{water} - \rho_{plug}$	$\rho_{plug} - \rho_{exp.}$	$\rho_{water} - \rho_{exp.}$	Reactivity change [pcm]
INI	0.06371	0.06414	-0.00100	-0.00043	-0.00143	-143
EQ	0.03970	0.04015	-0.00100	-0.00045	-0.00145	-145
BU	0.01538	0.01589	-0.00100	-0.00051	-0.00151	-151

Table 22: Reactivity effect of HFR-EU1bis in position G3

5.5 Radioactivity Characteristics

Radioactivity calculations were performed and are summarized in detail in [16] for the fuel, the graphite and the structural steel.

The FISPACT8 code was used for the calculations. The activation of the materials was calculated for the maximum irradiation time of 14 cycles (350 full-power days); the decay of the active nuclides was calculated for cooling times of 0, 5, 10, 30, 60, 100, 180, 365 and 730 days. The 172-groups neutron spectrum used by FISPACT as input was taken from the CACTUS cell calculations.

The specific activities of U, graphite and steel are listed in Table 23 for several decay times and are plotted in Figure 8. The approximate masses of the sample holder are: uranium 30 g, steel 1500 g, graphite 750 g.

cooling time [d]	activity [Bq/g U] fuel	activity [Bq/g steel]	activity [Bq/g graphite]
0	8.95E+13	4.18E+11	8.95E+09
1	2.37E+13	1.39E+11	8.95E+09
5	1.32E+13	1.23E+11	2.04E+09
10	9.28E+12	1.10E+11	1.48E+09
30	5.57E+12	7.36E+10	8.13E+08
60	3.77E+12	4.44E+10	5.16E+08
100	2.58E+12	2.73E+10	3.72E+08
180	1.49E+12	1.78E+10	2.62E+08
365	7.25E+11	1.42E+10	1.82E+08
730	3.62E+11	1.09E+10	1.48E+08

Table 23: Specific activity decay after 14 cycles (350 efpd) in reactor position G3

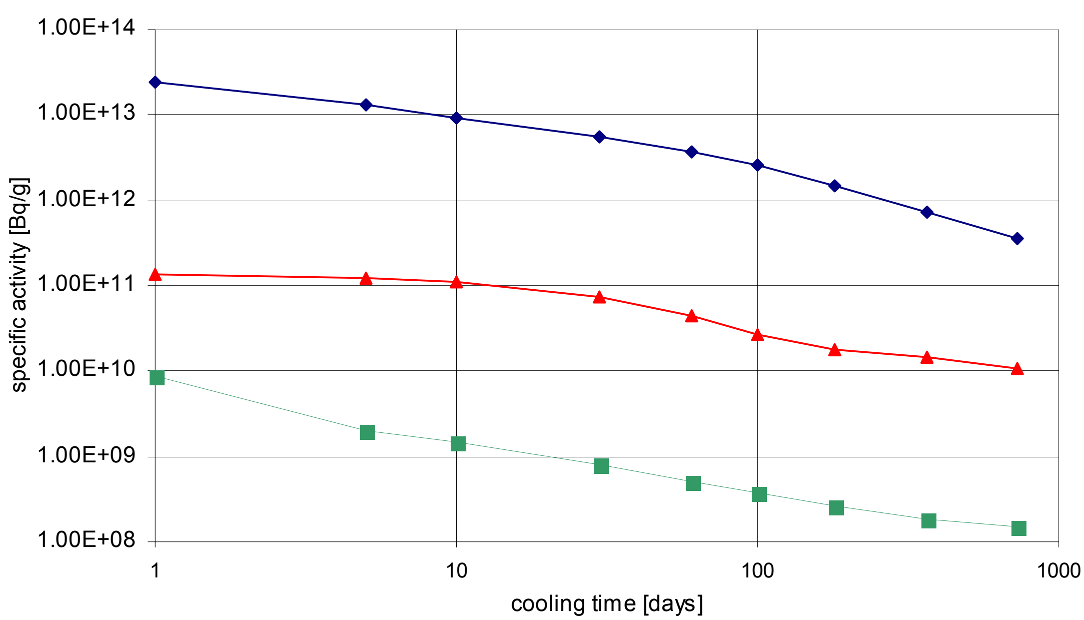

Figure 8: Decay of specific activities in fuel (top), steel (middle) and graphite (bottom) after 14 irradiation cycles

Table 24 summarizes the maximum specific activities for Kr, Xe and I isotopes after 14 irradiation cycles per pebble.

	Nuclide	Bq	Nuclide	Bq	Nuclide	Bq
	Kr-80	0	Xe-126	0	I-131	2.87E+12
	Kr-81	4.443E-02	Xe-127	1.443E+04	I-132	4.35E+12
	Kr-81m	1.611E+04	Xe-127m	4.262E+03	I-133	5.82E+12
	Kr-82	0	Xe-128	0	I-134	6.39E+12
	Kr-83	0	Xe-129	0	I-134m	7.73E+11
	Kr-83m	3.551E+11	Xe-129m	1.076E+07	I-135	5.77E+12
	Kr-84	0	Xe-130	0	I-136	3.87E+12
	Kr-85	1.246E+10	Xe-131	0	I-136m	1.24E+12
	Kr-85m	9.269E+11	Xe-131m	3.277E+10		
	Kr-86	0	Xe-132	0		
	Kr-87	1.301E+12	Xe-133	5.741E+12		
	Kr-88	1.753E+12	Xe-133m	1.683E+11		
	Kr-89	2.340E+12	Xe-126	0		
			Xe-134	0		
			Xe-134m	2.986E+10		
			Xe-135	4.339E+11		
			Xe-135m	9.339E+11		
			Xe-136	0		
			Xe-137	5.429E+12		
			Xe-138	5.238E+12		
			Xe-139	4.899E+12		
Total	**Kr**	**6.69E12**	**Xe**	**2.29E13**	**I**	**3.11E13**

Table 24: Maximum specific activity per pebble for Kr, Xe and I isotopes after 14 irradiation cycles

Total failure of all particles can be tolerated corresponding to a Release/Birth fraction R/B = 1. At EOI conditions and assuming that I nuclides will plate out on cold gas tubes, the maximum total dose rate equivalent (Kr + Xe nuclides) in the sample holder will be approx. 10 Sv/h [16].

