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Document title

HFR-EU-1-bis Benchmark Definition

Executive summary

HFR-EU1bis is the irradiation experiment for testing spherical High Temperature Reactor (HTR) fuel pebbles with TRISO coated particles (UO2 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 has been performed in the High Flux Reactor (HFR) at Petten in the Netherlands for a period of 10 cycles

Five fuel pebbles from the German AVR production (GLE-4 type) and six mini samples with each 10 coated particles sealed in a niobium tube have been tested in a sample holder that was loaded in a test rig, surrounded by a strongly moderating filler element. During irradiation the central pebble temperature has been kept at a characteristic 1250°C. The irradiation has started on 9 September 2004 and finished on 18 October 2005.

After a cool-down period the experiment has been dismantled and the mini samples and samples taken from the fuel sphere were transported to ITU for analysis of the nuclide inventory. Flux monitors and a scan wire have been measured at NRG-Petten.

The experiment is described in such a way that it is suitable for validation of coupled neutronics and depletion codes. In this benchmark inventories of different samples from pebbles and monitors are requested to be calculated and compared with the measured data.

Revisions

Rev.	Date	Short description	Author	WP Leader	SP Leader	Coordinator
00	15/05/2006	First issue	J.B.M. de Haas, NRG	J.B.M. de Haas, NRG *Signature*	A.I. van Heek, NRG *Signature*	E. Bogusch, FANP *Signature*
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02	18/01/2007	Rev.2	J.B.M. de Haas, NRG	J.B.M. de Haas, NRG *Signature*	A.I. van Heek, NRG [illegible]	E. Bogusch, FANP [illegible]

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1 Introduction

1.1 Purpose of experiment

A description is given 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 has been performed in the High Flux Reactor (HFR) at Petten for a period of 10 cycles in core position G3.
Five fuel pebbles from German AVR production (GLE-4 type) and six mini samples with each 10 coated particles sealed in a niobium tube have been tested in a sample holder that was loaded in a REFA-170 rig, surrounded by a strongly moderating filler element. The irradiation has started on 9 September 2004 and finished on 18 October 2005
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. 5-7.3 E+25 m^{-2} (E>0.1 MeV).

1.2 Phenomena measured and scope

During experiment: Temperatures, gas release

During the experiment, the sample holder and the REFA-containment have been 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.

Post_irradiation Experiments (PIE): Nuclide inventories, flux monitors, outer can

The flux monitors and the outer can are analysed at NRG-Petten in 2006.
Analysis of the nuclide inventory of the mini samples and samples taken from the fuel sphere is taking place at JRC-ITU in 2007.

2 Description of HFR facility

The irradiation has been performed in the facility of the High Flux Reactor (HFR) at Petten, The Netherlands running at its nominal power of 45 MW.

During all irradiation cycles the irradiation took place in a REFA-170 rig at position G3 in the core of the HFR. A schematic of the HFR-core can be seen in fig. 1.

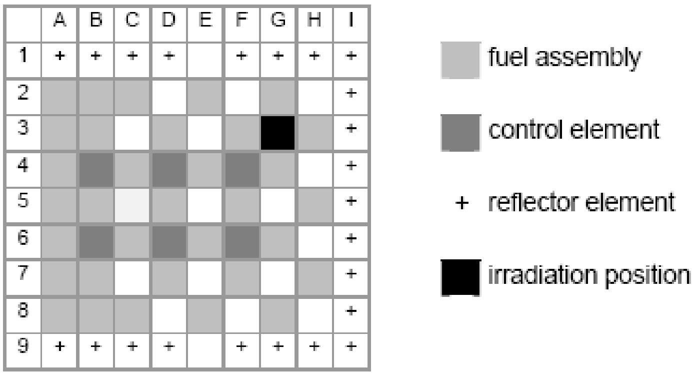


Figure 1: Standard HFR core configuration showing HFR-EU1bis in core position G3

3 Description of experiment

The experiment was housed in a REFA-170 rig with extra water in the filler space. The outer dimensions of the filler can be taken as rectangular with sizes 8.05 cm by 7.61 cm fitting in the core grid with an 8.10 cm by 7.71 cm pitch.

3.1 Experimental configuration

3.1.1 Type of assembly

A schematic of the REFA-rig with the HFR-EU1bis experiment can be seen in fig. 2.
For each cycle the orientation of the experiment was turned half a turn in order to flatten the fluence due to the fluence rate gradient near the reactor core wall.
The filler has a bore of 72.2 mm, is made of aluminium and, by milling out the corners to a rectangular section, provides a larger water fraction to enhance the thermal neutron fluence rate in the capsule, thus enhancing the pebble power and burn-up and reducing the fast neutron fluence and damage.
A cross sectional view of the REFA-filler with extra water can be seen in fig. 3.

