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HFR-EU1bis Final Irradiation Report

M. Fuetterer
A. Marmier
G. Berg
(JRC/IE)

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IRRADIATION RESULTS OF AVR FUEL PEBBLES AT INCREASED TEMPERATURE AND BURN-UP IN THE HFR PETTEN

Michael A. Fütterer,
Gerard Berg, Alain Marmier

European Commission
Joint Research Centre
Institute for Energy
P.O. Box 2
NL-1755 ZG Petten
The Netherlands
michael.fuetterer@jrc.nl

Enrique Toscano

European Commission
Joint Research Centre
Institute for Transuranium Elements
D-76344 Eggenstein-Leopoldshafen
Germany

Klaas Bakker

Nuclear Research and
consultancy Group
P.O. Box 25
NL-1755 ZG Petten
The Netherlands

ABSTRACT

The irradiation experiment HFR-EU1bis was successfully performed by JRC Institute for Energy (JRC-IE) in the HFR Petten to test 5 spherical High Temperature Reactor (HTR) fuel pebbles of former German production with TRISO coated particles for their potential for very high temperature performance and high burn up. The irradiation started on 9 September 2004 and was terminated on 18 October 2005 after 10 reactor cycles totaling 249 efpd and a pre-calculated maximum burn-up of 15.5% FIMA.

The objective of the HFR-EU1bis test was to irradiate 5 HTR fuel pebbles at conditions beyond the characteristics of current HTR reactor designs with pebble bed cores, e.g. HTR-Modul, HTR-10 and PMBR. This should demonstrate that pebble bed HTRs are capable of enhanced performance in terms of sustainability (further increased power conversion efficiency, better use of fuel) and thus reduced waste production. The central temperature of all pebbles was kept as closely as possible at 1250°C and held 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.

HFR-EU1bis should demonstrate the feasibility of low coated particle failure rates under normal operating conditions and more specifically:

- increased central fuel temperature of up to 1250°C compared to 1000-1200°C in earlier irradiation tests;
- irradiation to a burn-up of close to 16% FIMA, which is double the license limit of the HTR-Modul;
- confirmation of low coated particle failure rates due to temperature, burn-up and neutron fluence.

This paper provides the irradiation history of the experiment including data on fission gas release. Post-irradiation examinations underway at NRG Petten include the verification of the received neutron fluences, burn-up and spectrum. They will be followed by safety-relevant tests at the JRC Institute for Transuranium Elements (JRC-ITU) in Karlsruhe to verify fission product retention by out-of-pile heating tests beyond 1600°C.

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 [1] to provide high burn-up HTR fuel pebbles for KÜFA testing at JRC-ITU. KÜFA tests [2] investigate fission product retention of highly irradiated fuel elements beyond 1600°C under simulated accident conditions of modular HTRs.

Although the costs for this irradiation were covered by JRC-IE, HFR-EU1bis is followed up by HTR-TN and was technically integrated in the Euratom projects HTR-F/F1 and RAPHAEL [3], [4]. These projects focus on the innovation potential of past and current HTR fuel technology based on TRISO coated fuel particle design. Major partners in the consortium of these projects are CEA, AREVA NP, NRG, FZJ, JRC and BNFL.

HFR-EU1bis was dedicated to a particularly high central pebble temperature of up to 1250°C while an extremely high burn-up test (approx. 20% FIMA at lower temperature) was reserved for another planned irradiation test, HFR-EU1, to start in 2006. Compared to HFR-EU1, this irradiation is simplified (batchwise instead of continuous fission gas release analysis, manual temperature control) and accelerated (higher neutron flux and fission power). This had become useful because start-up of HFR-EU1 had accumulated considerable delay thus delaying the KÜFA tests of this fuel at high burn-up. The HFR-EU1bis irradiation was performed for 10 reactor cycles in core position G3 (cf. Figure 1).

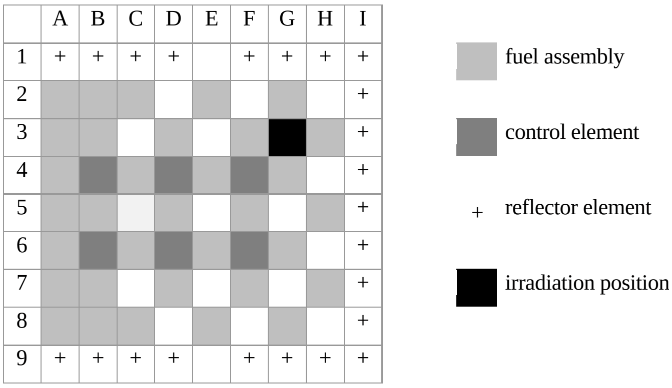


Figure 1: Standard HFR core configuration showing HFR-EU1bis in core position G3

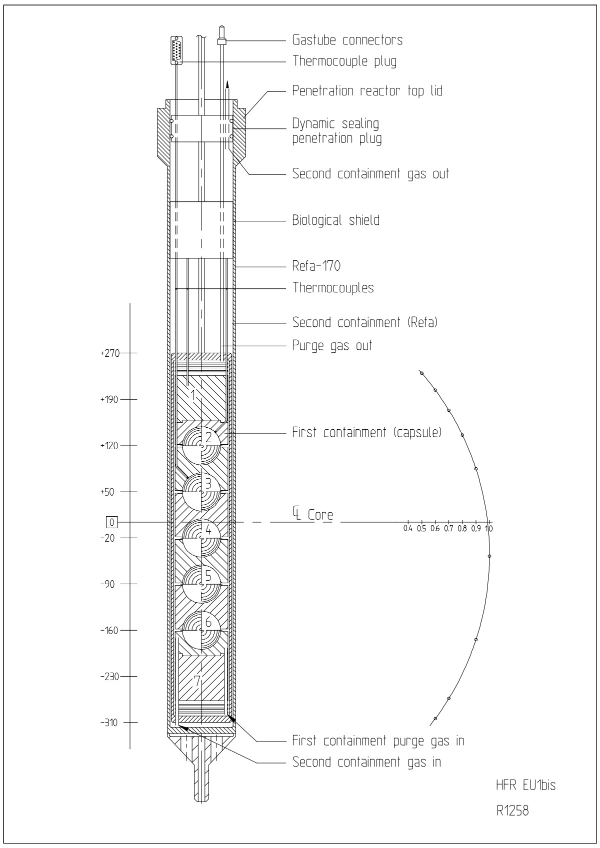


Figure 2: HFR-EU1bis sample holder

The experiments HFR-EU1 and HFR-EU1bis share the objective of exploring the potential for high performance and high burn-up of the existing German AVR fuel pebbles for advanced applications such as the conceptual Generation IV Very High Temperature Reactor (VHTR). 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 [6], [7], [8]. Irradiating this fuel under defined conditions to extremely high burn-ups and testing it afterwards in thermal ramp tests to simulate cooling accidents would be a license requirement for new fuel and provides better understanding of fission product release and failure mechanisms should coating failure occur.

The irradiated pebbles were 60 mm in diameter with LEU-TRISO coated particles and were of former German production, type AVR GLE-4.

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 1: Nominal characteristic data of AVR GLE-4 pebbles

2. EXPERIMENTAL

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* [9], [10], [11]. The five pebbles were tested in the "Full Size HTR Fuel Element Rig" (REFA-170), which has become a standard device in the HFR Petten. A schematic drawing is shown in Figure 2. The sample holder (1st containment) is an AISI 321 capsule containing several graphite half shells (SGL R6650) that hold the pebbles in place. It is located at the maximum axial flux in the REFA-170 rig, which forms the 2nd containment. The sample holder is equipped with 24 thermocouples, a gamma scan wire and 3 fluence detector sets. The heat generated by fission and photons dissipates 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 cooling water.

The temperature of the fuel surface could be controlled by adjusting the He/Ne mixture in both the 1st and 2nd containment. This temperature adjustment was 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 10-15×10^{25} n m^{-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 reactor control rods. The predicted useful range of temperature change by these gas changes was approx. 120 K.

The 1st and 2nd containment remained normally closed (stagnant gas) during the first two reactor cycles (venting only for weekly gas sampling) and normally purged with a constant gas flow during the remaining cycles which facilitated temperature adjustment and gas sampling.

To accelerate the burn-up, yet without exceeding the allowable power density in the fuel, the neutron spectrum was 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 reduced radial gradients in neutron fluence and burn-up across the pebbles.

The experiment was designed such that despite the decrease in power with time the desired central pebble temperature could be kept as constant as possible in all pebbles over the entire irradiation. This was achieved by sizing the gas gaps between graphite shells and 1st containment tube and 1st and 2nd containment tubes such that a suitably adjusted mixture of He and Ne gas enabled obtaining the required temperatures in the pebbles during the entire irradiation.

The central fuel temperature could not be directly measured with a thermocouple because drilling of a hole for the thermocouple would have damaged several particles. Therefore, and accepting the uncertainty in thermal conductivity data for the calculation of the order of 10%, the irradiation was conducted by controlling the surface temperature of the pebbles such that the calculated central temperature remained as constant as possible. Due to power depletion with burn-up, the surface temperature had to be raised during the experiment from initially 1015°C to 1109°C on the upper hemisphere of pebble GLE-4.4, which was used as the reference temperature.

3. NUCLEAR DATA

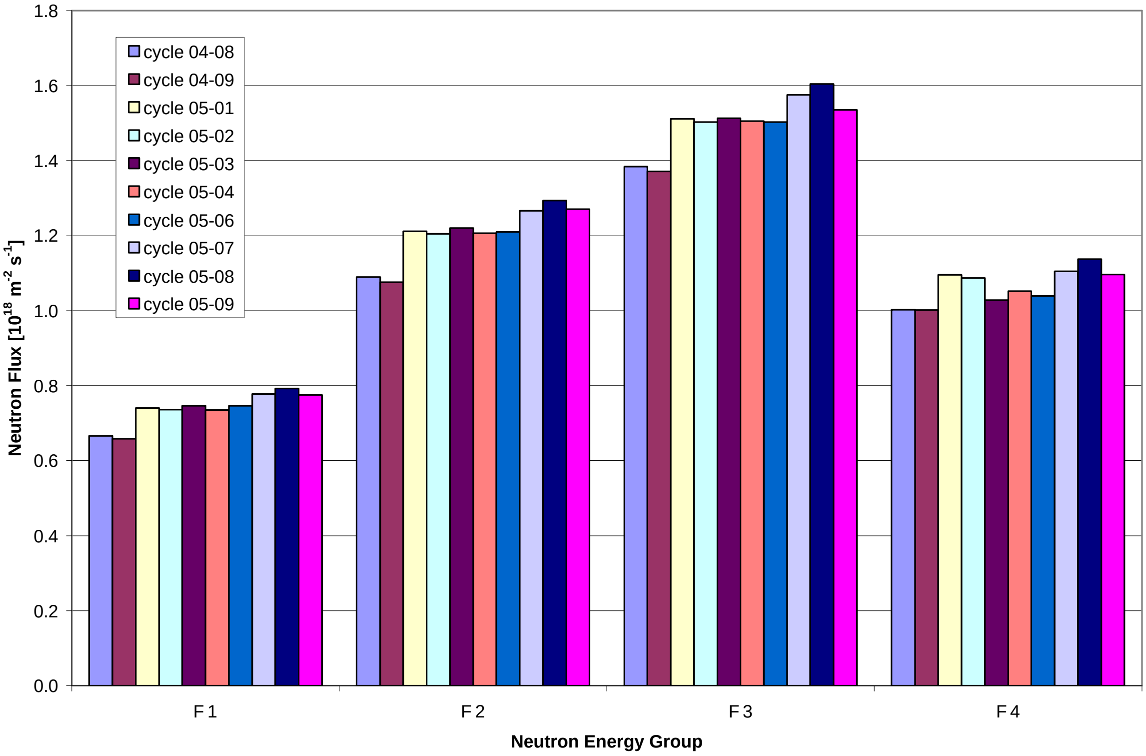
The 4-group neutron fluxes, thermal and fast fluences are listed in Table 2 for all 10 reactor cycles. The fluxes were somewhat lower during the first two cycles than for the rest of the irradiation. A shortened reactor cycle 05-08 is responsible for the lower fluences received during this cycle.

According to these post-cycle calculations, the attained thermal and fast fluence would be 2.23×10^{25} m^{-2} and 3.98×10^{25} m^{-2} respectively, accumulated during 249.55 equivalent full power days. The values and axial profiles for fluence and spectrum will be verified during PIE through the analysis of neutron detector sets and by the analysis of the sample holder tube.

Cycle	Efpd	F_1 [1)]	F_2	F_3	F_4	$Fluence_4$	$Fluence_{E>0.1\,MeV}$
	[days]	EOC [10^{18} m^{-2}s^{-1}]				[10^{25} m^{-2}]	
04-08	24.97	0.666	1.089	1.384	1.002	0.209	0.357
04-09	24.72	0.658	1.076	1.371	1.001	0.207	0.350
05-01	25.99	0.740	1.211	1.511	1.095	0.24	0.419
05-02	25.67	0.736	1.205	1.503	1.087	0.234	0.410
05-03	25.29	0.746	1.220	1.513	1.028	0.220	0.411
05-04	25.67	0.735	1.206	1.505	1.052	0.226	0.408
05-06	24.26	0.746	1.210	1.503	1.039	0.211	0.389
05-07	25.19	0.778	1.266	1.575	1.105	0.233	0.424
05-08	22.19	0.792	1.294	1.604	1.137	0.213	0.382
05-09	25.60	0.775	1.271	1.535	1.096	0.235	0.431
total	249.55					2.23	3.98
variation during entire irradiation	17.12%	20.36%	20.26%	16.99%	13.59%	15.94%	23.14%

[1)] energy groups with boundaries: 14.918×10^{6} – 1.353×10^{6} – 0.0674×10^{6} – 0.683 – 0 eV

Table 2: Comparison of fluxes and fluences



Energy groups with boundaries: $14.918\times10^6 - 1.353\times10^6 - 0.0674\times10^6 - 0.683 - 0$ eV

Figure 3: Comparison of neutron fluxes per reactor cycle

4. POWER EVOLUTION IN PEBBLES

Pre-irradiation neutronics calculations had determined the heat from fission and photons in the pebbles, which decreased during irradiation (cf. Table 3). The number of fissions at every moment was determined which allowed the calculation of the birth rate of the measured volatile fission isotopes of Kr and Xe by using their characteristic fission yields. The resulting power density and burn-up evolutions are plotted in Figure 4.

Reactor Cycle	Pebble Power (fissions + photons) [W]				
	GLE4.1 (top)	GLE4.2	GLE4.3	GLE4.4	GLE4.5 (bottom)
1	3318	3948	4305	4117	3783
2	3142	3762	4073	3893	3579
3	2990	3578	3872	3700	3401
4	2839	3396	3673	3508	3226
5	2708	3237	3499	3341	3073
6	2576	3078	3326	3174	2920
7	2462	2940	3175	3029	2787
8	2352	2808	3030	2890	2659
9	2256	2691	2903	2767	2547
10	2164	2580	2781	2650	2440

Table 3: Calculated power evolution in pebbles

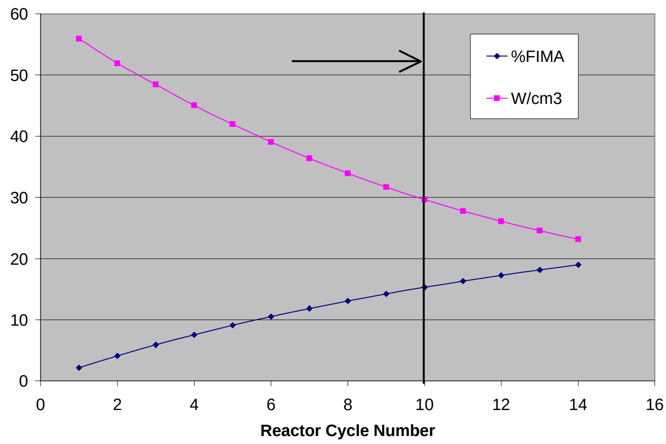


Figure 4: Power density (fission + photons) and burn up evolution with irradiation for pebble in maximum flux position (GLE-4.3)

5. TEMPERATURES

Measured temperatures in the sample holder were stored in the standard HFR data acquisition system.

Figure 5 shows the average temperatures during the 10 irradiation cycles without correction for thermal drift and neutron induced decalibration. The pebble surface temperatures are encircled. For better understanding of the results, additional thermo-mechanical modeling work was performed and is summarized in [5].

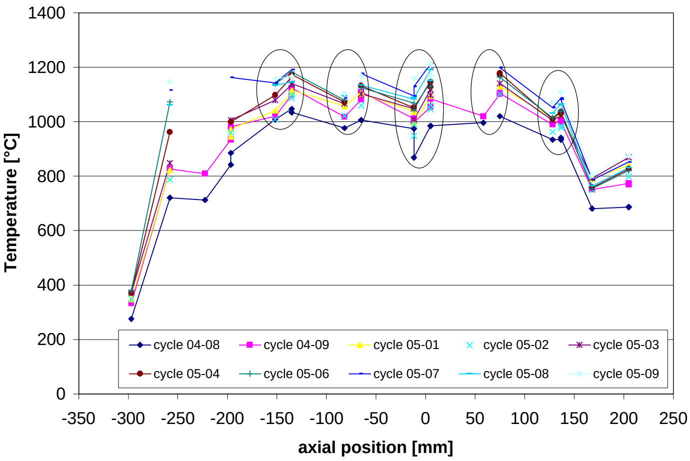


Figure 5: Average temperatures measured in irradiation rig for all 10 irradiation cycles. Ellipsoids mark pebble positions.

Twenty-four thermocouples were built into the experiment. They were supplied by Thermocoax and were of type N (Nicrosil/Nisil wires, MgO insulator, Inconel 600 sheath) with an outer diameter of 1.05 mm. In the end of the irradiation, 11 out of the 24 thermocouples provided physically impossible or unreliable signals, most of them being situated in the graphite between pebbles where the measured temperature was routinely between 50 and 100 K higher than at the pebble surface. Such thermocouple dropouts are frequently encountered in high temperature irradiation tests. Several mechanisms are suspected to have acted such as exposure to high temperature and neutron flux for extended periods of time, contact problems in connectors, vibrations in the experiment, and movement of thermocouples due to thermal expansion.

While thermocouple redundancy is for the time being the only way to circumvent these reliability problems, JRC-IE is involved in the qualification of new thermocouples better suited for high temperature irradiation tests.

6. FISSION GAS RELEASE MEASUREMENTS

For the performance of HFR-EU1bis, a custom-built gas panel installed in a glove box was used for gas mixing, flow and pressure control, and for gas sampling, in general performed once per week. The gas panel was operated from a PLC controlled command cabinet, which also contained a number of alarm functions such as the automatic cut-off of all gas lines to and from the irradiation rig in case of excessive radioactivity release.

In most cases, the temperature was adjusted by mixing He and Ne while keeping the total gas flow rate constant. The gas flow coming from the sample holder was normally routed through an activated charcoal filter to minimize radioactivity release to the HFR off-gas system. For gas sampling, this filter was bypassed and the gas was sent through a detachable sampling vessel with a volume of 100 cm^3. This sampling vessel was then placed on an external multi-channel gamma spectrometer calibrated for the measurement of five different isotopes, namely ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{133}Xe and ^{135}Xe. Of each sample, several measurements were made and the counts were corrected for decay to determine the specific isotope concentration in the purge gas at the moment of gas sampling. The statistical error of this measurement was between 4 and 9%. Together with the known gas flow, pressure and temperature, the fission gas release rate R from the five pebbles could be determined and related to the birth rate B from neutronics calculations (error 10–15%) thus yielding the characteristic R/B value which is considered a good indicator for the health of coated particles.

The burn-up is the one pre-calculated for the experiment. Later adjustments will be made once the burn-up measurements of the pebbles and the analyses of gamma scan wires and fluence detectors are available.

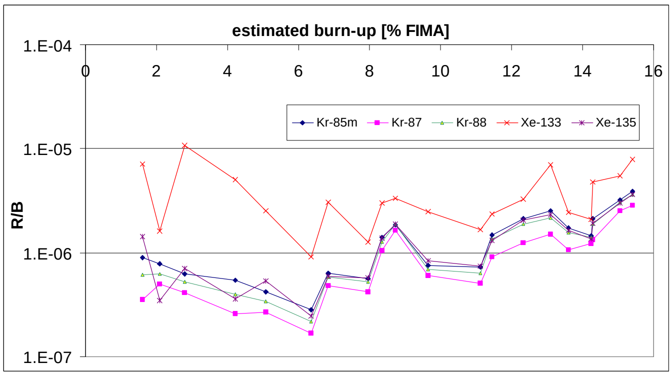


Figure 6: Preliminary R/B vs. burn-up

From the 5 scanned isotopes, 4 were generally consistent, however the ^{133}Xe counts were systematically higher, probably due to its additional precursors ^{133}I and ^{133m}Xe. An upward trend could be observed in the end of the irradiation. Only a few dubious results were obtained and could be linked to thermal transients in the sample holder during the gas sampling. This data was scrapped.

The quality of the R/B measurement (steady-state R/B) was verified by checking that there is little or no temperature dependence on fission gas transport.

In [6] we find the following expression for R/B:

$$\frac{R}{B} = 3\sqrt{\frac{D'}{l}}$$

with:

R: Fission gas release rate

B: Fission gas birth rate

D': apparent fission gas diffusivity
(temperature dependent)

$$D' = D'_0 \exp\left[\frac{-Q}{RT}\right]$$

$$l = \frac{\ln 2}{T_{½}}$$

with $T_{1/2}$: half life of concerned isotope

At constant temperature T, we can then derive:

$$\ln \frac{R}{B} = const. - n \ln l$$

with
n < 0.2 for graphite contamination
0.2 < n < 0.3 observed in previous irradiations
n > 0.5 in case of particle bursts

Consequently, when plotting the individual ln R/B values from a given measurement against ln λ, the result should be a straight line with the negative inclination n. This method was applied to each gas sample and only few results had to be discarded because of excessive values of n. A typical result is shown in Figure 7.

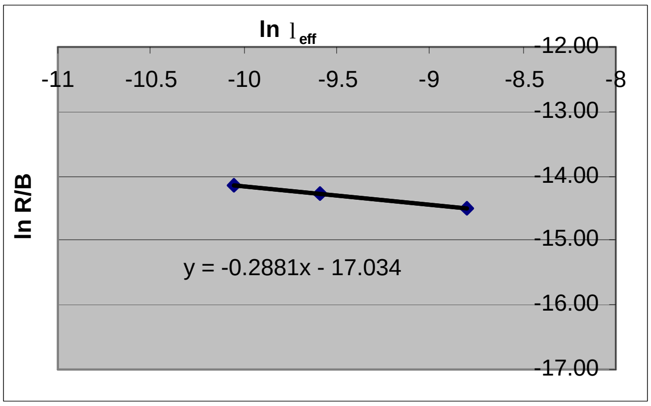


Figure 7: Typical ln R/B vs. ln λ_{eff} plots for Kr gas release measurement

In the end of irradiation an R/B of approx. 4×10^{-6} was measured, which is by a factor 5 lower than the theoretical R/B from complete failure of a single particle in the experiment (approx. 2×10^{-5}). In the earlier experiments HFR-K5 and HFR-K6, R/B values of 5×10^{-7} had been measured on fresh fuel. This suggests that in HFR-EU1bis despite the high temperature and burn-up no complete particle failure could be detected. However, from the start there may have been particles present in the sample holder that were leaking a small fraction of fission gas. If we assume that any leaking particle releases only a fraction of 1% of the measured Kr and Xe isotopes, then HFR-EU1bis would have contained 1-5 leaking particles at the beginning of irradiation and 14-19 particles at the end.

7. SPECIAL EVENTS

In the beginning of the second irradiation cycle an operating error had caused a strong unwanted temperature excursion. After the excursion, a leak was detected between the inside and the outside of the sample holder. A neutron radiograph attributed this leak to a partly molten steel minitube running all along the inside of the sample holder to provide gas for the 2nd containment outside the capsule. Also, the built-in gamma scan wire and the sheath of one fluence detector set were partly molten. After some modification of the gas panel, the irradiation could safely be resumed with a single containment. Even with a single containment, i.e. same gas mixture on inside and outside of the sample holder, there was sufficient temperature control margin left to maintain the target temperatures. The only inconvenience caused by the incident was that the temperature response after a gas mixture change had become rather slow due to the large gas volume in the rig. For the same reason, continuous purging as opposed to occasional venting was chosen to perform gas sampling in steady-state conditions.

For future irradiations, the robustness of the employed sample holder design will be further enhanced by using high temperature resistant materials for the sample holder internals.

8. POST-IRRADIATION EXAMINATIONS

Currently PIE is ongoing in the hot cells at NRG Petten with the following activities completed:

- Dismantling,
- Metrology,
- Gamma scanning of graphite shells and pebbles,
- Weighing,
- Visual inspection of the pebbles.

The following activities are yet to be completed:

- Gamma scanning of the outer stainless steel containment (to confirm burn-up calculations),
- X-ray photography,
- Neutron metrology on the fluence detector sets,
- Ceramography on one pebble,
- Electron Probe Micro Analysis (EPMA) on the same pebble.

The diameter of the pebbles was measured in three perpendicular axes. Diameter change compared to the initial values is shown in Table 4. The average diameter decrease is 1.29 mm (2.16%), corresponding to a 6.3% volume decrease. As expected, the pebbles with the highest burn-up show the highest diameter decrease. Comparing the diameter decreases of the three axes revealed that the "hot" axis, in line with the central vertical axis of the sample holder, showed approx. 0.2 mm smaller diameter decreases than the other two axes where strong negative temperature gradients existed.

Pebble	Average shrinkage in 3 dimensions [mm]	Estimated Burnup [% FIMA]
GLE-4.1 (top)	-1.18	11.7
GLE-4.2	-1.25	14.1
GLE-4.3	-1.36	15.4
GLE-4.4	-1.37	14.8
GLE-4.5 (bottom)	-1.30	13.3

Table 4: Average shrinkage in three directions

Gamma scanning of the graphite half shells allowed detecting a significant amount of ^{110m}Ag, ^{134}Cs and ^{137}Cs. A quantitative analysis of the release fractions of these isotopes is ongoing. Gamma scanning of the pebbles showed the existence of significant inhomogeneities in the coated particle distribution inside the pebbles. Visual inspection of the pebbles showed that their shiny surface was maintained hinting at the absence of corrosion phenomena.

After completion of non-destructive PIE on the five pebbles in Petten, four will be transported to JRC-ITU for safety testing. One pebble will be investigated destructively. This includes both ceramography and Electron Probe Micro Analysis (EPMA).

9. BURN-UP ANALYSIS AND SAFETY TESTING

Burn-up determination by gamma spectrometry

Several methods can be applied to non-destructively determine the burn-up of irradiated fuel elements. One such method is gamma scanning for the fission product inventory of ^{137}Cs as monitor isotope, which can be related to burn-up. ^{137}Cs has a half life (30.09 years) which is long in comparison to the duration of the irradiation and the time spent between irradiation and KÜFA testing. Therefore, its decay plays only a minor role and can be easily corrected.

This method had been already successfully applied to the quantitative determination of the burn-up of 19 HTR pebbles irradiated up to 10% FIMA in different experiments conducted in the past in three different reactors in Europe. The results are reported in [12]. The 4 pebbles from HFR-EU1bis will be analyzed as soon as they arrive from Petten.

Burnup and isotopic composition by wet chemistry

The fuel burn-up using wet chemistry is a destructive technique and usually determined by measuring the content of an accumulating fission product. Some isotopes of neodymium, in particular ^{148}Nd, have proven to be ideal monitors due to their chemical and neutron-physical properties. On the other hand, the amount of this particular isotope can only be determined by the analysis of dissolved samples, which, with the current state-of-the-art means using rather costly and time consuming methods.

^{148}Nd as burnup monitor has several advantages:

- It is a stable fission product (no decay corrections are necessary).
- It has a well-known fission yield.
- It is not volatile and has no volatile precursors.
- It has almost the same yield for ^{235}U and ^{239}Pu, and the yield is independent of neutron energy.
- The isotope ^{142}Nd can be used for natural Nd-contamination determination.
- It is formed exclusively by fission (low neutron capture cross section).
- It is not present in non-irradiated fuels.

To determine the burn-up, two different methods have to be used to measure the required U, Pu and Nd-vectors. For U and Pu, Thermal Ionisation Mass Spectrometry (TIMS) according to the procedure of Isotopic Dilution (IDMS), is extensively used. On the other hand, for the determination of the Nd-vector, Ion Chromatography (IC) is used on-line to separate this element from the other fission product isotopes, which can cause isobaric interferences. Subsequently, the isotopic composition of Nd is determined by isotopic dilution Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

The results of the HFR-EU1bis pebbles will be used to validate neutronics calculations for the European HTR technology project RAPHAEL [4]. This method had already been successfully used on irradiated pebbles after a KÜFA-test.

This analysis method will be applied to at least one HFR-EU1bis pebble. For this purpose, a hollow drill will be used to extort a cylinder of pebble material (cf. Figure 8). Dust from this carottage process will be dissolved and serves as a first integral burn-up measurement. From the extracted cylinder, samples can be taken at different radial positions and be powdered prior to dissolution for creating a radial burn-up profile.

Figure 8: Carottage of an irradiated pebble after KÜFA-test

Accident simulation (KÜFA-tests)

The key aspect of the safety philosophy for a High Temperature Reactor is the retention of fission products - particularly those of the iodine nuclides - in the fuel elements both in normal operating and accidental conditions.

While normal operational release was evaluated during the irradiation itself, the determination of the number of failing particles in accidental conditions will be performed in special hot cell equipment allowing the safe simulation of accidental conditions and more sophisticated analysis of released radioactive isotopes.

During a depressurization accident, the temperature in an HTR core will increase slowly due to the large amounts of graphite in the core. A temperature peak is then followed by a slow decline in temperature. This transient depends on the geometrical design of the reactor and the nature of the accident. For the extreme case of pressure loss in the core with failure of all heat sinks, temperatures as high as 2000°C can be reached in a medium-size HTR. On the other hand, for the case of small HTRs and the HTR-Modul concept in Germany, a relatively low peak accident temperature, typically 1620°C, had been predicted.

With the increase of core temperature, fission products may be released from the fuel elements into the primary circuit and, eventually, into the environment. For a realistic assessment of fission product release, the conditions in the reactor core during this accident scenario have to be reproduced.

To simulate such accident scenarios, the KÜFA device (German acronym for "Cold-Finger Device") was built at JRC-ITU. A schematic of the KÜFA device is shown in and is described in [1] and [13]. Active commissioning was performed recently and first results are reported in [3].

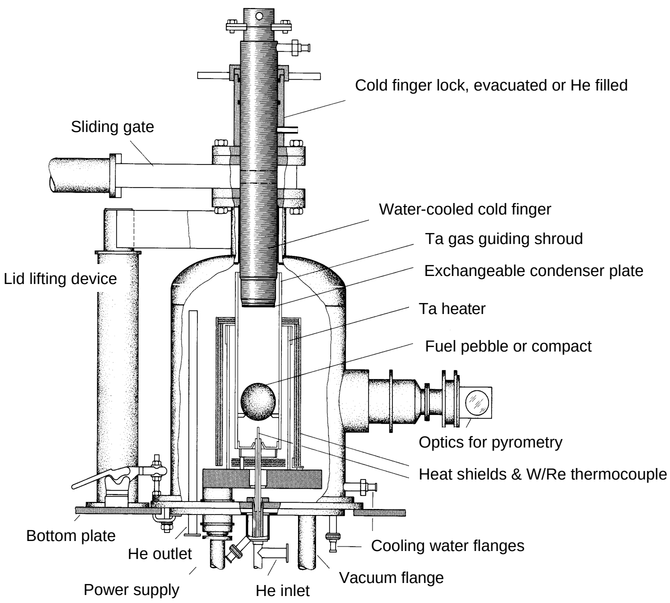


Figure 9: Schematic of KÜFA device

Its basic function is to heat the fuel elements up to and beyond the peak accident temperature under He atmosphere, and to measure fission product release. In the cold finger, protruding into the furnace, solid fission products plate out and can be subsequently measured, whereas continuous He-circulation through a cold trap enables measuring gaseous fission products through gamma detection of ^{85}Kr.

10.CONCLUSIONS

After a pause of several years, HTR fuel irradiations were resumed in 2004-2005 in the HFR Petten, this time with focus on determining the limits of old and newly produced fuel in terms of temperature and burn-up for a possible use in advanced pebble bed HTRs such as the Generation IV type VHTR concept with a coolant outlet temperature of up to 1000°C. Several technical difficulties were overcome and the HFR-EU1bis irradiation was completed after approx. 250 efpd. While no significant particle failure was observed during the irradiation itself, fission product release during safety-relevant tests will show soon whether the same holds for accidental conditions. PIE have begun and employ a series of analytical techniques to extract a maximum of useful information from the irradiated material.

The installations at Petten (JRC-IE and NRG) and Karlsruhe (JRC-ITU) are operational, qualified and represent key elements in the irradiation testing and qualification chain of gas-cooled reactor fuel.

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TECHNICAL MEMORANDUM
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HFR-EU1bis: Irradiation Progress Report
Cycles 04-08, 04-09, 05-01, 05-02

Project n° 337.2

rev. B

Michael A. Fütterer

	Author	Verified by	Approved by Unit Head
Name	M. A. Fütterer	F. Scaffidi-Argentina	R. May
Date	2.9.05	06.09.05	7.9.05
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Revision	Date	Description
A	21.03.05	initial release
B	02.09.05	missing Figures for TC-17 and TC-18 added
C		

Abstract

This is the first progress report of the HTR fuel pebble irradiation experiment HFR-EU1bis combining the results of the first four irradiation cycles. The irradiation has started on 9 September 2004 and was interrupted for 2 reactor cycles.

This document contains the history of the irradiation including significant special events, nuclear data as well as temperature and fission gas release measurements.

Some preliminary attempts were made to analyze and interpret the information obtained so far.

Further data is available to the HTR-F/F1 partners on request.

Table of Contents

1 Irradiation History

9/9/04 17:10 start cycle 04-08 pure stagnant He in both containments sufficient to reach target temperatures: uncertainties in radiative emmissivity of sample holder steel (0.3-0.8) and calculated pebble power (approx. 10%) addendum to user's manual issued: no Ne to be used 20:47 nominal reactor power 45 MW Several gas samples analyzed 4/10/04 18:00 end cycle 04-08
7/10/04 22:33 start cycle 04-09 pure He purging in both containments 8/10/04 1:40 nominal reactor power 45 MW 8/10/04 2:00 start purging 1st containment with pure Ne → temperature excursion (action complied with user's manual but disregarded addendum) 8/10/04 2:10 start purging 1st containment with pure He Pressures in 1st and 2nd containment follow each other → leak According to DSR, no interruption of experiment required, irradiation continued First use of He/Ne mix for temperature adjustment, takes now several hours Rig pressurized to 4.5 bar and isolated Several gas samples taken, no damage to fuel observed 1/11/04 end cycle 04-09
Next two cycles 04-10 and 04-11 used for neutron radiograph, reason for leak not detected Modification of alarm logics, addition of 2 solenoid valves and 1 GM counter in gas panel Modification and approval of new DSR and user's manual.
30/12/04 6:05 start cycle 05-01 Adjustment of He/Ne mixture Several gas samples analyzed Blockage of 2nd containment lines identified (connection in rig head) → no consequence, to be repaired during reactor maintenance 25/1/05 8:00 end cycle 05-01
27/1/05 14:25 start cycle 05-02 Adjustment of He/Ne mixture Several gas samples analyzed Gas leak in out-of-pile section of 2nd containment identified, to be repaired during reactor maintenance 22/2/05 8:00 end cycle 05-02 with 101.35 fpd completed

1.1 Special Events

An unwanted temperature excursion occurred in the beginning of cycle 04-09, which caused a leak between the 1st and 2nd containment. After completion of cycle 04-09, the irradiation was interrupted for 2 cycles to try and check the location of the leak by neutron radiography and to modify the gas panel such that it could more easily handle the new situation.

7/10/04 22:33 start cycle 04-09

pure He purging in both containments

8/10/04 1:40 nominal reactor power 45 MW

8/10/04 2:00 start purging 1st containment with pure Ne ➔ temperature excursion (complies with user's manual but disregards addendum)

8/10/04 2:10 start purging 1st containment with pure He

Pressures in 1st and 2nd containment follow each other ➔ leak

According to DSR, no interruption of experiment required, irradiation continued

- No unsafe situation was caused (double containment).
- The cause for the wrong handling was that the operator had well read the user's manual but not the addendum issued in the beginning of the 1st cycle.
- The Ne line was not physically disconnected because it was thought that Ne would be needed earlier.
- The temperature adjustment was tested and works fine with apparently sufficient control margin, which was confirmed in later cycles. However, the time necessary for the adjustment has increased substantially from a few minutes to about 4 hours.
- Due to the large gas volume in the rig, the gas sampling requires now much more time because a steady-state situation has to be reached with a large internal rig volume.

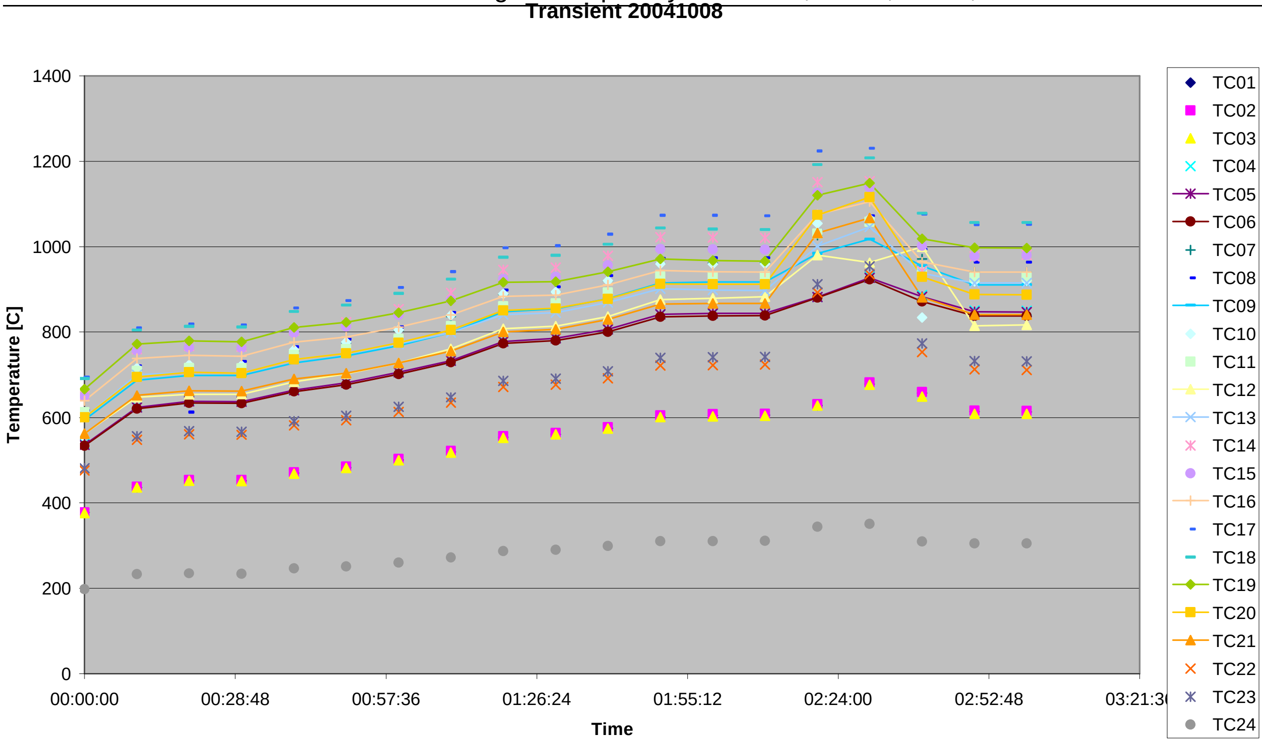

Figure 1: Temperature plot during incident 8/10/04 cycle 04-09

In Figure 1, the peak is probably chopped off in this 10-min data. The maximum fuel surface temperature was measured on TC-19 (lowest pebble) at approx. 1148°C. The solid lines represent the fuel pebbles, the dots represent graphite and structures.

1.2 Modifications of Installation

- **Gas Panel:** Due to a request of the reactor manager, the gas panel was slightly modified such that two additional magnetic valves were added to the gas outlets of either containment, and an additional GM counter was installed. The alarm system was also modified to comply with this new situation.
- **Gas sampling:** The procedure was only little modified: due to the significantly increased volume to be purged in the rig for obtaining steady-state conditions, it was decided to purge overnight for about 18 hours before gas sampling. The R/B results are consistent.
- **Automation:** During the next reactor maintenance stop (19.4. – 12.5.2005) a further modification of the gas system is planned to ease the temperature adjustment (separate mass flow controllers in He and Ne admission strings). Additionally, a pressure controller at the gas outlet will be installed. This will allow:
    1. walk-away safe pressurization of the rig;
    2. gas sampling at nominal temperature/pressure conditions in the capsule if required.