If a burst-like release of all accumulated fission products happened at EOI and assuming at the same time that the filter is bypassed, the allowable limit of 50 μSv/h in the glove box would be quickly exceeded and the 1st containment would be automatically isolated. Yet, such a burst effect was never observed before.

If all particles fail successively and assuming that the dose rate production would be diluted in a purge gas flow of 200 sccm/min without filtering, and assuming storage of this gas in the shielded tank of 1000 cm^3 at atmospheric pressure, the resulting dose rate from the shielded tank would become 100 μSv/h, which is by a factor 2 higher than the allowable limit of 50 μSv/h in the glove box. However, this does not account for the efficiency of the filters and the shielding of the tank, so that in reality values are expected that are several orders of magnitude lower.

In case of massive particle failure, the Reactor Safety Committee will be consulted directly. The irradiation can technically be continued with closed 1st containment. As massive particle failure can be handled by the irradiation facility (2 closed containments, built-in filters, only occasional purging for gas mixture adjustment), the HTR-F project coordinator shall assess the consequences on post-irradiation examinations, such as accident simulation tests in the KÜFA facility [2], [3], and shall decide about a possible earlier stop of the irradiation.

6 Fabrication, Inspection and Testing

The entire in-pile irradiation facility was designed by JRC-Petten. The facility consists of the following components:

- REFA-170 rig
- Rig head, commissioning report [20]
- Sample holder with the capsule, commissioning report [19]

The design of these components is based on a series of former HTR-fuel and graphite irradiations, performed under project numbers 138 [24] and 247 [25].

The REFA-170 and the rig head are standard and modular components. They exist already and have been commissioned for in-pile use. They are designed for multiple use [26].

The fabrication of parts and the assembly of the sample holder and the inner capsule were performed by external contractors. The commissioning of the sample holder will be performed by JRC Petten and the HFR staff.

The modified PSF glove box 8 will be used for the operation of the HFR-EU1bis experiment.

During the fabrication phase, special attention must be paid to final dimensional records. In particular the fabrication of the graphite half-shells requires high precision and careful treatment of the fuel elements. The required joining techniques are TIG welding and high-temperature brazing with Nicro-Braz LM filler material of the thermocouple penetrations of the upper cap of the capsule. All joints and brazings must be free of oxidation and grease and must not damage the instrumentation leads.

6.1 Assembly and Commissioning of Capsule and Sample Holder

Assembly will be performed in a 'Clean Room Workshop' that is licensed to handle nuclear materials. Gloves are compulsory. The graphite parts will be annealed at 200°C under flowing He for at least 24 hours to reduce the humidity adsorbed on the graphite. All dimensions will be checked and registered.

The assembly of the six capsules that contain loose coated particles will be performed in a glove box under inert atmosphere. The final weld of the Nb container will be performed in that box under He atmosphere. It must be guaranteed that the Nb containment contains pure He after welding and that the capsules are leak-tight, to be checked by He-sniff test and dye-penetrant.

It is important that the specified clearances are respected, in particular in components, where differential thermal expansion can be expected during irradiation. Parts must be in stress-free state after assembly.

6.2 Testing and work prior to final assembly:

All parts, including capillary tubes will be cleaned prior to assembly. The steel parts shall be cleaned by etching and passivating; bits and pieces must be free of grease and dirt.

- Completeness of all parts and consistency with part lists.
- Selection of pebbles on basis of X-rays and metrology.
- Assembly of six Nb capsules, each filled with 10 loose coated-particles and graphite powder.
- Assembly of filters, filled with activated charcoal; heat treatment of filters after filling with activated charcoal and leak testing; filters should be heated above 200°C and simultaneous purging with He at a flow rate of 100 cm^3/min for 24 hours.
- Numbering of thermocouples, fluence detector sets, gamma scan wire, graphite half-shells, pebbles, Nb capsules, solenoid valves.
- Dimensional checks of all relevant parts of sample holder, including pebbles and graphite parts.
- Visual inspection of cleanliness of all parts.
- Check of contamination level of pebbles and Nb capsules.
- Check of instrumentation cables, loop and insulation resistance of thermocouples and solenoid valves.
- Functional test of pre-assembled components like instrumentation head and snap-tight couplings.

6.3 Testing during assembly

- Check numbering and identification/orientation marks of instrumentation monitors, pebbles, graphite half-shells, Nb capsules.
- Check free passage of capillary tubes.

- Check loop and insulation resistance of the instrumentation cables and thermocouples before and after each manipulation like welding or brazing.
- Check position of instrumentation detectors like thermocouples, fluence detector sets, gamma scan wire in axial and azimuthal direction.
- Check position and orientation of pebbles and clearance between pebbles and graphite half-shells.
- Check mark *“direction North”* at various heights of sample, especially at capsule tube and at upper suspension.
- Check leak-tightness of capsule, filters, solenoid valves and accompanying tubes and couplings. The admissible leak rate is $< 3\times10^{-8}$ mbar l/s.
- Pressure test of sample holder containment with 10 bar He, use of Ar or N_2 as test gas is ***explicitely prohibited*** to avoid unnecessary activation products.
- Dye-penetration checks of containment welds, in particular of the 6 Nb capsules.
- Check the proper connection of the instrumentation cables with the connectors (cable and pin number) and polarity of thermocouples.
- Check sample holder internals by X-ray photography.
- Functional tests of all components.
- Check all overall dimensions of sample holder.
- Final cleaning with ethylene, check of cleanliness and visual inspection.
- Check availability of all rig handling parts like transport cover etc.
- All tests, defects and modifications must be registered and described.

6.4 Commissioning test of the assembled sample holder

Following the Q/A system and ISO 9001 regulations at JRC-IE Petten, all devices have to be commissioned prior to approval for irradiation by the local commissioning officer at JRC-IE and a final commissioning at the HFR. The commissioning includes all points mentioned before under assembly and includes conformity to drawings, assembly report and specifications.