Simplifications made are that only the portion from –27 to +27 cm below or above centre line core (between items 11 and 20 in drawing GCO-66866) of the experiment will be represented in detail.
For the surroundings only homogenized macroscopic cross sections are given (see chapter 5).

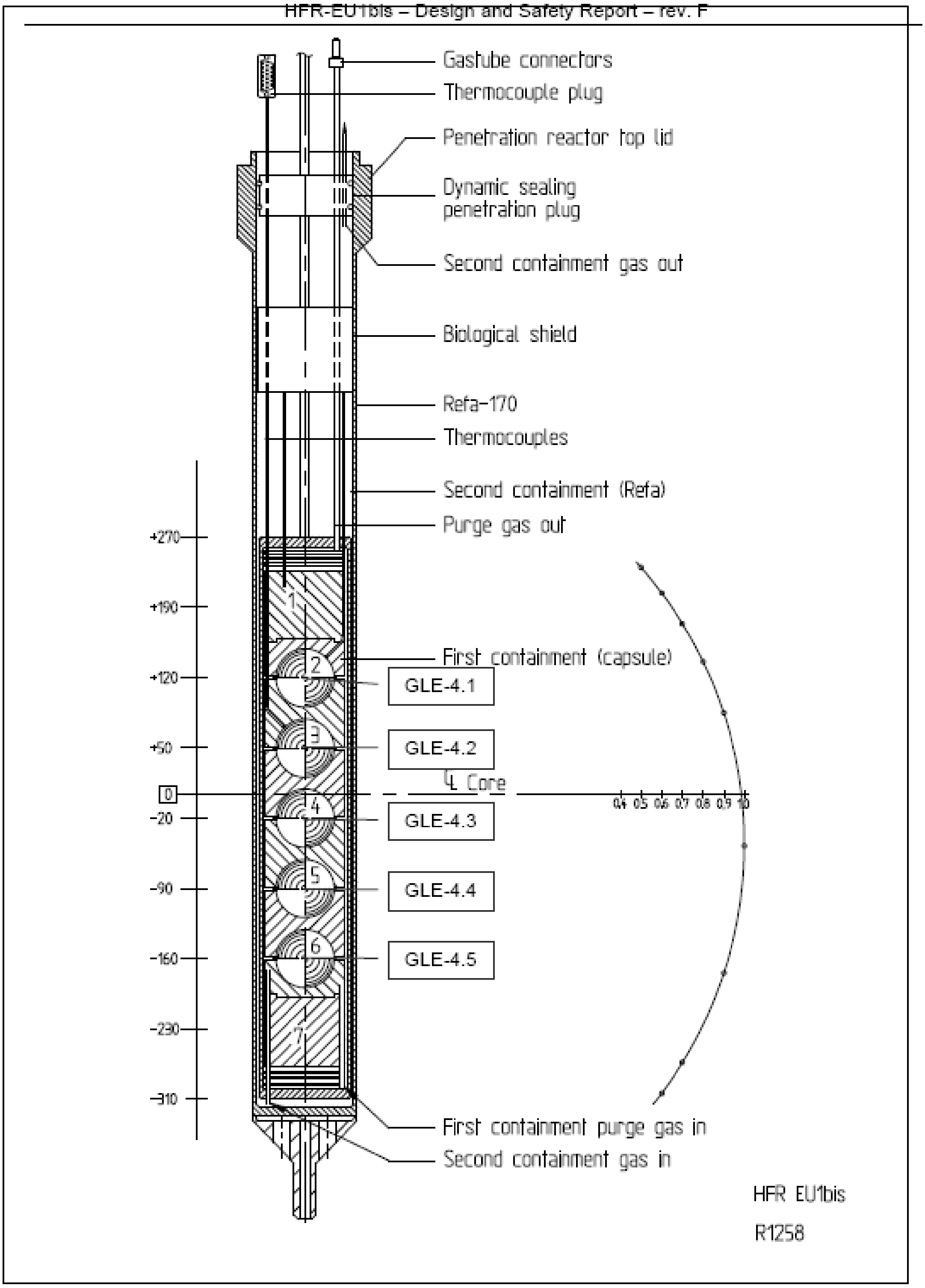


Figure 2: Conceptual sketch of HFR-EU1bis

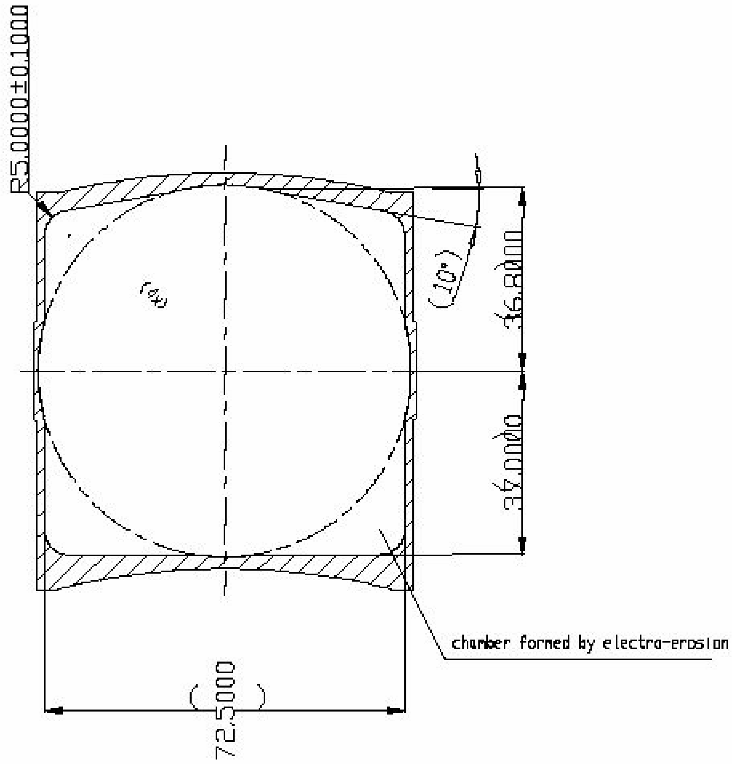


Figure 3: cross sectional view of the REFA-filler

3.1.2 Assembly details

A detailed drawing of the experiment showing the positions of the thermo-couples, mini samples and flux detectors, can be seen in fig. 4 and at a better resolution, in the drawings appendix. A reference of the parts to their drawings can be found in table 1 and 2.

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 1: Reference for drawings and dimensions for the 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 2: Axial positions referred to centre line core and diameters of the graphite parts

Atomic densities (*10^{24}) for the graphite of the half shells, the stainless steel (AISI 316) and aluminium parts are given in table 3.

Graphite		Steel 316		Aluminium	
C	8.774E-02	C	3.129E-04	Al	5.805E-02
		Cu	1.673E-03	Mg	6.021E-04
		Cr	1.536E-02	Si	5.934E-04
		Mn	1.710E-03	Ti	3.395E-05
		Fe	5.503E-02	Cr	4.691E-05
		Ni	9.602E-03	Mn	2.072E-04
		Mo	1.224E-03	Fe	1.456E-04
		Co	traces	Cu	2.559E-05

Table 3: Atomic densities of structural materials (atoms *10^{24})