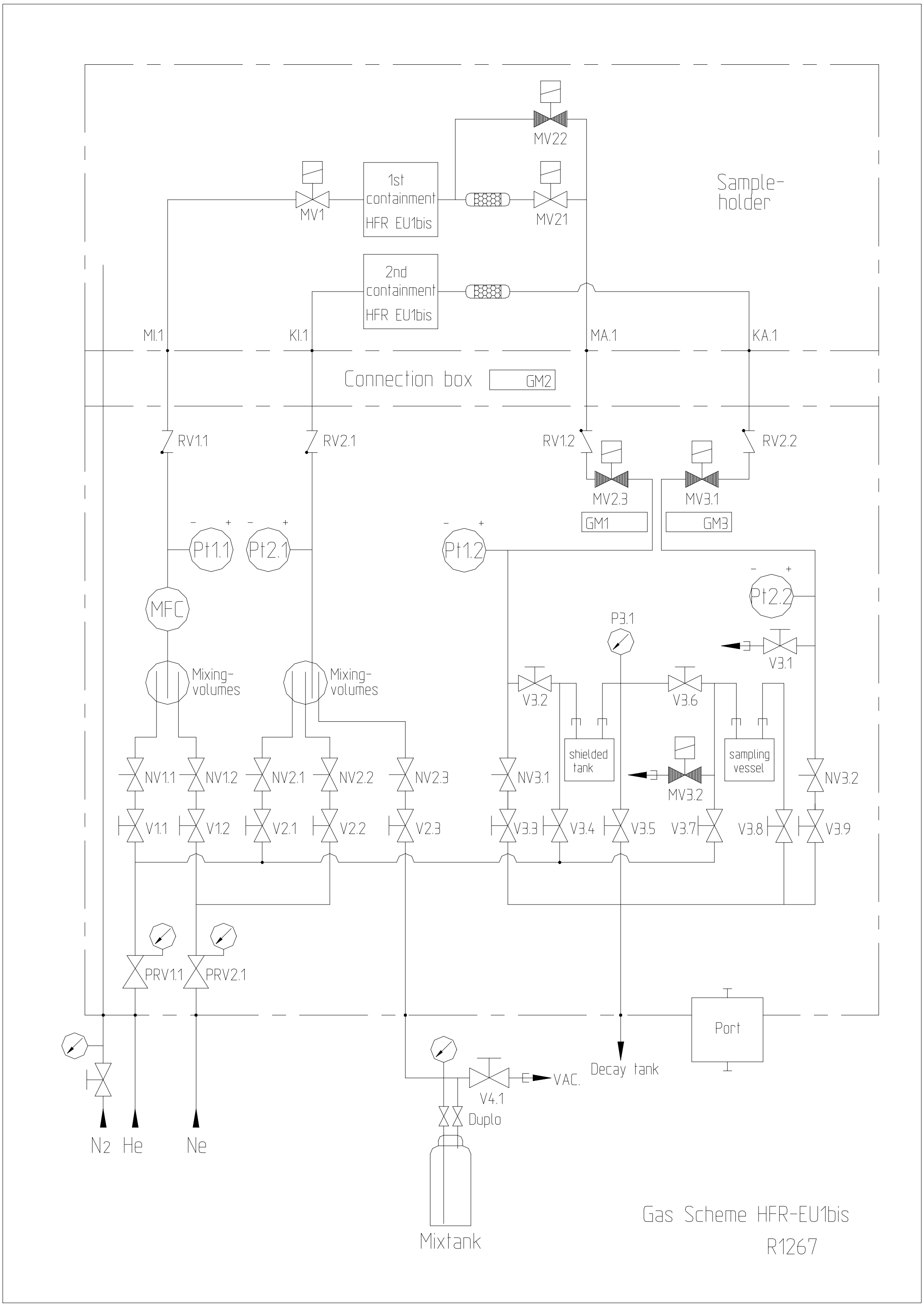

Figure 2: HFR-EU1bis gas panel with modifications

2 Nuclear Data

2.1 Fluxes, fluences and other data cycle 04-08

Cycle 04-08, position G3, **orientation North**, data from [2]

	flux start-up initial [10^{18} $m^{-2}s^{-1}$]	flux start-up equilibrium [10^{18} $m^{-2}s^{-1}$]	flux end of cycle [10^{18} $m^{-2}s^{-1}$]	fluence [10^{25} m^{-2}]
F_1 1)	0.651	0.662	0.666	0.143
F_2 1)	1.066	1.084	1.089	0.234
F_3 1)	1.345	1.369	1.384	0.297
F_4 1)	0.931	0.935	1.002	0.209
F_{Fe}	1.027	1.045	1.050	0.226
F_{Co}	0.799	0.805	0.851	0.179
$F_{E > 1\ MeV}$	0.819	0.833	0.838	0.180
$F_{E > 0.1\ MeV}$	1.622	1.649	1.657	0.357

1) energy groups with boundaries: $14.918\times10^6 – 1.353\times10^6 – 0.0674\times10^6$ – 0.683 – 0 eV

Table 1: Neutron fluxes and fluences cycle 04-08

full power days	24.97
dpa (stainless steel)	0.278
gamma heating in small graphite samples [W/g]	3.803 initial start-up 3.877 start-up equilibrium 4.039 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

Table 2: Nuclear characteristics for cycle 04-08

2.2 Fluxes, fluences and other data cycle 04-09

Cycle 04-09, position G3, **orientation South**, data from [3]

	flux start-up initial [10^{18} $m^{-2}s^{-1}$]	flux start-up equilibrium [10^{18} $m^{-2}s^{-1}$]	flux end of cycle [10^{18} $m^{-2}s^{-1}$]	fluence [10^{25} m^{-2}]
F_1 1)	0.649	0.657	0.658	0.140
F_2 1)	1.064	1.075	1.076	0.230
F_3 1)	1.346	1.362	1.371	0.292
F_4 1)	0.939	0.938	1.001	0.207
F_{Fe}	1.024	1.036	1.038	0.221
F_{Co}	0.804	0.806	0.849	0.177
$F_{E > 1 MeV}$	0.817	0.826	0.827	0.177
$F_{E > 0.1 MeV}$	1.618	1.636	1.637	0.350

1) energy groups with boundaries: $14.918\times10^6 – 1.353\times10^6 – 0.0674\times10^6 – 0.683 – 0$ eV

Table 3: Neutron fluxes and fluences cycle 04-09

full power days	24.72
dpa (stainless steel)	0.272
gamma heating in small graphite samples [W/g]	3.772 initial start-up 3.829 start-up equilibrium 3.982 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

Table 4: Nuclear characteristics for cycle 04-09

2.3 Fluxes, fluences and other data cycle 05-01

Cycle 05-01, position G3, **orientation North**, data from [4]

	flux start-up initial $[10^{18}\ m^{-2}s^{-1}]$	flux start-up equilibrium $[10^{18}\ m^{-2}s^{-1}]$	flux end of cycle $[10^{18}\ m^{-2}s^{-1}]$	fluence $[10^{25}\ m^{-2}]$
F_1 1)	0.748	0.759	0.740	0.168
F_2 1)	1.225	1.242	1.211	0.275
F_3 1)	1.512	1.536	1.511	0.342
F_4 1)	1.036	1.040	1.095	0.240
F_{Fe}	1.179	1.197	1.168	0.265
F_{Co}	0.891	0.897	0.930	0.205
$F_{E > 1\ MeV}$	0.941	0.955	0.931	0.212
$F_{E > 0.1\ MeV}$	1.863	1.890	1.843	0.419

1) energy groups with boundaries: $14.918\times10^6 - 1.353\times10^6 - 0.0674\times10^6 - 0.683 - 0$ eV

Table 5: Neutron fluxes and fluences cycle 05-01

full power days	25.99
dpa (stainless steel)	0.327
gamma heating in small graphite samples [W/g]	4.348 initial start-up 4.425 start-up equilibrium 4.480 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

Table 6: Nuclear characteristics for cycle 05-01

2.4 Fluxes, fluences and other data cycle 05-02

Cycle 05-02, position G3, **orientation South**, data from [5]

	flux start-up initial $[10^{18}\ m^{-2}s^{-1}]$	flux start-up equilibrium $[10^{18}\ m^{-2}s^{-1}]$	flux end of cycle $[10^{18}\ m^{-2}s^{-1}]$	fluence $[10^{25}\ m^{-2}]$
F_1 1)	0.739	0.749	0.736	0.165
F_2 1)	1.212	1.227	1.205	0.270
F_3 1)	1.496	1.518	1.503	0.335
F_4 1)	1.023	1.025	1.087	0.234
F_{Fe}	1.166	1.181	1.162	0.260
F_{Co}	0.880	0.885	0.924	0.201
$F_{E > 1\ MeV}$	0.930	0.942	0.926	0.207
$F_{E > 0.1\ MeV}$	1.843	1.866	1.834	0.410

1)energy groups with boundaries: $14.918\times10^6 – 1.353\times10^6 – 0.0674\times10^6 – 0.683 – 0$ eV

Table 7: Neutron fluxes and fluences cycle 05-02

full power days	25.67
dpa (stainless steel)	0.320
gamma heating in small graphite samples [W/g]	4.295 initial start-up 4.363 start-up equilibrium 4.450 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

1)energy groups with boundaries: $14.918\times10^6 – 1.353\times10^6 – 0.0674\times10^6 – 0.683 – 0$ eV

Table 8: Nuclear characteristics for cycle 05-02

2.5 Analysis of nuclear data

From Table 1 through Table 8 the following can be concluded:

The end-of-cycle neutron flux varied between the four cycles by about 12% for the two high-energy groups and by about 10% for the two low-energy groups. Note that the increase in F_4 must have caused an almost proportional increase in fission power.

Cycle	F_1 [1)]	F_2	F_3	F_4	$Fluence_4$	$Fluence_{E>0.1\,MeV}$
	$[10^{18}\,m^{-2}s^{-1}]$				$[10^{25}\,m^{-2}]$	
04-08	0.666	1.089	1.384	1.002	0.209	0.357
04-09	0.658	1.076	1.371	1.001	0.207	0.35
05-01	0.74	1.211	1.511	1.095	0.24	0.419
05-02	0.736	1.205	1.503	1.087	0.234	0.41
variation	12.46%	12.55%	10.21%	9.39%	15.94%	19.71%

[1)] energy groups with boundaries: $14.918\times10^{6} - 1.353\times10^{6} - 0.0674\times10^{6} - 0.683 - 0$ eV

Table 9: Comparison of fluxes and fluences

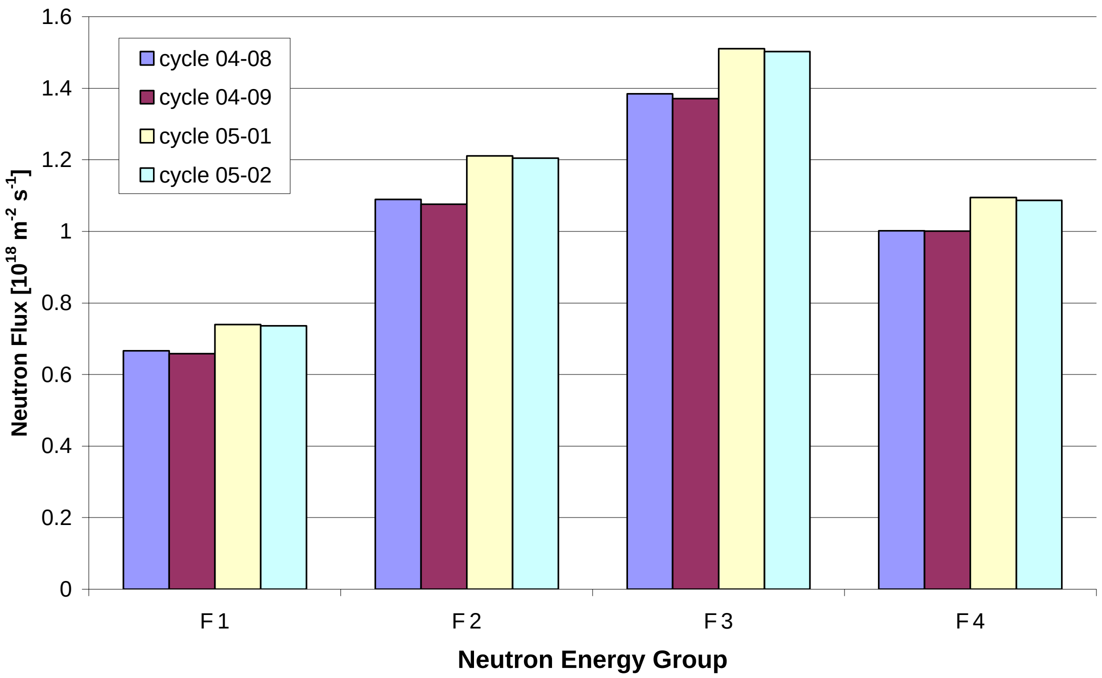

Figure 3: Comparison of neutron fluxes in the four cycles

Since cycle 05-01 the thermal fluence Φ_4 increased by about 16%, the fast fluence (E > 0.1 MeV) by almost 20%. A fraction of 4% points of these fluence figures is due to the extension of the cycle duration from 25 to 26 days since cycle 05-01.

3 Reactor Power and Control Rod Positions

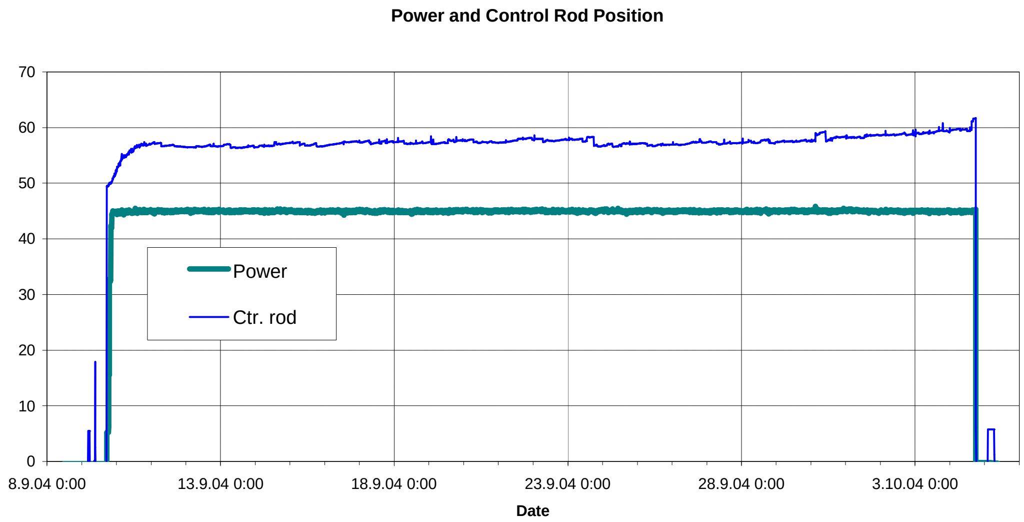

Figure 4: Reactor Power/Control Rod position cycle 04-08

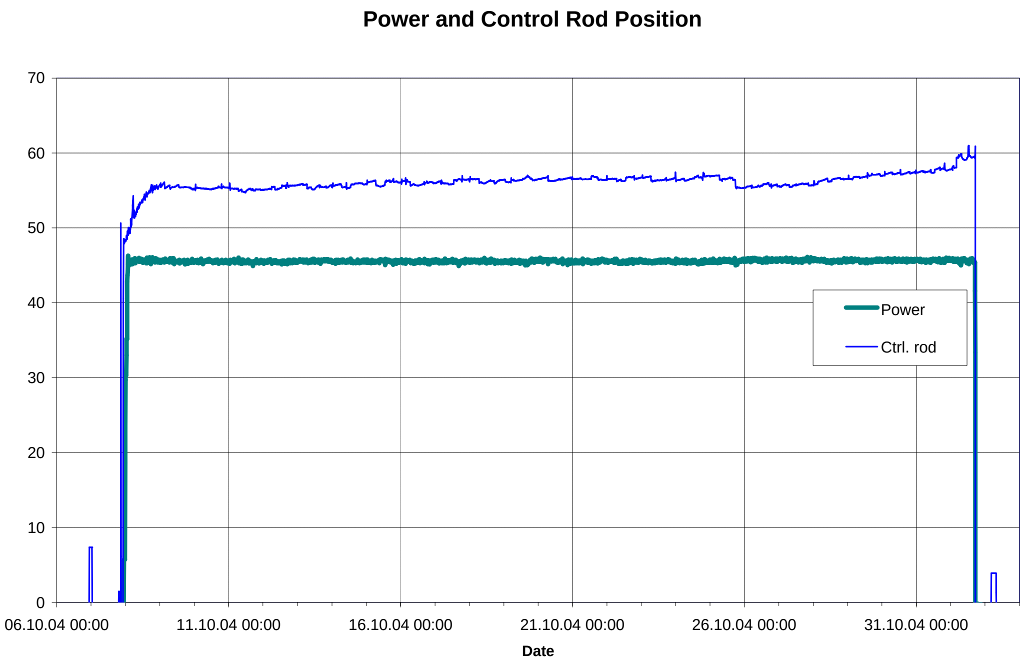

Figure 5: Reactor Power/Control Rod position cycle 04-09

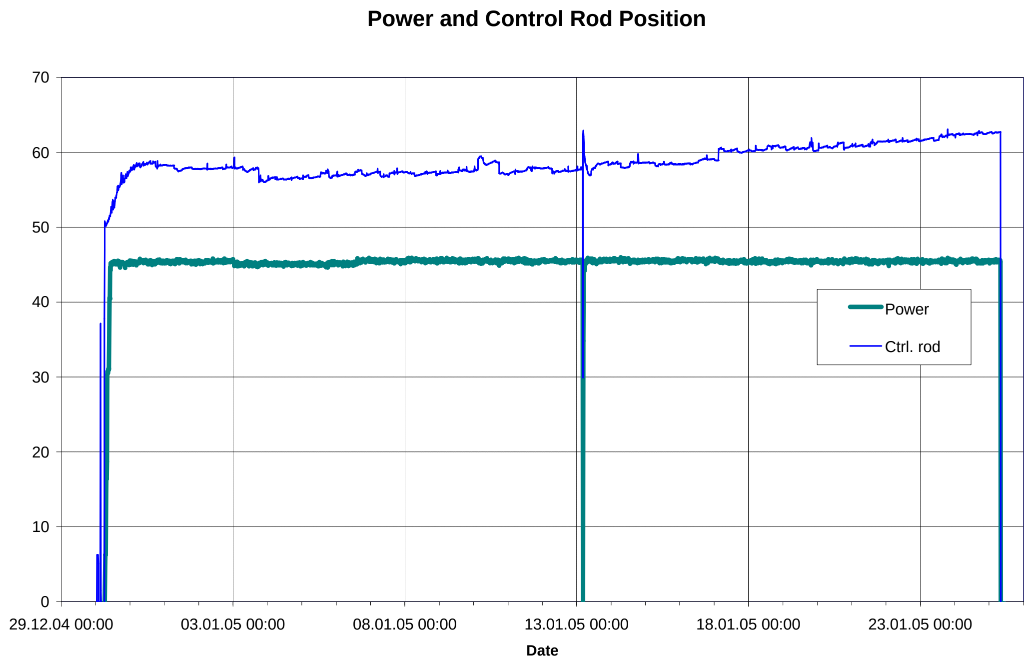

Figure 6: Reactor Power/Control Rod position cycle 05-01

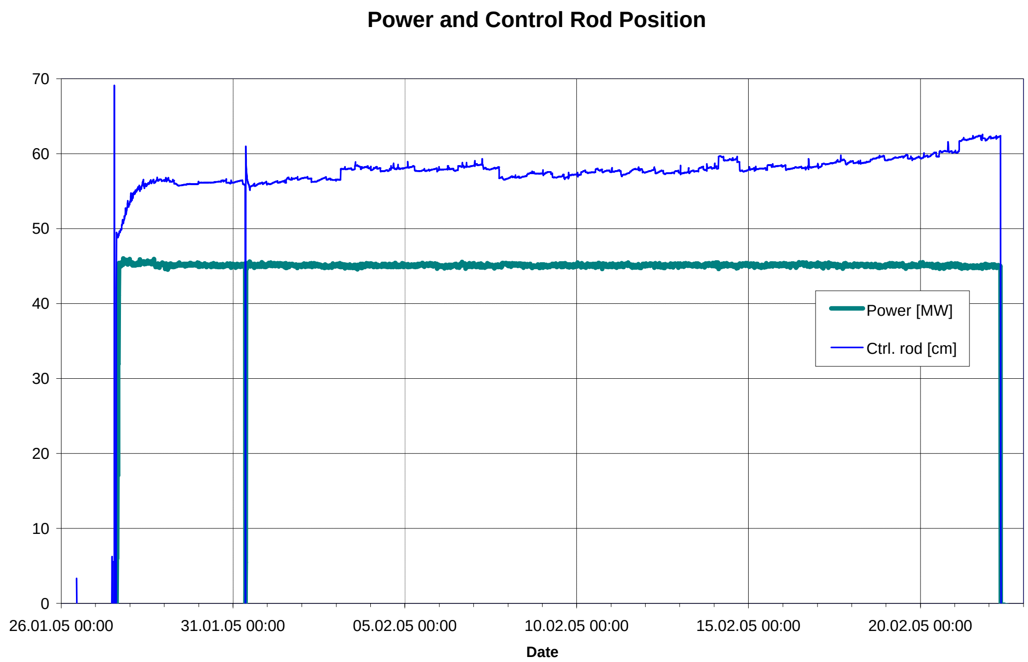

Figure 7: Reactor Power/Control Rod position cycle 05-02

4 Vertical Displacement Unit (VDU) Position

The VDU was not used since the beginning of the irradiation and was held in the lowest possible position. The very small measured differences are artifacts related to the data acquisition system.

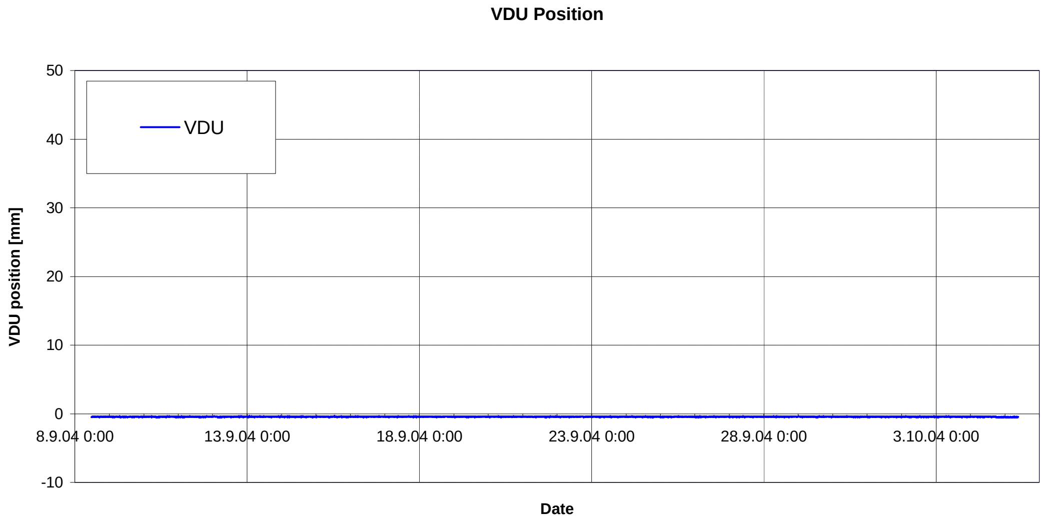

Figure 8: VDU position cycle 04-08

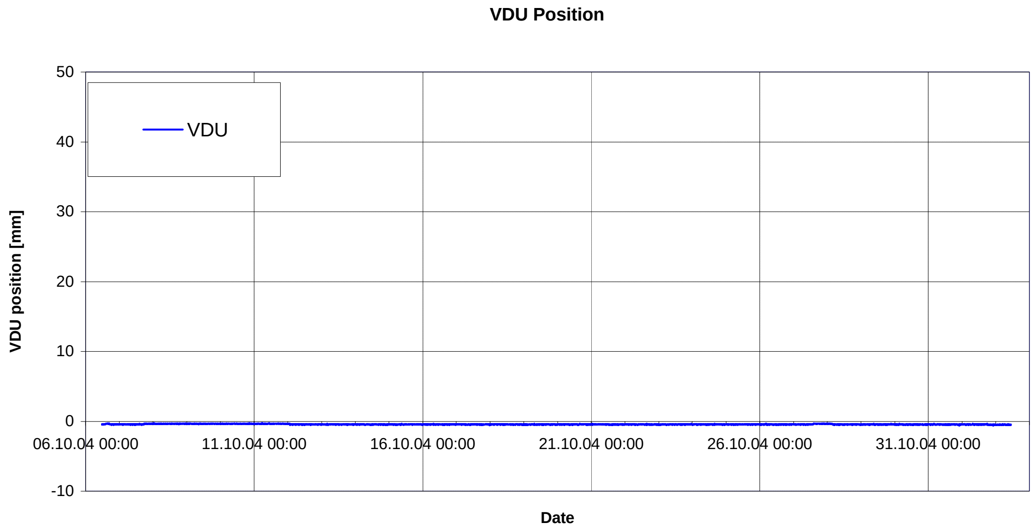

Figure 9: VDU position cycle 04-09

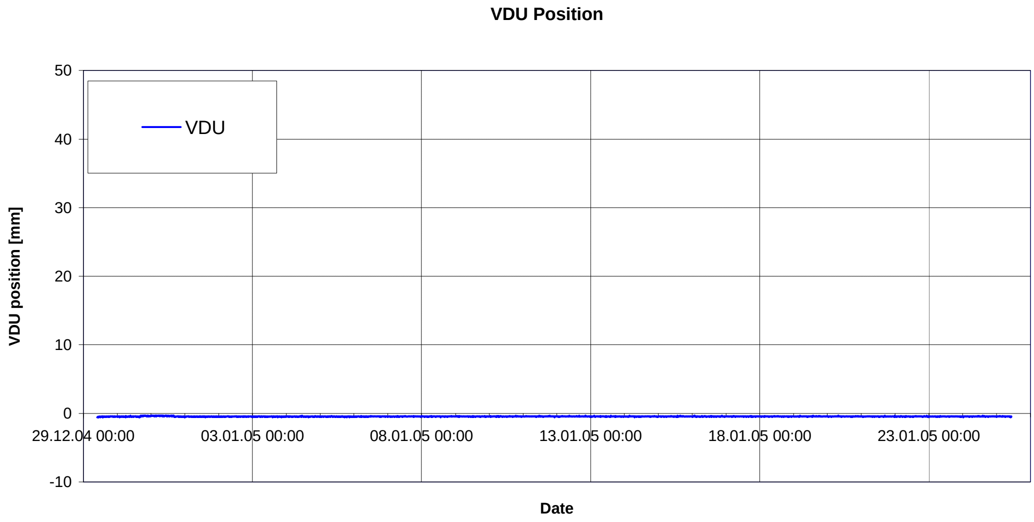

Figure 10: VDU position cycle 05-01

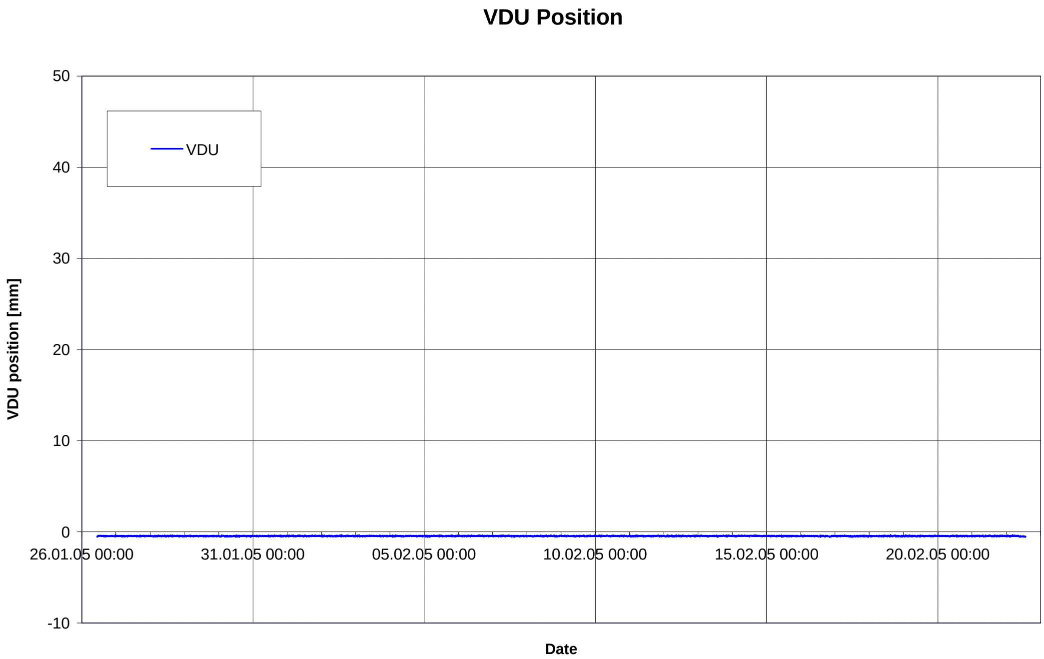

Figure 11: VDU position cycle 05-02

5 Counter Readings in Gas Panel (GM1 and GM3)

The Geiger-Müller counter readings of the two counters in the gas panel (GM1 and GM3) are at background level when the gas is stagnant. Higher activities are only measured during purging, generally before taking a gas sample. Only GM1 was installed during cycles 04-08 and 04-09. The counters were not connected to DACOS during cycle 05-01. The change of the apparent background level is due to the exchange of the equipment after cycle 04-09 in the frame of the gas panel modifications.

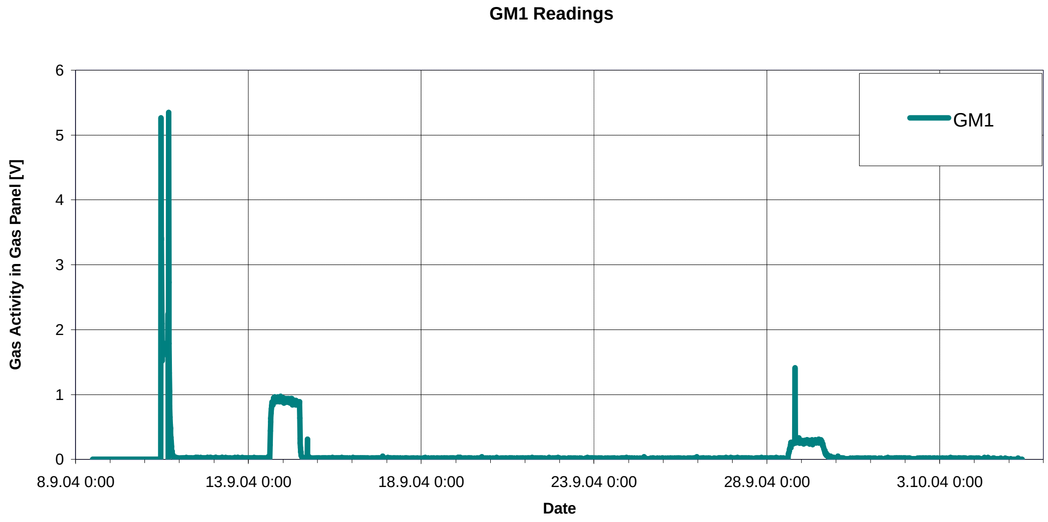

Figure 12: GM1 readings cycle 04-08

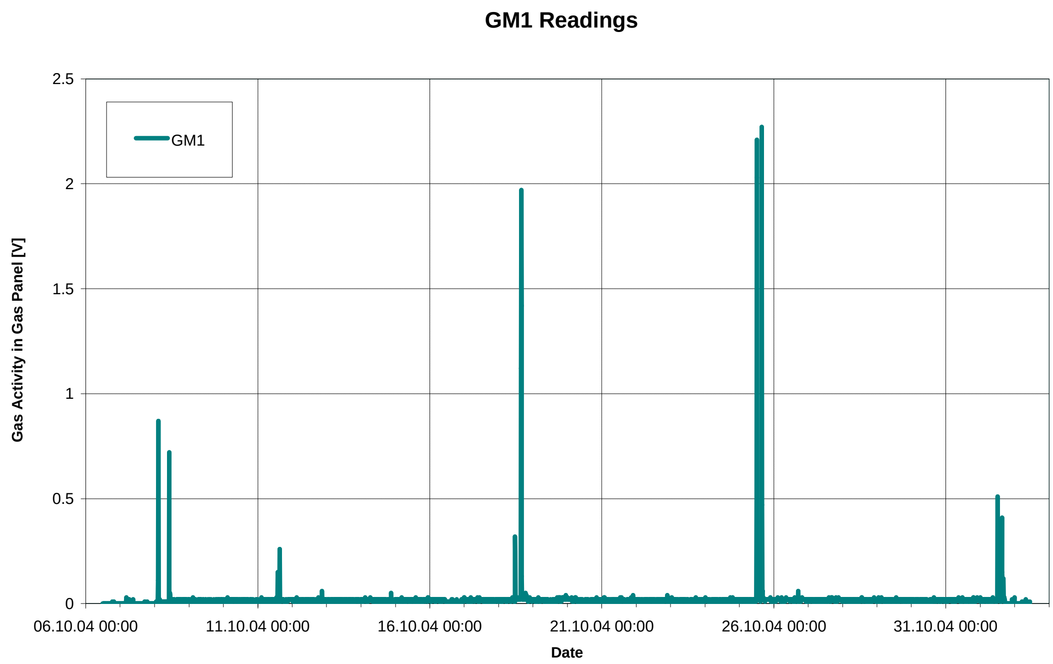

Figure 13: GM1 readings cycle 04-09

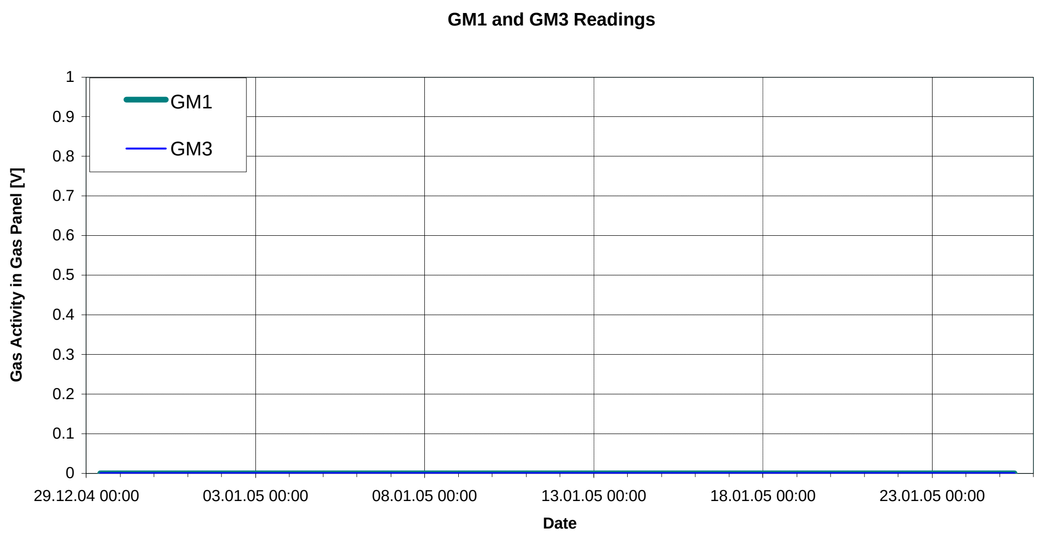

Figure 14: GM1 and GM3 readings cycle 05-01

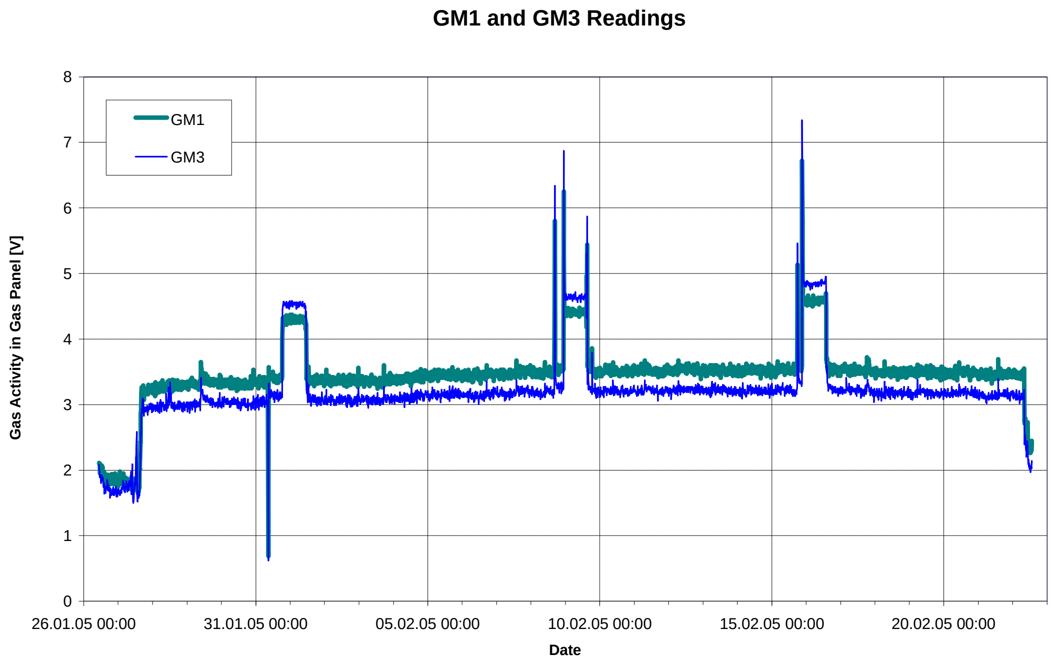

Figure 15: GM1 and GM3 readings cycle 05-02

6 Temperature Measurements

After 4 cycles, **5** out of 24 thermocouples give no or wrong information, only one of those failed (TC-09) has no backup.

Location	TC #	
1 Graphite	**1**, 2, 3	TC-01 no contact since 29.12.2004
GLE4.1	4, 5, 6	
Graphite between GLE4.1 and GLE4.2	7, 8	TC-08 sometimes erratic values since beginning
GLE4.2	**9**	TC-09 erroneous value since 29.12.2004
Graphite between GLE4.2 and GLE4.3	10, 11	
GLE4.3	**12**, 13	TC-12 too low since beginning
Graphite between GLE4.3 and GLE4.4	14, **15**	TC-15 slipped? values too low since 17.02.2005
GLE4.4	16	
Graphite between GLE4.4 and GLE4.5	17, 18	
GLE4.5	19, 20, 21	
Graphite between GLE4.5 and Al block	**22**, 23	TC-22 no contact since 29.12.2004
Aluminum Block	24	

Table 10: Location of thermocouples, malfunction is indicated in **bold red**

Table 11 shows the calculated surface temperatures of the 5 pebbles that would keep their central temperatures constant at 1250°C [1].