- Check availability of assembly report and updated as-built workshop drawings, accordingly to modifications made during assembly.
- Functional tests of snap-tight couplings, connectors and solenoid valves.
- Visual examination on cleanliness and completeness.
- Check identification marks of instrumentation cables and capillary tubes.
- Check passage of capillary tubes.
- Check connectors for instrumentation monitors.
- Leak-tightness of all containments, i.e. capsule, filters, tubes, couplings and valves. Allowable leak rate is $\leq 10^{-8}$ mbar l/s.
- Pressure test of all capsule containments with 0.9 MPa He,

- Pressure test of rig head containment with 0.6 MPa He,
- Leak tightness of rig head: pressure drop within 72 hours at 0.3 MPa < 0.05 MPa (test gas is N_2),
- Check all major dimensions of sample holder, the dimensions must be checked in accordance with the appropriate fabrication control sheet, GCO-66866.
- Check loop and insulation resistance of thermocouples and polarity of thermocouples.
- Check condition of O-ring sealing.
- Check function and leads of solenoid valves.
- X-ray examination of welds of 1st containment.
- Check position of instrumentation monitors, pebbles and Nb capsules by X-ray at 0° and 90°
- Check orientation marks *"NORTH"* at sample holder.
- Documentation and records of all tests (must give measured and permissible values) with all modifications and alterations and signatures of performer and Q/A officer.

6.5 Final Testing

Final testing of experimental equipment after insertion into REFA-170, connecting with the rig head and the out-of-pile installation consists of a repetition of all previous commissioning checks concerning leak-tightness, loop and insulation resistance of thermocouples, identification and polarity of thermocouples, checks of solenoid valves and their instrumentation, checks of identification of tubes, connectors and checks of free passage of tubes. Checks of correct connection of process parameters with the data logger and DACOS and correct data files of DACOS sub-programs. Additional tests and checks will be performed according to instructions of the operating and handling manual. These tests include the PSF glove box panel and special instrumentation for operation of solenoid valves and the safety instrumentation.

7 Operation and Periodical Testing

The irradiation HFR-EU1bis will be performed in core position G3. In order to fulfill the irradiation requirements (cf. Table 2) with regard to correlation burnup/fluence and short irradiation time, special measures are taken, as e.g. flux tailoring by using a custom moderating filler element E-816. Irradiation of the HFR-EU1bis sample holder will be performed in a standard REFA-170-rig. Its orientation will be changed cycle wise from North to South with respect to the core. This measure helps homogenizing the radial gradient of cumulative burnup and fluence across pebbles and graphite. The 1st and 2nd containments of HFR-EU1bis will be operated and controlled by means of a modified PSF gas panel. Additional instrumentation will be provided to operate the solenoid valves, to monitor the pressures and to enable gas sampling of the 1st containment for occasional fission gas release measurements. The containments will be kept closed during normal operation. Only for temperature adjustment and gas sampling, the 1st and 2nd containment will be purged, either with pure Ne (1st containment) or a custom He/Ne mixture (2nd containment). The rig head containment will be operated from the BOP gas panel and pressurized with N_2. The axial temperature profile will be adjusted by using the VDU.

Detailed instructions for experiment checkout, start-up procedure and normal operation will be given in the operating and handling manual that will be published prior to irradiation.

The irradiation performance of the experiment will be reported cycle by cycle in progress reports.

Significant experimental parameters:

- Temperature, monitored and recorded by DACOS;
- History of reactor power and control rod level, monitored and recorded by DACOS;
- Vertical position of the sample holder, monitored and recorded by DACOS;
- Orientation of the sample holder in the core position, cycle wise changed from North to South and vice-versa;
- Cumulative neutron fluence for different energy groups, cumulative burn-up and fission power history; these parameters will be determined after each cycle on basis of post-cycle HFR-TEDDI data.
- Fractional fission gas release from 1st containment; this data will be determined by weekly gas sampling of the 1st containment and off-line gamma spectrometry. Reference measurement for background determination can be done after 3 days of full power operation. Background activity of fission gas release originates from heavy metal contamination of the matrix graphite used in the pebbles, which is $U/U_{tot} < 10^{-6}$.

Major operations during initial start-up of the first cycle:

- Prior to first irradiation cycle a neutron radiograph image will be taken that serves together with the X-ray image as reference for graphite dimensions and pebble positions;
- Check-out of experiment in accordance with manual;
- Check required orientation of the rig; arrow at rig head should show North during first cycle;
- Check VDU position, must be at lowest position;
- Purge 1st and 2nd containment with pure He;
- Reactor start-up at standard power intervals, e.g., 5, 15, 30, 42 and 45 MW; check correlation between temperatures and reactor power after every power step; purge 1st and 2nd containment after each power step; use fast purging option for 1st containment by closing MV 21 and opening MV 22 and check off-gas activity during purging;
- Check of upstream and downstream gas transport times;
- If necessary, correct setting for alarm temperature and operating limits of thermocouples on DACOS after full power and stabilized control rod setting has been achieved.
- Continue purging the 1st containment in regular intervals to decrease water vapor concentration;

- Nominal temperatures will be adjusted by using the VDU and He/Ne gas mixtures in the 2nd containment;

Major operations prior to cycle start-up during normal base irradiation:

- Check-out of experiment in accordance with manual and cycle information;
- Set VDU at required position;
- Check rig orientation, given in the *“Concept Planning of Experiments”* that is issued prior to each cycle;
- Purge 1st and 2nd containments;
- Purge 1st containment with fast option after having achieved stable control rod position and check activity of off-gas, then close 1st containment;
- Adjust nominal temperatures by changing gas mixture in 2nd containment;
- Take weekly gas samples from 1st containment for fission gas release measurements;
- Report results and events of every cycle in progress reports.