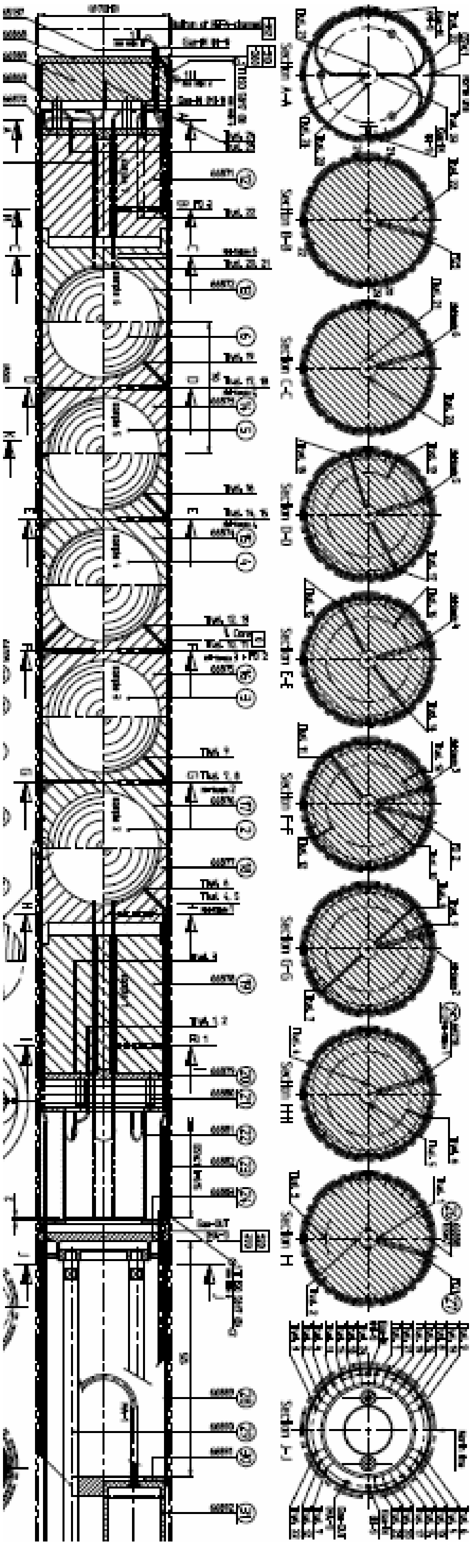


Figure 4 drawing of the HTR-EU experiment in the REFA-capsule.

3.1.2.1 Type of fuel pebbles

The irradiated fuel consists of pebbles of 60 mm diameter with LEU-TRISO coated particles of former German production, type AVR GLE-4. The fuelled zone containing the coated particles has a diameter of 4.4 cm. The pebbles are embedded in graphite shells for extra neutron moderation. Pebble and kernel characteristics can be found in table 4.

Coated Particle	
Particle batch	HT 354-383
Kernel composition	UO_2
Kernel diameter (µm)	501
Enrichment (U-235 w%)	16.75
Thickness of coatings (µm)	
buffer	92
Inner PyC	38
SiC	33
outer PyC	41
Particle diameter (µm)	909
Pebble	
Diameter (cm)	6.0
Diameter fuelled region (cm)	4.4
Heavy metal loading (g/pebble)	6.0
U-235 content (g/pebble)	1.00 ± 1%
Matrix graphite grade	A3-3
Matrix density (kg/m^3)	1750
Temperature at final heat treatment (ºC)	1900

Densities:

kernel UO_2 = 10880 kg/m^3
buffer = 1020
inner PyC = 1920
SiC = 3200
outer PyC = 1920

Table 4: Nominal characteristic data of AVR GLE-4 pebbles

3.1.2.2 Mini samples

Six mini samples were installed in the experiment at different axial levels over the graphite moderator shells. Each contained 10 coated particles, identical to the particles in the pebbles, as shown in fig. 5. Tube and stops are made of Niobium (ρ=8.57 g/cm^3).

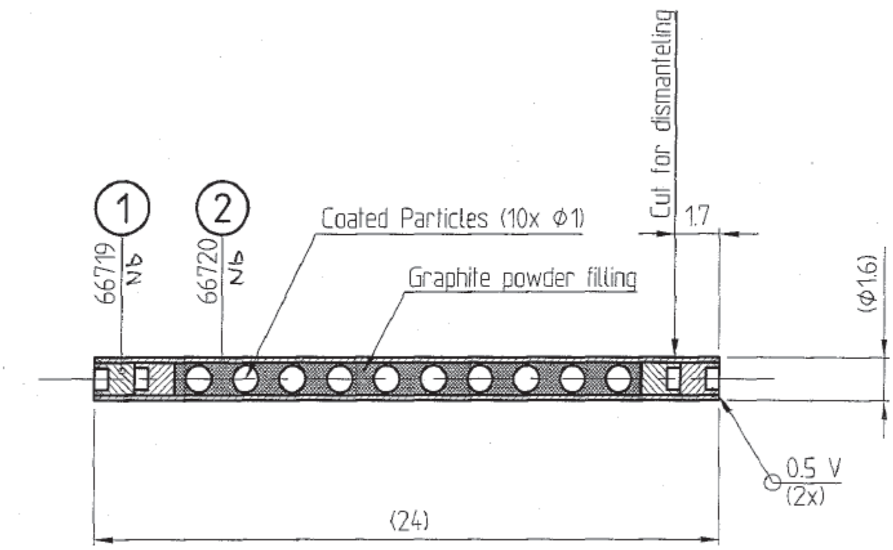


Figure 5: Drawing of the mini sample

3.1.2.3 Flux monitors and scan wire

Three flux detectors (FD) are mounted over the length of the experiment.
Their contents are (masses in mg):

Code	NiCo	Fe	Ti	Nb (in mg)
FD1	0.0640	0.6825	0.9773	0.5338
FD2	0.0654	0.5717	1.0718	0.4342
FD3	0.0631	0.6189	0.9810	0.3874

Dimensions:

NiCo (1% Co) wire piece*)	d=0.1 mm, l=1.0 mm,
Fe wire piece*)	d=0.25 mm, l=1.5 mm,
Ti wire piece	d=0.56 mm, l=1.0 mm,
Nb wire piece*)	d=0.2 mm, l=1.5mm.