	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	3948	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 11: Predicted power and temperature evolution per pebble and required gas mixture per cycle; *: cycles 13 and 14 require pure N_2 in 1^{st} containment

6.1 Temperatures during Cycle 04-08

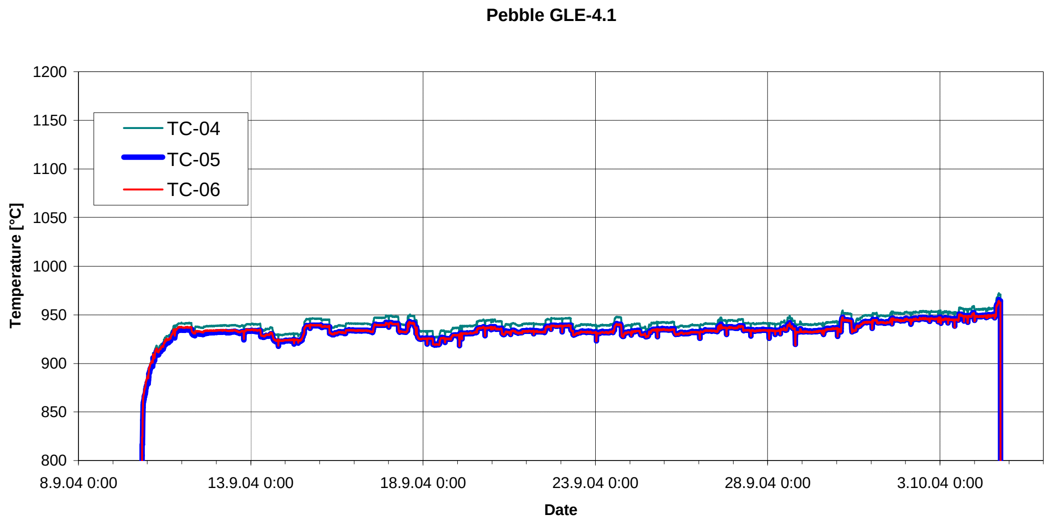

Figure 16: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

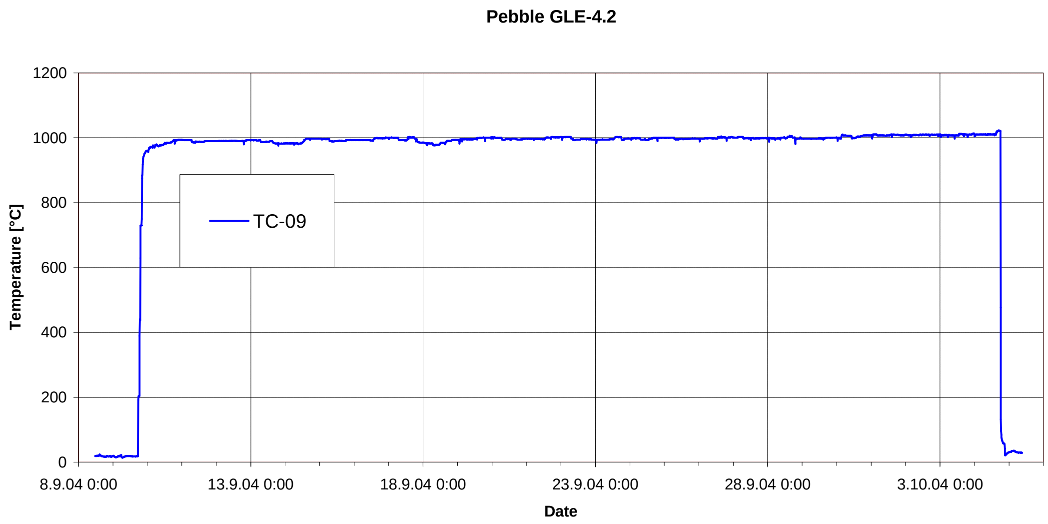

Figure 17: Temperature pebble GLE4.2 (TC-09)

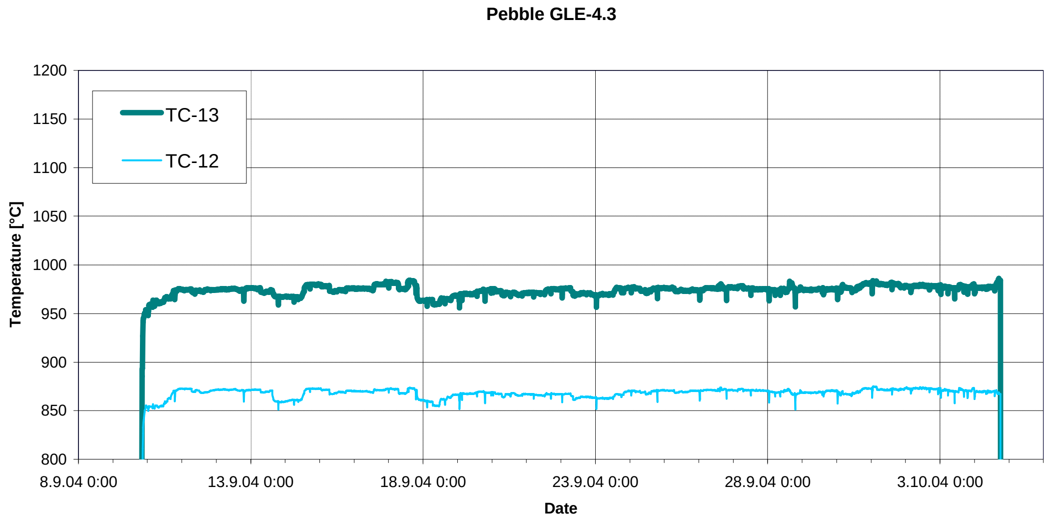

Figure 18: Temperatures pebble GLE4.3 (TC-12, TC-13)

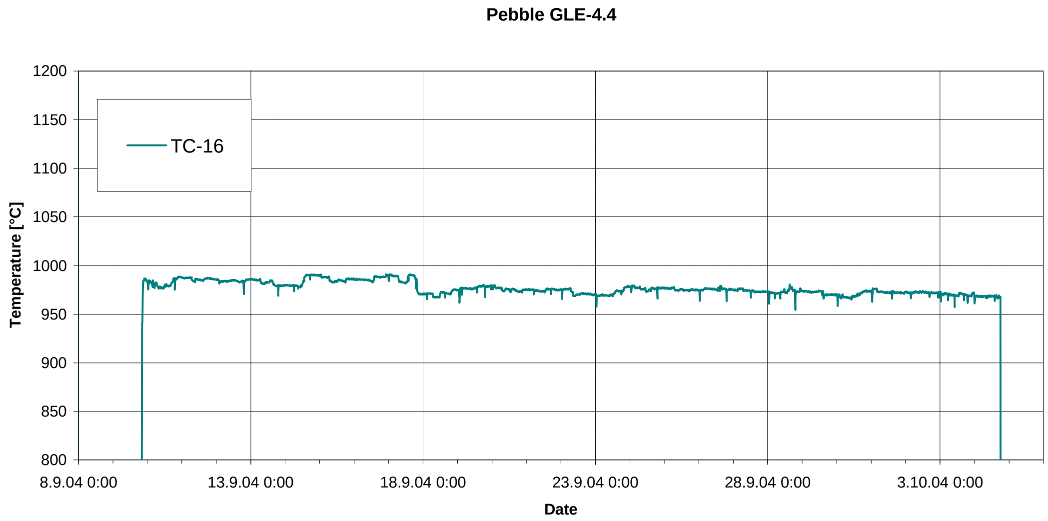

Figure 19: Temperature pebble GLE4.4 (TC-16)

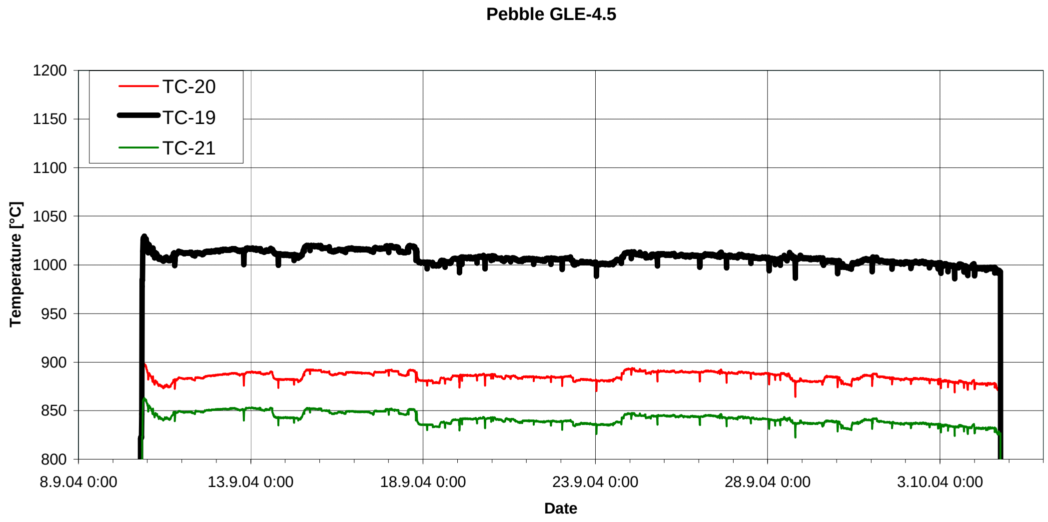

Figure 20: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

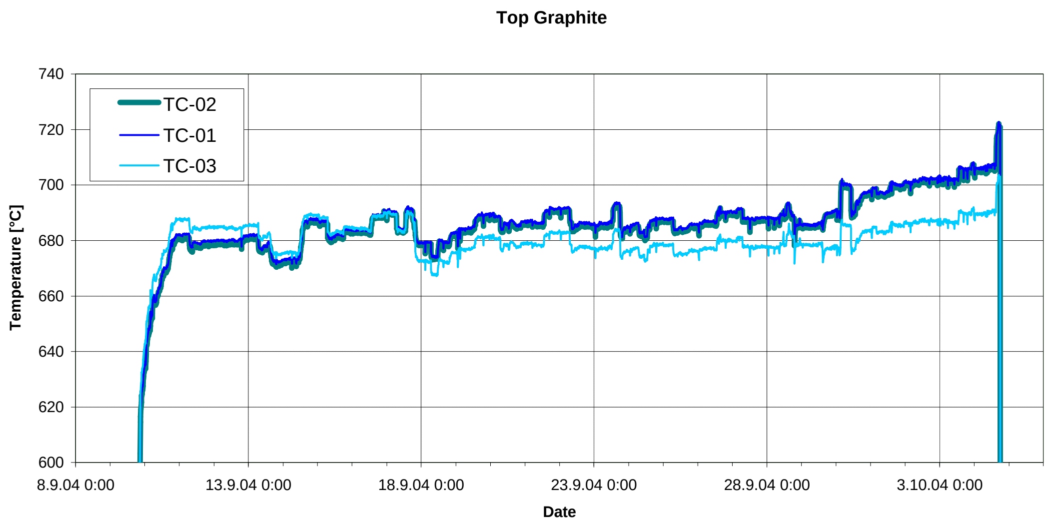

Figure 21: Temperatures top graphite (TC-01, TC-02, TC-03)

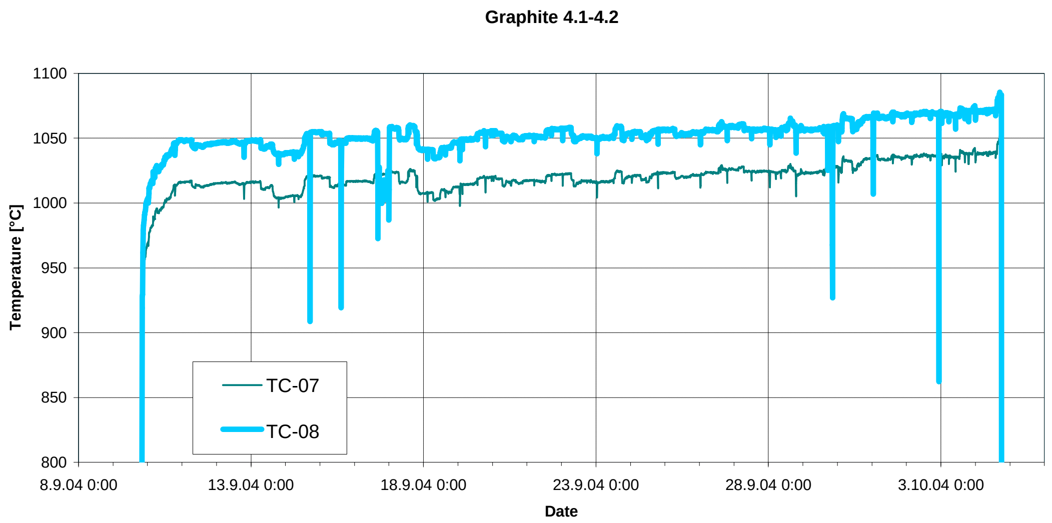

Figure 22: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

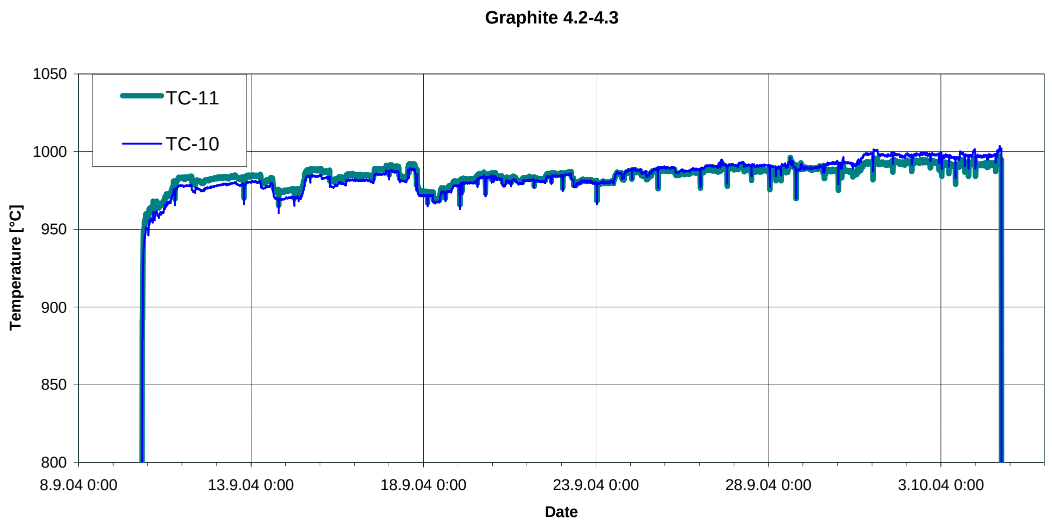

Figure 23: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

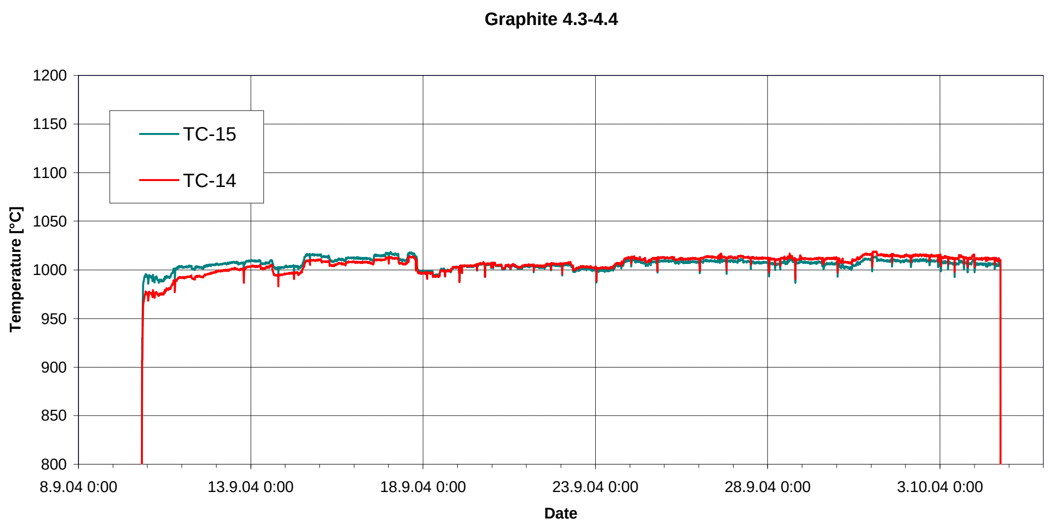

Figure 24: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

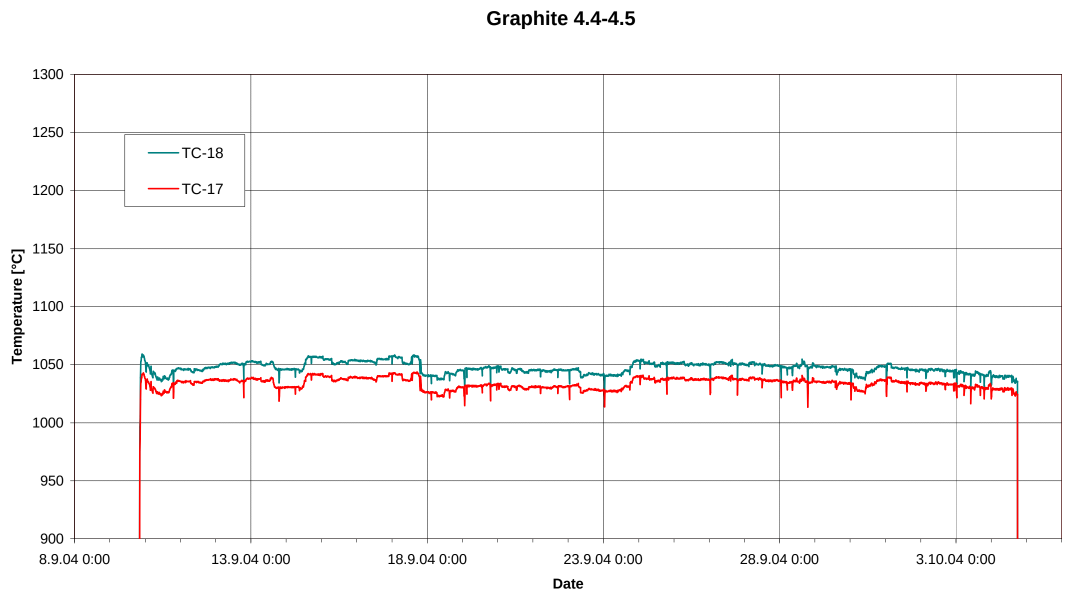

Figure 25: Temperatures graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

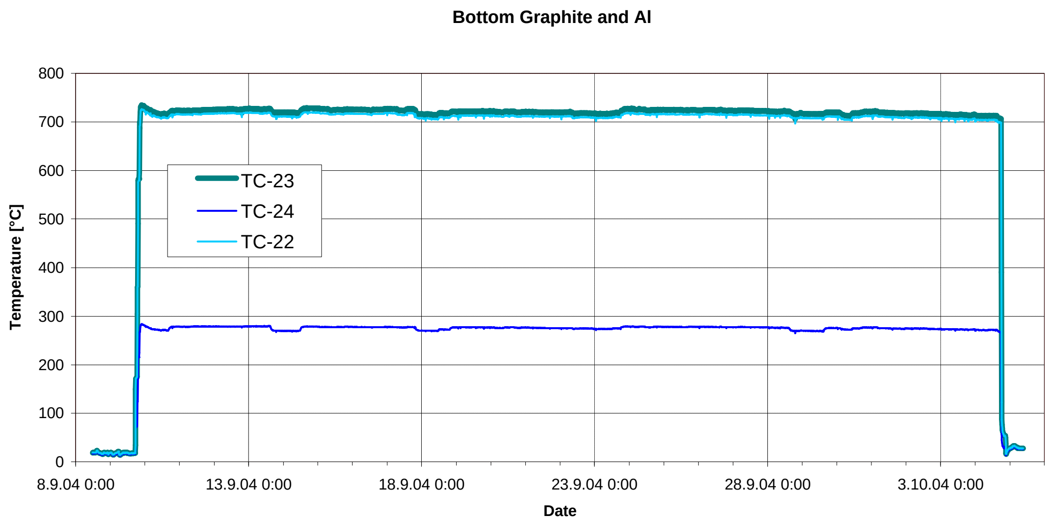

Figure 26: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
TC-01	687.0	687.0		Graphite
TC-02	686.0	686.0		
TC-03	680.7	680.7		
TC-04	941.3	941.3	1014	GLE4.1
TC-05	934.3	934.3		
TC-06	934.4	934.4		
TC-07	1020.3	1020.3		Graphite
TC-08	1052.5	1052.5		
TC-09	996.7	996.7	1016	GLE4.2
TC-10	984.7	984.7		Graphite
TC-11	984.9	984.9		
TC-12	868.2	868.2	1009	GLE4.3
TC-13	973.8	973.8		
TC-14	1006.0	1006.0		Graphite
TC-15	1006.1	1006.1		
TC-16	976.7	976.7	1015	GLE4.4
TC-17	1033.9	1033.9		Graphite
TC-18	1047.2	1047.2		
TC-19	1007.8	1007.8	1006	GLE4.5
TC-20	885.0	885.0		
TC-21	842.1	842.1		
TC-22	712.4	712.4		Graphite
TC-23	721.1	721.1		
TC-24	275.5	275.5		Al block

Table 12: Time averaged temperature readings during cycle 04-08

6.2 Temperatures during Cycle 04-09

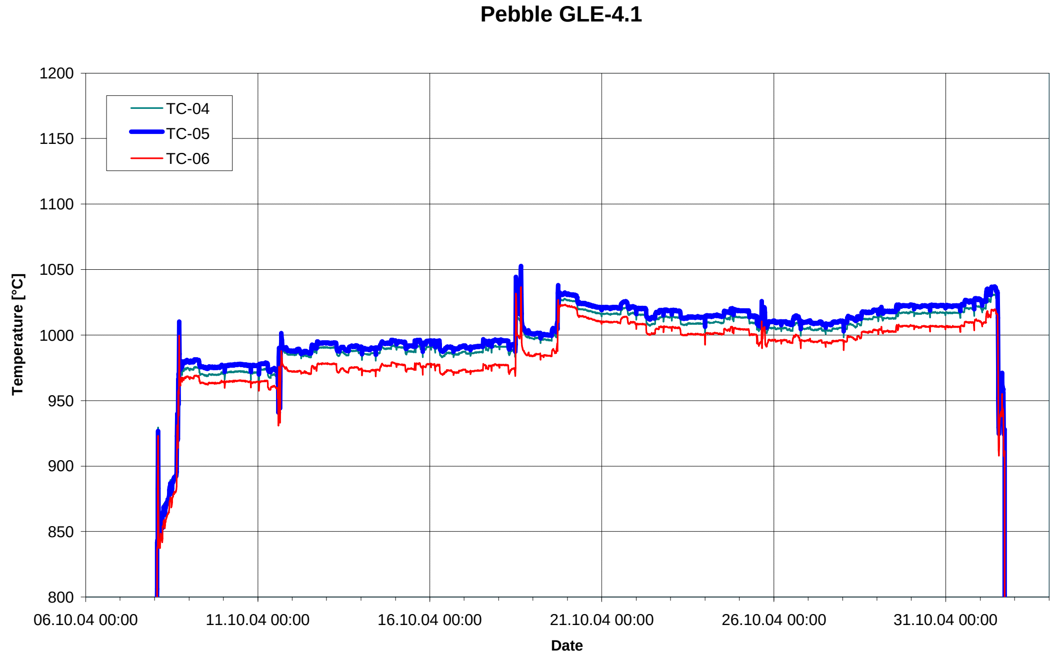

Figure 27: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

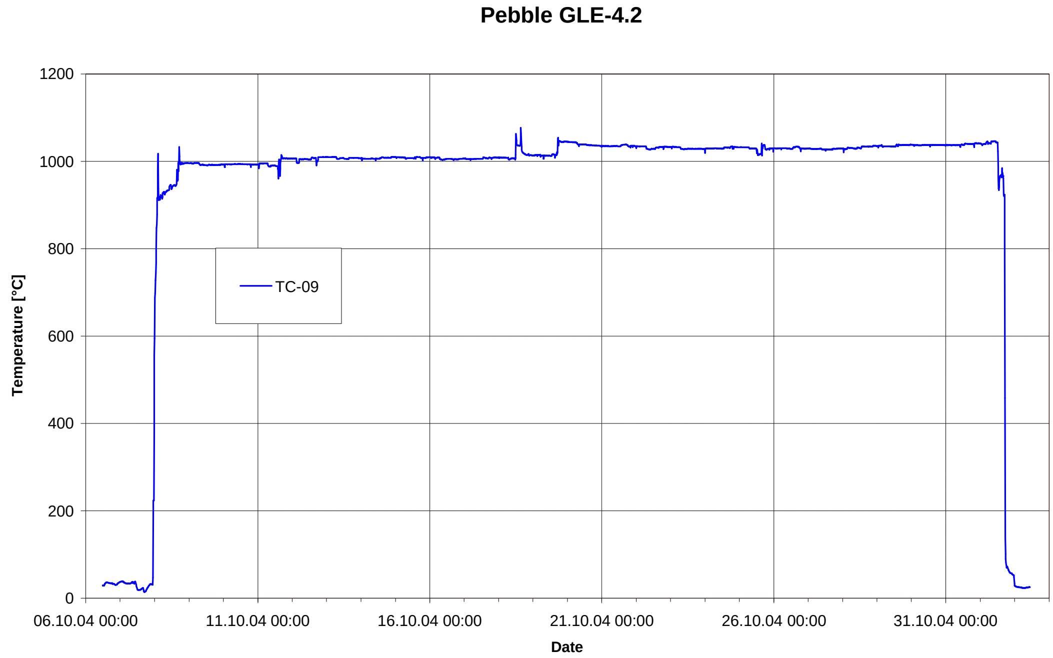

Figure 28: Temperature pebble GLE4.2 (TC-09)

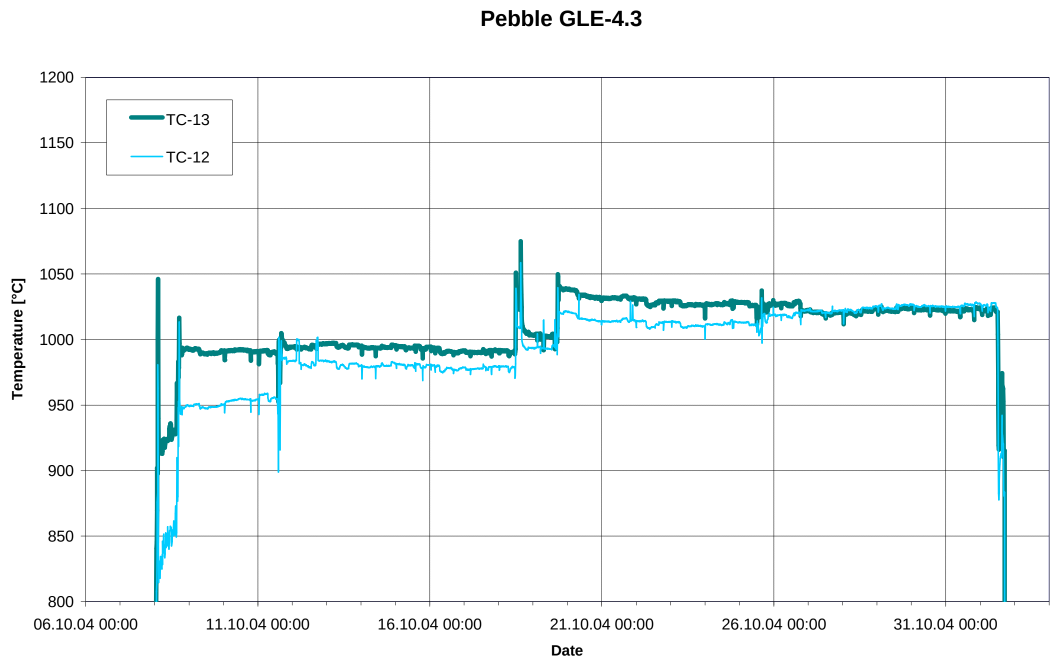

Figure 29: Temperatures pebble GLE4.3 (TC-12, TC-13)

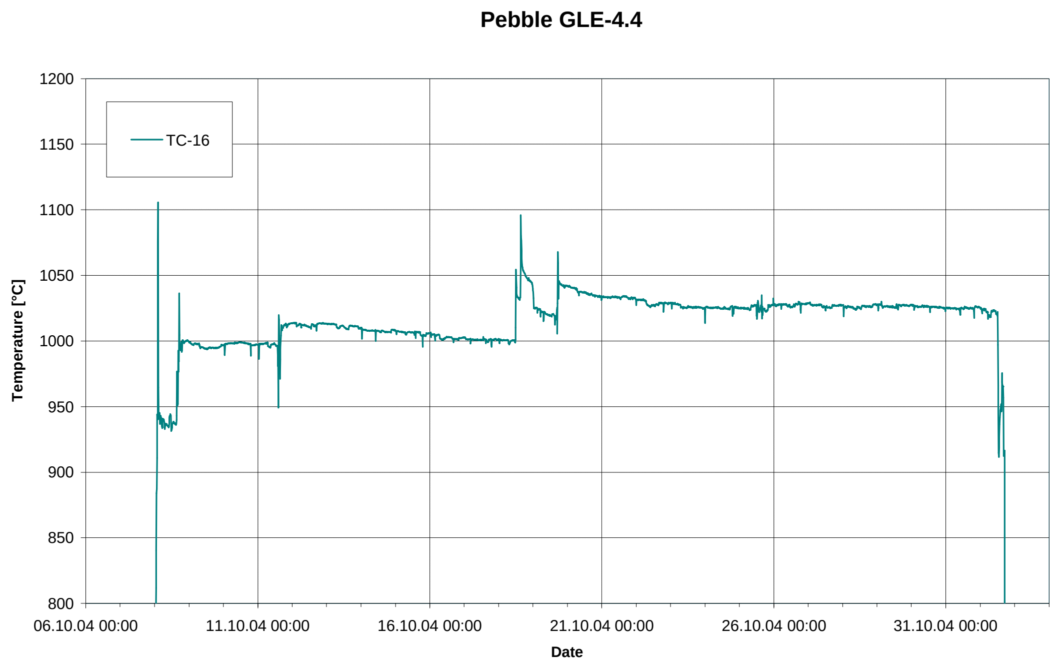

Figure 30: Temperature pebble GLE4.4 (TC-16)

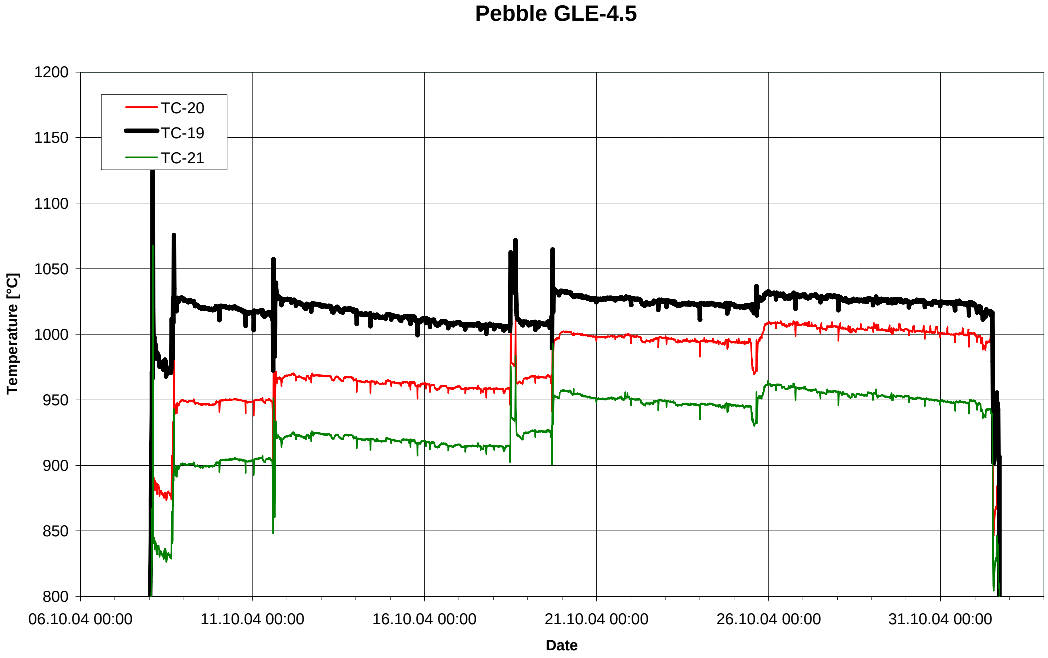

Figure 31: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

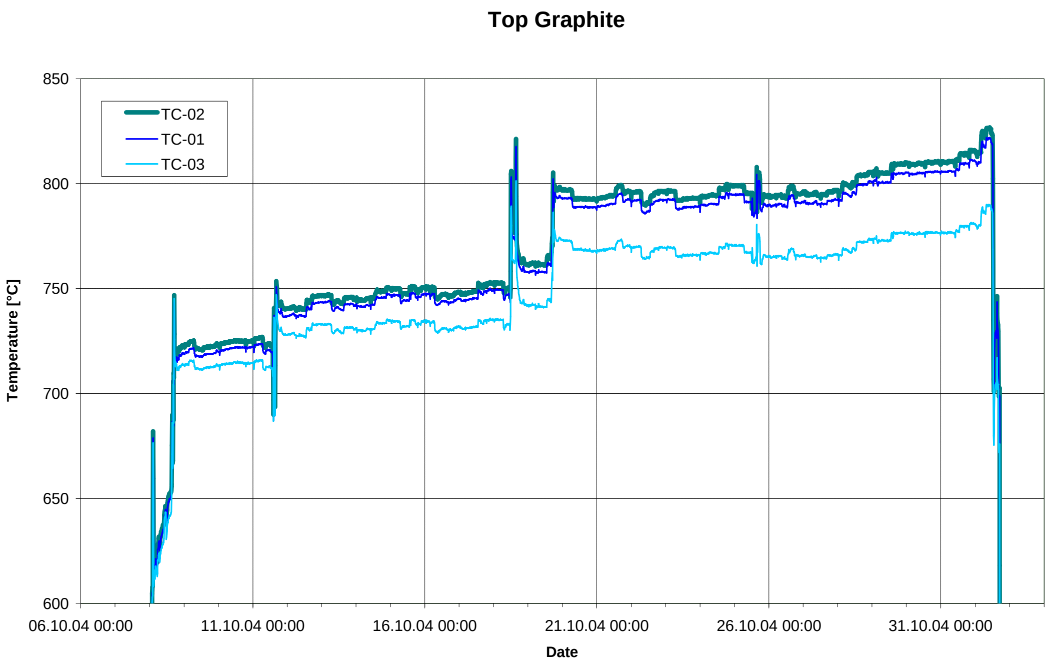

Figure 32: Temperatures top graphite (TC-01, TC-02, TC-03)

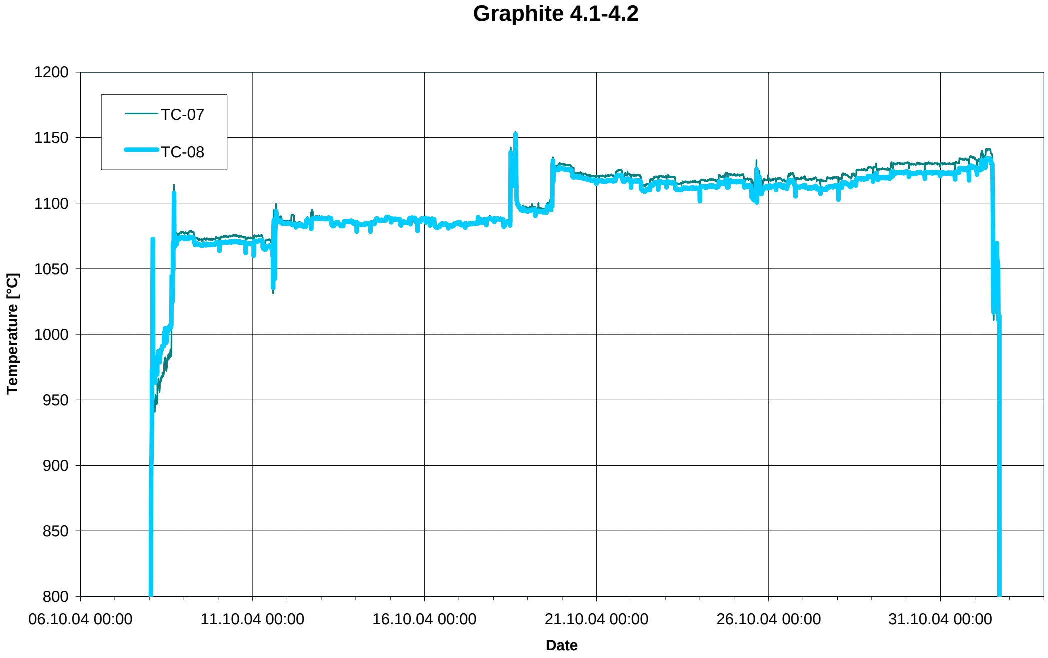

Figure 33: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

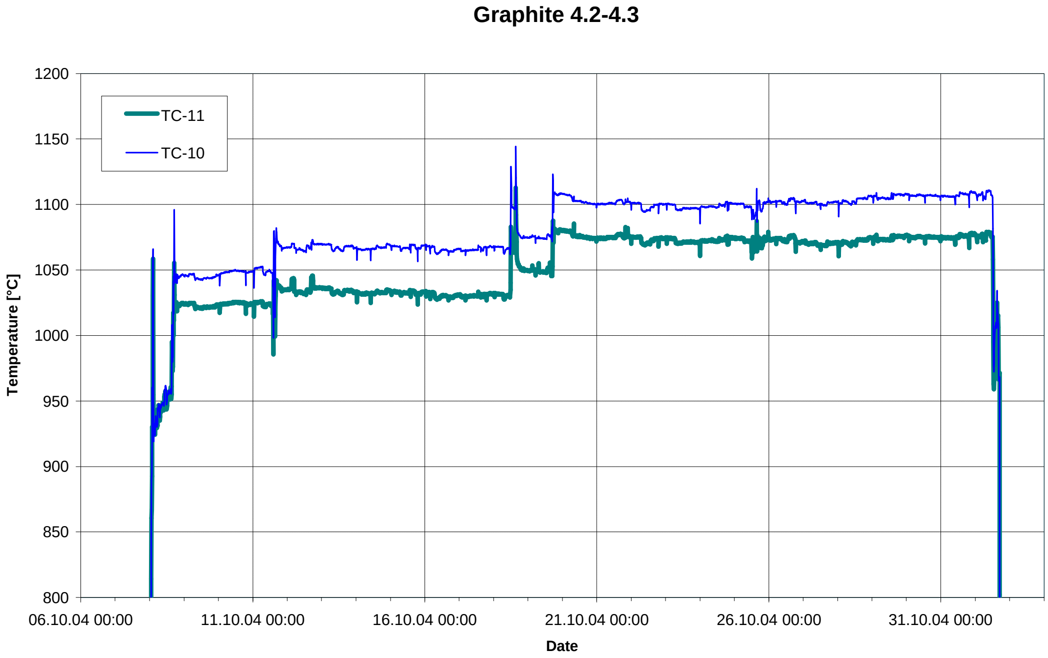

Figure 34: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

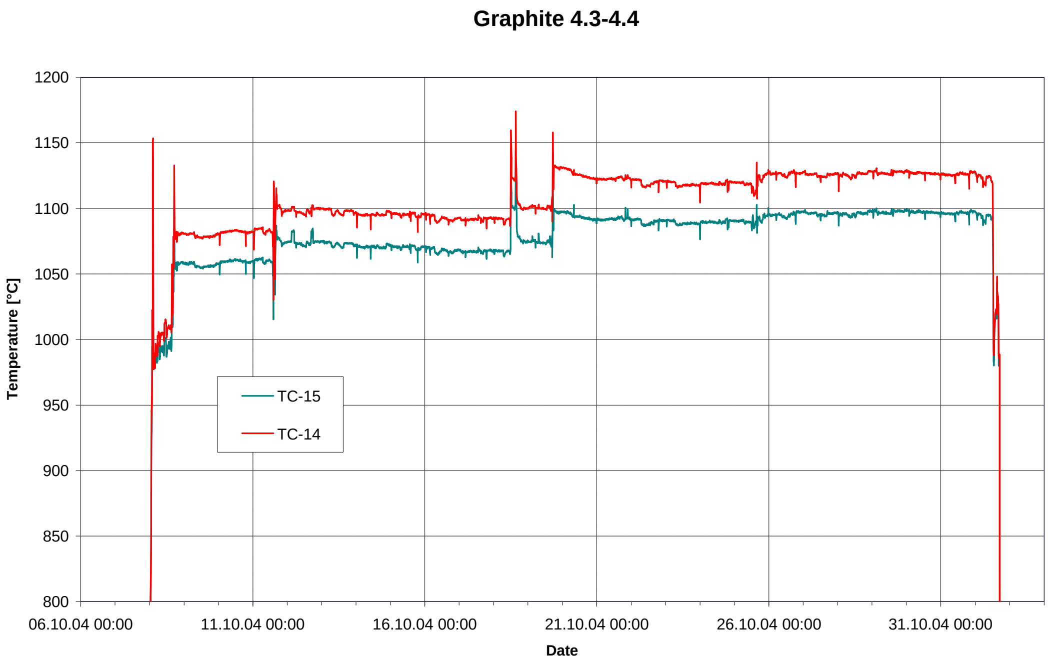

Figure 35: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

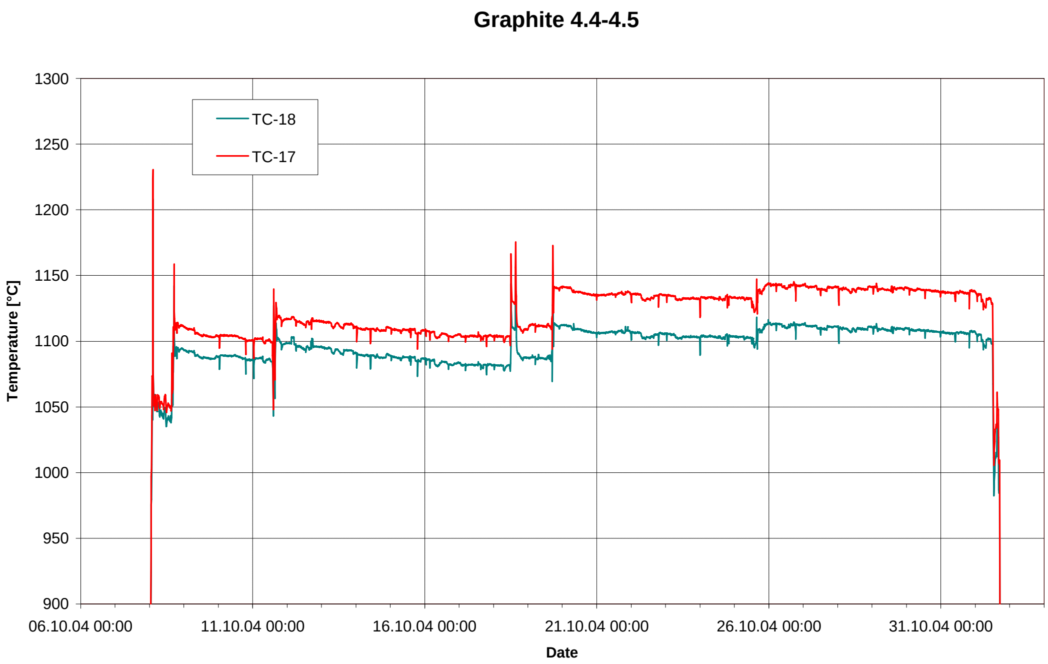

Figure 36: Temperatures graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

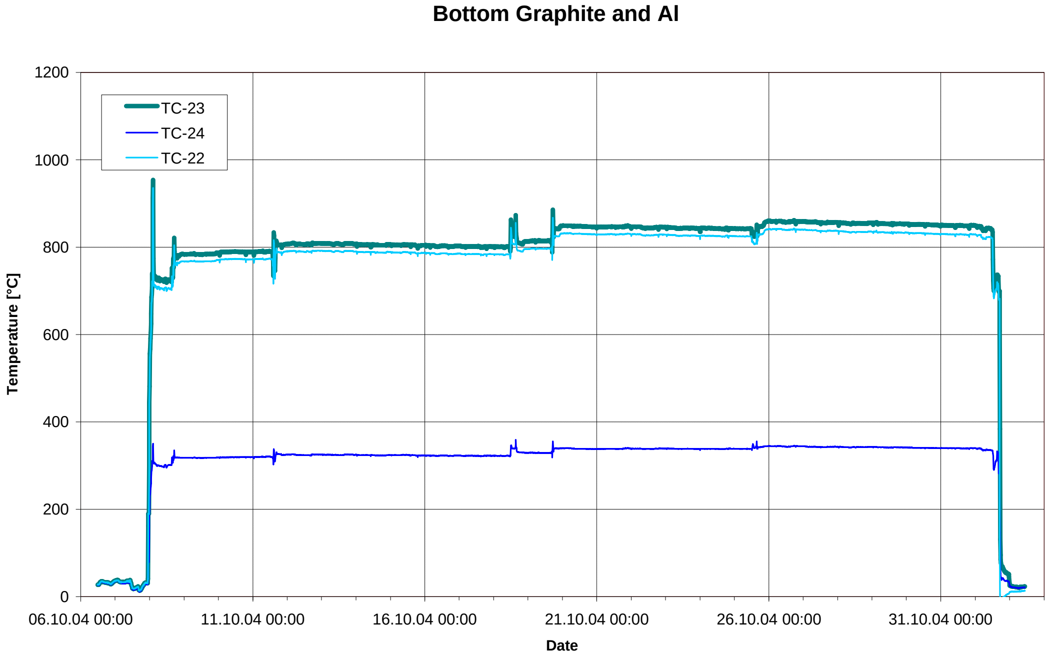

Figure 37: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
TC-01	766.2	769.6		Graphite
TC-02	769.9	773.4		
TC-03	748.1	751.2		
TC-04	997.0	1000.2	1026	GLE4.1
TC-05	1001.5	1004.8		
TC-06	986.9	990.1		
TC-07	1101.9	1105.3		Graphite
TC-08	1098.7	1101.5		
TC-09	1017.8	1020.0	1031	GLE4.2
TC-10	1080.7	1084.1		Graphite
TC-11	1051.8	1054.6		
TC-12	994.4	998.2	1024	GLE4.3
TC-13	1009.0	1011.2		
TC-14	1106.6	1109.2		Graphite
TC-15	1079.7	1081.9		
TC-16	1016.2	1018.1	1030	GLE4.4
TC-17	1121.9	1123.6		Graphite
TC-18	1097.3	1098.6		
TC-19	1020.0	1021.0	1020	GLE4.5
TC-20	978.7	981.2		
TC-21	932.0	934.4		
TC-22	806.4	808.9		Graphite
TC-23	824.2	826.7		
TC-24	331.6	332.3		Al block