Emergency procedures:

Threshold transgression of operating parameters as defined in Table 25, results in release of audible and visible alarms at the control panel and in the operator’s control room and HFR control room. No APD or reactor scram are required because:

- the fuel mass is low (1 g U-235 per pebble) and the fuel is dispersed in approx. 10000 particles
- several past experiments have demonstrated that matrix and coatings sustain temperatures of 1600°C without damage
- the reactivity of the experiment is low
- all operating data are far below the allowable limits for REFA-170 (heat flux < 100 W cm^{-2}, low gas pressure), even when considering operating errors, large safety factors for mechanical parts
- consequent double containment
- pebbles in many reactors worldwide successfully tested for > 20 years, also in the HFR
- continuous surveillance of pressure and temperature
- built-in filters to trap fission products within the irradiation rig
- remotely controlled solenoids enable isolation of in-pile section
- destruction of in-pile section only imaginable in case of HFR core melt-down
- irradiation rig in operation for several decades without incident

In case less than the minimum required instrumentation is operational, corrective measures must be taken. If these are unsuccessful, the irradiation must be interrupted immediately. The irradiation must also be interrupted in case of a failure of the 1st, 2nd or rig head containment. The following measures will be taken: (a) ad-hoc evaluation of the incident and establishment of a plan *how to continue*. (b) If possible, a neutron radiograph will be taken. The project engineer reports to the reactor manager.

Special procedures:

The combination of the irradiation position and the size of the specimens cause azimuthal gradients of temperature and neutron flux. To avoid asymmetric graphite shrinkage and burn-up, the rig will be turned after each cycle by 180°.

The VDU will be operated only on special request of the project leader and is disconnected during normal operation.

The cycles will be started and ended with the lowest possible temperatures, i.e. 100% He in the 1st and 2nd containment. Nominal temperatures and tentative gas compositions to reach them are defined for each cycle (Table 1). Nominal temperatures will be adjusted as soon as possible after the reactor power and control rod positions are stabilized.

Parameters	Indication	Nominal value	Alarm thresholds	Corrective actions
Pressure 1st containment	2 pressure transducers at gas panel in PSF glove box	3.5 bar	h: 4.0 bar l: 3.0 bar	adjust manually and check pressure history, if pressure equalization with 2nd containment, automatic closure of MV 1, MV 21 and MV22
Pressure 2nd containment	2 pressure transducers at gas panel in PSF glove box	5 bar	h: 5.5 bar l: 4.5 bar	adjust manually and check pressure history; check sealing, if pressure equalization with 1st containment, automatic closure of MV 1, MV 21 and MV22
Rig head containment	membrane manometer with alarm at BOP gas panel	2 bar N_2	h: 2.5 bar l: 1.5 bar	adjust manually; check sealing
Pebble temperature	TC12 (reserve TC13)	1050°C (increasing according to Table 1)	h: +80 K l: -80 K	Check temperature history of thermocouples and gas mixtures
Axial temperature profile	TC4 (reserve TC5, 6) and TC19 (reserve TC20, 21)	1000°C	h: +100 K l: -30 K	Adjust vertical position of sample holder by means of VDU
Activity in glove box during sampling	Geiger-Müller counter, GM1	<1 μSv/h	h: >50 μSv/h	Automatic closure of MV 1, MV 21 and MV22
Off-gas pressure	Annunciator 31 of HFR instrumentation	-50 cm water column	l: < -20 cm water column	Automatic closure of MV 1, MV 21 and MV22
Off-gas activity	Annunciator 22.30 of HFR instrumentation	<1 MBq/m^3	h: 37 MBq/m^3	Automatic closure of MV 1, MV 21 and MV22

<u>Legend:</u> h→high alarm threshold; l→low alarm threshold;

Table 25: Operating parameters, alarm thresholds and corrective actions

8 Handling, Dismantling, Transport and Disposal

Handling

The instrumentation cables are long enough to place the rig either into its core position, or into the rig storage rack at the North side of the pool and into the neutron-radiography facility. In case of serious damage of the capsule it is proposed to load the complete rig into a special storage container, which is available in the reactor hall. The loading procedure is to be carried out under water in the pool. The penetration head of the storage container is of the same design as the central top lid cover of the HFR. Once inserted (without tools!), the rig is tightly locked in the container. Draining and pressurization of this container is possible by snap-tight couplings. Safe storage is guaranteed by this method and dismantling may then be done anytime.

Dismantling and Transport

A special dismantling procedure must be followed after completion of the irradiation because of the presence of capillary tubes that may contain fission gases.

- Cool-down period of 4 weeks.
- The dismantling procedure starts by intense purging of all containments with pure He for 24 hours.
- A gas sample of the 1st containment shall be taken to determine the activity level of the purge gas by gamma spectrometry.
- Unloading procedure of the sample holder from the REFA rig can start once the dose rate of the purge gas measured by the GM counter in the glove box is < 1 μSv/h.
- Place the REFA rig into the special seat at the pool wall.
- Depressurize the REFA channel, sample holder containment and the rig head containment.
- Open the rig head and disconnect connectors and snap-tight couplings from the sample holder and REFA rig.
- Close rig head and pressurize to 2 bar He and transfer rig head to a storage place. A transport cover replaces the rig head and closes the REFA channel.
- Pressurize the REFA channel with 3 bar He and prepare transport to neutron-radiograph facility. Final neutron-radiographs can now be taken.
- Transfer entire REFA rig with sample holder into the Dismantling Cell for unloading the sample holder from the REFA channel.
- After closing the REFA rig, it can be transferred back to the storage rack for rigs for future use.
- The sample holder can be prepared for transport to the Hot Cell Laboratory, HCL. Therefore, the upper part is cut just below the shielding plug and given into the wastebasket. The filter units can now be recovered and stored for transport to the HCL. The lower part of the sample holder, the capsule can now be recovered by cutting at approximately 150 mm above the position 24 GCO-66866. The lower center pin can as well be shortened. The gas tubes at the upper part of the capsule can now be closed

by using a two-component resin. Transport of the capsule and the filters to the HCL can now be prepared for further dismantling.

Waste disposal

Waste disposal of those sample holder parts, which remain in the Dismantling Hot-Cell at the HFR, shall occur in accordance with the standard procedures.