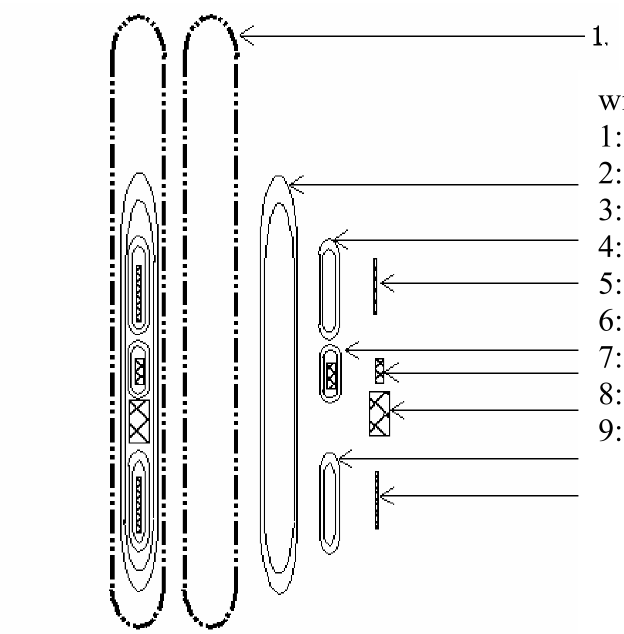
*) encapsulated in a quartz mini-tube, d=0.9/0.6 mm, l=5 mm.

The overall arrangement of the flux detectors (monitors) is given in fig. 6.

Encapsulation of monitor set:

- quartz outer mini-tube (ø=1.4/1.0 mm, l≈20 mm), closed by melting;
- quartz inner mini-tube (ø=0.9/0.6 mm, l≈5 mm), closed by melting;
- stainless steel outer tube (ø=2.0/1.6 mm, l≈25 mm), closed by welding.

The density of the quartz (SiO_2) is 2.20 g/cm^3



with
1: Stainless steel tube
2: Outer quartz mini-tube
3: Inner quartz mini-tube
4: NiCo monitor
5: Inner quartz mini-tube
6: Fe monitor
7: Ti monitor
8: Inner quartz mini-tube
9: Nb monitor

Figure 6 Composition and encapsulation details of activation monitor sets

The measured gamma's are from the following reaction products:

Fe-58 (n,g) Fe-59	Fe-54 (n,p) Mn-54
Co-59 (n,g) Co-60	Ti-46 (n,p) Sc-46
Nb-93 (n,g) Nb-94	Nb-93 (n,n') Nb-93m
Ni-58 (n,p) Co-58	

A gamma scan wire made of stainless steel AISI-316 of well known composition (table 3) was mounted in the length of the experiment in the graphite directly at the north line adjacent to the outer tube of the experiment. Its purpose was to monitor the axial distribution of the neutron fluence, but during the second irradiation cycle a short heating-up of the experiment occurred due to which the wire has been molten and made non-recoverable. Instead of this wire, gamma scans of the outer stainless steel (AISI-316L) can of the experiment (item 23 in drawing GCO-66866) have been made.

3.2 Core irradiation cycles

Surroundings, orientation of the experiment, power fractions (P-frac, in percentage of the total reactor power of 45 MW) of the different surrounding fuel and control assemblies, surrounding other experiments, duration of cycle and duration of outage (Zero power days) of the experiment are given in table 5.