Table 13: Time averaged temperature readings during cycle 04-09

6.3 Temperatures during Cycle 05-01

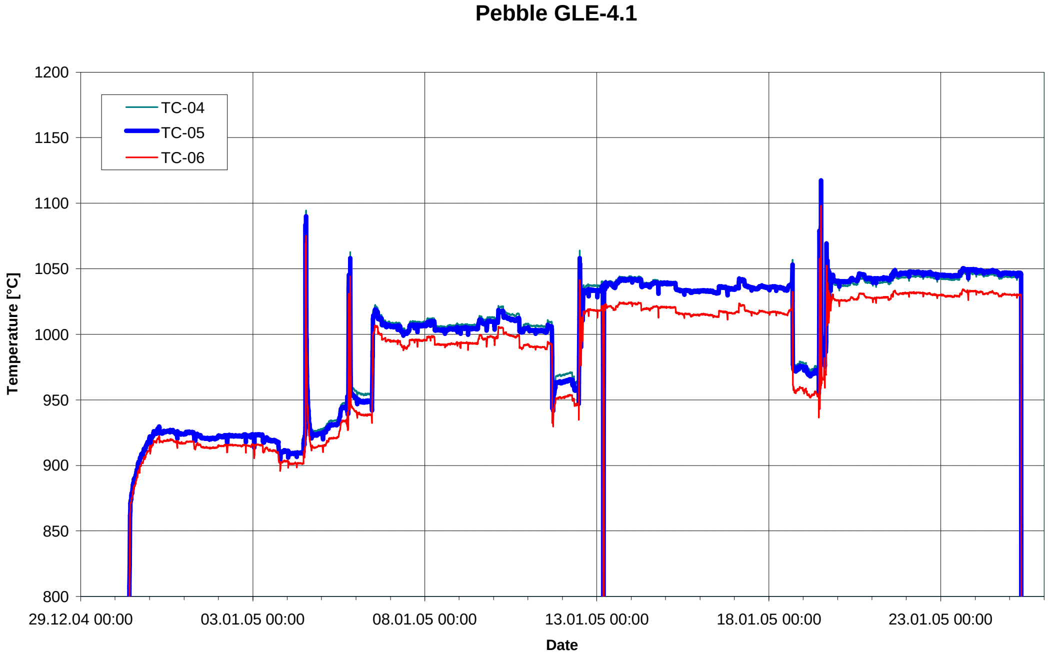

Figure 38: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

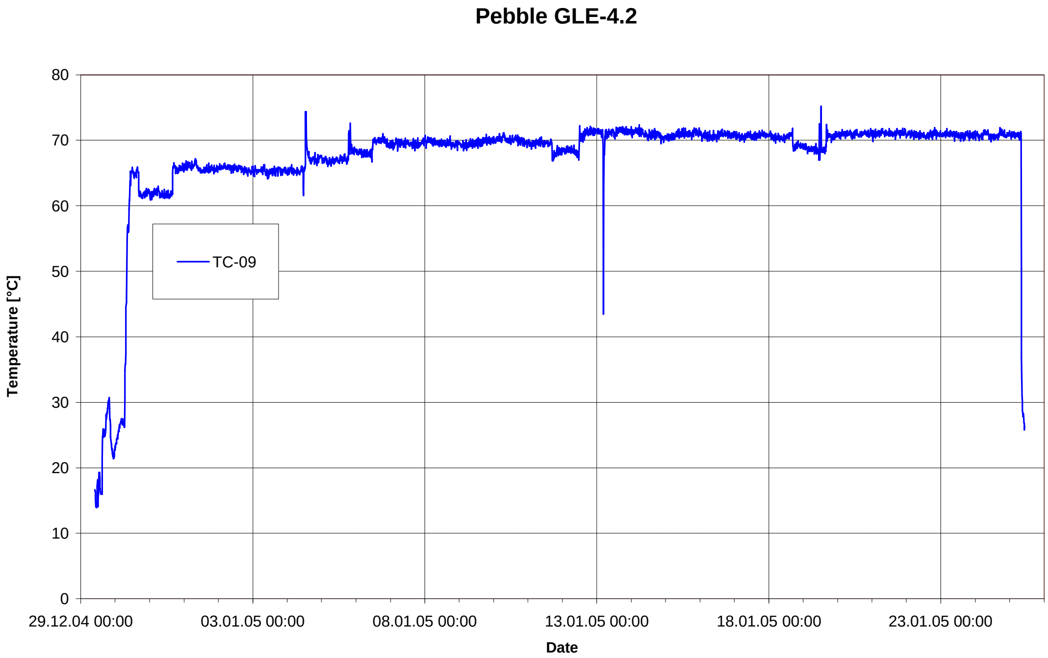

Figure 39: Temperature pebble GLE4.2 (TC-09)

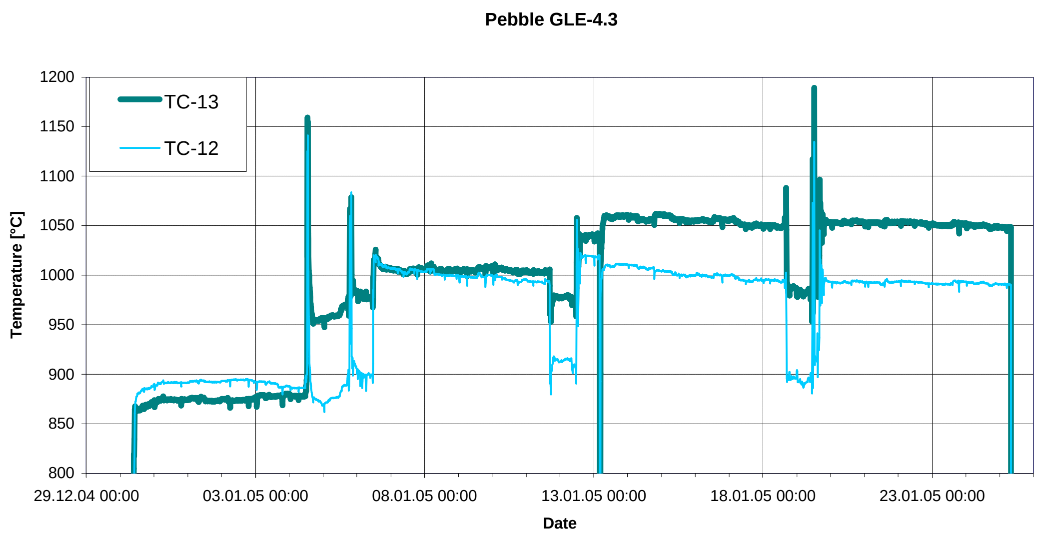

Figure 40: Temperatures pebble GLE4.3 (TC-12, TC-13)

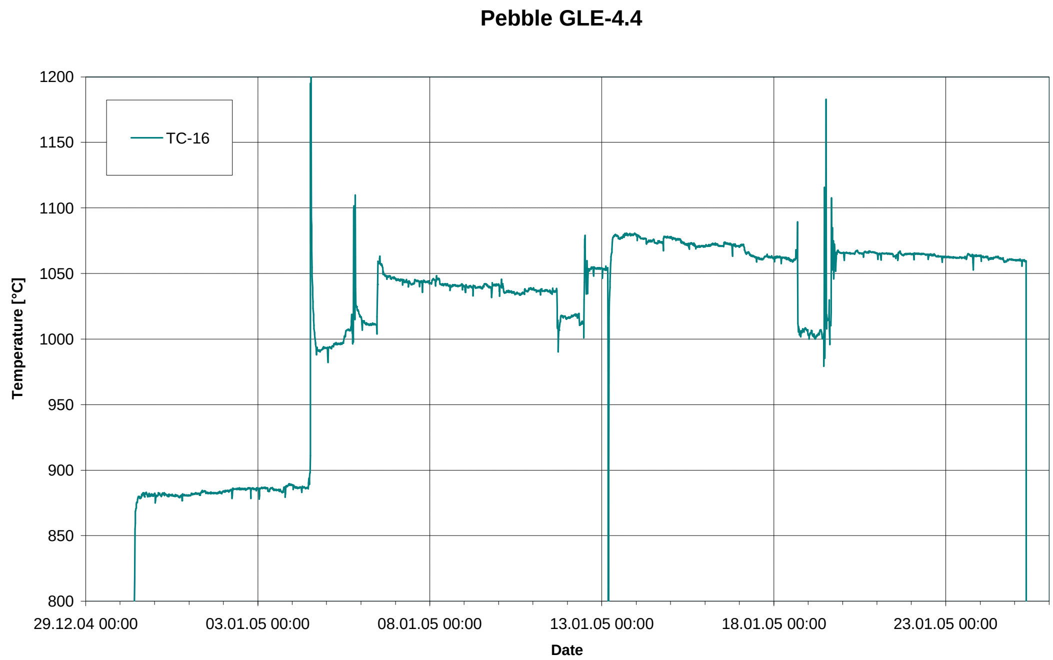

Figure 41: Temperature pebble GLE4.4 (TC-16)

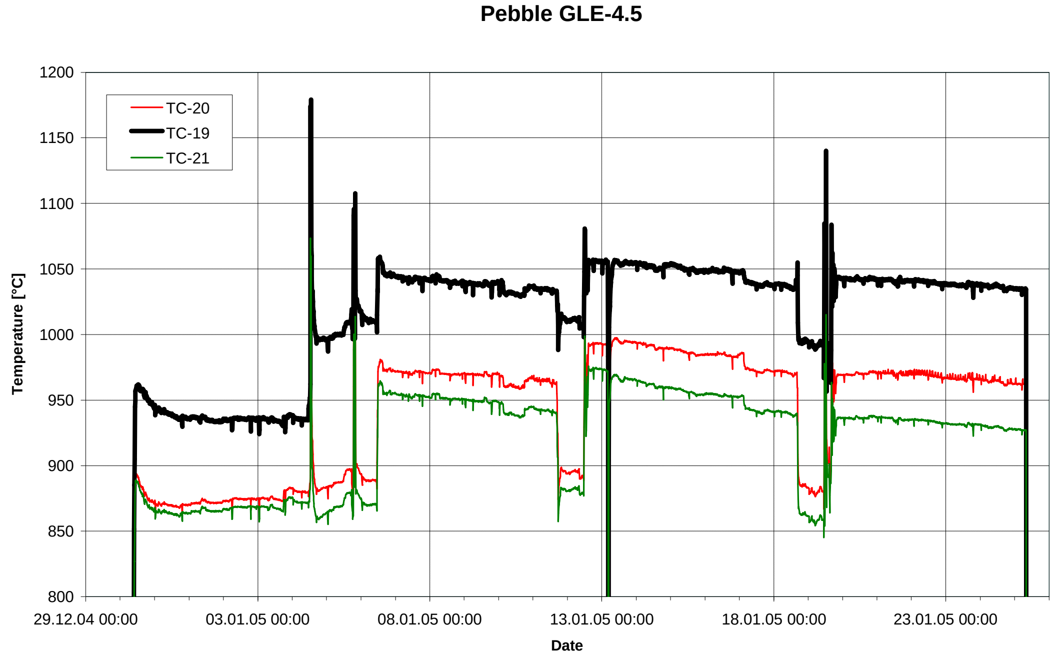

Figure 42: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

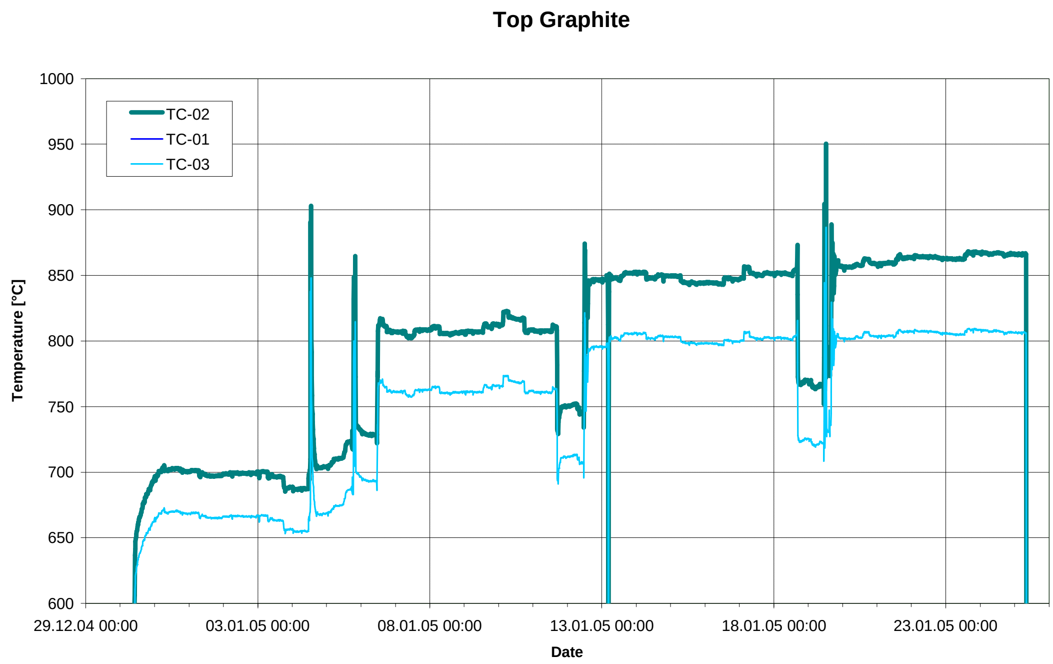

Figure 43: Temperatures top graphite (TC-01, TC-02, TC-03)

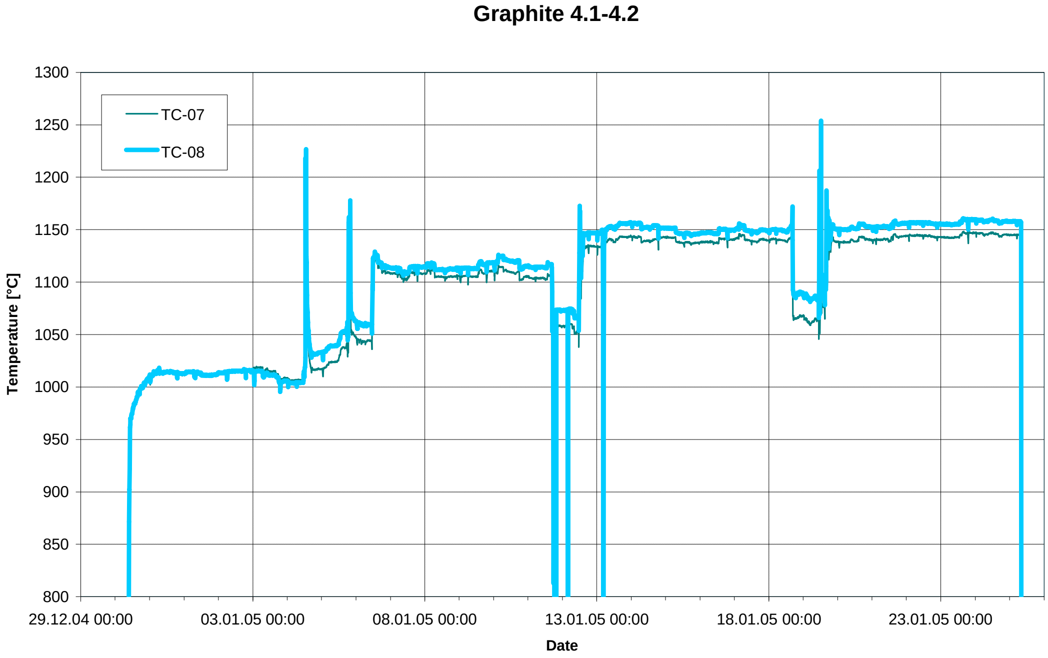

Figure 44: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

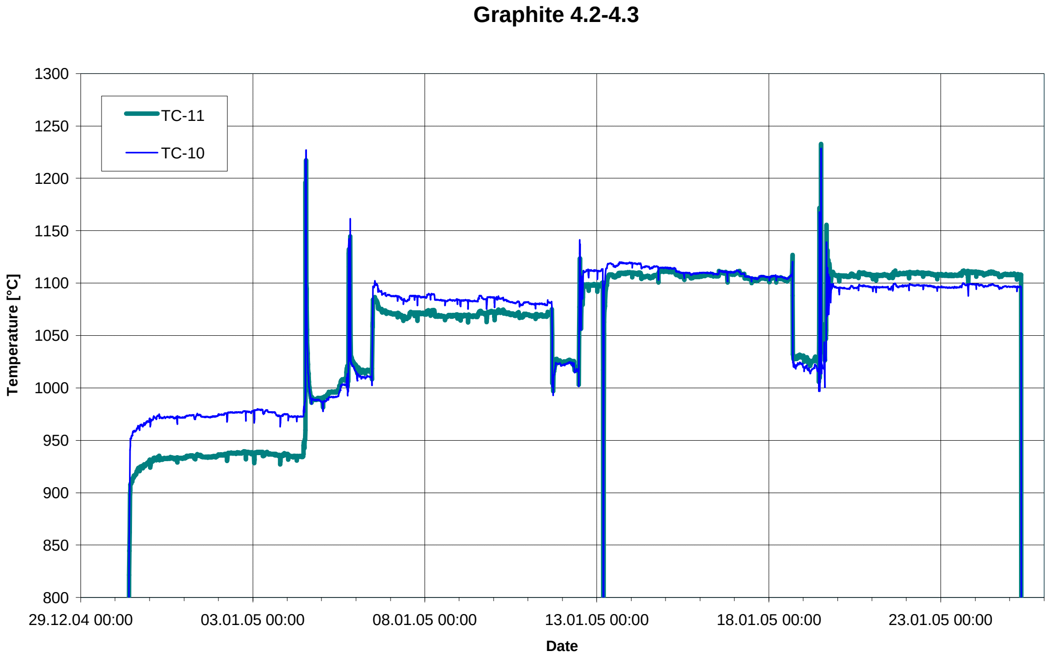

Figure 45: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

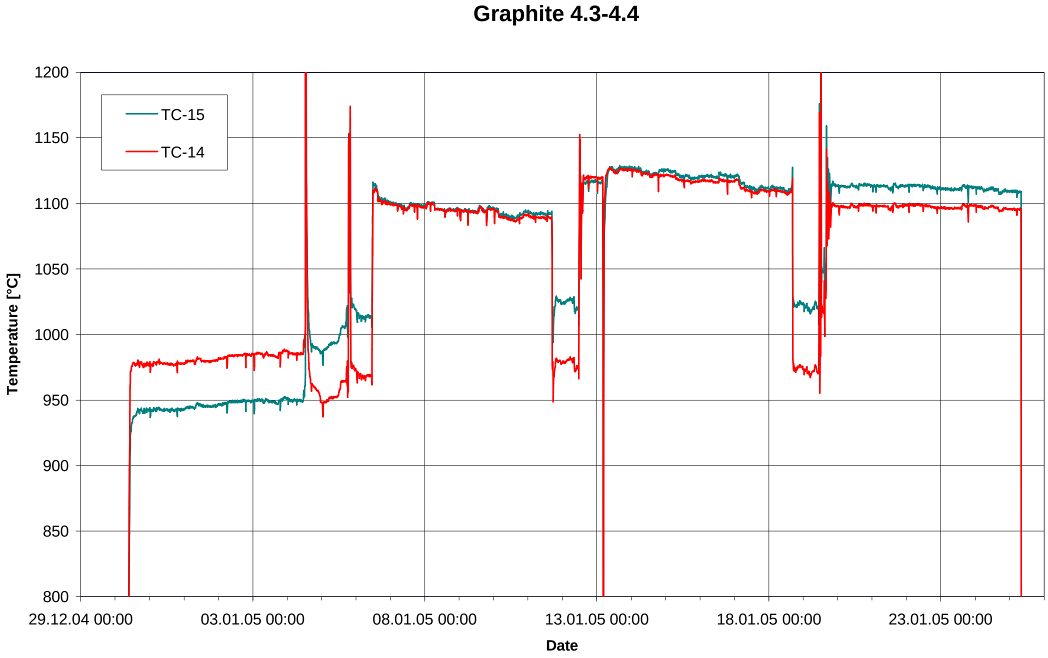

Figure 46: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

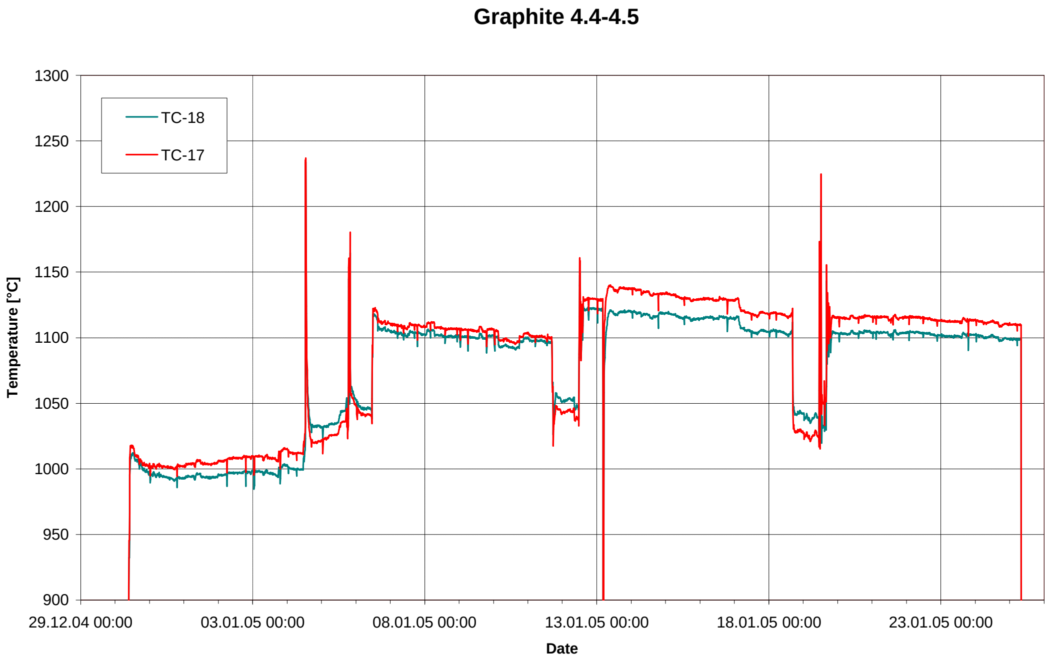

Figure 47: Temperatures graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

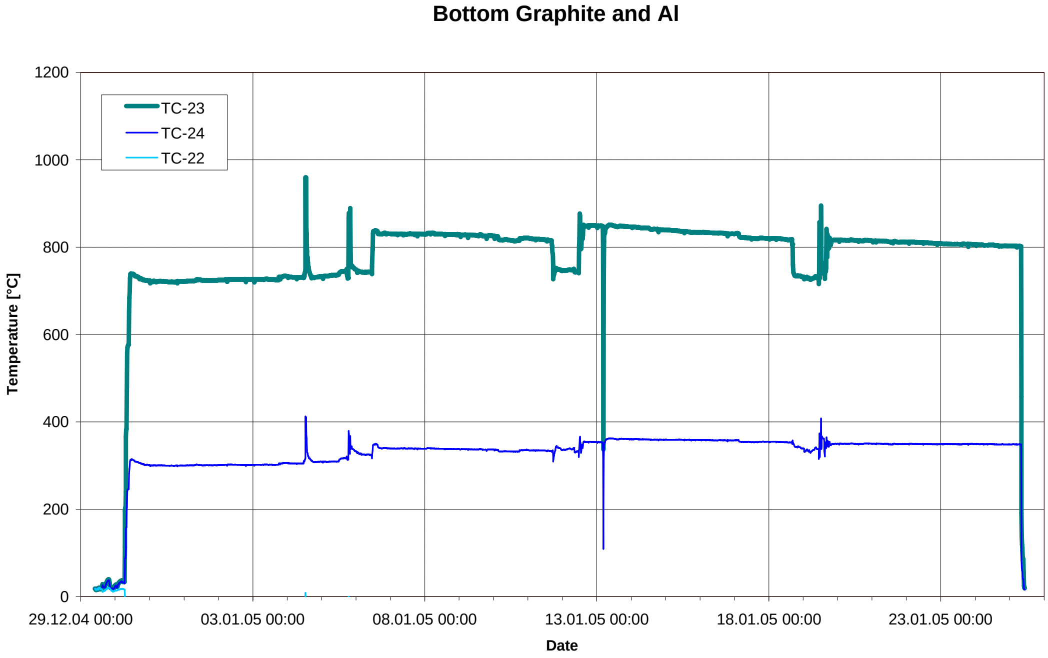

Figure 48: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
TC-01	3.8	2.5		Graphite
TC-02	797.9	829.2		
TC-03	752.8	780.2		
TC-04	997.9	1021.4	1036	GLE4.1
TC-05	997.0	1020.7		
TC-06	983.8	1006.2		
TC-07	1095.0	1120.6		Graphite
TC-08	1103.3	1130.3		
TC-09	69.0	70.1	1044	GLE4.2
TC-10	1061.0	1087.7		Graphite
TC-11	1052.5	1083.7		
TC-12	962.9	989.1	1038	GLE4.3
TC-13	996.8	1026.3		
TC-14	1060.9	1091.7		Graphite
TC-15	1063.8	1097.0		
TC-16	1016.7	1047.0	1043	GLE4.4
TC-17	1083.2	1107.1		Graphite
TC-18	1075.4	1097.4		
TC-19	1016.1	1035.1	1032	GLE4.5
TC-20	942.4	965.2		
TC-21	920.1	938.8		
TC-22	-352.7	-351.9		Graphite
TC-23	792.7	815.2		
TC-24	336.5	344.9		Al block

Table 14: Time averaged temperature readings during cycle 05-01

6.4 Temperatures during Cycle 05-02

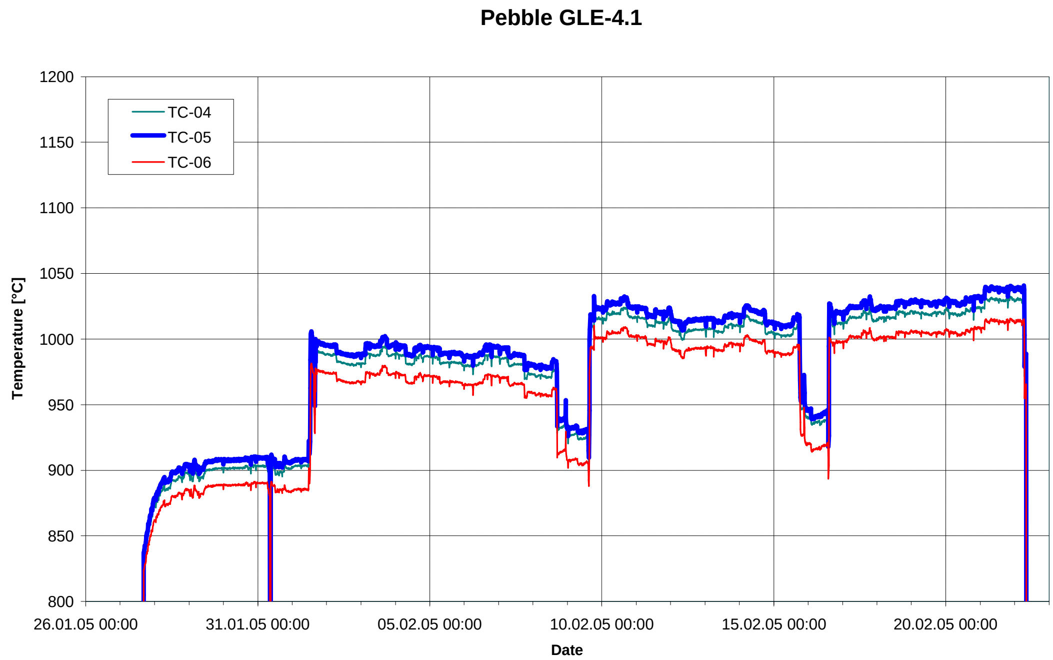

Figure 49: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

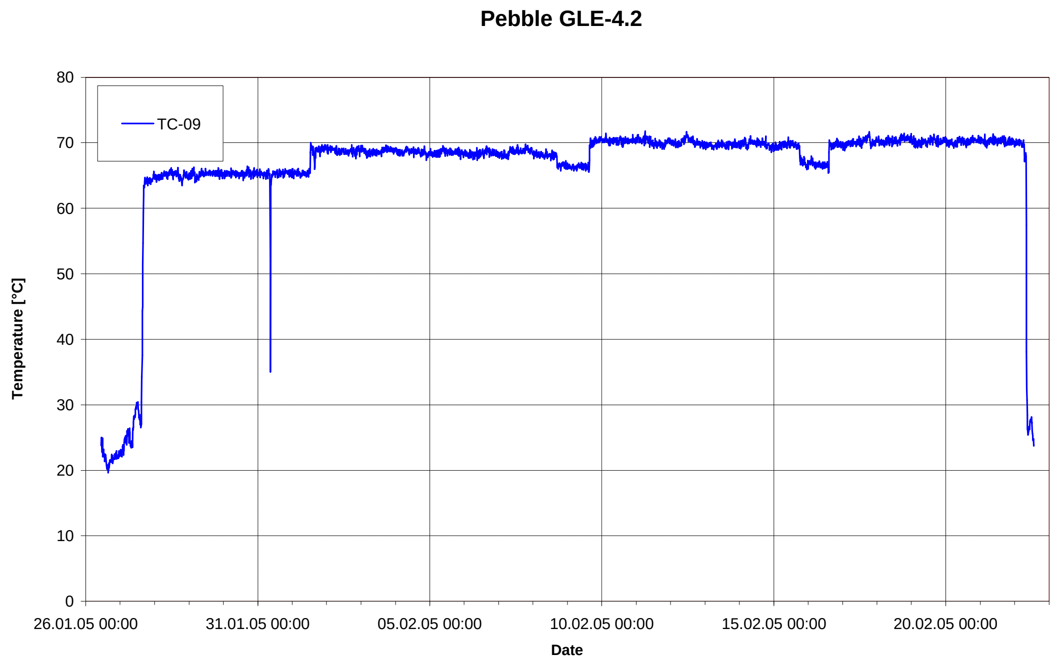

Figure 50: Temperature pebble GLE4.2 (TC-09)

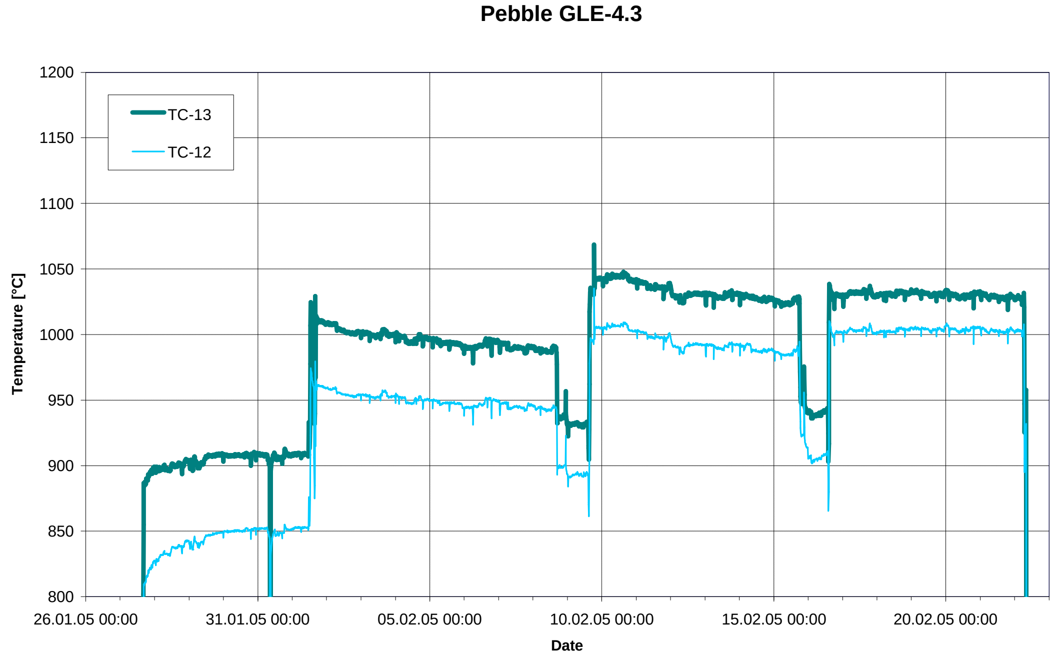

Figure 51: Temperatures pebble GLE4.3 (TC-12, TC-13)

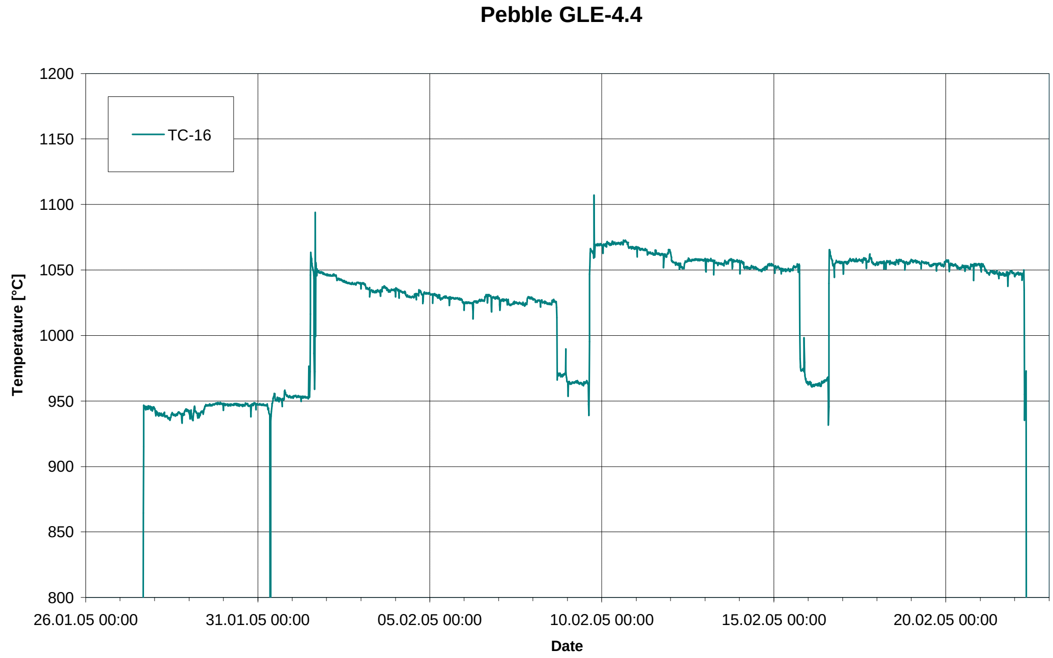

Figure 52: Temperature pebble GLE4.4 (TC-16)