9 Post-Irradiation Treatment

Neutron radiographs will be taken prior to irradiation and after completion of irradiation. Intermediate radiographs are only required to help analyze possible functional anomalies. PIE will start with the recovery of the capsule and filter of 1st containment at the Dismantling Cell of the HFR. Fine dismantling will be performed at the Hot Cell Laboratory, HCL, of NRG. After opening of the capsule and visual inspection, the fluence detector sets, the gamma scan wire and the 6 Nb capsules will be recovered. Then the 5 pebbles and the graphite half-shells will be recovered. The monitors, capsules, pebbles and graphite samples will be stored in numbered Al cans. Gamma scans will be taken from the capsule tube and the gamma scan wire. It concerns longitudinal and circumferential scans. Circumferential scans of the capsule tube will be performed at the equatorial positions of the pebbles, in order to quantify axial gradients in fluence and burn-up. Gamma scans of the pebbles will also be performed. In case that failure of a coated particle has been observed during irradiation, scans of the graphite half-shells and steel internals of the capsule will as well be done. Further non-destructive testing at the HCL consists of dimensional measurements of graphite half-shells and fuel elements and measurement of the weight of the fuel element.

The fluence detector sets will be analyzed in the NRG laboratory.

The further non-destructive PIE at NRG Petten will be defined at a later stage and according to the results of the irradiation in agreement with the coordinator of the FP5 HTR-F project and its planned FP6 follow-up, the V/HTR Integrated Project. The major PIE for the 5 pebbles and the 6 Nb capsules will be performed at JRC-ITU (KÜFA tests). The modalities of the transport will equally be established at a later stage.

10 Safety Analysis

The safety analysis is restricted to the experimental facility, operating and handling equipment. The principle of double and controlled containment of fuel and gaseous fission products inside and outside the HFR reactor vessel is respected.

The five pebbles irradiated in HFR-EU1bis contain the fuel in the form of approx. 9560 coated particles each. Each coated particle represents a tight pressure vessel for fission gas. During previous tests in the HFR (e.g. HFR-P4 [8]), reaching a burn-up of 14% FIMA and a fast neutron fluence of > 8×10^{25} m^{-2} at a temperature of 1250°C (as opposed to 16-19% FIMA, fast neutron fluence < 7.3×10^{25} at 1250°C in HFR-EU1bis), the measured failure rate of the LEU-TRISO particles was nil [5]. The coating of the 9560 coated particles in one pebble can, therefore, be considered the first barrier against fission gas release, comparable to the single cladding of a LWR fuel rod. Nevertheless, the safety assessment presented hereafter is based on the presence of two independent and permanently monitored safety containments, both inside and outside the reactor vessel.

These safety containments are the sample holder (first) and the REFA thimble (second) within the reactor vessel. Both containments are kept under overpressure. Also outside the reactor vessel, the fission gases are confined in two independent containments, namely the steel minitubes, which are guided in a flexible hose, and the glove boxes. The flexible hose and the minitubes are kept under controlled overpressure.

The key operating parameters of HFR-EU1bis are the maximum linear power of <750 W/cm (fission and gamma power per pebble 4500 W divided by pebble diameter 6 cm), a maximum heat flux to the coolant of < 52 W/cm^2 and a maximum possible gas pressure of < 0.9 MPa. The heat flux will decrease during irradiation due to fission power depletion. The characteristic operating condition ($P_f \times R/B$) for fission power P_f of five pebbles in kW and a tentative fractional fission gas release (R/B release/birth) of 10^{-9} is 1.5×10^{-8} for BOI conditions. This leads to extremely low radiation levels during gas sampling. Experience with previous experiments has shown that the use of built-in filters reduces this value by several orders of magnitude.

10.1 Failure Analysis

Malfunctions with subsequent process parameter threshold transgressions, system failures and power failure trigger visible and audible alarms. There is no need for automatic action on reactor operation like scram or APD. The experiment will be loaded into a storage container until further dismantling in case of an unrecoverable failure. Shut-down of the sweep gas flow (continuous purging only at reactor start-up) would only have a long-term influence on the temperature distribution in the capsule, because cooling effects of the sweep gas are negligible and a separation of the gas mixture components (He/Ne) does not occur.

The sample holder design was done such that the required central pebble temperatures can be maintained despite the power depletion due to burn-up. The fact that temperatures and containment pressures are continuously monitored and recorded and that audible and visible alarms are triggered in case of transgression of pre-set thresholds, ensures that failures do not lead to uncontrolled situations.

The specific heat flux at the surface of the 2nd containment is well within the operating limits of the REFA-170 rig [26].

Failures of targets, containments, power supply, instrumentation, utility, component, operating and handling errors and their effects and consequences are listed in Table 27 and Table 28.

Operating parameter	Value	Remark
Total heat generated in the in-pile section [kW]	16.6	At BOI
Linear heat of the in-pile section at BOI [W cm^{-1}]	< 750	Along the capsule section that contains fuel
Maximum heat flow at coolant surface at BOI [W cm^{-2}]	< 52	well below the admissible value of 100 W/cm^2
Maximum central temperature of fuel element [°C]	1250	Temperatures is in all fuel elements identical due to tailored gas gaps
Maximum temperature of thermocouples at BOI [°C]	1050	Well below the admissible temperature 1300ºC for the thermocouple
Temperature of 1st containment wall [°C]:	< 435	
Temperature of 2nd containment wall [°C]	< 70	
Temperature increase of coolant [°C]	< 5 K	Decreases with burn-up

Table 26: Key operating parameters at nominal operating conditions

Nº	Failure scenario	Consequences
1	1st containment failure in in-pile section	Pressure equalization between 1st and 2nd containment, equalization of gas mixture compositions and possibly increase of temperature; Purge containments with He; depending on the leak size, complete cycle; pressurize containments via 2nd containment; released gases may diffuse at minor fraction into 2nd containment at a later stage No immediate consequence for safety; continue irradiation until next reactor stop;
2	2nd containment fails at in-pile section	Pressure loss of 2nd containment: Repair if leak is out-of-pile or stop reactor, repair or unload sample holders from rig; load sample holder into other REFA-170 rig, resume irradiation.
3	2nd containment fails at O-ring seal in upper section of sample holder	Pressure loss of 2nd containment, increase of BOA pressure: interrupt irradiation during next reactor stop, renew both O-rings and resume irradiation; since vertical displacement is not applied regularly, the O-ring seals are little solicited and should not become defective.
4	Rig head containment fails	Pressure loss of containment: Discontinue irradiation. Since this component is out-of-pile, repair is normally possible during reactor stop periods; continue irradiation with repaired or replaced rig head.