Legend of the table

Cycle number		Full Power days	Zero Power days		
Exp name	Fuel ass.	Exp name	Rig type	P-frac	Rig type
Fuel ass.	HTR-EU	Fuel ass.	P-frac	Orient.	P-frac
Contrl. Ass.	Fuel ass.	Exp name	P-frac	P-frac	P-frac

Table 5: Surroundings during irradiation of HTR-EU1bis

Cyclus 04-08		24.970	3.245		
Al/Al	F1474	Al/Al	Al/Al	1.415	Al/Al
F1526	HTR-EU	CHIP	2.660	NORTH	0.615
C525C	F1530	HCPB	1.710	2.345	REFA-172
Cyclus 04-09		24.720	58.628		
Al/Al	F1465	Al/Al	Al/Al	1.415	Al/Al
F1532	HTR-EU	CHIP	2.660	SOUTH	0.590
C526C	F1523	HCPB	1.680	2.260	REFA-172
Cyclus 05-01		25.990	2.330		
Al/Al	F1476	Al/Al	Al/Al	1.515	Al/Al
F1546	HTR-EU	F1489	2.785	NORTH	1.325
C529C	F1547	Al/Al	1.750	2.540	Al/Al
Cyclus 05-02		25.670	2.210		
Al/Al	F1518	Al/Al	Al/Al	1.580	Al/Al
F1552	HTR-EU	F1470	2.740	SOUTH	1.355
C530C	F1522	Al/Al	1.710	2.420	Al/Al
Cyclus 05-03		25.790	2.330		
Al/Al	F1339	Al/Al	Al/Al	1.460	Al/Al
F1577	HTR-EU	F1338	3.010	NORTH	1.265
C531C	F1558	Al/Al	1.705	2.530	Al/Al
Cyclus 05-04		25.670	52.740		
Al/Al	F1526	EXOTIC	Al/Al	1.500	TETRA-124
F1561	HTR-EU	F1525	2.725	SOUTH	1.290
C532C	F1556	Al/Al	1.715	2.480	Al/Al
Cyclus 05-06		24.260	2.810		
Al/Al	F1521	EXOTIC	Al/Al	1.490	TETRA-124
F1568	HTR-EU	F1539	2.865	NORTH	1.255
C534C	F1574	Al/Al	1.720	2.475	Al/Al
Cyclus 05-07		25.190	26.810		
Al/Al	F1495	EXOTIC	Al/Al	1.605	TETRA-124
F1576	HTR-EU	F1513	3.205	SOUTH	1.290
C535C	F1569	Al/Al	1.800	2.560	Al/Al
Cyclus 05-08		22.190	2.400		
Al/Al	F1542	Al/Al	Al/Al	1.765	Al/Al
F1573	HTR-EU	F1546	3.245	NORTH	1.465
C536C	F1583	Al/Al	1.815	2.590	Al/Al
Cyclus 05-09		25.600	EOI	18-okt-05	8:00:00
Al/Al	F1508	EXOTIC	Al/Al	1.665	TETRA-124
F1586	HTR-EU	F1454	3.205	SOUTH	1.375
C537C	F1585	Al/Al	1.830	2.545	Al/Al

3.3 Experiment temperatures

During the irradiation the temperatures at the centres of the pebbles has been kept constant at about 1250 ºC by means of adjusting the composition of a He/Ne gas mixture. The central temperature was calculated by means of the pebble surface temperature plus the (parabolic) temperature profile due to the power generated in the pebble. Surface temperatures were monitored by thermo-couples touching the non-fuelled outer region of the pebble. These temperatures were raised for every cycle to compensate for the reduction of the pebble power due to depletion.
For the 10 cycles the temperatures of the half shells (surrounding graphite) was measured as (table 6):

Cycle	T (Cº)
1	967
2	1041
3	1055
4	1022
5	1071
6	1096
7	1105
8	1139
9	1104
10	1147

Table 6: Cycle averaged temperatures of the graphite that surrounds the pebbles.

These temperatures resulted in averaged central pebble temperatures for the pebbles GLE-4.1 – GLE-4.5 of:
1209, 1242, 1251, 1248, 1224 Cº respectively for all cycles.

The temperature during the irradiation cycles for the mini samples and flux detectors can be taken the same as the graphite temperatures.

The graphite block on top of the sample holder (sample 1) measured 750 Cº while the graphite at the bottom (sample 7) had an average temperature of 850 Cº during irradiation.

The stainless steel REFA containment tube and the aluminium filler with moderating water are on cooling water temperature of 50 Cº.

4 Experimental limitations or shortcomings

The entire experiment was housed in a closed containment, which prohibited flux monitor replacements by cycle.

The HFR-core is too complex to be given in detail and third party experiments are placed in it as well, of which the characteristics are not public. Therefore the HTR-EU experiment is given in detail and the eight surrounding core positions are given as sets of homogenised macroscopic cross sections. The marked area in fig. 7 indicates the region of interest.