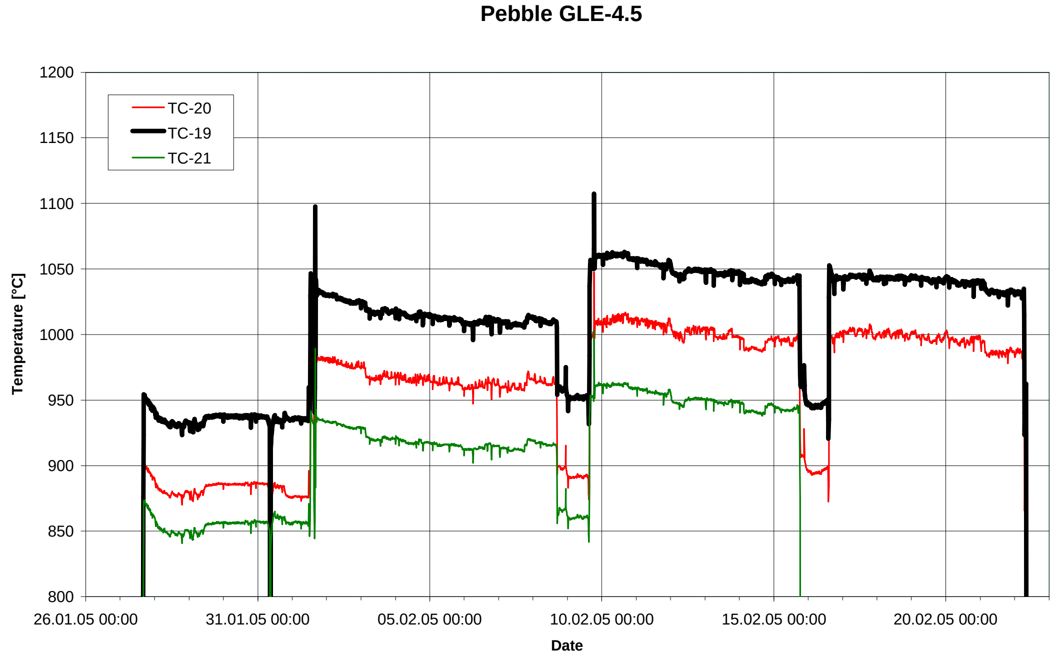

Figure 53: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

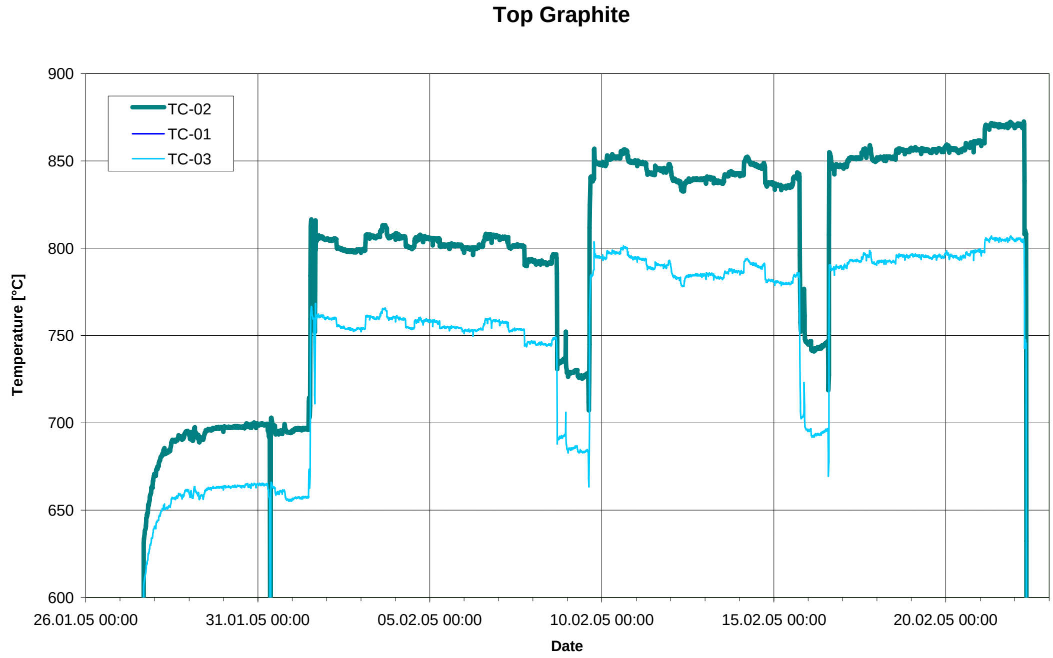

Figure 54: Temperatures top graphite (TC-01, TC-02, TC-03)

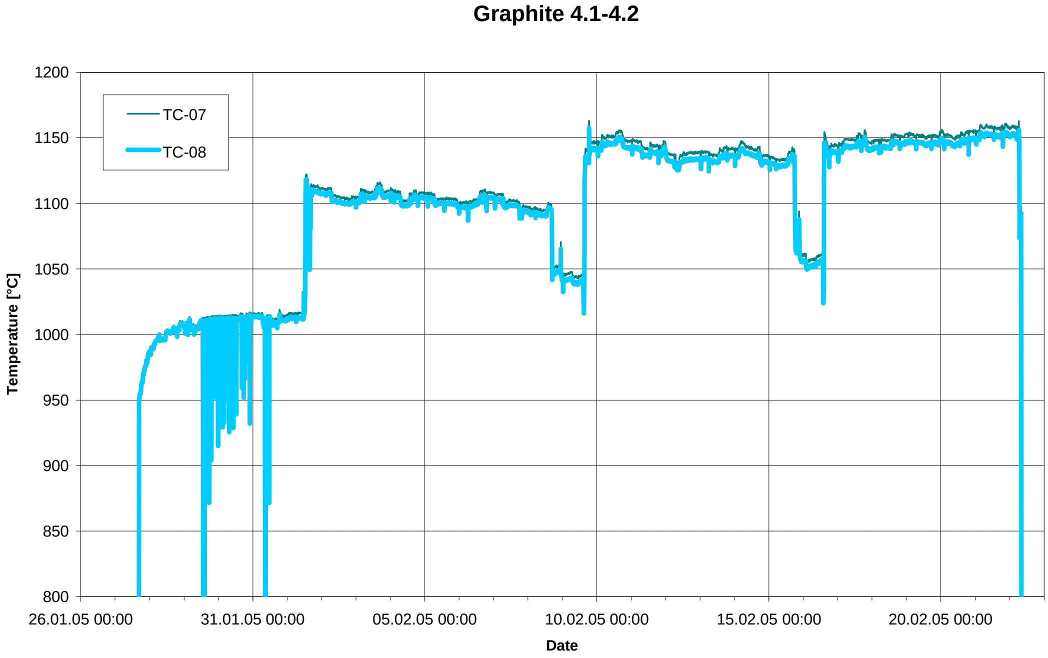

Figure 55: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

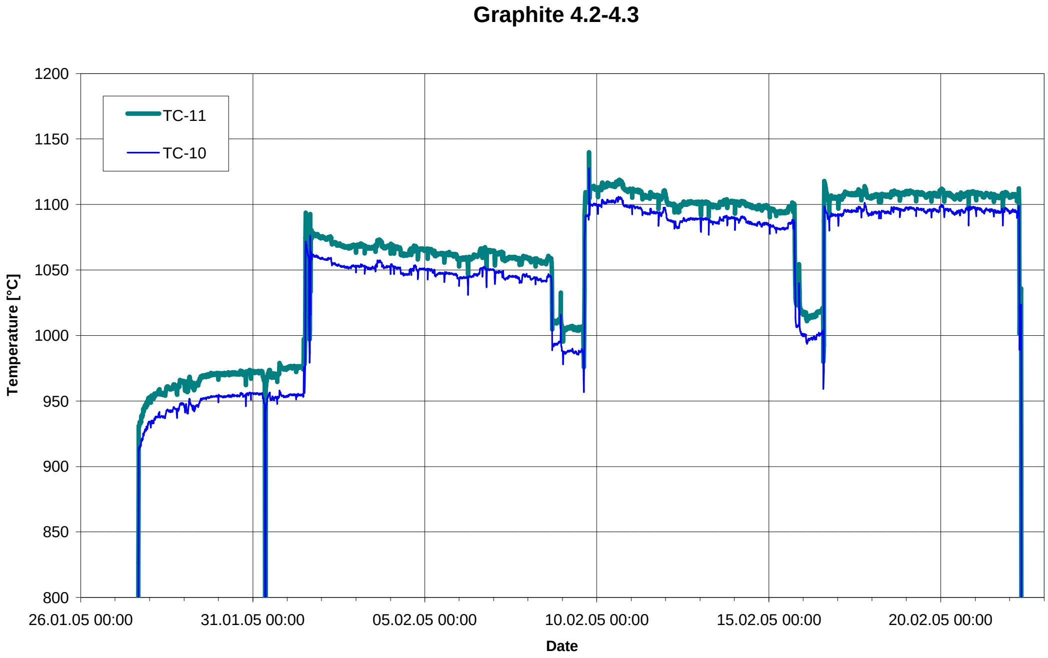

Figure 56: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

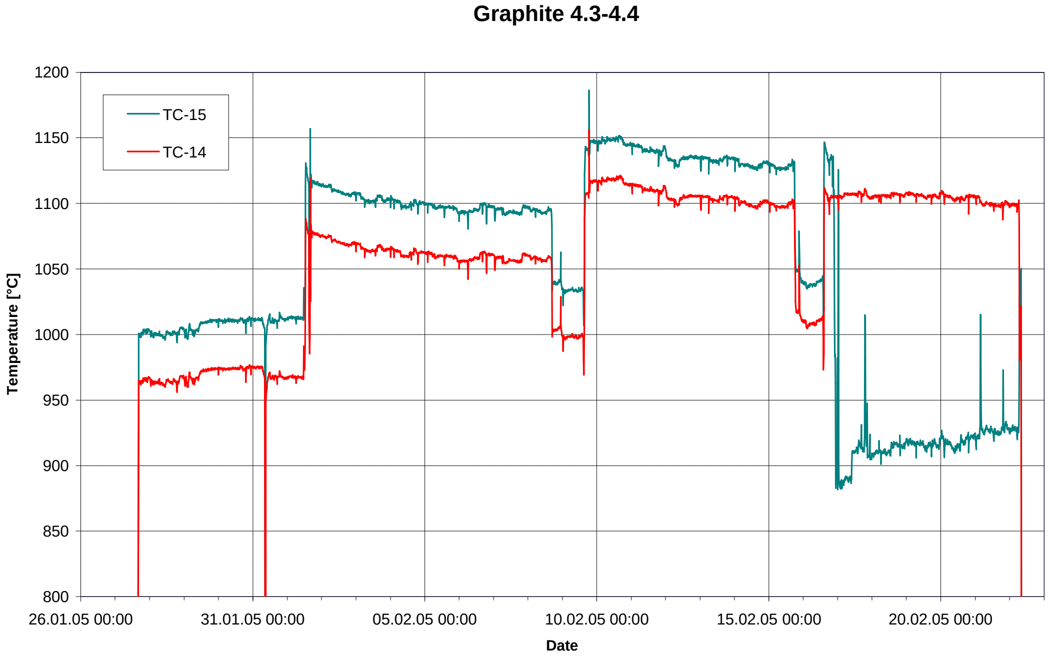

Figure 57: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

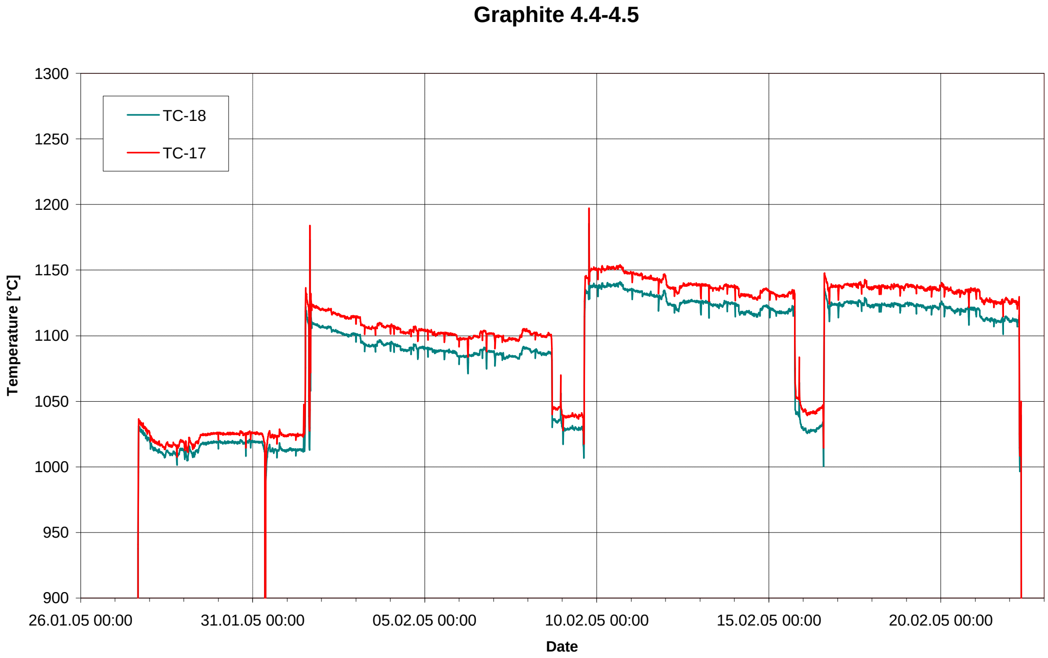

Figure 58: Temperatures graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

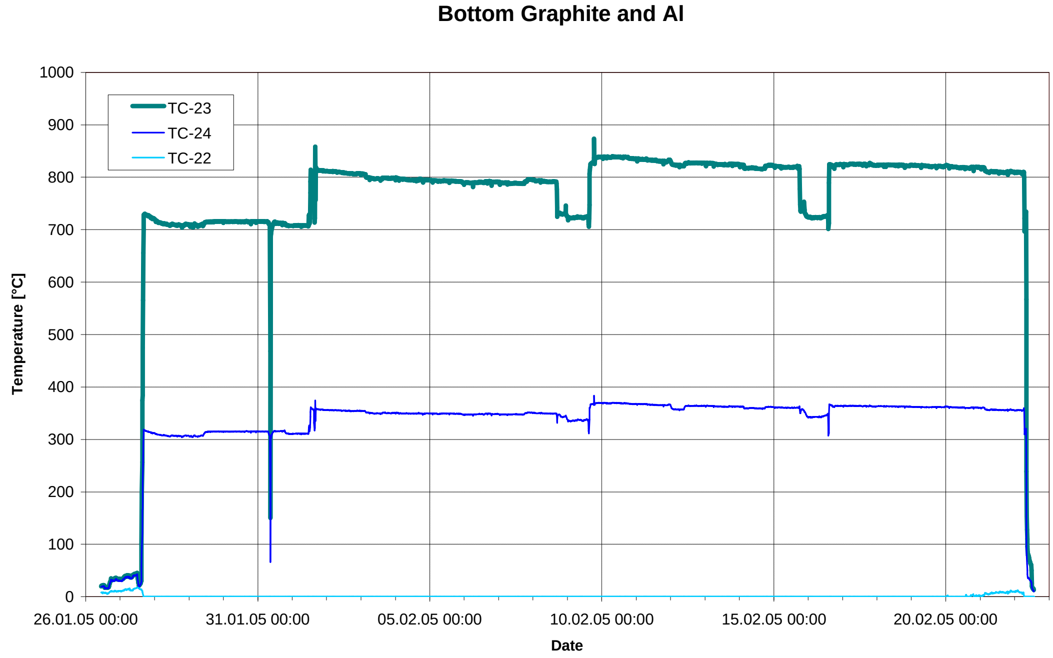

Figure 59: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
TC-01	**3.3**	2.0		Graphite
TC-02	798.5	825.3		
TC-03	748.9	772.1		
TC-04	977.5	997.9	1042	GLE4.1
TC-05	984.6	1005.4		
TC-06	962.7	983.1		
TC-07	1101.6	1124.9		Graphite
TC-08	1096.2	1120.0		
TC-09	**68.5**	69.3	1052	GLE4.2
TC-10	1046.0	1070.3		Graphite
TC-11	1060.6	1084.0		
TC-12	**948.4**	973.9	1047	GLE4.3
TC-13	990.5	1012.4		
TC-14	1060.1	1083.4		Graphite
TC-15	**1048.5**	1053.5		
TC-16	1021.8	1041.5	1052	GLE4.4
TC-17	1099.4	1119.6		Graphite
TC-18	1087.2	1106.5		
TC-19	1009.0	1028.5	1040	GLE4.5
TC-20	960.2	981.1		
TC-21	766.7	755.9		
TC-22	**0.4**	0.5		Graphite
TC-23	787.6	807.5		
TC-24	347.8	355.7		Al block

Table 15: Time averaged temperature readings during cycle 05-02

7 Fission Gas Release Measurements

The fission gas release is measured according to the following procedure:

1. **Depressurization:** approx. 18 hours before the gas sampling, the capsule is depressurized from 4.5 bar to close to atmospheric pressure.
2. **Purging:** A flow of 200 ml/min pure He is injected in the capsule and the gas is routed through the built-in charcoal filter and through the gas sampling vessel into the off-gas system. The temperature drops to its lowest possible value. Once the GM counters show low values (<70 mSv/h) after about 1 hour, the filter is bypassed. After 18 hours of stable conditions, we assume to obtain a steady-state R/B.
3. **Sampling:** The sampling vessel is removed and replaced. The noted data include date, time, ID of sampling vessel, He flow rate and gas pressure. The gas sample is analyzed in its vessel by gamma spectrometry.
4. **Temperature/Pressure Adjustment:** The rig is brought back to the desired temperature and is pressurized.
5. **Evaluation of R/B:**
   From the measured concentration of 3 Kr and 2 Xe isotopes (statistical error 4 - 9%), the gas pressure and the He flow-rate, the release rate R can be determined. The birth rate B is calculated using the nominal number of fissions on the date of sampling (neutronics error 10 - 15%) and the fission yield for the measured 5 isotopes.

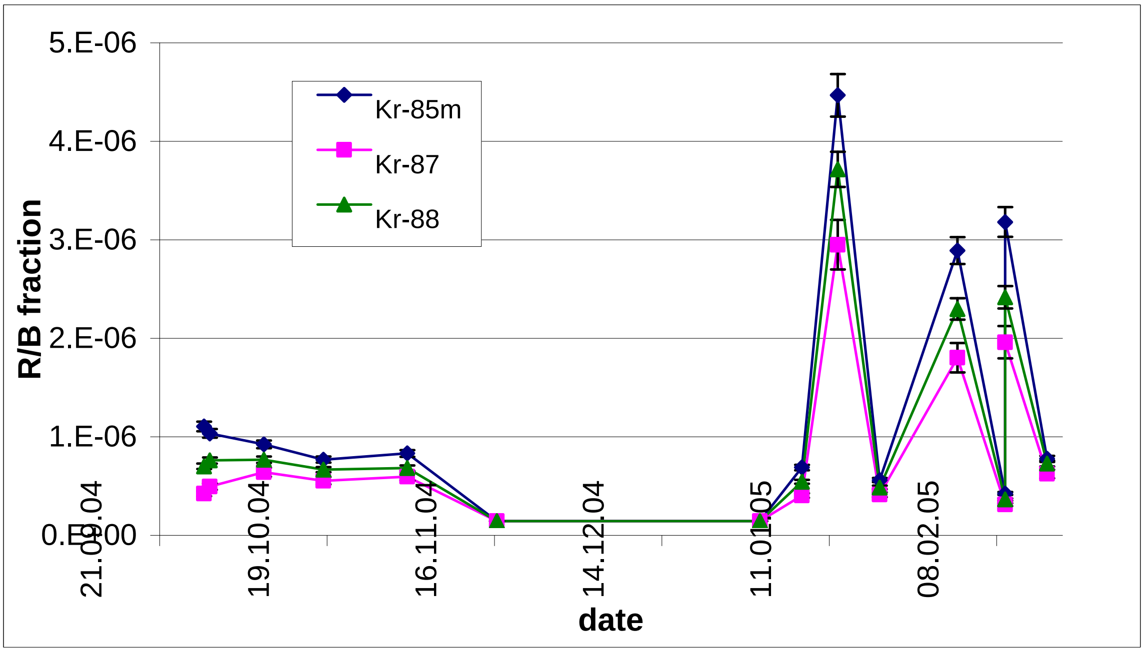

Figure 60: R/B calculation vs. time

Overview from the gammaspectrometric measurements to 25 gas vessels from GCOP.

	NRG	week	sample date	tank	flow	presure	Kr-85m		Kr-87		Kr-88		Xe-133		Xe-135		Xe-133		Xe-135	
nr	code	nr		nr	[ml/min]	[bar]	[Bq/sample]		[Bq/sample]		[Bq/sample]		[Bq/sample]		[Bq/sample]		[Bq/sample]		[Bq/sample]	
																	not corrected for ingrow			
1	H4103	37	**10.09.04 13:56**	?	?	?							1.23E+00	39%			1.23E+00	39%		
2	H4104	38	**14.09.04 12:26**	2	?	?							1.48E+00	39%	1.39E+00	38%	1.48E+00	39%	1.39E+00	38%
3	H4109	40	**28.09.04 14:45**	1	?	?	1.40E+05	10%	2.48E+05	9%	2.94E+05	7%	6.13E+05	6%	1.80E+05	3%	6.19E+05	6%	1.94E+05	4%
4	H4110	40	**27.10.04 11:21**	2	?	?	1.10E+05	4%	2.96E+05	9%	3.23E+05	6%	1.72E+05	12%	4.30E+05	3%	1.74E+05	14%	4.34E+05	3%
5	H4111	41	**08.10.04 10:45**	7	?	?	5.77E+03	4%	2.49E+04	9%	1.94E+04	6%	2.11E+03	6%	6.24E+03	3%	2.11E+03	6%	6.24E+03	3%
6	H4112	42	**11.10.04 16:03**	1	?	?							1.18E+05	6%			1.18E+05	6%		
7	H4113	43	**18.10.04 16:00**	?	150	0.13	6.83E+03	5%	3.13E+04	9%	2.48E+04	9%	2.08E+04	6%	1.65E+04	3%	2.08E+04	6%	1.86E+04	3%
8	H4117	44	**25.10.04 15:40**	2	150	0.30	9.27E+04	4%	4.03E+05	9%	3.11E+05	7%	6.55E+05	6%	6.94E+05	4%	6.56E+05	6%	7.76E+05	3%
9	H4118	44	**25.10.04 12:15**	1	0	0.15	3.45E+03	5%	1.32E+04	14%	1.12E+04	8%	7.32E+04	6%	9.76E+03	3%	7.33E+04	6%	9.76E+03	3%
10	H4122	45	**01.11.04 15:05**	7	200	0.16	5.59E+03	5%	2.49E+04	9%	1.84E+04	9%	9.49E+03	6%	1.81E+04	3%	9.51E+03	6%	2.13E+04	3%
11	H4160	1	**06.01.05 11:05**	7	200	0.12	4.18E+03	4%	1.35E+04	9%	1.29E+04	4%	6.86E+03	6%	6.69E+03	4%	6.86E+03	6%	7.62E+03	3%
12	H5001	2	**12.01.05 11:23**	1	200	0.37	4.00E+04	5%	1.76E+05	9%	1.39E+05	5%	4.64E+05	7%	1.54E+06	6%	4.64E+05	7%	1.55E+06	4%
13	H5002	3	**19.01.05 10:55**	2	200	0.11	3.07E+03	4%	1.34E+04	9%	1.06E+04	4%	3.32E+03	6%	9.54E+03	4%	3.32E+03	6%	1.07E+04	3%
14	H5007	5	**01.02.05 11:07**	1	200	0.27	2.25E+04	4%	9.21E+04	9%	7.42E+04	6%	6.37E+06	6%	9.24E+04	4%	6.39E+06	6%	9.81E+04	5%
15	H5009	6	**09.02.05 14:56**	1	200	0.28	2.46E+04	5%	9.97E+04	9%	7.74E+04	8%	1.97E+06	6%	1.04E+05	3%	1.97E+06	6%	1.12E+05	6%
16	H5010	6	**09.02.05 14:33**	3	200	0.11	1.97E+03	4%	7.98E+03	9%	6.48E+03	4%	1.14E+03	6%	4.21E+03	3%	1.14E+03	6%	4.21E+03	3%
17	H5015	7	**16.02.05 13:51**	2	200	0.08	4.24E+03	4%	2.18E+04	9%	1.65E+04	4%	3.64E+03	6%	9.66E+03	4%	3.64E+03	6%	1.11E+04	3%
18	H5023	10	**08.03.05 09:58**	3	200	0.12	3.72E+03	4%	1.88E+04	9%	1.47E+04	4%	1.49E+03	7%	9.29E+03	4%	1.49E+03	7%	1.05E+04	3%
19																				
20																				
21																				
22																				
23																				
24																				
25																				

If Xe-133m and/or Xe-135m are measured, Xe-133 and/or Xe-135 are corrected for the ingrow from the mother nuclides

Table 16: Measurement data and R/B calculation

28.09.04 14.45 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.45E+05		3373828915	100	33738289	10	5.6230E+06	4.43E+14	1.32E-02	9.61E-07
Kr-87	4578	2.85E+05		1882327501	100	18823275	10	3.1372E+06	4.43E+14	2.54E-02	2.79E-07
Kr-88	10080	3.53E+05		5133455202	100	51334552	10	8.5558E+06	4.43E+14	3.47E-02	5.56E-07
Xe-133	457056	6.47E+05		426626898722	100	4266268987	10	7.1104E+08	4.43E+14	6.62E-02	2.42E-05
Xe-135	33012	2.07E+05		9858633479	100	98586335	10	16431056	4.43E+14	6.58E-02	5.63E-07

29.09.04 14.25 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.34E+05		3117883273	100	31178833	10	5.1965E+06	4.42E+14	1.32E-02	8.91E-07
Kr-87	4578	3.58E+05		2364467527	100	23644675	10	3.9408E+06	4.42E+14	2.54E-02	3.51E-07
Kr-88	10080	3.90E+05		5671522745	100	56715227	10	9.4525E+06	4.42E+14	3.47E-02	6.16E-07
Xe-133	457056	1.90E+05		125284560676	100	1252845607	10	2.0881E+08	4.42E+14	6.62E-02	7.14E-06
Xe-135	33012	5.27E+05		25099033060	100	250990331	10	4.1832E+07	4.42E+14	6.58E-02	1.44E-06

08.10.04 10.45 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	5.77E+03		134255123	100	1342551	200	4.4752E+06	4.35E+14	1.32E-02	7.80E-07
Kr-87	4578	2.49E+04		164455982	100	1644560	200	5.4819E+06	4.35E+14	2.54E-02	4.96E-07
Kr-88	10080	1.94E+04		282121901	100	2821219	200	9.4041E+06	4.35E+14	3.47E-02	6.23E-07
Xe-133	457056	2.11E+03		1391318016	100	13913180	200	4.6377E+07	4.35E+14	6.62E-02	1.61E-06
Xe-135	33012	6.24E+03		297187792	100	2971878	200	9.9063E+06	4.35E+14	6.58E-02	3.46E-07

11.10.04 14.15 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Xe-133	457056	1.18E+05		77808306104	100	778083061	10	1.2968E+08	4.31E+14	6.62E-02	4.54E-06

18.10.04 16.00 h 0.13 bar

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	6.79E+03	1.13	157988264	100	1398126	150	3.4953E+06	4.24E+14	1.32E-02	6.24E-07
Kr-87	4578	3.03E+04	1.13	200121134	100	1770983	150	4.4275E+06	4.24E+14	2.54E-02	4.11E-07
Kr-88	10080	2.39E+04	1.13	347562548	100	3075775	150	7.6894E+06	4.24E+14	3.47E-02	5.22E-07
Xe-133	457056	2.07E+04	1.13	13649423189	100	120791356	150	3.0198E+08	4.24E+14	6.62E-02	1.07E-05
Xe-135	33012	1.86E+04	1.13	885848226	100	7839365	150	1.9598E+07	4.24E+14	6.58E-02	7.02E-07

25.10.04 12.15 h 0.15 bar after 1 week of stagnance

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	3.45E+03	1.15	80273860	100	698034	0	0.0000E+00	4.24E+14	1.32E-02	0.00E+00
Kr-87	4578	1.32E+04	1.15	87181484	100	758100	0	0.0000E+00	4.24E+14	2.54E-02	0.00E+00
Kr-88	10080	1.12E+04	1.15	162874499	100	1416300	0	0.0000E+00	4.24E+14	3.47E-02	0.00E+00
Xe-133	457056	7.33E+04	1.15	48333464724	100	420290998	0	0.0000E+00	4.24E+14	6.62E-02	0.00E+00
Xe-135	33012	9.76E+03	1.15	464832187	100	4042019	0	0.0000E+00	4.24E+14	6.58E-02	0.00E+00

25.10.04 15.40 h 0.3 bar after purging for 3:25 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	9.27E+04	1.30	2156923727	100	16591721	150	4.1479E+07	4.19E+14	1.32E-02	7.50E-06
Kr-87	4578	4.03E+05	1.30	2661677133	100	20474439	150	5.1186E+07	4.19E+14	2.54E-02	4.81E-06
Kr-88	10080	3.11E+05	1.30	4522675830	100	34789814	150	8.6975E+07	4.19E+14	3.47E-02	5.99E-06
Xe-133	457056	6.55E+05	1.30	431902038119	100	3322323370	150	8.3058E+09	4.19E+14	6.62E-02	3.00E-04
Xe-135	33012	7.51E+05	1.30	35767312766	100	275133175	150	6.8783E+08	4.19E+14	6.58E-02	2.50E-05

01.11.04 15.05 h 0.16 bar after purging for 4:05 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	5.59E+03	1.16	130066922	100	1121267	200	3.7376E+06	4.12E+14	1.32E-02	6.87E-07
Kr-87	4578	2.49E+04	1.16	164455982	100	1417724	200	4.7257E+06	4.12E+14	2.54E-02	4.52E-07
Kr-88	10080	1.84E+04	1.16	267579535	100	2306720	200	7.6891E+06	4.12E+14	3.47E-02	5.38E-07
Xe-133	457056	9.49E+03	1.16	6257634110	100	53945122	200	1.7982E+08	4.12E+14	6.62E-02	6.59E-06
Xe-135	33012	1.81E+04	1.16	862035101	100	7431337	200	2.4771E+07	4.12E+14	6.58E-02	9.14E-07

06.01.05 11.05 h 0.12 bar after purging for 18 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.18E+03	1.12	97259344	100	868387	200	2.8946E+06	4.03E+14	1.32E-02	5.44E-07
Kr-87	4578	1.35E+04	1.12	89162882	100	796097	200	2.6537E+06	4.03E+14	2.54E-02	2.59E-07
Kr-88	10080	1.29E+04	1.12	187596522	100	1674969	200	5.5832E+06	4.03E+14	3.47E-02	3.99E-07
Xe-133	457056	6.86E+03	1.12	4523432033	100	40387786	200	1.3463E+08	4.03E+14	6.62E-02	5.04E-06
Xe-135	33012	6.69E+03	1.12	318619604	100	2844818	200	9.4827E+06	4.03E+14	6.58E-02	3.57E-07

Table 17: Spreadsheet table for the calculation of R/B values (1 of 2)

12.01.05 11:23 h 0.37 bar **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.00E+04	1.37	930711425	100	6793514	200	2.2645E+07	3.97E+14	1.32E-02	4.32E-06
Kr-87	4578	1.76E+05	1.37	1162419790	100	8484816	200	2.8283E+07	3.97E+14	2.54E-02	2.81E-06
Kr-88	10080	1.39E+05	1.37	2021388876	100	14754663	200	4.9182E+07	3.97E+14	3.47E-02	3.57E-06
Xe-133	457056	4.64E+05	1.37	305958085018	100	2233270694	200	7.4442E+09	3.97E+14	6.62E-02	2.83E-04
Xe-135	33012	1.54E+06	1.37	73344422982	100	535360752	200	1.7845E+09	3.97E+14	6.58E-02	6.84E-05

19.01.05 10:55 h (**after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	3.07E+03	1.11	71432102	100	643532	200	2.1451E+06	3.90E+14	1.32E-02	4.16E-07
Kr-87	4578	1.34E+04	1.11	88502416	100	797319	200	2.6577E+06	3.90E+14	2.54E-02	2.68E-07
Kr-88	10080	1.06E+04	1.11	154149080	100	1388730	200	4.6291E+06	3.90E+14	3.47E-02	3.42E-07
Xe-133	457056	3.32E+03	1.11	2189182850	100	19722368	200	6.5741E+07	3.90E+14	6.62E-02	2.54E-06
Xe-135	33012	9.54E+03	1.11	454354413	100	4093283	200	1.3644E+07	3.90E+14	6.58E-02	5.31E-07

01.02.05 11:07 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	2.25E+04	1.27	523525176	100	4122245	200	1.3741E+07	3.79E+14	1.32E-02	2.75E-06
Kr-87	4578	9.21E+04	1.27	608288992	100	4789677	200	1.5966E+07	3.79E+14	2.54E-02	1.66E-06
Kr-88	10080	7.42E+04	1.27	1079043558	100	8496406	200	2.8321E+07	3.79E+14	3.47E-02	2.15E-06
Xe-133	457056	6.37E+06	1.27	4200329744756	100	33073462557	200	1.1024E+11	3.79E+14	6.62E-02	4.39E-03
Xe-135	33012	9.24E+04	1.27	4400665379	100	34650908	200	1.1550E+08	3.79E+14	6.58E-02	4.63E-06

09.02.2005 14:33 PI Tank 3 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.97E+03	1.11	45837538	100	412951	200	1.3765E+06	3.72E+14	1.32E-02	2.80E-07
Kr-87	4578	7.98E+03	1.11	52705170	100	474821	200	1.5827E+06	3.72E+14	2.54E-02	1.68E-07
Kr-88	10080	6.48E+03	1.11	94234532	100	848960	200	2.8299E+06	3.72E+14	3.47E-02	2.19E-07
Xe-133	457056	1.14E+03	1.11	751707364	100	6772138	200	2.2574E+07	3.72E+14	6.62E-02	9.17E-07
Xe-135	33012	4.21E+03	1.11	200506507	100	1806365	200	6.0212E+06	3.72E+14	6.58E-02	2.46E-07

09.02.2005 14:56 PI Tank 1 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	2.46E+04	1.28	572387526	100	4471778	200	1.4906E+07	3.72E+14	1.32E-02	3.04E-06
Kr-87	4578	9.97E+04	1.28	658484392	100	5144409	200	1.7148E+07	3.72E+14	2.54E-02	1.82E-06
Kr-88	10080	7.74E+04	1.28	1125579129	100	8793587	200	2.9312E+07	3.72E+14	3.47E-02	2.27E-06
Xe-133	457056	1.97E+06	1.28	1299003076479	100	10148461535	200	3.3828E+10	3.72E+14	6.62E-02	1.37E-03
Xe-135	33012	1.04E+05	1.28	4953129864	100	38696327	200	1.2899E+08	3.72E+14	6.58E-02	5.27E-06

16.02.2005 13:51 PI Tank 2 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.24E+03	1.08	98655411	100	913476	200	3.0449E+06	3.65E+14	1.32E-02	6.32E-07
Kr-87	4578	2.18E+04	1.08	143981542	100	1333162	200	4.4439E+06	3.65E+14	2.54E-02	4.80E-07
Kr-88	10080	1.65E+04	1.08	239949039	100	2221750	200	7.4058E+06	3.65E+14	3.47E-02	5.85E-07
Xe-133	457056	3.64E+03	1.08	2400188426	100	22223967	200	7.4080E+07	3.65E+14	6.62E-02	3.07E-06
Xe-135	33012	9.66E+03	1.08	460069562	100	4259903	200	1.4200E+07	3.65E+14	6.58E-02	5.91E-07

08.03.05 09:58 Tank 3 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	3.72E+03	1.12	86556163	100	772823	200	2.5761E+06	3.48E+14	1.32E-02	5.60E-07
Kr-87	4578	1.88E+04	1.12	124167568	100	1108639	200	3.6955E+06	3.48E+14	2.54E-02	4.17E-07
Kr-88	10080	1.47E+04	1.12	213772780	100	1908686	200	6.3623E+06	3.48E+14	3.47E-02	5.26E-07
Xe-133	457056	1.49E+03	1.12	982494713	100	8772274	200	2.9241E+07	3.48E+14	6.62E-02	1.27E-06
Xe-135	33012	9.29E+03	1.12	442447850	100	3950427	200	1.3168E+07	3.48E+14	6.58E-02	5.74E-07

Table 18: Spreadsheet table for the calculation of R/B values (2 of 2)

8 Data Analysis and Interpretation

8.1 Fission gas release

From Figure 61 it can be concluded that the release of fission gases has not changed since the beginning of the irradiation. Whether this is interpreted as no particle failure at all or failure of a small number of particles, depends on the assumptions made for release:

- If we assume that all fission gases from a possibly failed particle are released, then we would come to the conclusion that no particles have failed so far.
- If we assume, however, that only a certain fraction of the fission gases are released, and by comparing these R/B results with earlier measurements (cf. Figure 62), then we may come to the conclusion that up to 2 or 3 particles were already damaged at the beginning of the irradiation.

Figure 63 shows the expected R/B value for Kr-85m at 2% FIMA for various temperatures.