Table 27: Overview of considered containment failures in failure analysis

No.	Failure	Effect	Detection	Automatic actions	Manual actions	Consequences
10.1.1 Target failure	Coated particle / pebble	Fission gas release into 1st containment	During gas sampling	None	None	None, to be reported in cycle reports Adapt gas sampling procedure
10.1.2 Containment failure	1st containment in in-pile section	Pressure equalization between 1st and 2nd containment, equalization of gas mixture compositions and possibly decrease in temperature	Pressure transducers of 1st and 2nd containment	Alarm	Purge 1st & 2nd containment with He; Check history of pressure transducers and temperature field	No consequences for safety, continue irradiation; in-situ filters will adsorb any released fission gases, if one or several particles have failed; Take neutron-radiograph and ad-hoc decision for further measures
	Leak of 2nd containment	Decrease in pressure of 2nd containment	Pressure transducer of 2nd containment	Alarm	Open He supply to maintain gas pressure in 2nd containment and search for source of failure	Repair if leak is out-of-pile or stop reactor, repair or unload sample holders from rig; load sample holder into other REFA-170 rig, resume irradiation
	Leak of 2nd containment at O-ring seal	Decrease in pressure in 2nd containment and increase of rig head pressure	Pressure transducer of 2nd containment and rig head	Alarm	Open He supply to maintain gas pressure in 2nd containment	Interrupt irradiation during next reactor stop, renew both O-rings and resume irradiation
	Leak rig head	Decrease of pressure	Membrane manometer with alarm at BOP panel	Alarm	Adjust gas pressure	Repair or exchange rig head and continue irradiation

Table 28: Failure analysis (part 1)

Table 28 (continued)

No.	Failure	Effect	Detection	Automatic actions	Manual actions	Consequences
10.1.3 Cooling failure	Loss of primary cooling water	Increase in temperature	Scram triggered by HFR instrumentation	Scram	None	None for the experiment; heat flux can be dissipated at stagnant coolant conditions
10.1.4 Electrical power failure	Interruption of power supply	Loss of data	Scram triggered by HFR instrumentation	Scram	None	None for the experiment
10.1.5 Instrument failure	Defective pressure transducer	Loss of pressure indication	At instrument	Alarm	Isolate specific containment	Repair and continue irradiation
	Defective pressure transducer	Loss of data	Pressure at DACOS	Alarm	Check instrumentation	Repair and continue irradiation
	Defective thermocouple	Loss of data	Temperature at DACOS	Alarm	Change over to spare thermocouple	None, change over to spare thermocouple and continue irradiation
10.1.6 Utility failure	Defective gas supply	Insignificant	Manometer	Alarm	None	None, repair and continue irradiation
10.1.7 Component failure	Outage of DACOS	Loss of data	DACOS	Alarm	None	None, repair and continue irradiation
10.1.8 Operating errors	Wrong vertical position of sample holder	Incorrect temperature profile	Temperature graphic at DACOS	Alarm	Adjust vertical position	None
10.1.9 Handling errors	Orientation of REFA rig	Possibly incorrect temperature field	Temperature graphic at DACOS	Alarm	Check orientation and correct orientation at next cycle	None

Table 28: Failure analysis

10.2 Maximum Credible Accident (MCA) Analysis

The MCA is defined as the simultaneously occurring failure of two independent systems.

The considered MCA for HFR-EU1bis is: (a) process instrumentation failure simultaneously with (b) rupture of the 1st and 2nd containment gas tubes between the rig head and the connection box of the PSF facility, at EOI conditions (end of cycle 14). Such a rupture could be caused by a hoisting accident.

The possible radioactivity source term was evaluated as follows:

- From Table 24 we can deduce that the total maximum volatile Kr + Xe inventory at EOI (14 cycles) is approx. 1.5×10^{14} Bq distributed in 50000 particles assuming that all particles remained intact (maximum inventory build-up) up to the previous gas sampling. On average, this corresponds to a birth rate of Kr + Xe activity of approx. 100 Bq/s per particle.
- Conservatively, we assume that no radioactivity is withheld by the graphite structures and the filters.
- The last gas sampling was done one week earlier. Since then, radioactivity has accumulated in the gas of the 1st containment.
- Since the last gas sampling a certain number of particles have failed and this event remained undetected.
- If n particles had failed since the last gas sampling, the source term for release would amount to approx. $n\times3\times10^{9}$ Bq.

Figure 9 shows the potential inventory release as a linear function of failed particles since the last gas sampling.

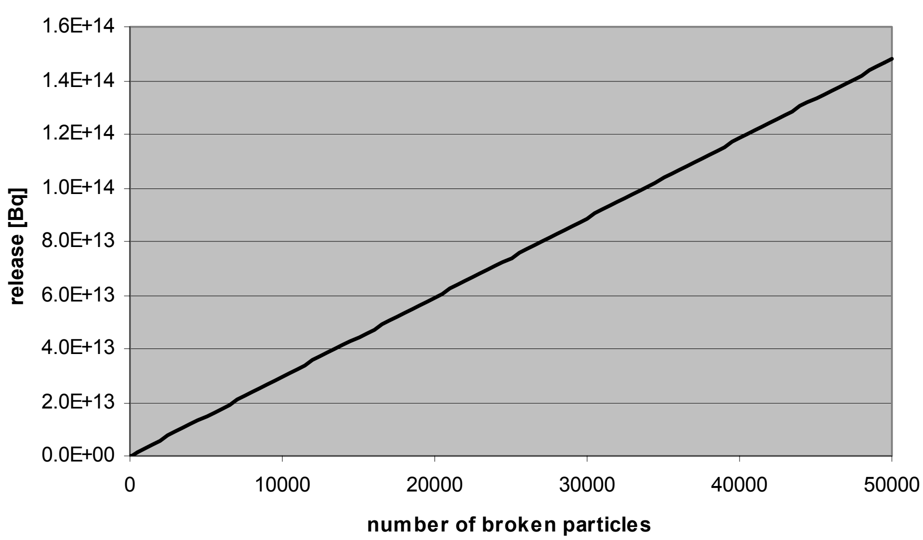

Figure 9: Potential Kr + Xe radioactivity release from 1st containment as a function of number of broken particles during maximum credible accident

This source term evaluation is extremely conservative. In fact, particle failure has never been observed before and the fractional release in similar experiments, many of them performed in the HFR, was always of the order of 10^{-7} [5], i.e. even lower than the nominal defective SiC layer value of 7.8×10^{-6} (unirradiated, as received) for these pebbles (cf. Table 6).