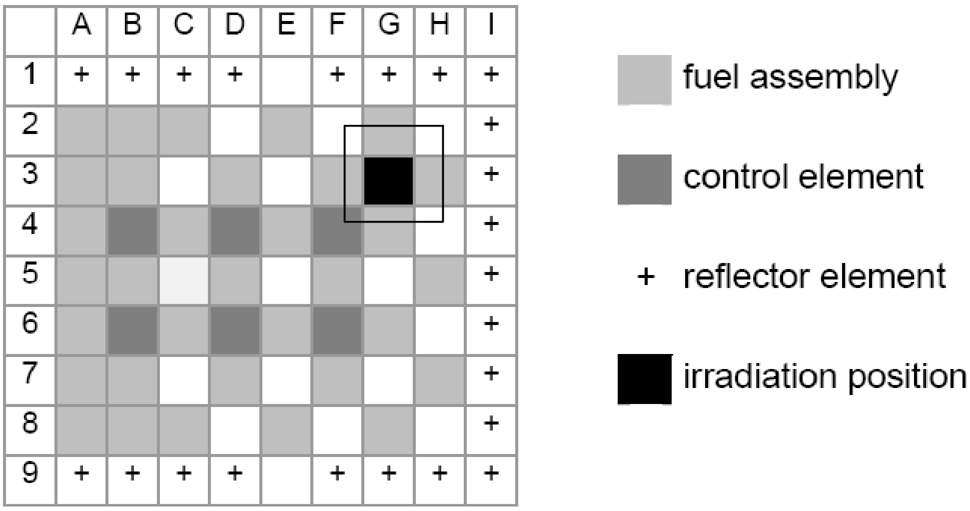


Figure 7: Area of interest for core position G-3.

5 Neutron cross sections

Group wise neutron cross sections will be provided for the eight surrounding positions for core position G-3. Materials for which macroscopic cross sections will be defined for each cycle consist of a quarter of the corner neighbours and for half of the side neighbours (fig. 8). By means of MCNP calculations with detailed descriptions of these surroundings, homogenised cross sections are generated for a number of levels (16) in the axial direction and in a number of neutron energy groups (7): the file CSXfiles.zip. An ASCII-file with the group wise macroscopic cross sections and a MCNP-library,with the same cross sections in ACE format is delivered as well: the file CSXfiles_group.zip. Used material or zone numbers can be found in table 7

Axial position [cm]	**F4**	**G4**	**H4**	**F3**	**G3**	**H3**	**F2**	**G2**	**H2**
30 → 45	136	137	138	139	140	141	142	143	144
22 → 30	127	128	129	130	131	132	133	134	135
14.5 → 22	118	119	120	121	122	123	124	125	126
11 → 14.5	109	110	111	112	113	114	115	116	117
7.5 → 11	100	101	102	103	104	205	106	107	108
4 → 7.5	91	92	93	94	95	96	97	98	99
0.5 → 4	82	83	84	85	86	87	88	89	90
-3 → 0.5	73	74	75	76	77	78	79	80	81
-6.5→ -3	64	65	66	67	68	69	70	71	72
-10 → -6.5	55	56	57	58	59	60	61	62	63
-13.5→ -10	46	47	48	49	50	51	52	53	54
-17 → -13.5	37	38	39	40	41	42	43	44	45
-20.5→ -17	28	29	30	31	32	33	34	35	36
-25 → -20.5	19	20	21	22	23	24	25	26	27
-30 → -25	10	11	12	13	14	15	16	17	18
-45 → -30	1	2	3	4	5	6	7	8	9

Table 7: Zone numbers for the homogenised group cross sections as used in the data files

Four sets of cross sections are given and should be used for the following cycles:
CYCLE0408: for cycle 04-08,
CYCLE0409: for cycle 04-09,
CYCLE0503: for cycles 05-01, 05-02, 05-03, 05-08,
CYCLE0504: for cycles 05-04, 05-06, 06-07, 05-09.

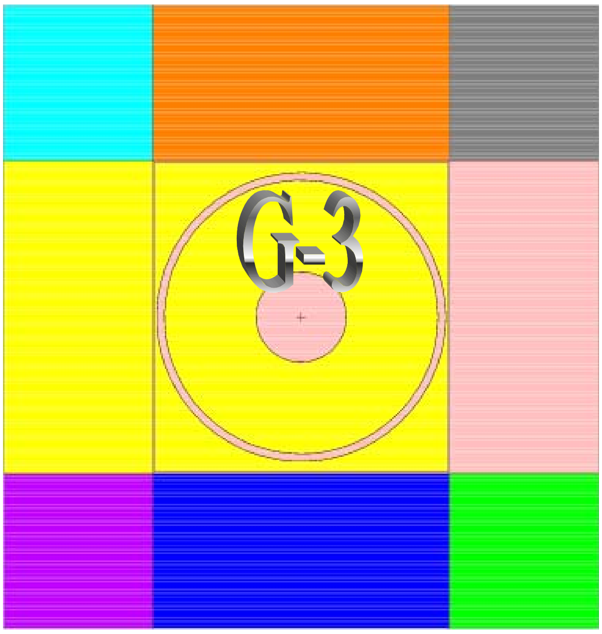


Figure 8: Material definition areas around core position G-3.