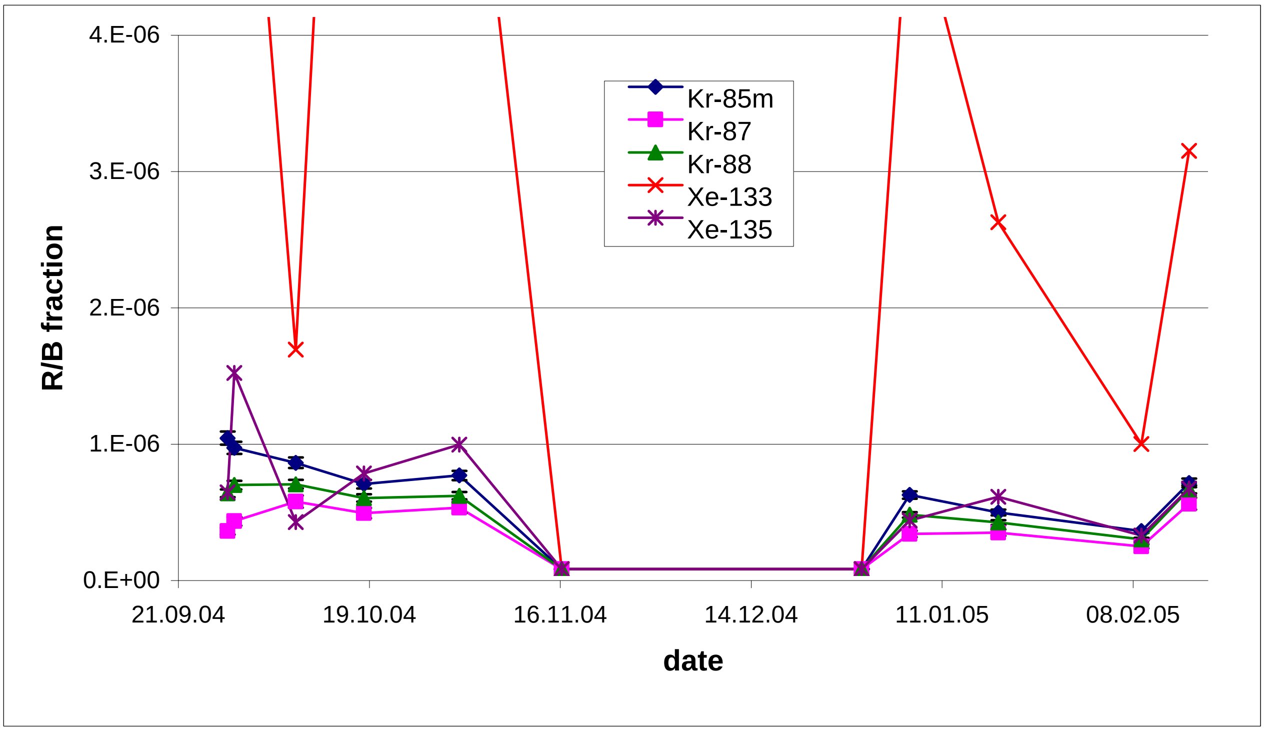

Figure 61: Expunged R/B vs. time

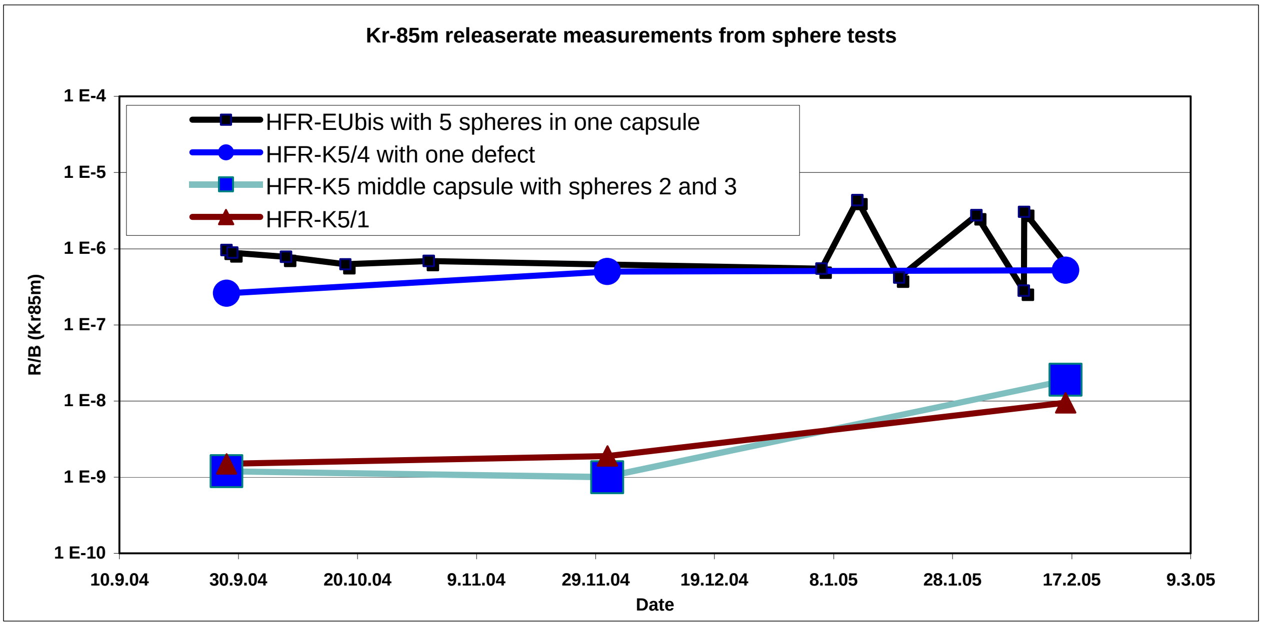

Figure 62: Comparison of HFR-EU1bis measurements with HFR-K5 data [source: H. Nabielek, FZJ]

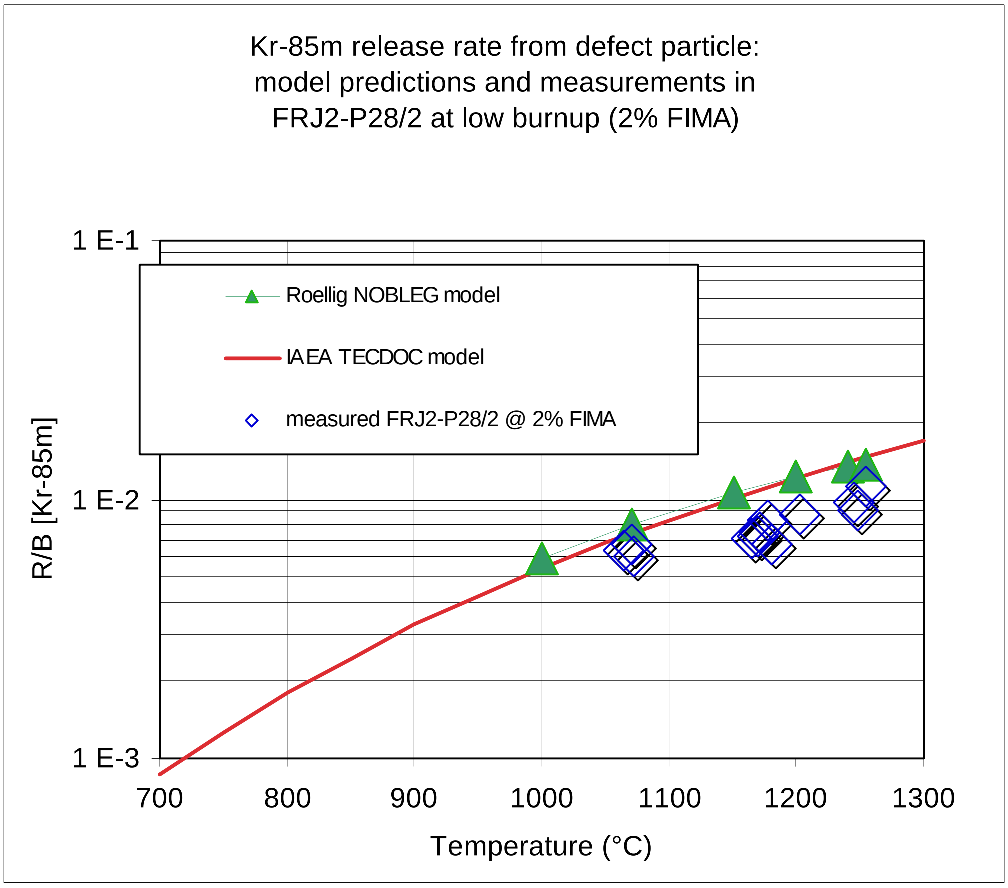

Figure 63: Comparison of 2 R/B models with measurements at low burn-up [source: H. Nabielek, FZJ]

8.2 Analysis of temperature data

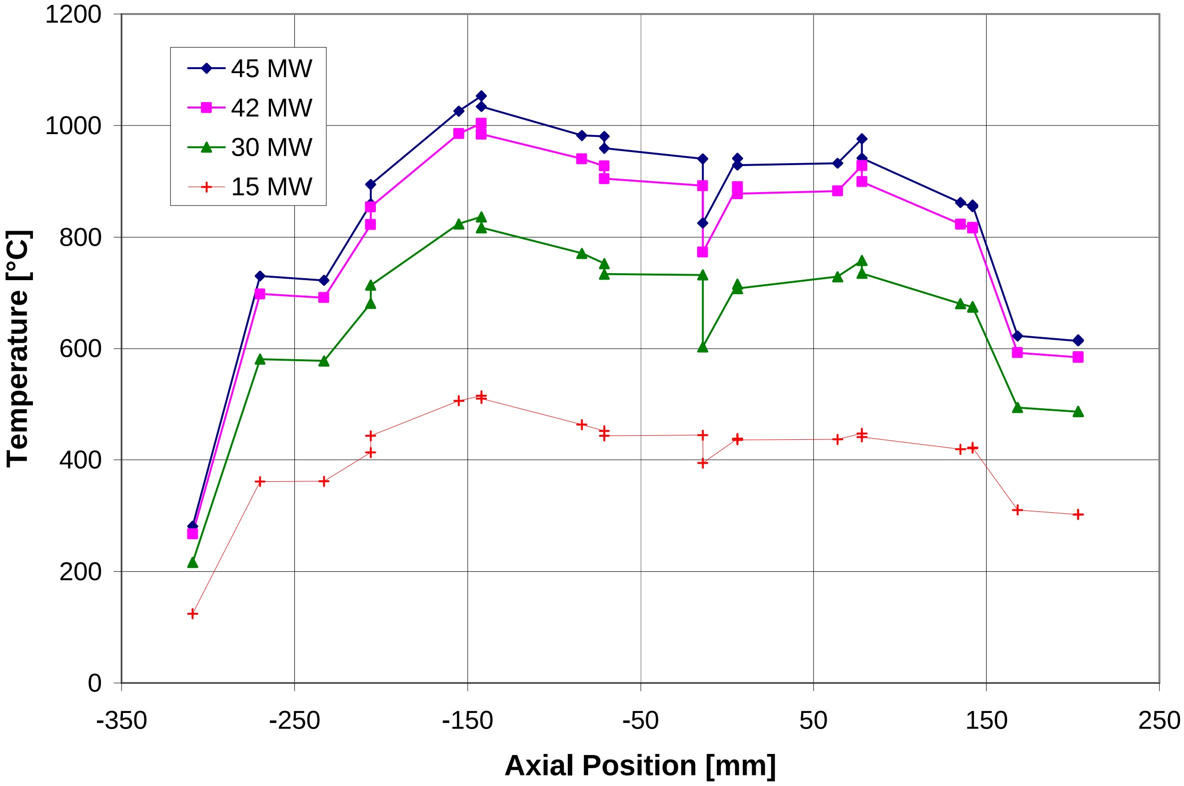

Figure 64: Axial temperature profiles during first start-up

In the beginning of the irradiation, the axial temperature profile was measured. TC-12 was found to indicate a temperature that was about 50 K lower than its immediate neighbor TC-13.

The calculated gas compositions could not be confirmed: target temperatures for the 1st cycle could already be reached with pure He in both containments. The reasons for this were found to be uncertainties in power predictions (from neutronics) and uncertainties in the radiative emmissivity of the steel capsule.

Figure 65 shows that rather good consistency between calculation and measurement could be reached when assuming that the combined effect of both uncertainties was equivalent to a 20% increase in fission power.

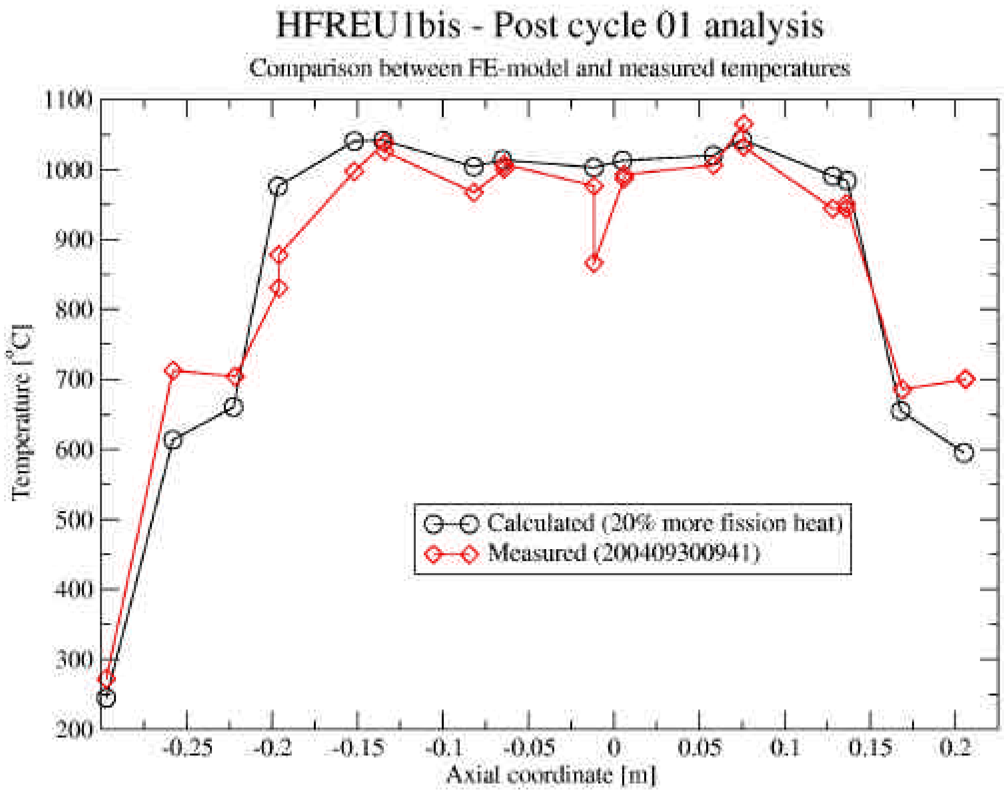

Figure 65: Calculated/measured pebble temperatures assuming 20% more fission power

9 References

[1] M. A. Fütterer, H. Lohner, R. Conrad, K. Bakker, S. de Groot, C. M. Sciolla, HFR-EU1bis: Irradiation of High Temperature Reactor Fuel Pebbles at VHTR Conditions in the HFR Petten, rev. D, Technical Memorandum HFR/03/4757, 8. November 2004.

[2] C. M. Sciolla, HFR TEDDI post-cycle output, Cycle 04-08, NRG technical report 25138/04.62360/I, 13 October 2005.

[3] C. M. Sciolla, HFR TEDDI post-cycle output, Cycle 04-09, NRG technical report 25138/04.62759/I, 2 November 2004.

[4] C. M. Sciolla, HFR TEDDI post-cycle output, Cycle 05-01, NRG technical report 25138/05.64619/I, 25 January 2005.

[5] C. M. Sciolla, HFR TEDDI post-cycle output, Cycle 054-02, NRG technical report 25138/05.65257/I, 22 February 2005.

10 List of Figures

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TECHNICAL MEMORANDUM
HFR / 05 / 4812

HFR-EU1bis: Irradiation Progress Report

Cycles 05-03, 05-04, 05-06, 05-07

Project n° 337.2

rev. A

Michael A. Fütterer

	Author	Verified by	Approved by Unit Head
Name	M. A. Fütterer	F. Scaffidi-Argentina	R. May
Date	2.9.05	06.09.05	7.9.05
Signature	M. Fütterer	F. Scaffidi-Argentina	M. Fütterer p.o.

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Revision	Date	Description
A	02.09.05	initial release
B		
C		

Abstract

This is the second progress report of the HTR fuel pebble irradiation experiment HFR-EU1bis combining the results of the second set of four irradiation cycles. The first cycle report [1] combined the first 4 reactor cycles.

The irradiation had started on 9 September 2004 and was interrupted for 2 reactor cycles. Due to scheduled reactor maintenance and for a gas panel modification, the irradiation was paused again during cycle 05-05.

This document contains the history of the irradiation including significant special events, nuclear data as well as temperature and fission gas release measurements.

Some preliminary attempts were made to analyze and interpret the information obtained so far.

Further data is available to the HTR-F/F1 partners on request.

Table of Contents

1 Irradiation History

24.02.05 12:00 start cycle 05-03 **no scram** **3 gas samples taken** **22.03.05 08:00 end cycle 05-03**
24.03.05 14:50 start cycle 05-04 **no scram** **1 gas sample taken** **19.04.05 08:00 end cycle 05-04**
19.04.05 start scheduled reactor maintenance *HFR-EU1bis was disconnected during reactor maintenance* 12.05.05 end scheduled reactor maintenance
12.05.05 23:10:00 start cycle 05-05 HFR-EU1bis was paused during this cycle, no data reported here 07.06.05 08:00:00 end cycle 05-05
09.06.05 22:10 start cycle 05-06 **1 scram** **4 gas samples taken (2 hot, 2 cold)** **05.07.05 08:10 end cycle 05-06**
08.07.05 01:50 start cycle 05-07 **3 scrams** **2 gas samples taken (2 hot)** **02.08.05 08:10 end cycle 05-07 with 202 efpd completed (approx. 13.4% FIMA)**

1.1 Special Events

On 02.06.05 17:42, after the reactor maintenance and during cycle 05-05, the experiment had to be reconnected to the gas system and a check of the gas connectors in the rig head was carried out. A technician had forgotten that the HFR-EU1bis rig, which was paused for this cycle, was held under gas pressure to exclude water and air leakage into the experiment. Upon opening the pressurized rig head, the overpressure escaped and contaminated several persons in the reactor hall with activation products of steel. The safety authorities were notified, the incident was reported to the press and measures were taken to avoid similar events in the future.

1.2 Modifications of Installation

- **Gas Panel Automation:** During the reactor maintenance stop (19.04. – 12.05.05) and during cycle 05-05 a further modification of the gas system was performed to ease the temperature adjustment (separate mass flow controllers in He and Ne admission strings). Additionally, a pressure controller at the gas outlet was installed. This enabled:
    1. walk-away safe pressurization of the rig;
    2. gas sampling at both nominal temperature/pressure conditions in the capsule and cold conditions;
    3. easier temperature adjustment.
- **Gas sampling:** Contrary to the first 4 irradiation cycles, the experiment was run in closed conditions during cycles 05-03 and 05-04 and in purged conditions after the gas panel modifications in cycles 05-06 and 05-07. Results of the fission gas release measurements are reported in section 7.

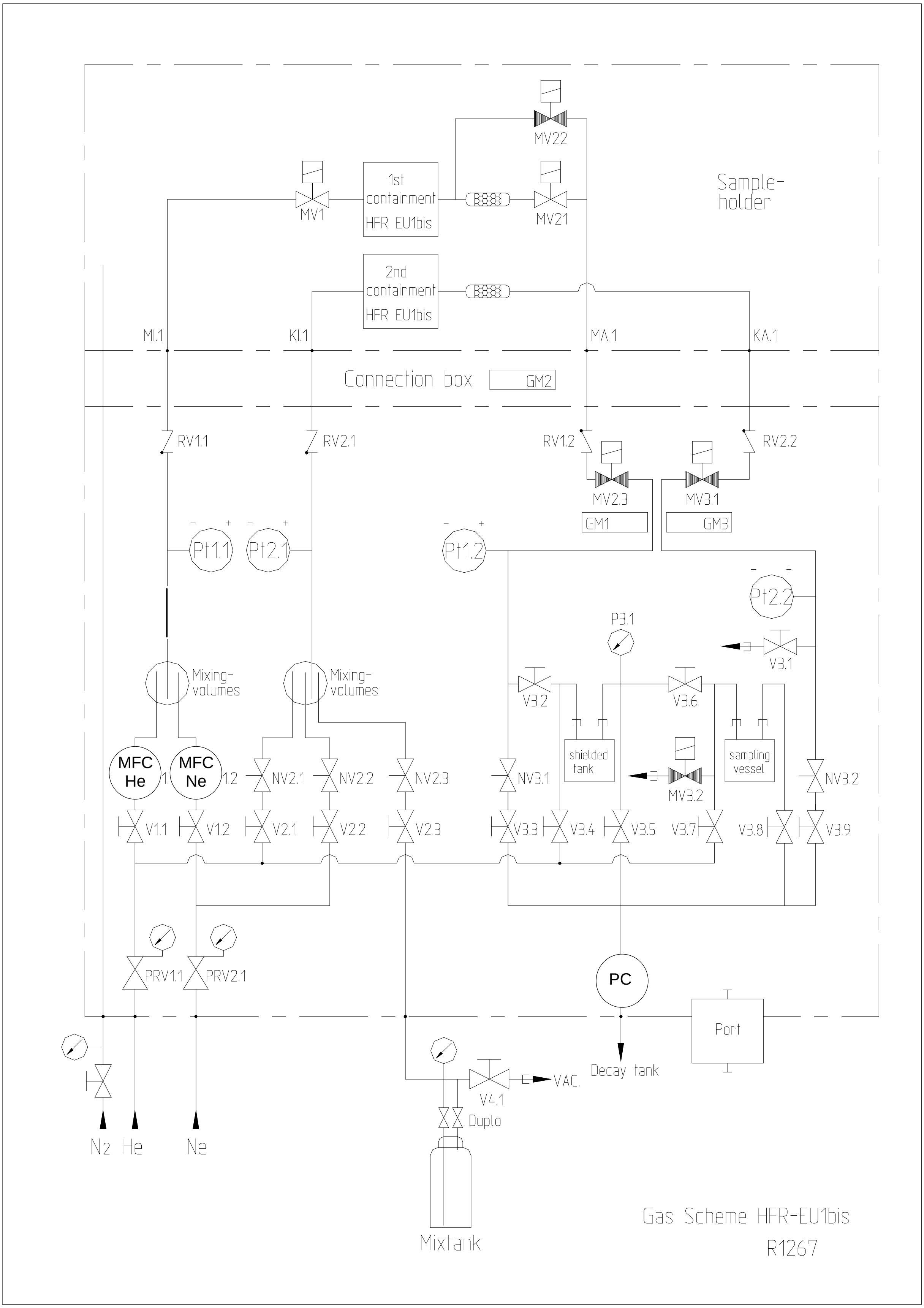


Figure 1: HFR-EU1bis gas panel with mass-flow and pressure controllers

2 Nuclear Data

2.1 Fluxes, fluences and other data cycle 05-03

Cycle 05-03, position G3, **orientation North**, data from [3]

	flux start-up initial $[10^{18}\ m^{-2}s^{-1}]$	flux start-up equilibrium $[10^{18}\ m^{-2}s^{-1}]$	flux end of cycle $[10^{18}\ m^{-2}s^{-1}]$	fluence $[10^{25}\ m^{-2}]$
F_1 1)	0.743	0.735	0.746	0.165
F_2 1)	1.217	1.204	1.220	0.270
F_3 1)	1.494	1.484	1.513	0.334
F_4 1)	0.972	0.945	1.028	0.220
F_{Fe}	1.172	1.160	1.176	0.260
F_{Co}	0.846	0.826	0.886	0.191
$F_{E > 1\ MeV}$	0.935	0.925	0.938	0.208
$F_{E > 0.1\ MeV}$	1.852	1.832	1.856	0.411

1) energy groups with boundaries: $14.918\times10^6 - 1.353\times10^6 - 0.0674\times10^6 - 0.683 - 0$ eV

Table 1: Neutron fluxes and fluences cycle 05-03

full power days	25.29
dpa (stainless steel)	0.320
gamma heating in small graphite samples [W/g]	4.367 initial start-up 4.337 start-up equilibrium 4.572 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

Table 2: Nuclear characteristics for cycle 05-03

2.2 Fluxes, fluences and other data cycle 05-04

Cycle 05-04, position G3, **orientation South**, data from [4]

	flux start-up initial [10^{18} m^{-2}s^{-1}]	flux start-up equilibrium [10^{18} m^{-2}s^{-1}]	flux end of cycle [10^{18} m^{-2}s^{-1}]	fluence [10^{25} m^{-2}]
F_1 [1)]	0.726	0.739	0.735	0.163
F_2 [1)]	1.195	1.214	1.206	0.268
F_3 [1)]	1.477	1.504	1.505	0.334
F_4 [1)]	0.976	0.983	1.052	0.226
F_{Fe}	1.146	1.166	1.159	0.258
F_{Co}	0.846	0.854	0.901	0.195
$F_{E > 1\ MeV}$	0.915	0.931	0.925	0.206
$F_{E > 0.1\ MeV}$	1.814	1.845	1.833	0.408

[1)] energy groups with boundaries: $14.918\times10^6 - 1.353\times10^6 - 0.0674\times10^6 - 0.683 - 0$ eV

Table 3: Neutron fluxes and fluences cycle 05-04

full power days	25.67
dpa (stainless steel)	0.318
gamma heating in small graphite samples [W/g]	4.219 initial start-up 4.303 start-up equilibrium 4.438 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

Table 4: Nuclear characteristics for cycle 05-04

2.3 Fluxes, fluences and other data cycle 05-06

Cycle 05-06, position G3, **orientation North**, data from [5]

	flux start-up initial $[10^{18}\ m^{-2}s^{-1}]$	flux start-up equilibrium $[10^{18}\ m^{-2}s^{-1}]$	flux end of cycle $[10^{18}\ m^{-2}s^{-1}]$	fluence $[10^{25}\ m^{-2}]$
F_1 1)	0.743	0.754	0.746	0.157
F_2 1)	1.207	1.224	1.210	0.255
F_3 1)	1.485	1.509	1.503	0.316
F_4 1)	0.975	0.978	1.039	0.211
F_{Fe}	1.171	1.189	1.176	0.248
F_{Co}	0.846	0.852	0.892	0.183
$F_{E > 1\ MeV}$	0.933	0.947	0.937	0.197
$F_{E > 0.1\ MeV}$	1.841	1.868	1.848	0.389

1) energy groups with boundaries: $14.918\times10^6 - 1.353\times10^6 - 0.0674\times10^6 - 0.683 - 0$ eV

Table 5: Neutron fluxes and fluences cycle 05-06

full power days	24.26
dpa (stainless steel)	0.304
gamma heating in small graphite samples [W/g]	4.288 initial start-up 4.354 start-up equilibrium 4.461 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

Table 6: Nuclear characteristics for cycle 05-06

2.4 Fluxes, fluences and other data cycle 05-07

Cycle 05-07, position G3, **orientation South**, data from [6]

	flux start-up initial [10^{18} $m^{-2}s^{-1}$]	flux start-up equilibrium [10^{18} $m^{-2}s^{-1}$]	flux end of cycle [10^{18} $m^{-2}s^{-1}$]	fluence [10^{25} m^{-2}]
F_1 [1)]	0.784	0.792	0.778	0.171
F_2 [1)]	1.278	1.290	1.266	0.278
F_3 [1)]	1.575	1.593	1.575	0.345
F_4 [1)]	1.038	1.038	1.105	0.233
F_{Fe}	1.236	1.249	1.227	0.269
F_{Co}	0.900	0.903	0.945	0.201
$F_{E > 1\ MeV}$	0.985	0.995	0.977	0.215
$F_{E > 0.1\ MeV}$	1.947	1.967	1.931	0.424

[1)]energy groups with boundaries: $14.918\times10^6 – 1.353\times10^6 – 0.0674\times10^6$ – 0.683 – 0 eV

Table 7: Neutron fluxes and fluences cycle 05-07

full power days	25.19
dpa (stainless steel)	0.331
gamma heating in small graphite samples [W/g]	4.608 initial start-up 4.671 start-up equilibrium 4.764 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

[1)]energy groups with boundaries: $14.918\times10^6 – 1.353\times10^6 – 0.0674\times10^6$ – 0.683 – 0 eV

Table 8: Nuclear characteristics for cycle 05-07

2.5 Analysis of nuclear data

From Table 1 through Table 8 the following can be concluded:

The nuclear data of this set of four reactor cycles turned out to vary much less than in the first four irradiation cycles.

Cycle	F_1 [1)]	F_2	F_3	F_4	Fluence_4	$\text{Fluence}_{E> 0.1\ MeV}$
	$[10^{18}\ m^{-2}s^{-1}]$				$[10^{25}\ m^{-2}]$	
05-03	0.746	1.220	1.513	1.028	0.220	0.411
05-04	0.735	1.206	1.505	1.052	0.226	0.408
05-06	0.746	1.210	1.503	1.039	0.211	0.389
05-07	0.778	1.266	1.575	1.105	0.233	0.424
variation	5.85%	4.98%	4.79%	7.49%	10.43%	9.00%

[1)] energy groups with boundaries: $14.918\times10^6 - 1.353\times10^6 - 0.0674\times10^6 - 0.683 - 0$ eV

Table 9: Comparison of fluxes and fluences

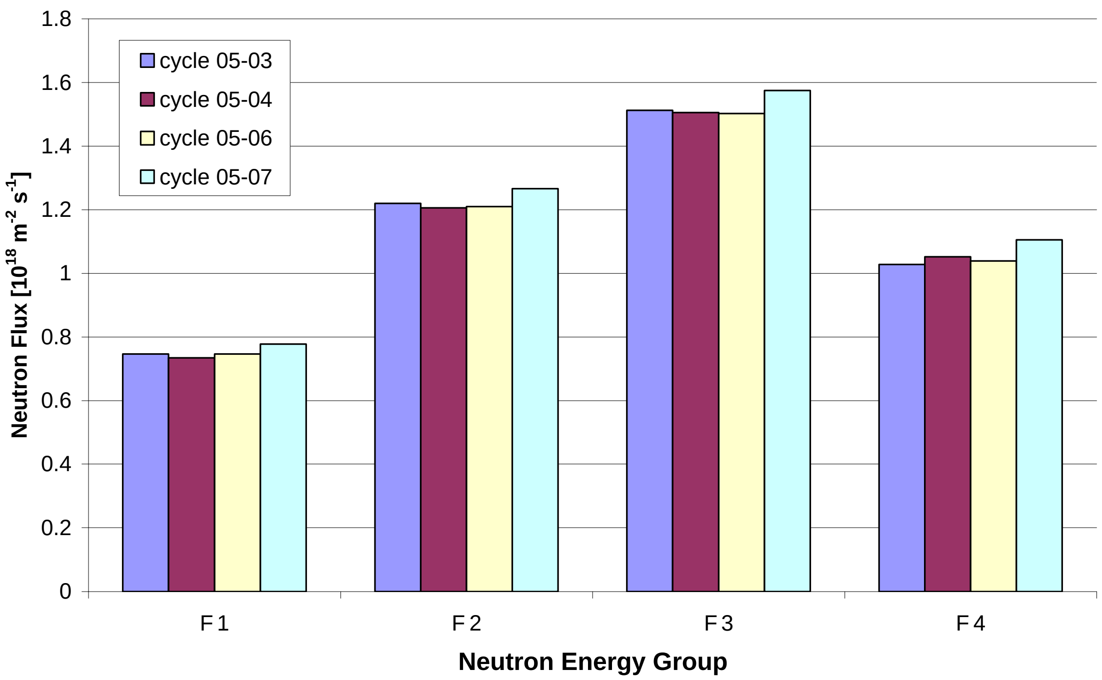


Figure 2: Comparison of neutron fluxes in the four cycles

3 Reactor Power and Control Rod Positions

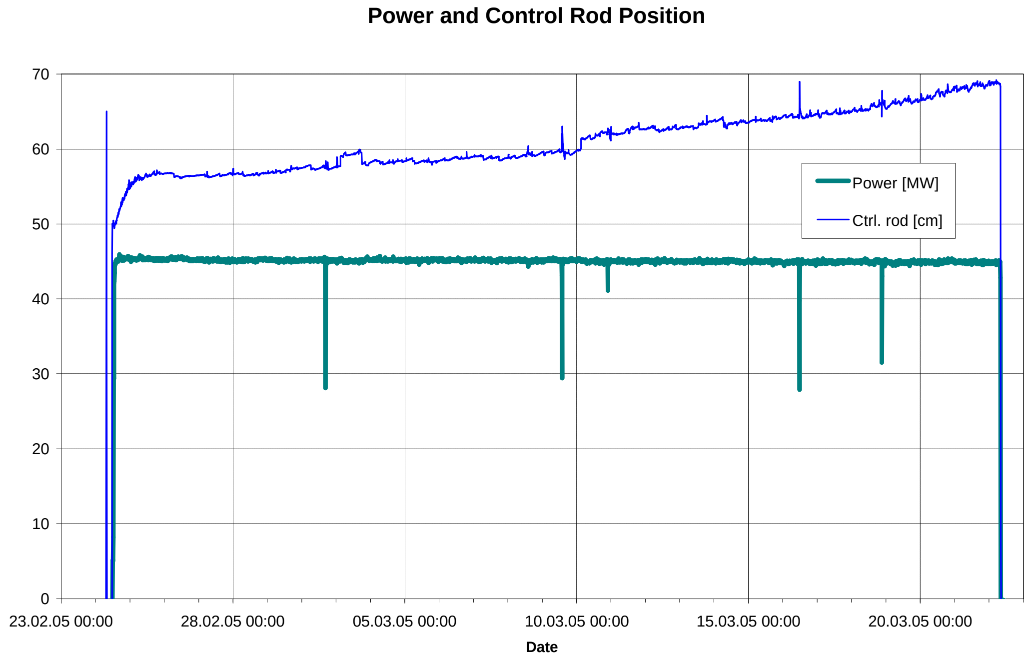


Figure 3: Reactor Power/Control Rod position cycle 05-03

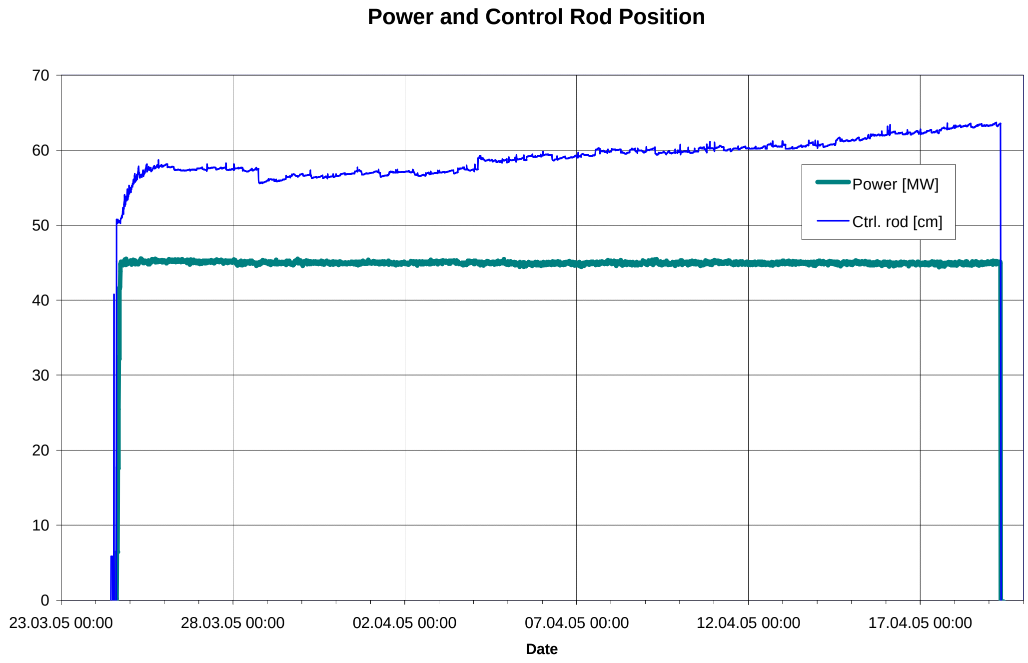


Figure 4: Reactor Power/Control Rod position cycle 05-04

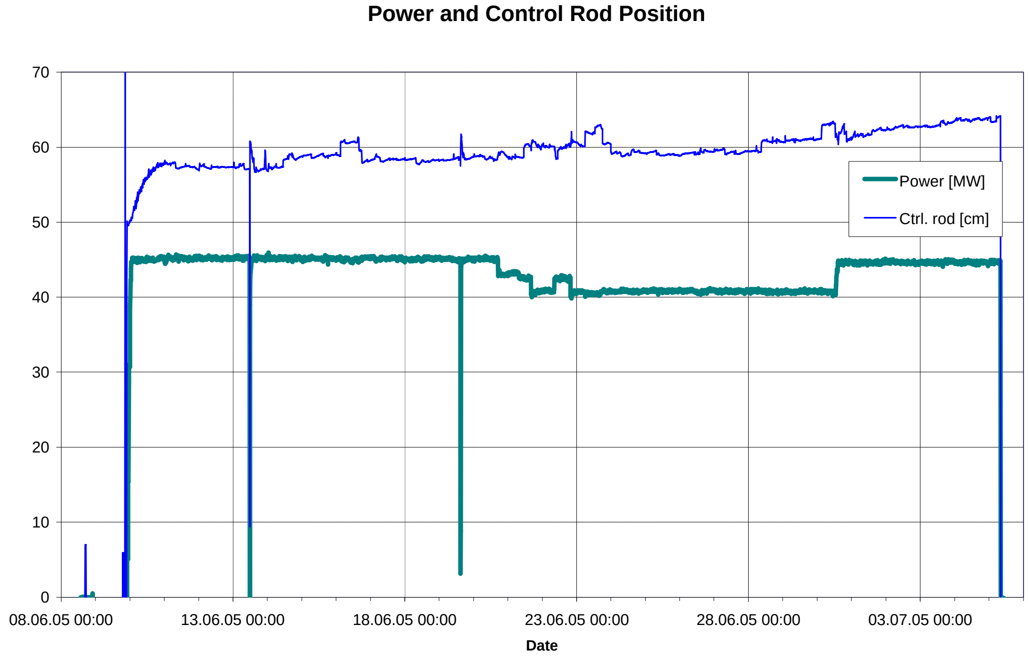


Figure 5: Reactor Power/Control Rod position cycle 05-06

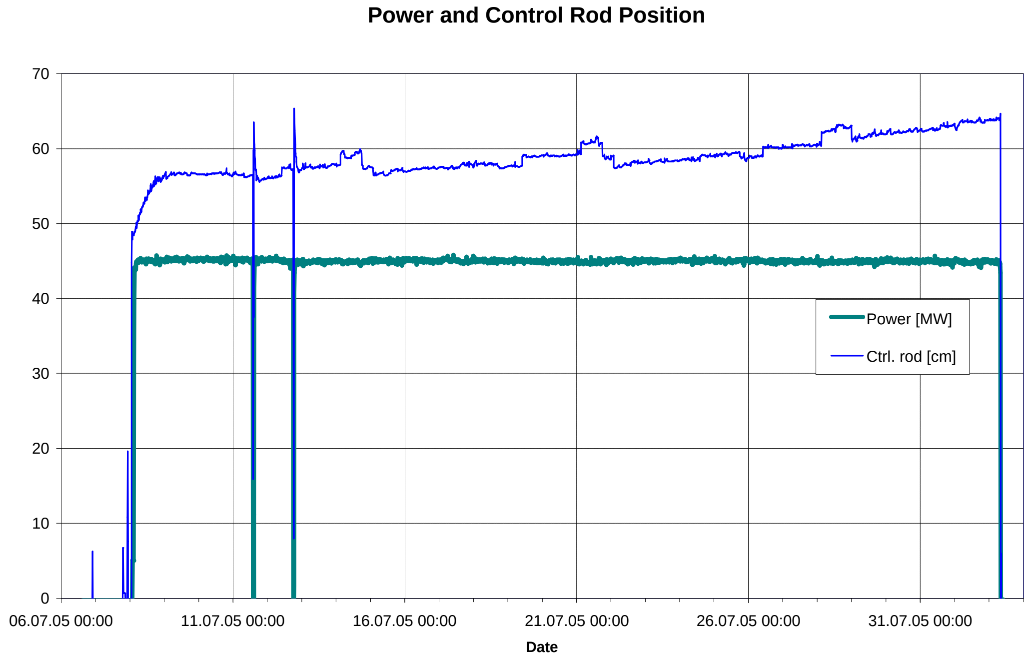


Figure 6: Reactor Power/Control Rod position cycle 05-07

4 Vertical Displacement Unit (VDU) Position

The VDU was not used since the beginning of the irradiation and was held in the lowest possible position. The very small measured differences are artifacts related to the data acquisition system.