The scenario in this more realistic case is as follows:

- The source term that can be released is the accumulated activity of Kr and Xe isotopes (approx. 1.5×10^{14} Bq) with an expected maximum fractional release of 10^{-7} demonstrated in previous experiments ➔ 1.5×10^{7} Bq. Each single broken coated particle would add 3×10^{9} Bq in a burst (release of all previously accumulated inventory at EOI) and in addition 5.9×10^{7} Bq per week of isolated capsule. One week is a typical interval between purging.
- The gas pressure in the 1st and 2nd containments is 3.5 bar and 5 bar, respectively.
- Release of gas volume (approx. 300 Ncm^3) and filter gas volumes (approx. 1500 Ncm^3) into the pool, mainly He/Ne with gaseous fission products within 5 seconds,
- Release of approx. 20000 Ncm^3 N_2 of rig head gas volume (2 bar),
- Gaseous fission products either bubble to the pool surface within 5 seconds when the leak is still submerged or escape directly into the reactor hall,
- A minor amount of the released gas volume is sucked off into the pool surface off-gas system; the rest escapes into the hall and mixes with the atmosphere in a short time,
- Threshold transgression of HFR activity monitors after a short time with subsequent reactor scram and hall evacuation, fission product generation is immediately stopped; the water ingress into the 3 containments will be slow and limited due to the surface tension of the water and the small gas pipes;
- If water has reached the 1st containment, water-graphite reactions will stop very soon, since the specimen temperature will drop to < 350 K in less than 5 minutes,
- The hall activity level will decrease within one hour below the alarm threshold values due to decaying of short-lived isotopes and venting-off of gaseous fission products by the ventilation system,
- The experiment must be unloaded and stored into the special storage container available at JRC-IE,
- The failed gas lines and flexible hoses must be closed,
- The failed flexible hose of the connection boxes must be closed after the pool water has been lowered and the boxes have been drained,
- The failed flexible hose must be disconnected from the connection boxes,
- Further dismantling of the experiment can be handled according to the normal procedures, the dismantling of the capsules has to follow special instructions to recover approx. 3000 cm^3 water under controlled conditions.

Conclusions:

Gaseous fission products (mainly Kr and Xe) could be released under the considered MCA, max. 1.5×10^{14} Bq; solid and volatile fission products as iodine are held back in the capsules by filtering and precipitation on cold gas tubes, the ventilation system is effective enough to vent off the released radioactive gases within one hour.

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12 List of Figures

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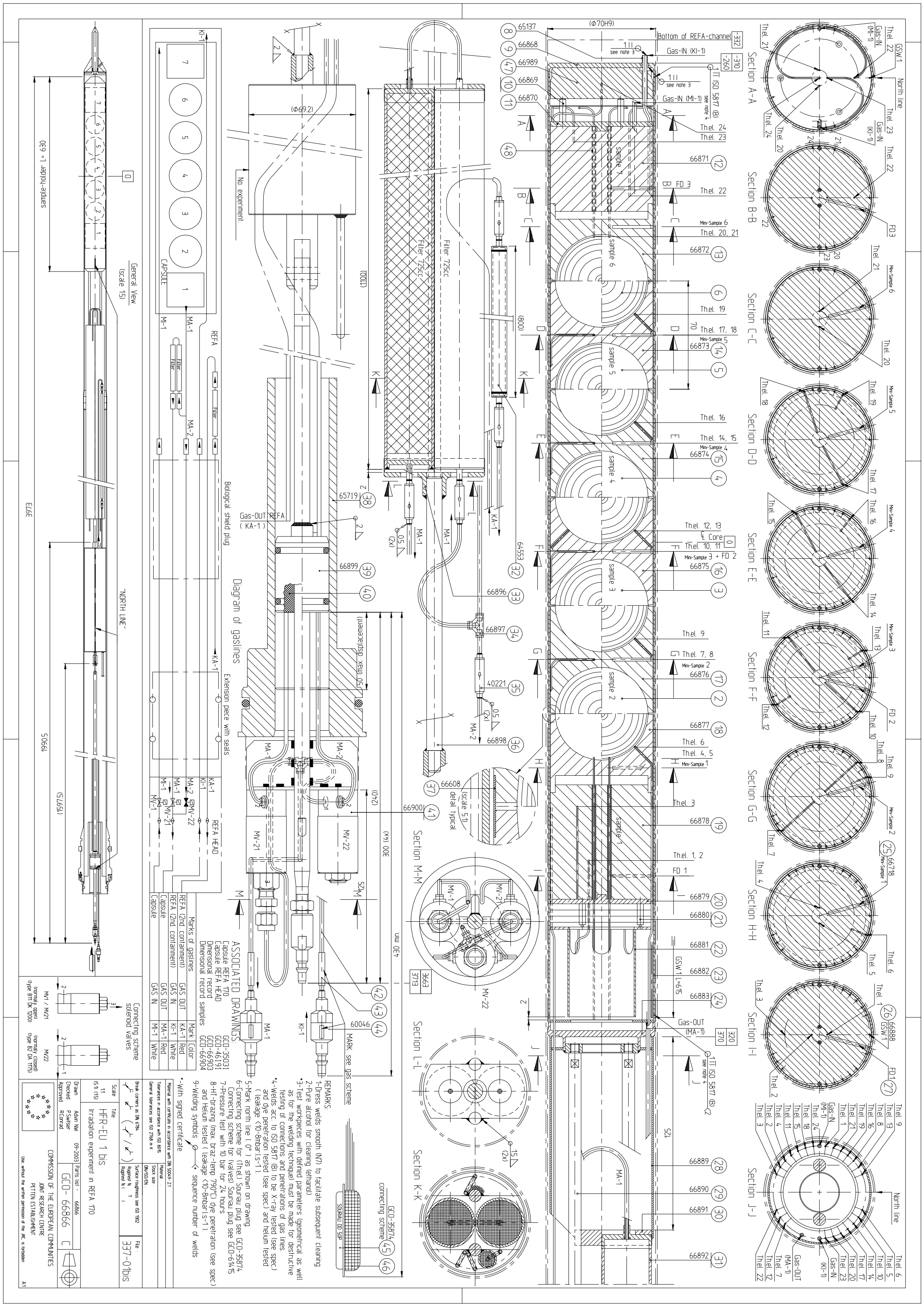
14 Drawings