6 Phenomena to be calculated

6.1 Description of results and analysis

6.1.1 Flux monitors

The reaction rates of the flux monitor sets are to be calculated. Spectral indices can be obtained from the different monitor material activities as stated in chapter 3.1.2.3 above.
The specific reaction rates are to be given in reactions per atom per second for the monitor material.

Measured values are to be found in file MONITORS at the SINTER-RAPHAEL site.

Due to an erroneous handling of the gas mixture system to control the temperature, during a short time in the second cycle a fast heat-up caused the flux monitor in the middle of the experiment (FD2) to melt and is not available anymore for experimental verification.

6.1.2 Outer can

Also due to this fast heat-up caused the scan wire to melt and is not available anymore for experimental verification, but instead of this wire the outer can of the experiment has been scanned.

Results of a scan of the entire experiment, including the fuel spheres and the half-spheres are given in EXCEL-file T01085b which shows the distribution of a number of fission products and the activity of Mn-54 and Co-60, typical for the stainless steel outer can, revealing the position of the fuel spheres in relation to the outer can.
After removing the content of the experiment from the can new scans have been obtained using an insert of lead in the can to avoid to 'see' the backside of the tube. First a scan along an arbitrarily orientation (65° clockwise from North) of the tube, then one circumferential scan at the height of maximum Co-60 activity and a scan along the 200° orientation where the Co-60 and Mn54 activities are in anti-phase.
Results of the axial scans can be found in the EXCEL-file T01263b and for the circumferential scan in file T01258b.

Note that the axial position in the scans of T01085b and T01263b do not coincide but can be matched by means of the Mn-54 and/or Co-60 distribution present in both files. Doing so one finds a shift of 75 mm.
The left side of the distributions is always the bottom of the experiment. All countings are relative and are not corrected for decay during/after irradiation.
The 'dog-bones' at either end-sides in the axial scans of T01263 are due to the limited length of the lead pillar central in the tube, so part of the activity seen are from the rear-side of the can. The EXCEL-files can be found on the SINTER-RAPHAEL site.

The relevance of the Mn-54 activity distribution is the sensitivity for the fast neutron fluence (E > 2 MeV) whereas the activity of Co-60 is indicative for the thermal fluence.

The activity of Co-58 which is an indicator for the fast fluence as well is hampered by the fact that due to its short life-time (70 days) relative to the duration of the irradiation it is only sensitive for the final stage of the experiment and by the effect that the intermediately formed Co-58m has a huge cross section of 145000 barns (2200 m/s) and will by partly depleted during its life-time of about 9 hours.

To be calculated are the axial profiles (relative) of the thermal and fast fluence by means of the activity in a relevant number of points along the experiment (from -20 cm to + 20 cm from centre-line core) for the relevant isotopes Co-60 and Mn-54.

6.1.3 Mini samples

To be calculated are the isotopic inventories (Bq/gram initial HM) of the coated particles in the six mini-samples 1-10. Specific measured data are be obtained for:

the fission products:
the vectors of:: Cs, Nd, and Ce-144, Sr-90,

and for the actinides:
the vectors of:: U, Pu and Np-237, Am-241, Cm-244.

Measured data can be found on the file SAMPLES on the SINTER-RAPHAEL site.

6.1.4 Fuel pebbles

To be calculated are the isotopic inventories (Bq/gram initial HM) of the five pebbles 1-5. Specific measured data are obtained for:

the fission products:
the vectors of:: Cs, Nd, and Ce-144, Sr-90,

and for the actinides:
the vectors of:: U, Pu and Np-237, Am-241, Cm-244.

With a hollow drill (inner/outer diameter 7.0/9.0 mm) samples have been drilled from the GLE-4.2 pebble in the vertical orientation through the middle point of the sphere. Measured data from these samples can be found on the file PEBBLES on the SINTER-RAPHAEL site.