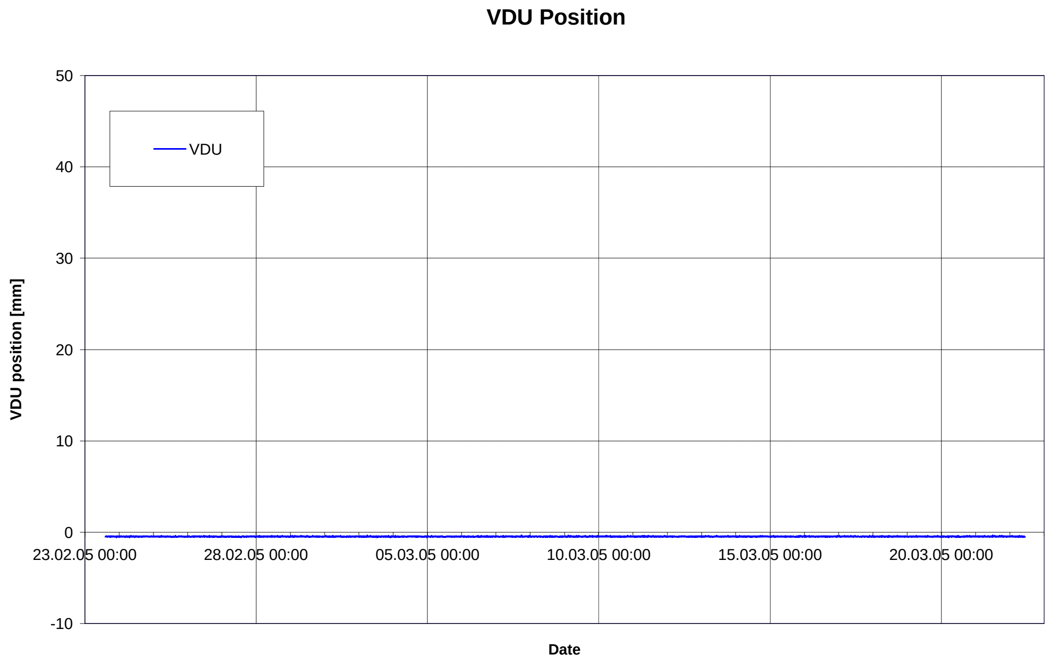


Figure 7: VDU position cycle 05-03

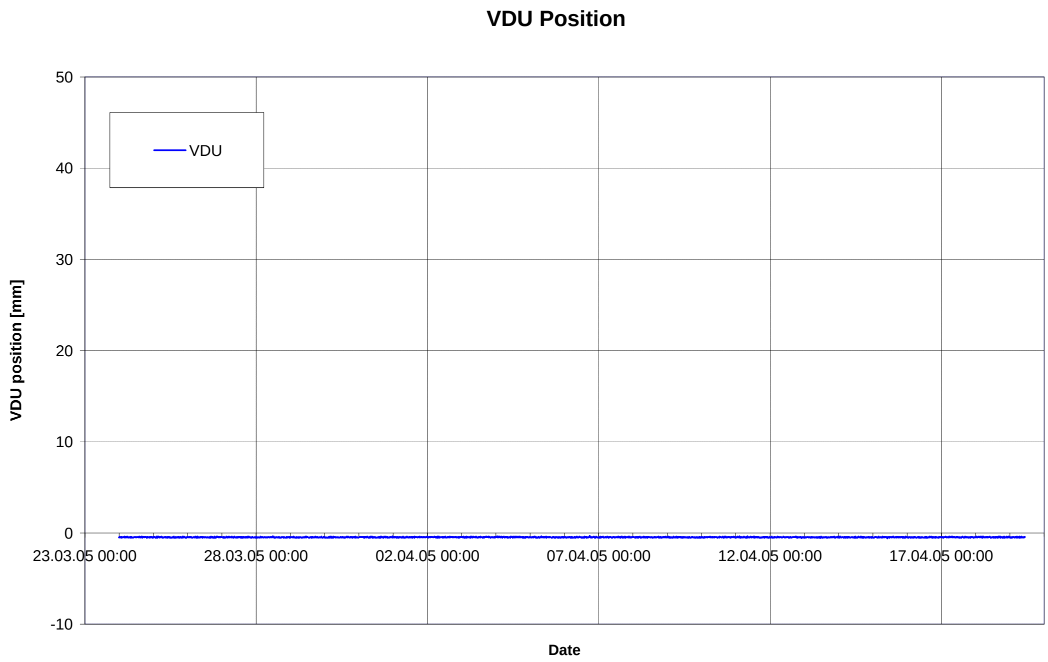


Figure 8: VDU position cycle 05-04

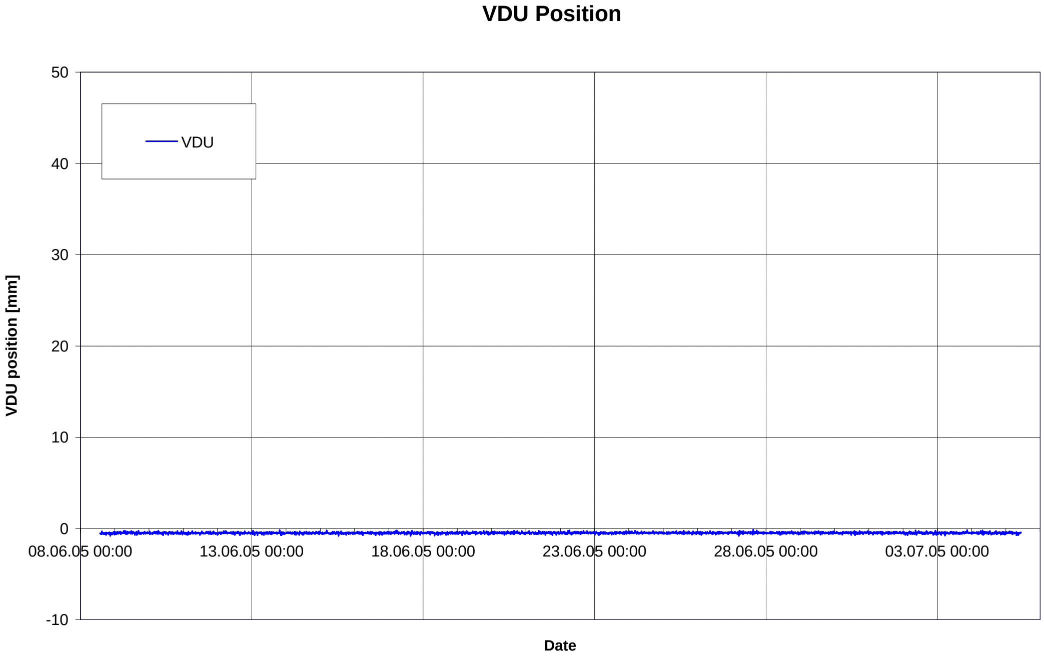


Figure 9: VDU position cycle 05-06

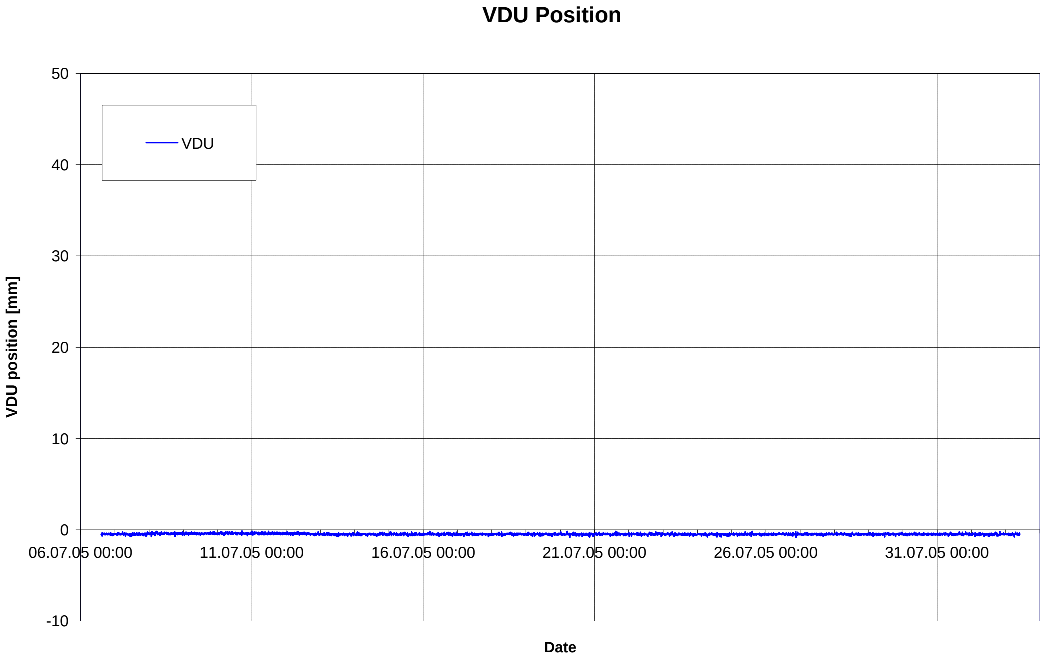


Figure 10: VDU position cycle 05-07

5 Counter Readings in Gas Panel (GM1 and GM3)

The Geiger-Müller counter readings of the two counters in the gas panel (GM1 and GM3) are at background level (2 V) when the gas is stagnant. Higher activities are only measured during purging (3.5 V) and in particular when activating the filter bypass (5.5 V stabilized), generally before taking a gas sample.

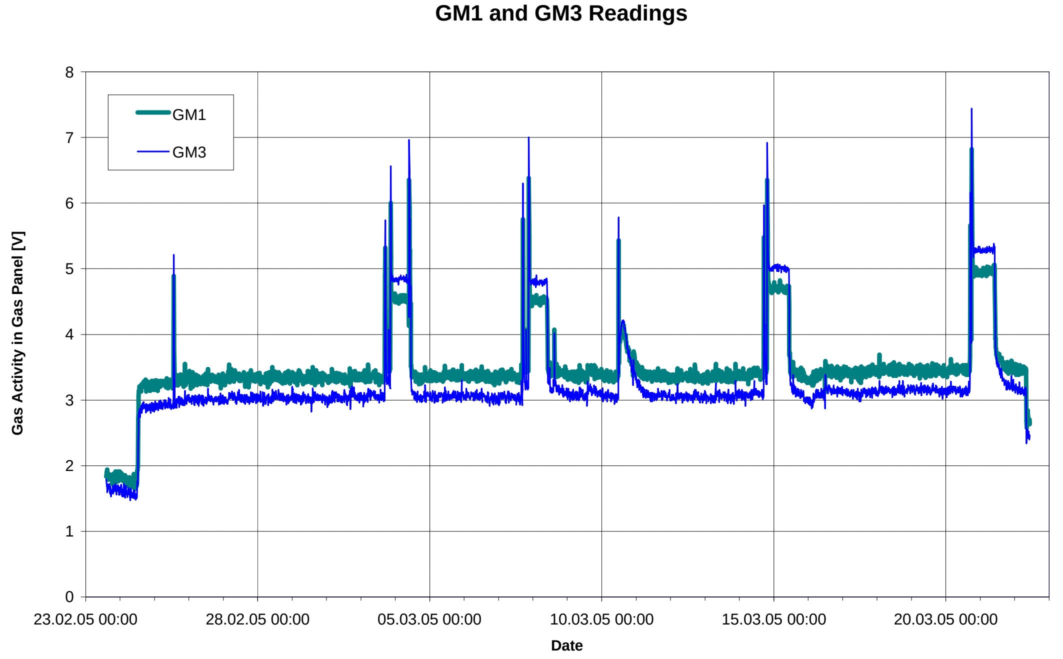


Figure 11: GM1 readings cycle 05-03

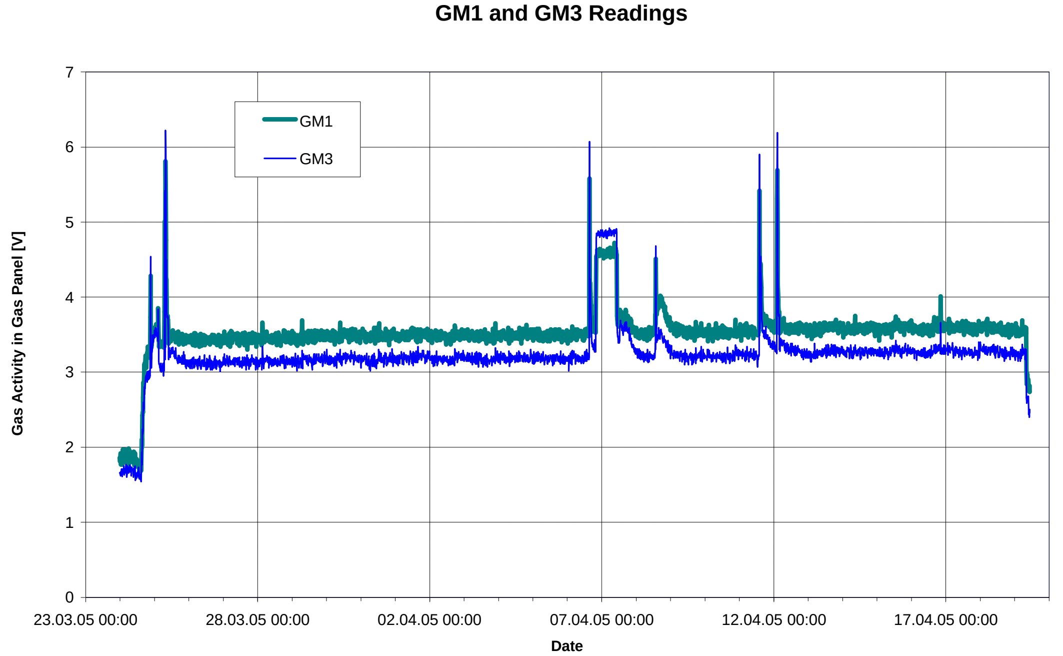


Figure 12: GM1 readings cycle 05-04

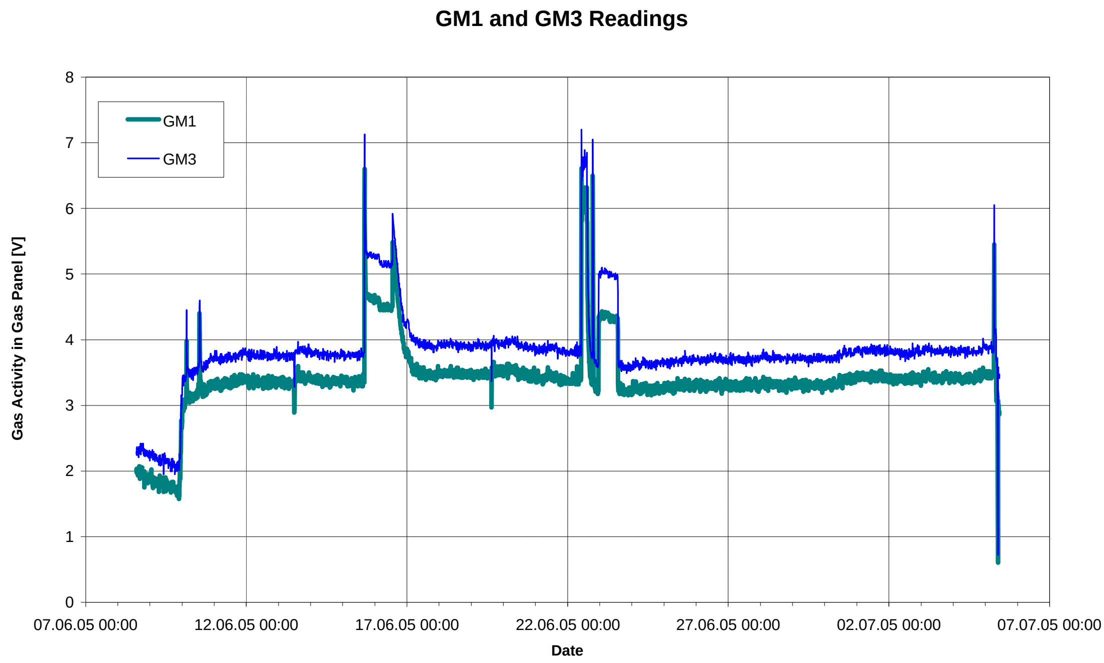


Figure 13: GM1 and GM3 readings cycle 05-06

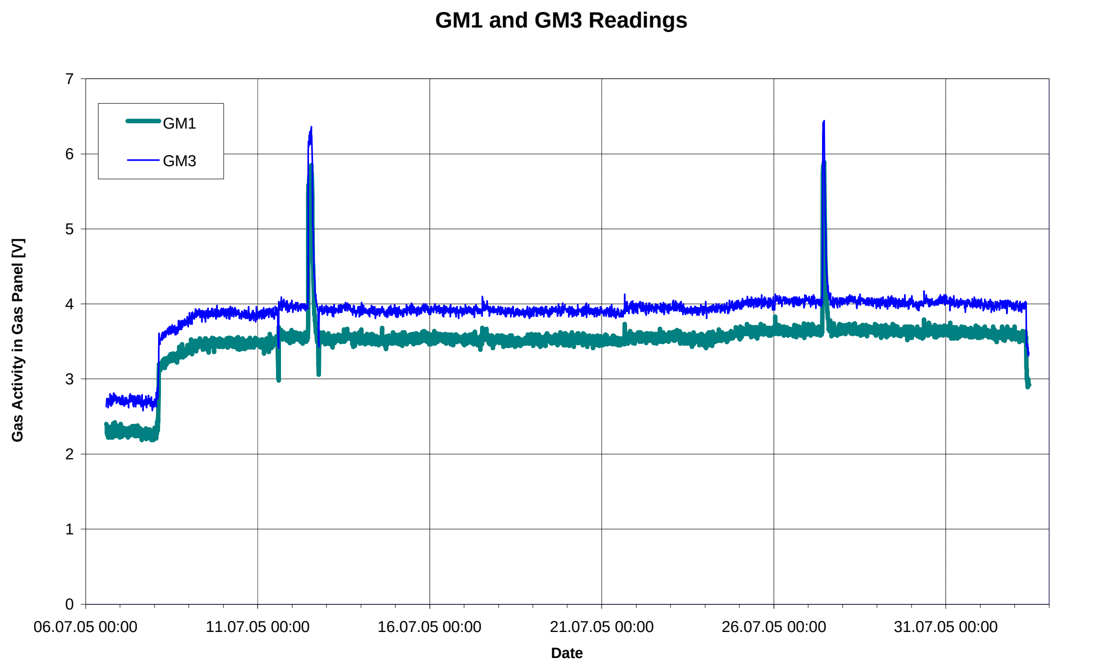


Figure 14: GM1 and GM3 readings cycle 05-07

6 Temperature Measurements

After the first 4 cycles, **5** out of 24 thermocouples provided no or wrong information, only one of those failed (TC-09) has no backup.

TC-12 seems to have been recovered from cycle 05-04 on (contact problem in connector). In return, TC-21 shows now values that are seemingly too low and erratic.

Location	TC #	
1 Graphite	**1**, 2, 3	TC-01 no contact since 29.12.2004
GLE4.1	4, 5, 6	
Graphite between GLE4.1 and GLE4.2	7, 8	TC-08 sometimes erratic values since beginning
GLE4.2	**9**	TC-09 erroneous value since 29.12.2004
Graphite between GLE4.2 and GLE4.3	10, 11	
GLE4.3	**12**, 13	TC-12 too low since beginning, returned to correct values from cycle 05-04 onwards
Graphite between GLE4.3 and GLE4.4	14, **15**	TC-15 slipped? values too low since 17.02.2005
GLE4.4	16	
Graphite between GLE4.4 and GLE4.5	17, 18	
GLE4.5	19, 20, **21**	TC-21 values too low and erratic since 05-03
Graphite between GLE4.5 and Al block	**22**, 23	TC-22 no contact or erroneous values since 29.12.2004
Aluminum Block	24	

Table 10: Location of thermocouples, malfunction is indicated in **bold red**

Table 11 shows the calculated surface temperatures of the 5 pebbles that would keep their central temperatures constant at 1250°C [1].

	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	3948	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 11: Predicted power and temperature evolution per pebble and required gas mixture per cycle; *: cycles 13 and 14 require pure N_2 in 1st containment

6.1 Temperatures during Cycle 05-03

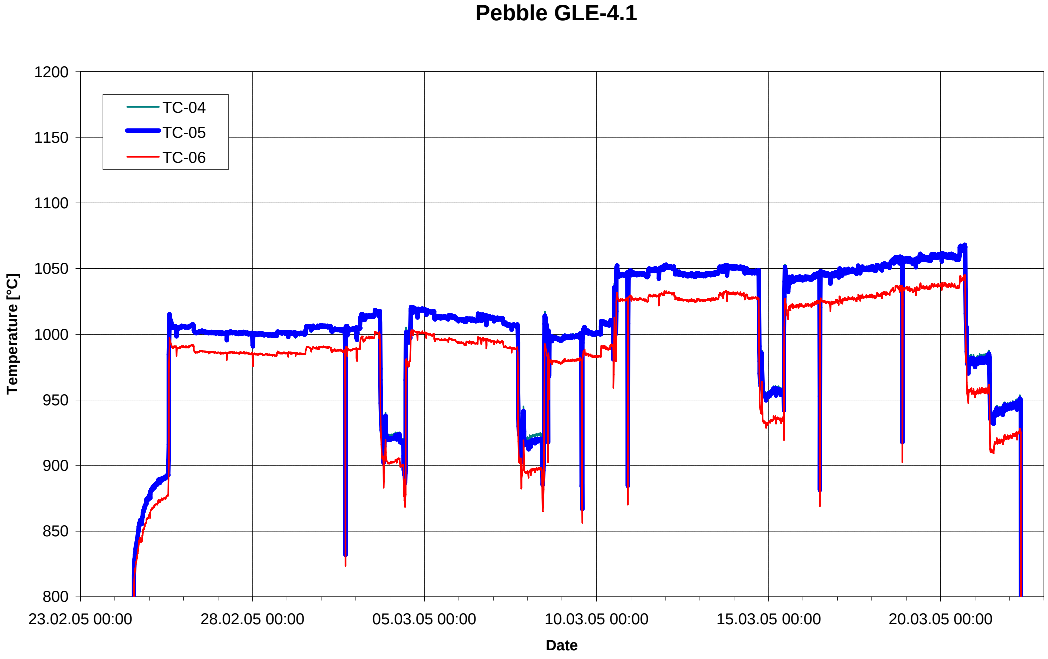


Figure 15: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

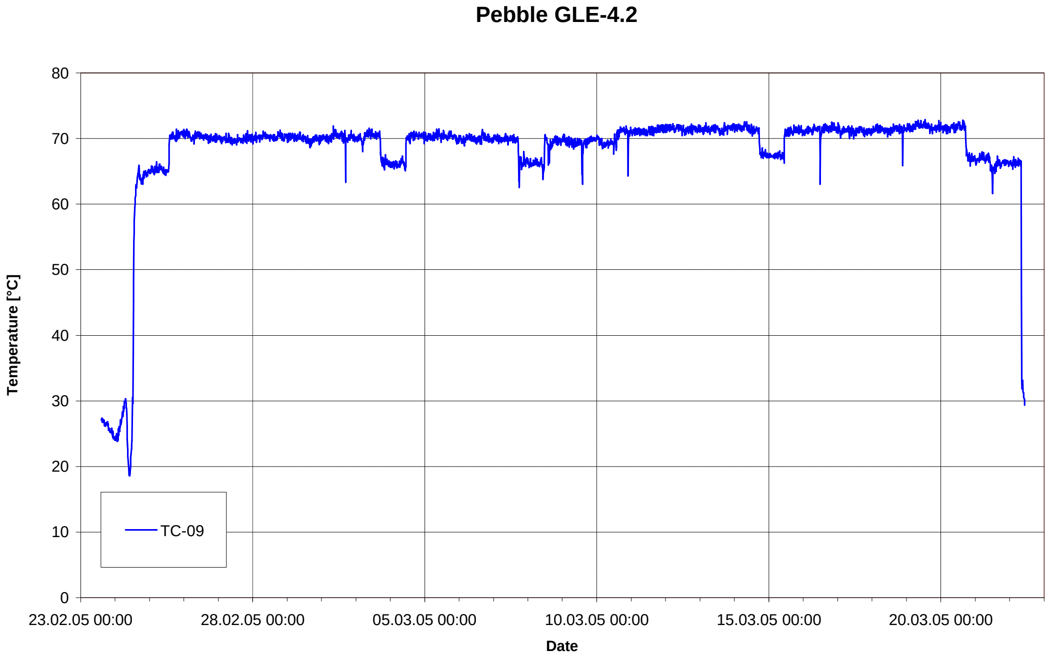


Figure 16: Temperature pebble GLE4.2 (TC-09)

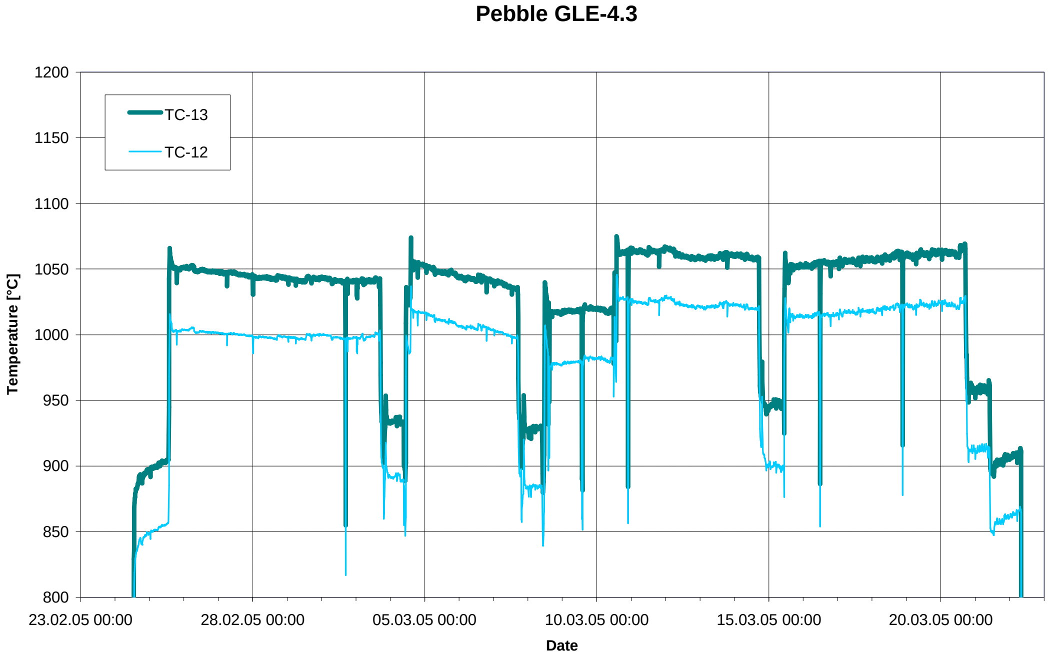


Figure 17: Temperatures pebble GLE4.3 (TC-12, TC-13)

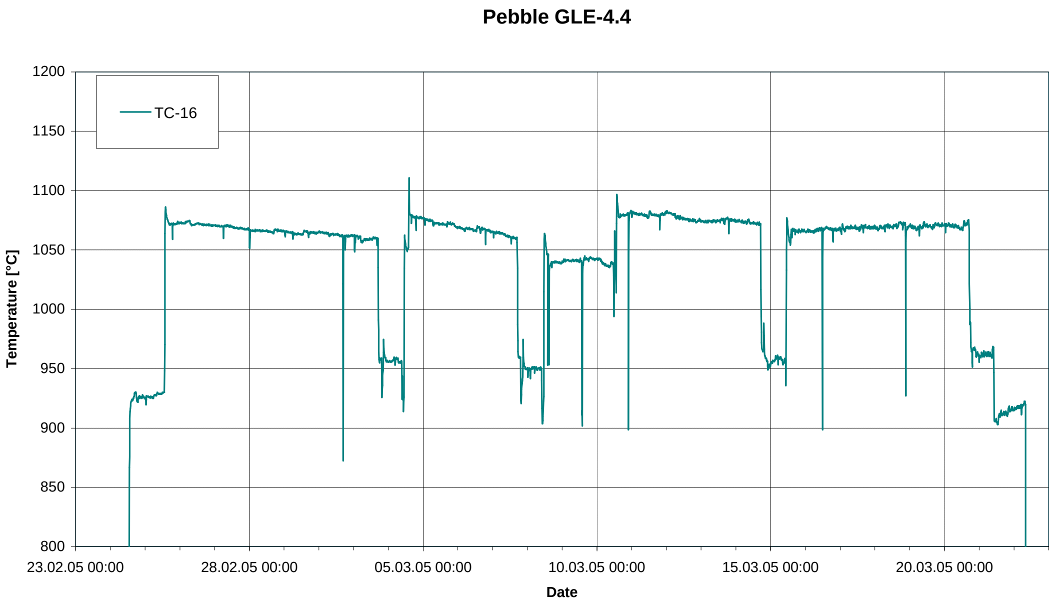


Figure 18: Temperature pebble GLE4.4 (TC-16)

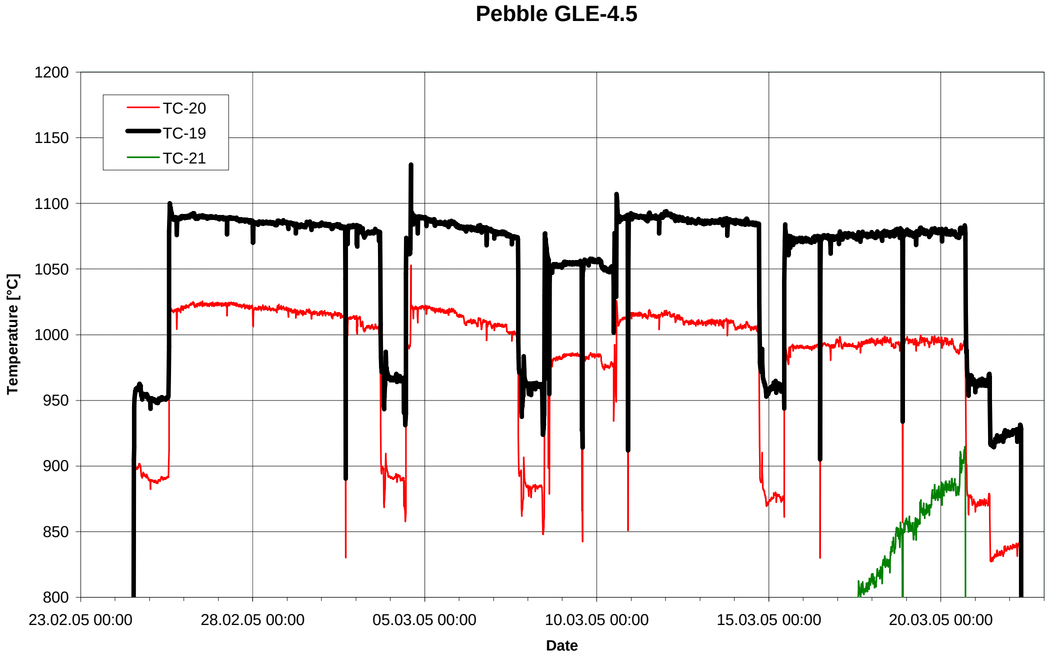


Figure 19: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

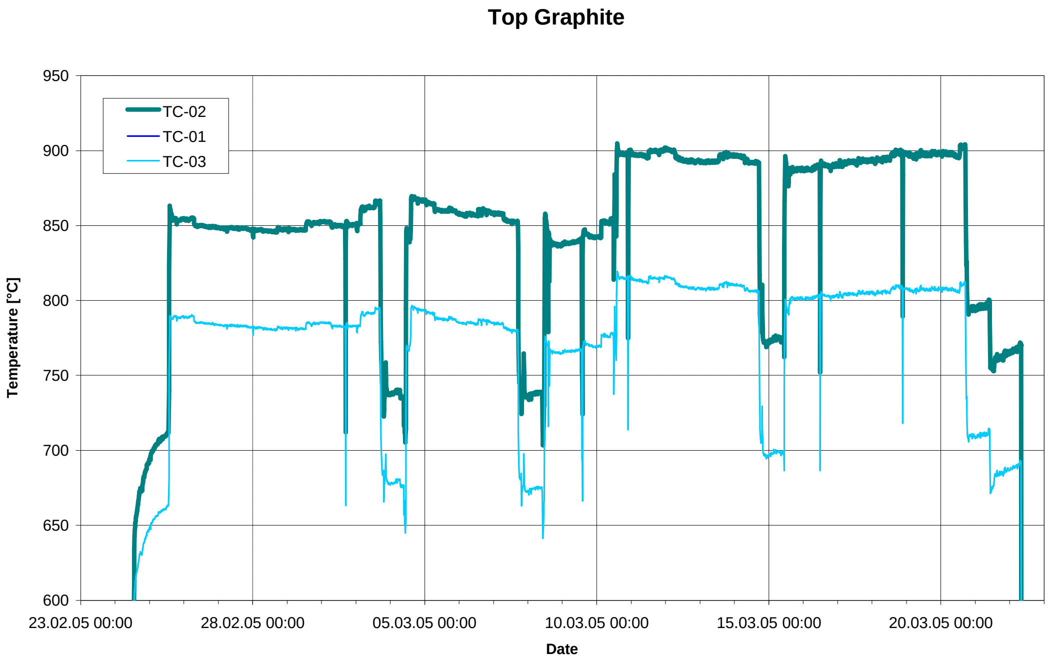


Figure 20: Temperatures top graphite (TC-01, TC-02, TC-03)

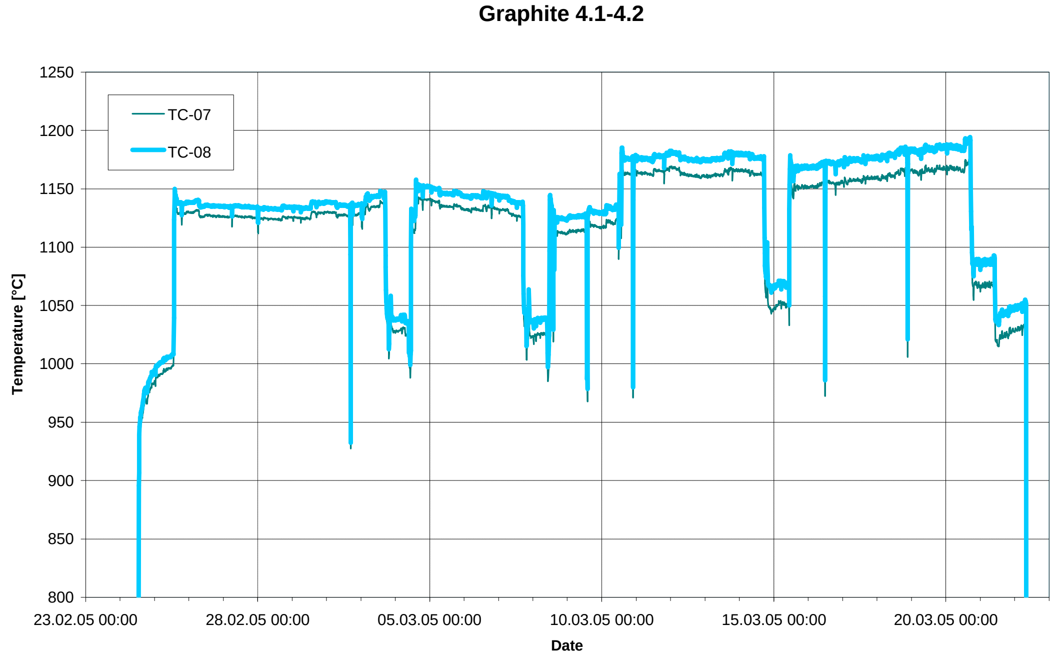


Figure 21: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

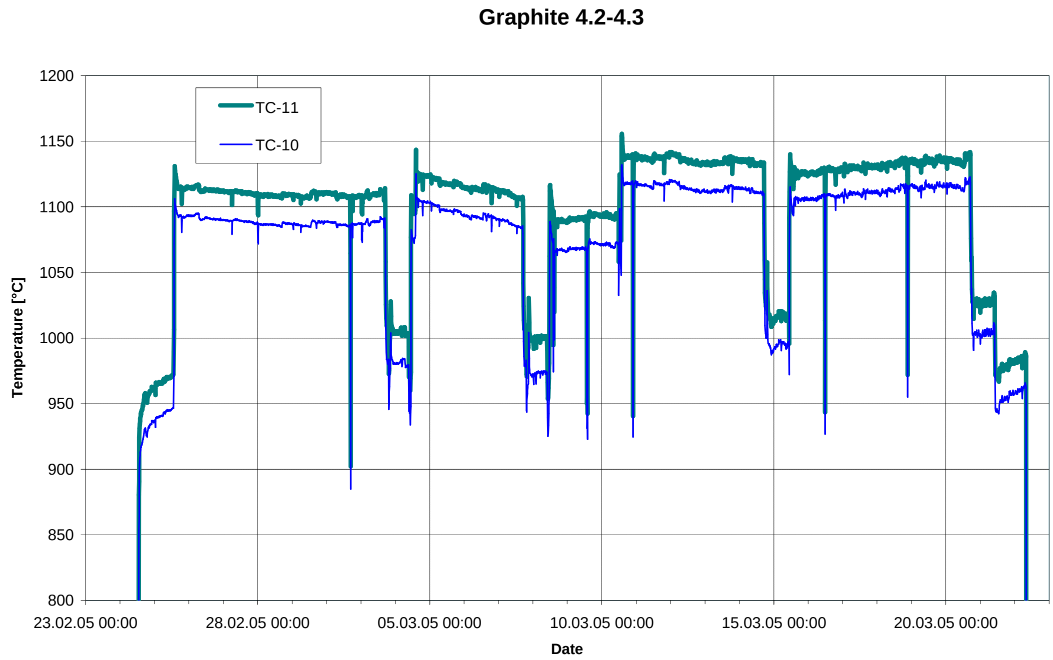


Figure 22: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

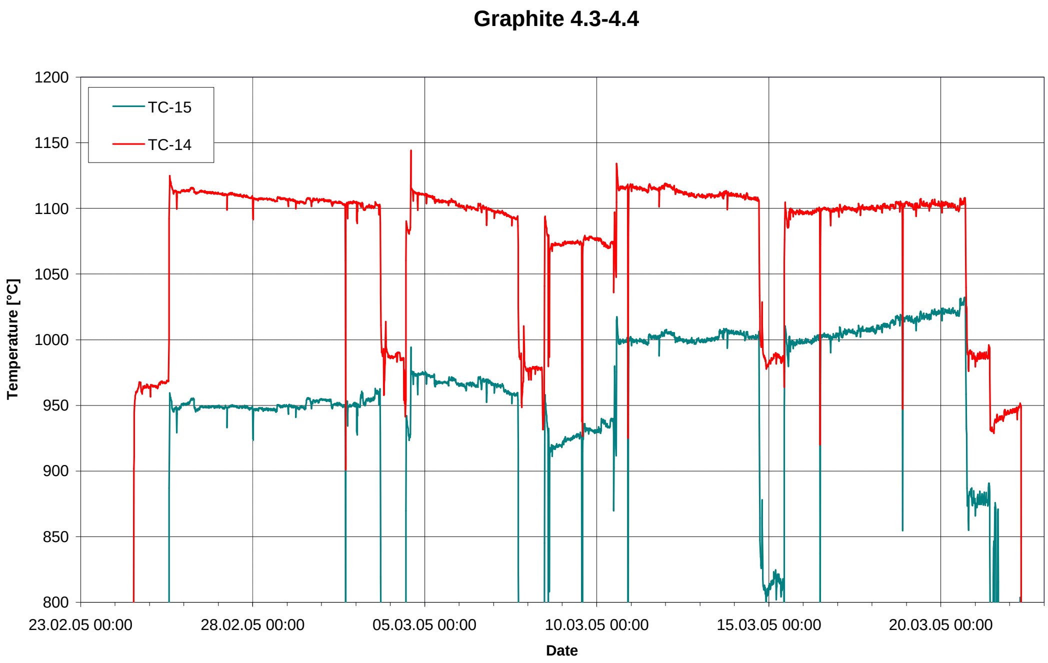


Figure 23: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

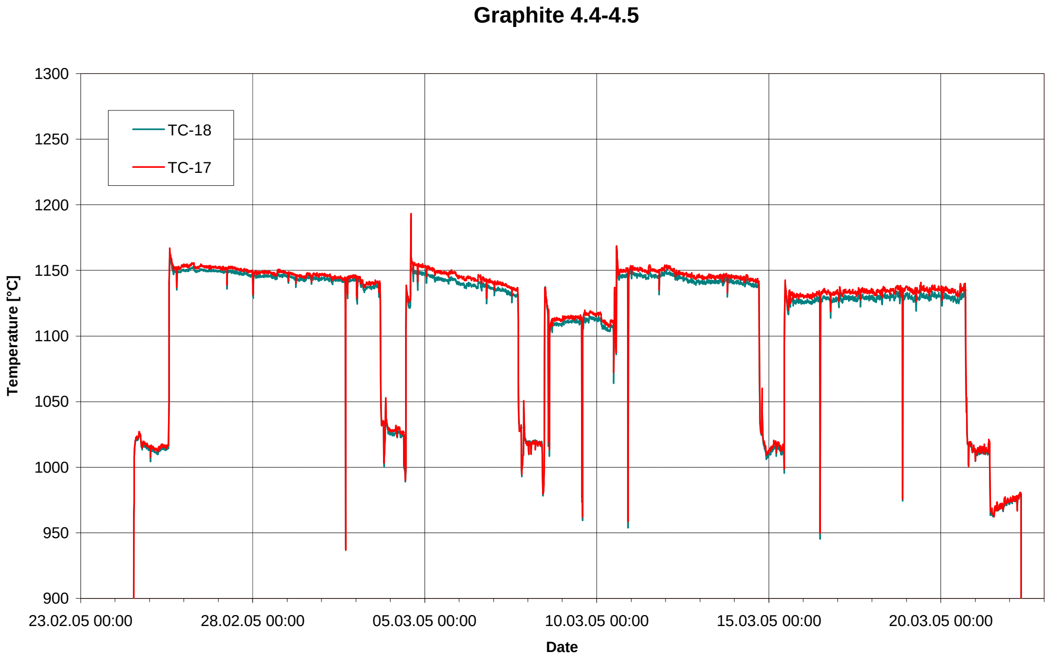


Figure 24: Temperature graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

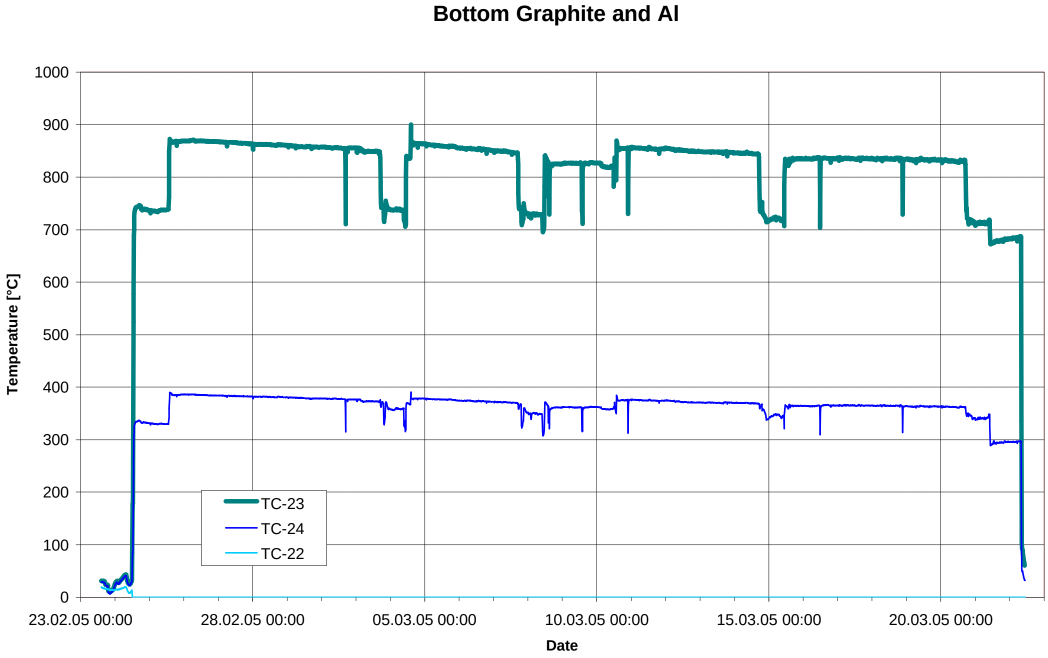


Figure 25: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
TC-01	1.2	0.4		Graphite
TC-02	847.7	865.6		
TC-03	772.2	788.8		
TC-04	1007.5	1021.2	1053	GLE4.1
TC-05	1007.1	1021.0		
TC-06	988.4	1002.5		
TC-07	1120.8	1137.6		Graphite
TC-08	1133.7	1150.3		
TC-09	69.8	70.4	1065	GLE4.2
TC-10	1074.1	1093.1		Graphite
TC-11	1095.8	1114.3		
TC-12	984.1	1003.4	1062	GLE4.3
TC-13	1024.9	1043.2		
TC-14	1077.7	1097.0		Graphite
TC-15	929.7	965.8		
TC-16	1043.0	1061.9	1066	GLE4.4
TC-17	1115.5	1135.2		Graphite
TC-18	1112.0	1131.2		
TC-19	1055.5	1074.5	1052	GLE4.5
TC-20	980.6	1000.4		
TC-21	567.3	625.2		
TC-22	0.0	0.0		Graphite
TC-23	823.3	842.7		
TC-24	364.7	370.3		Al block