GCO 66866 C	General assembly drawing of sample holder
RH-M-U76 A	Filler element E 816


HFR-EU 1 bis
Irradiation experiment in REFA 170
GCD-66866
337-01bis
COMMISSION OF THE EUROPEAN COMMUNITIES
JOINT RESEARCH CENTRE
PETTEN ESTABLISHMENT
General View (scale 1:5)
Diagram of gaslines
ASSOCIATED DRAWINGS
REMARKS:
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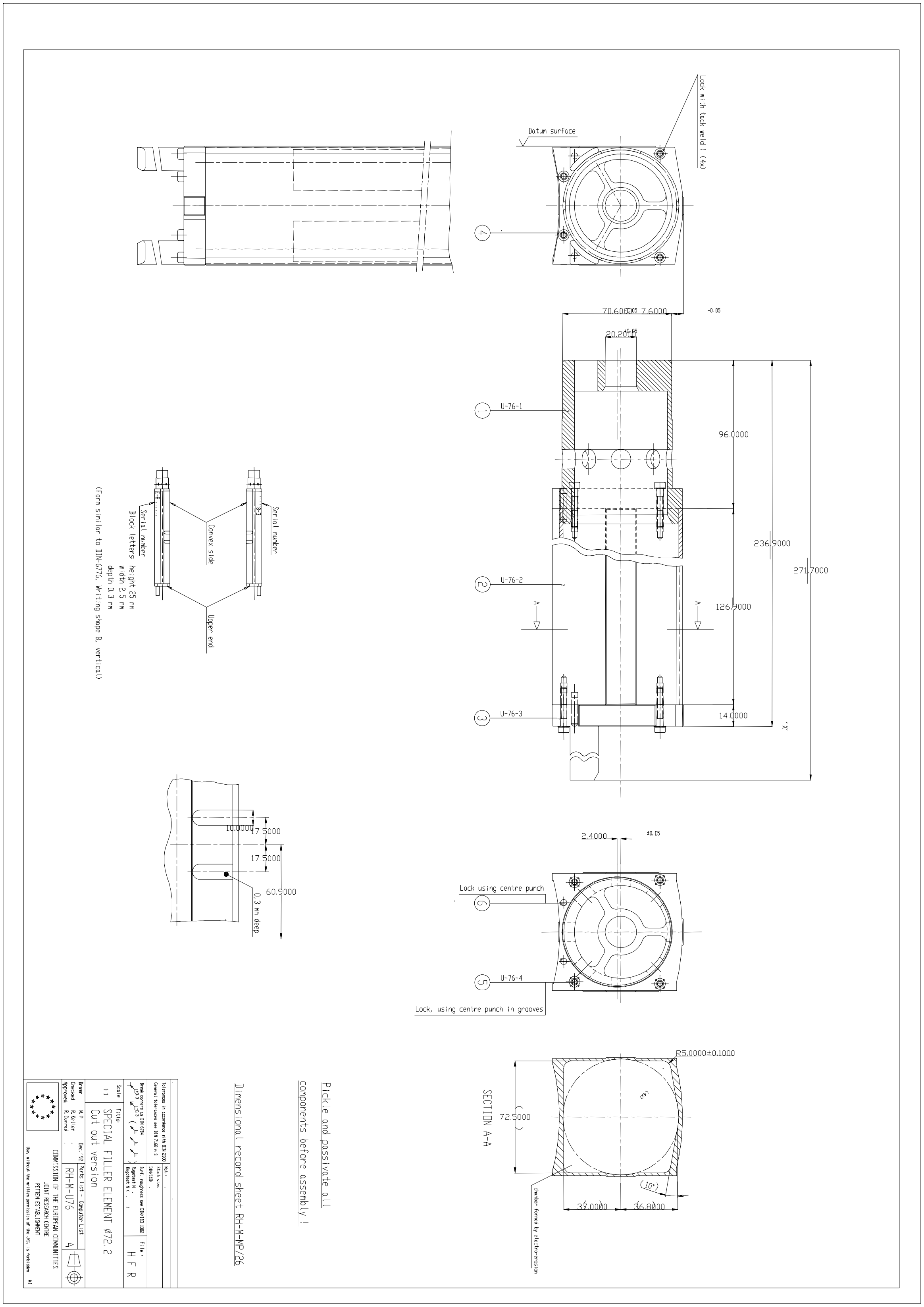
Section B-B
Section C-C
Section D-D
Section E-E
Section F-F
Section G-G
Section H-H
Section I-I
Section J-J
Section K-K
Section L-L
Section M-M
Connecting scheme solenoid valves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U-76-1
U-76-2
U-76-3
U-76-4
96.0000
236.9000
271.7000
126.9000
14.0000
2.4000
Lock using centre punch
Lock, using centre punch in grooves
SECTION A-A
72.5000
R5.0000±0.1000
37.0000
36.8000
Serial number
Convex side
Upper end
10.0000
17.5000
17.5000
60.9000
0.3 mm deep
Pickle and passivate all components before assembly !
Dimensional record sheet RH-M-MP/26
SPECIAL FILLER ELEMENT Ø72.2
Cut out version
RH-M-U76
COMMISSION OF THE EUROPEAN COMMUNITIES
JOINT RESEARCH CENTRE
PETTEN ESTABLISHMENT
H F R