Table 12: Time averaged temperature readings during cycle 05-03

6.2 Temperatures during Cycle 05-04

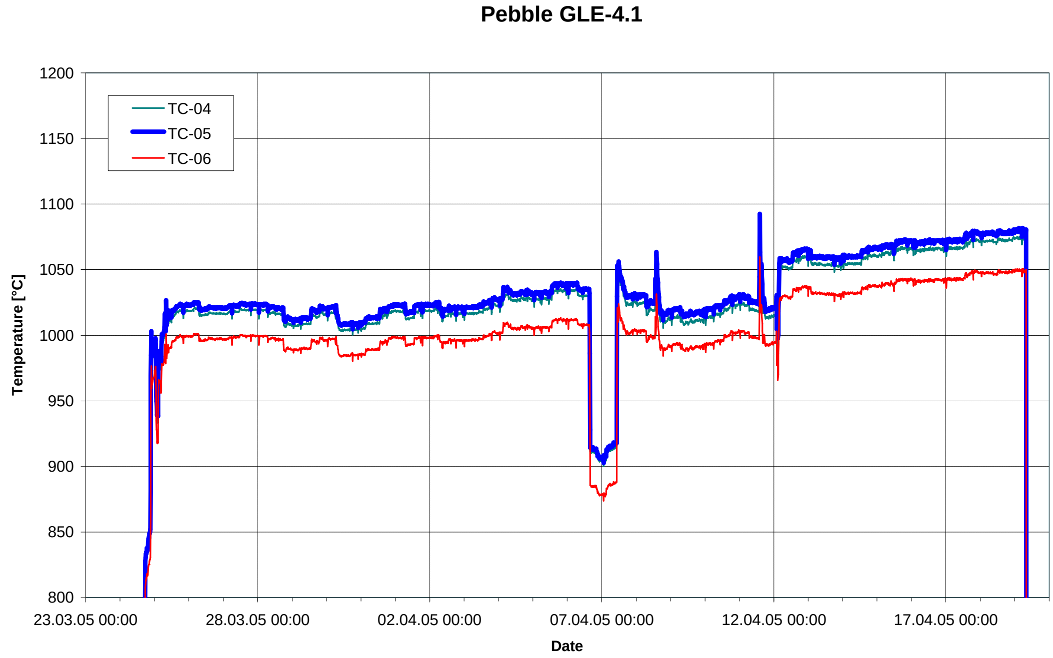


Figure 26: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

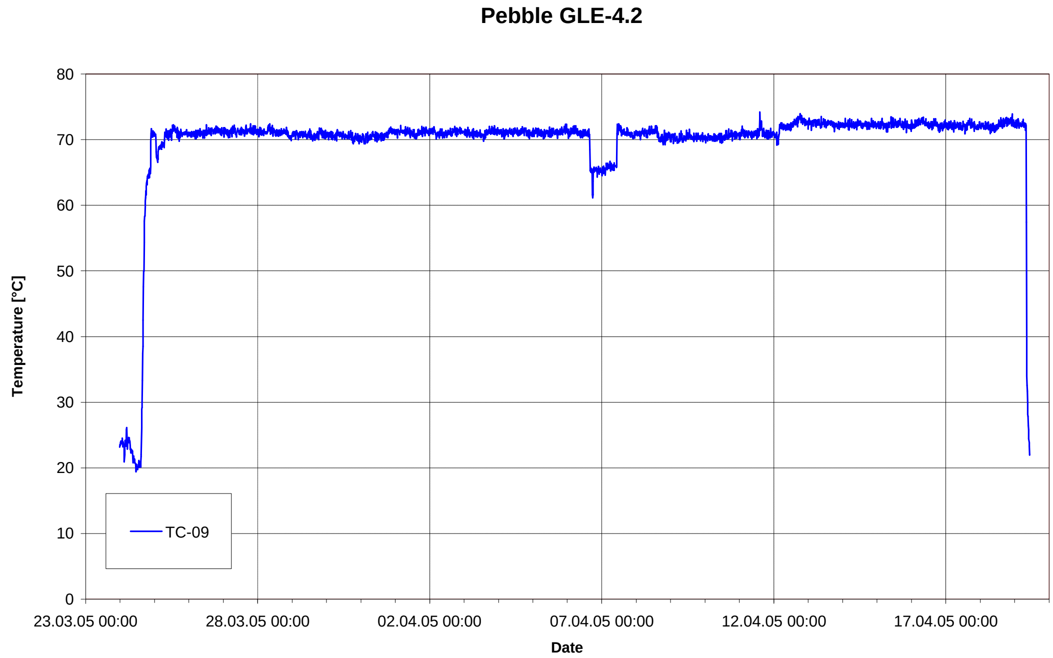


Figure 27: Temperature pebble GLE4.2 (TC-09)

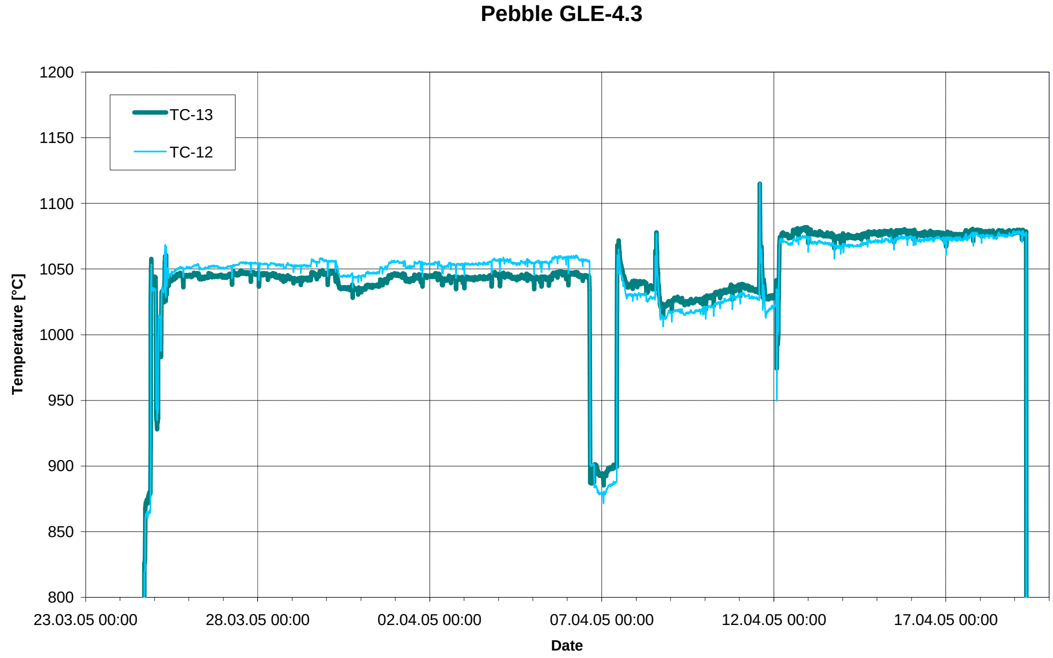


Figure 28: Temperatures pebble GLE4.3 (TC-12, TC-13)

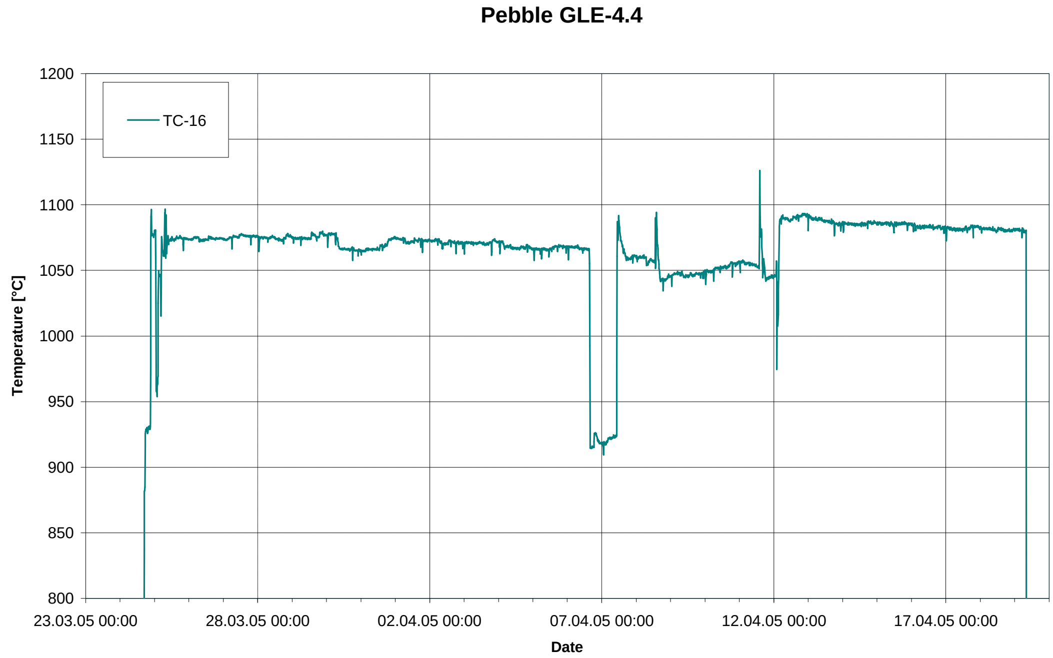


Figure 29: Temperature pebble GLE4.4 (TC-16)

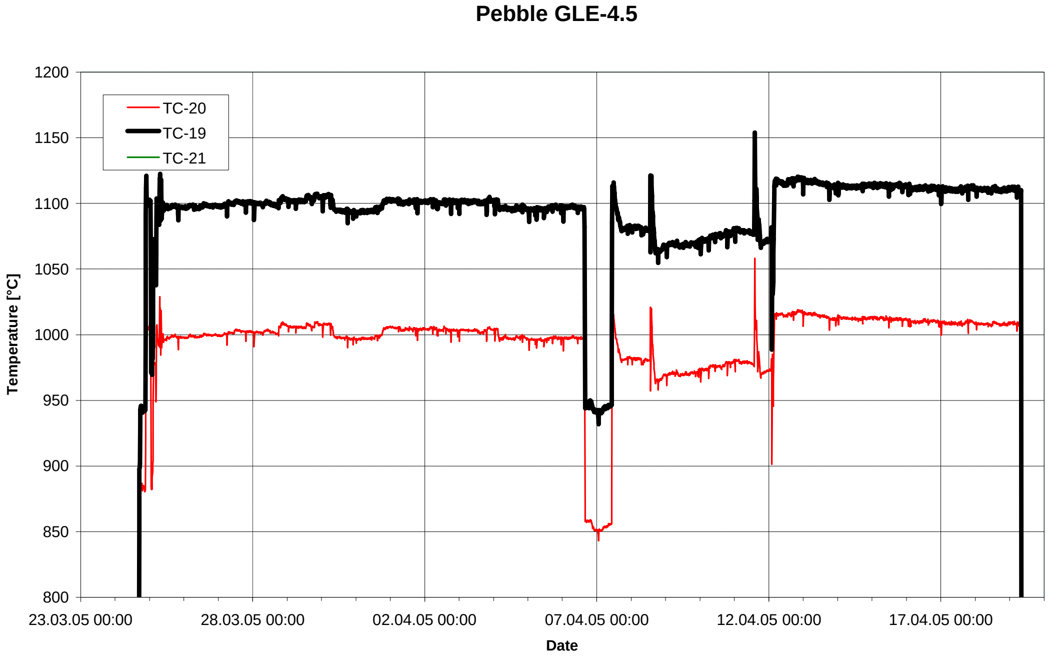


Figure 30: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

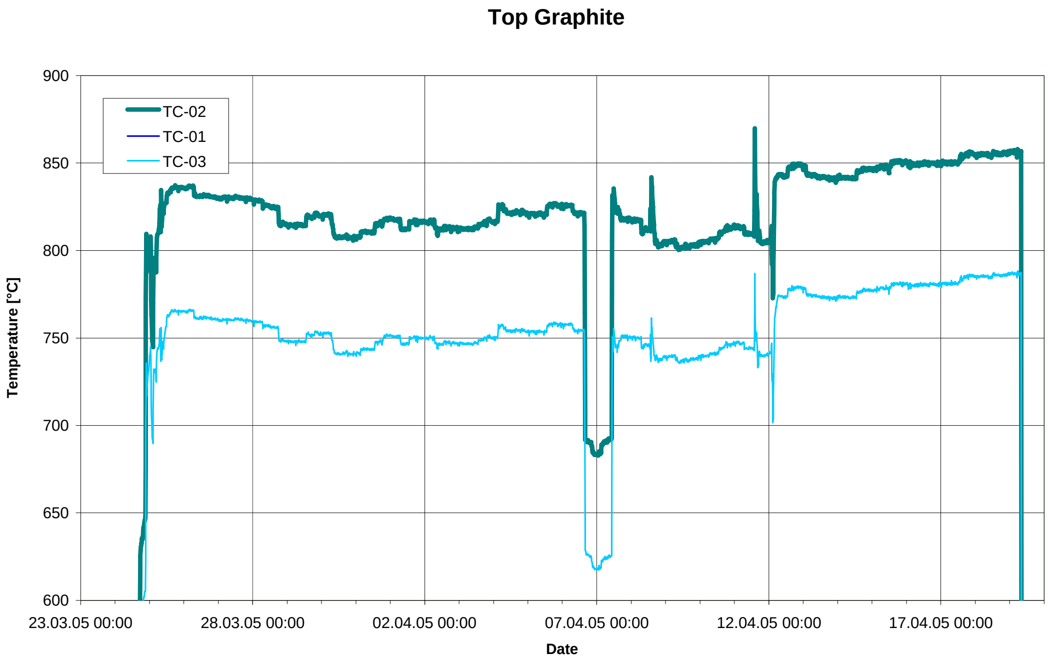


Figure 31: Temperatures top graphite (TC-01, TC-02, TC-03)

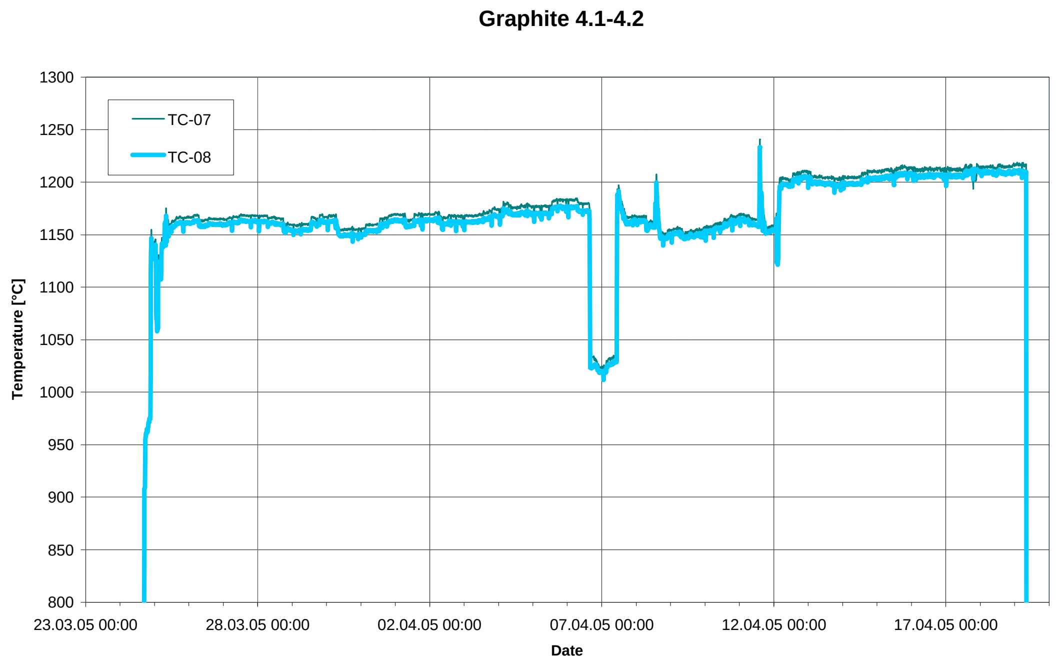


Figure 32: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

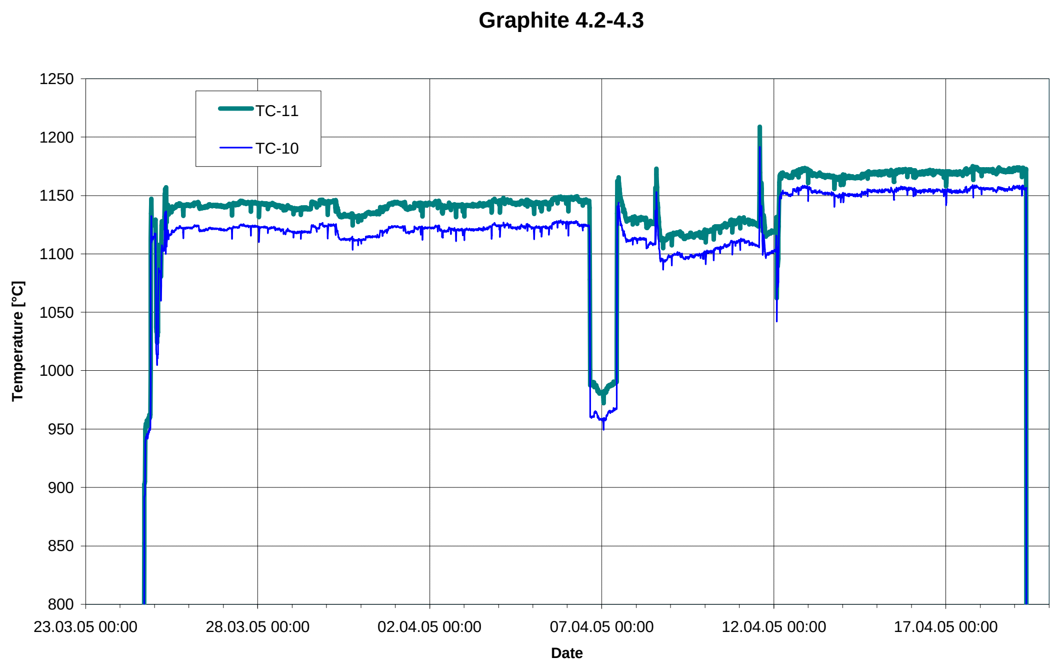


Figure 33: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

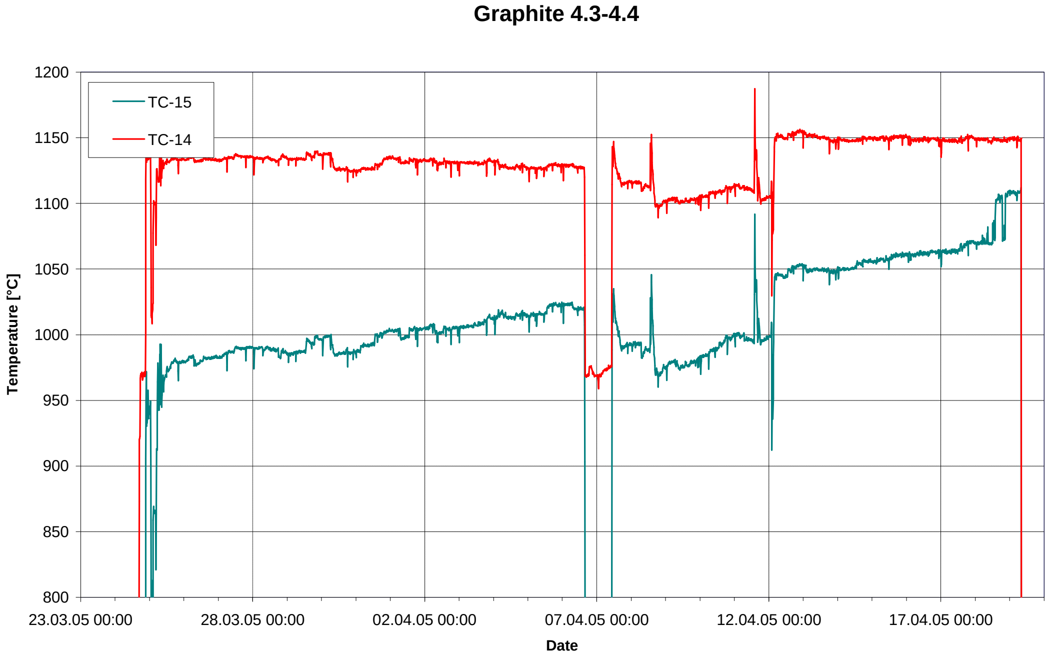


Figure 34: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

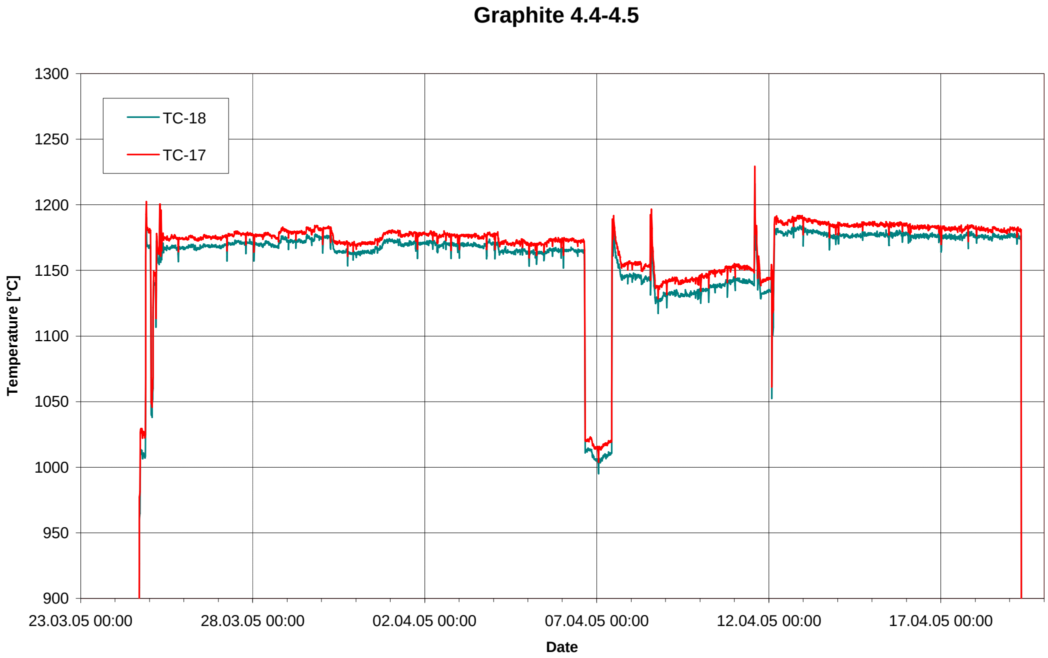


Figure 35: Temperatures graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

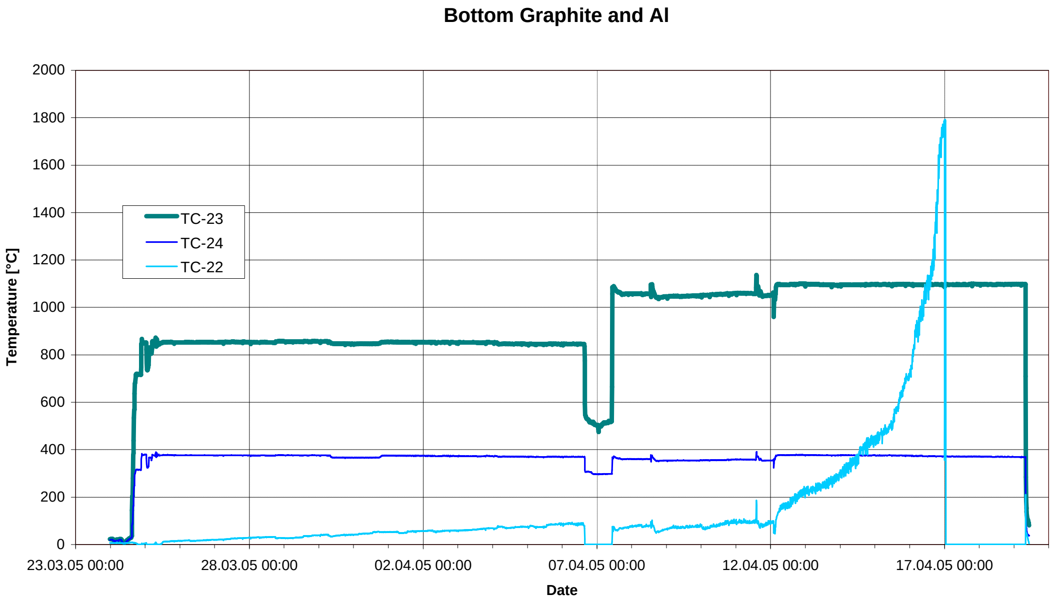


Figure 36: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
TC-01	2.3	2.8		Graphite
TC-02	820.9	817.2		
TC-03	753.1	749.3		
TC-04	1025.8	1016.1	1058	GLE4.1
TC-05	1030.9	1021.2		
TC-06	1004.4	995.8		
TC-07	1172.7	1166.0		Graphite
TC-08	1167.1	1159.9		
TC-09	71.1	71.1	1074	GLE4.2
TC-10	1121.2	1123.2		Graphite
TC-11	1139.7	1139.6		
TC-12	1046.5	1046.7	1072	GLE4.3
TC-13	1044.9	1047.5		
TC-14	1126.1	1132.6		Graphite
TC-15	997.9	989.8		
TC-16	1065.9	1073.6	1075	GLE4.4
TC-17	1166.9	1175.2		Graphite
TC-18	1159.1	1165.9		
TC-19	1092.5	1099.0	1060	GLE4.5
TC-20	993.9	1001.6		
TC-21	473.8	405.4		
TC-22	136.1	97.9		Graphite
TC-23	946.2	927.0		
TC-24	368.2	372.9		Al block

Table 13: Time averaged temperature readings during cycle 05-04

6.3 Temperatures during Cycle 05-06

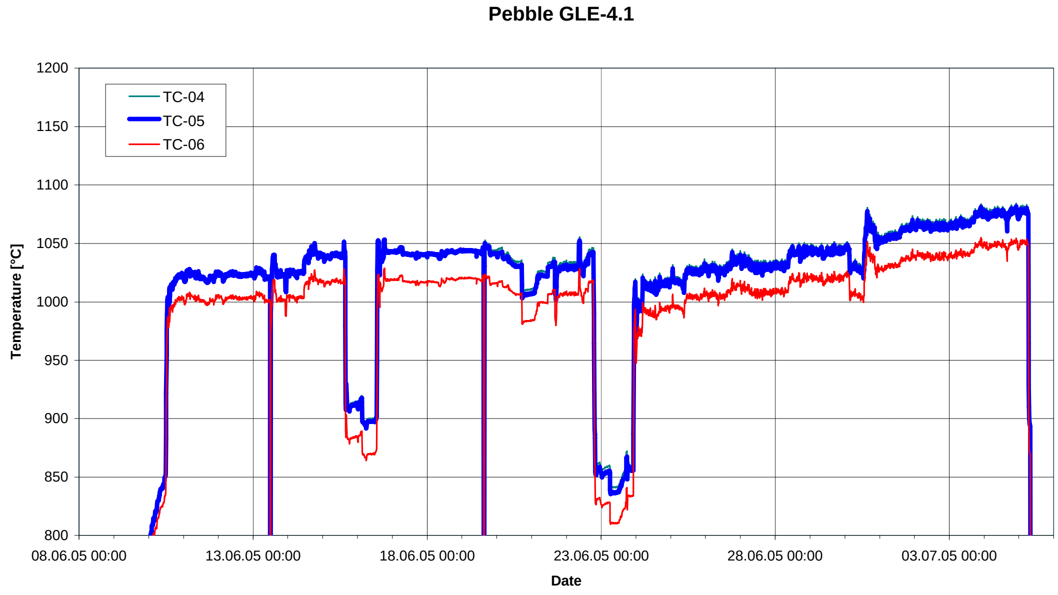


Figure 37: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

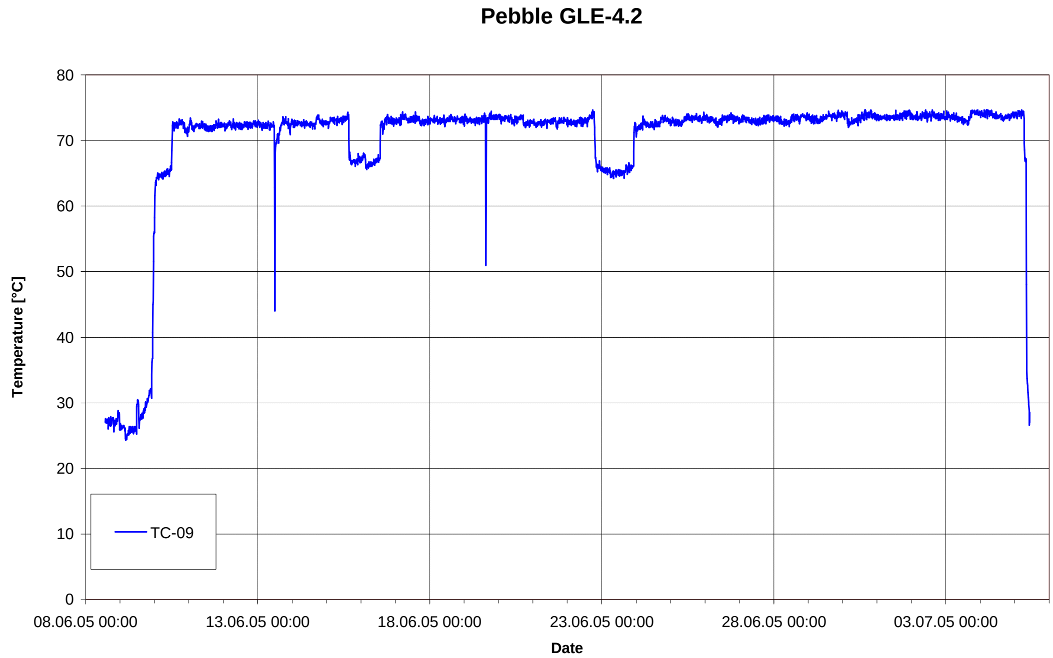


Figure 38: Temperature pebble GLE4.2 (TC-09)

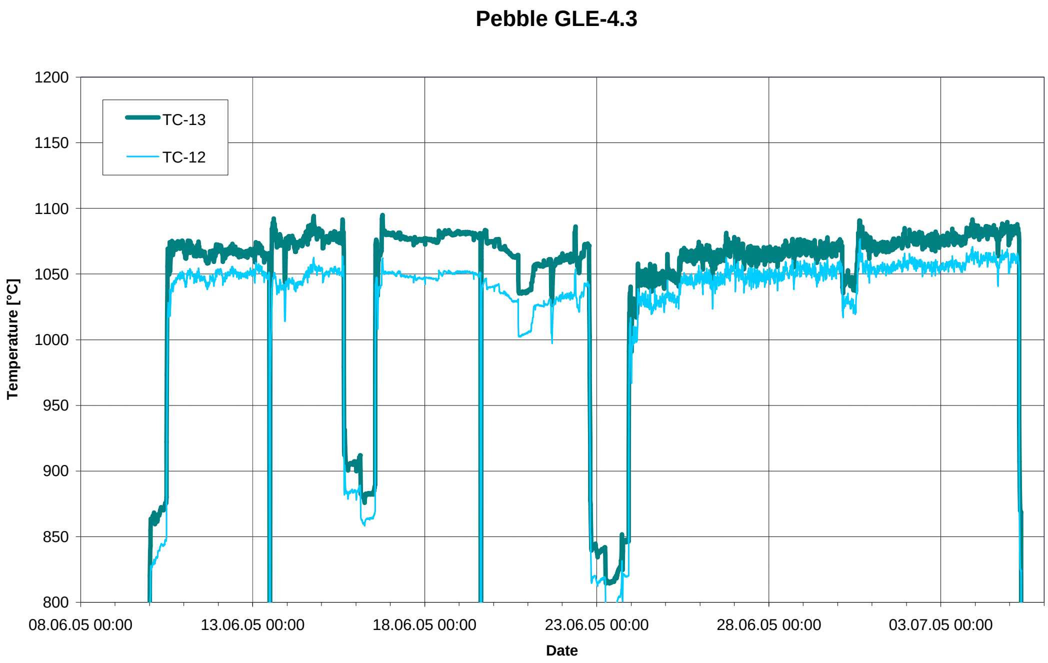


Figure 39: Temperatures pebble GLE4.3 (TC-12, TC-13)

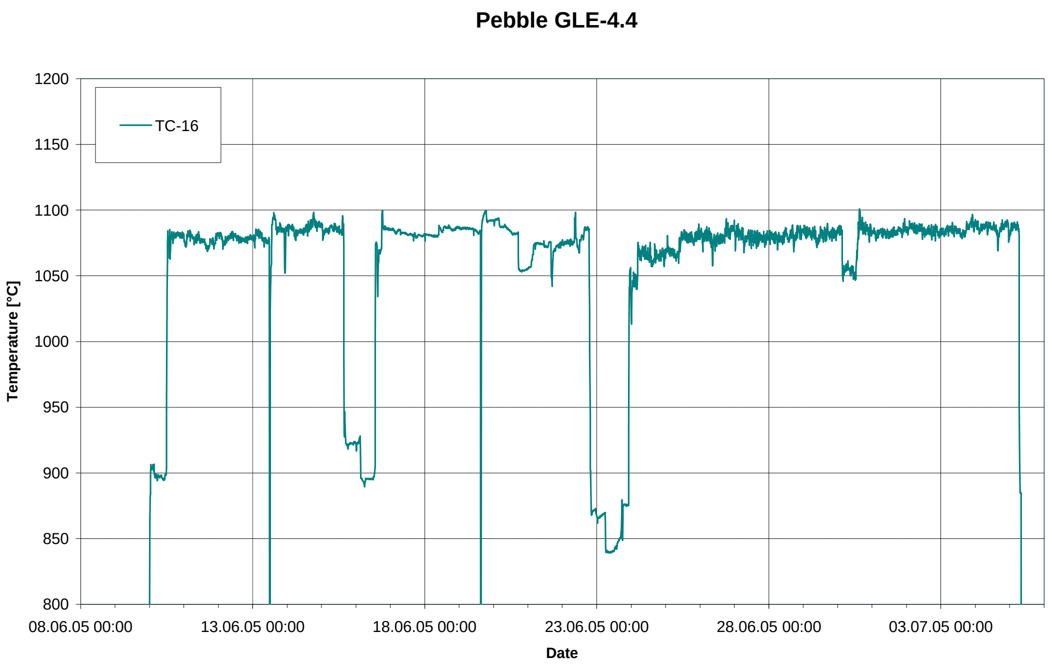


Figure 40: Temperature pebble GLE4.4 (TC-16)

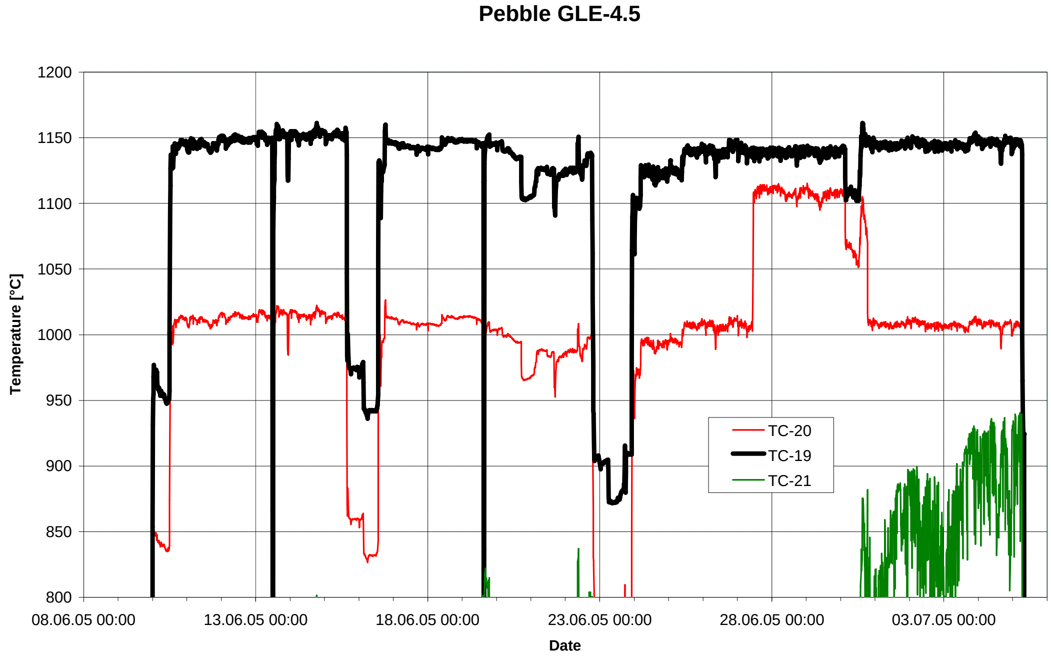


Figure 41: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

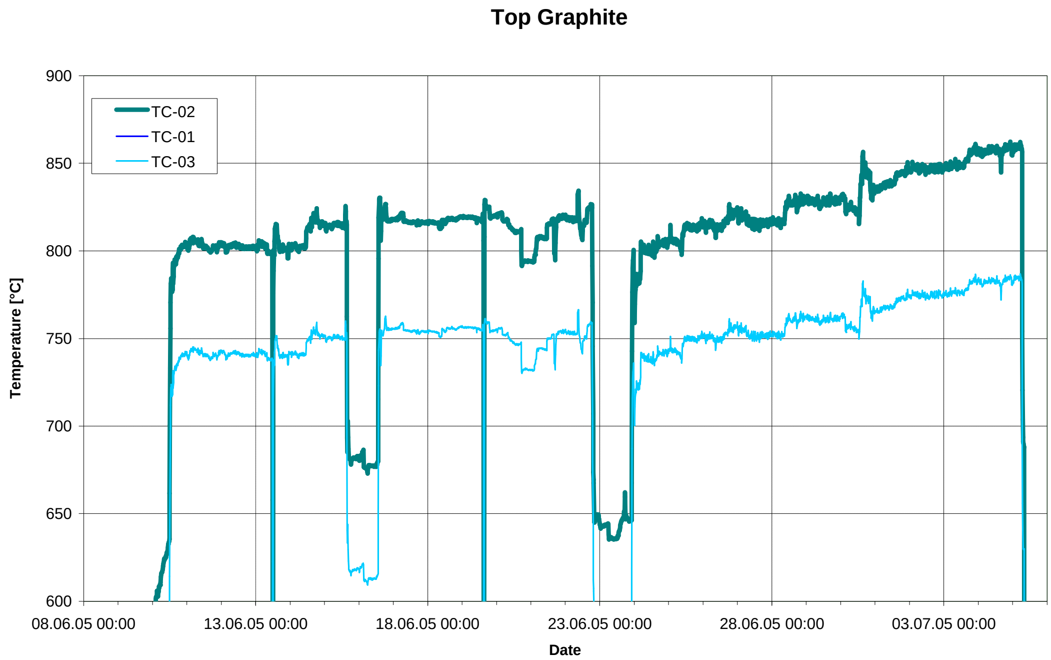


Figure 42: Temperatures top graphite (TC-01, TC-02, TC-03)

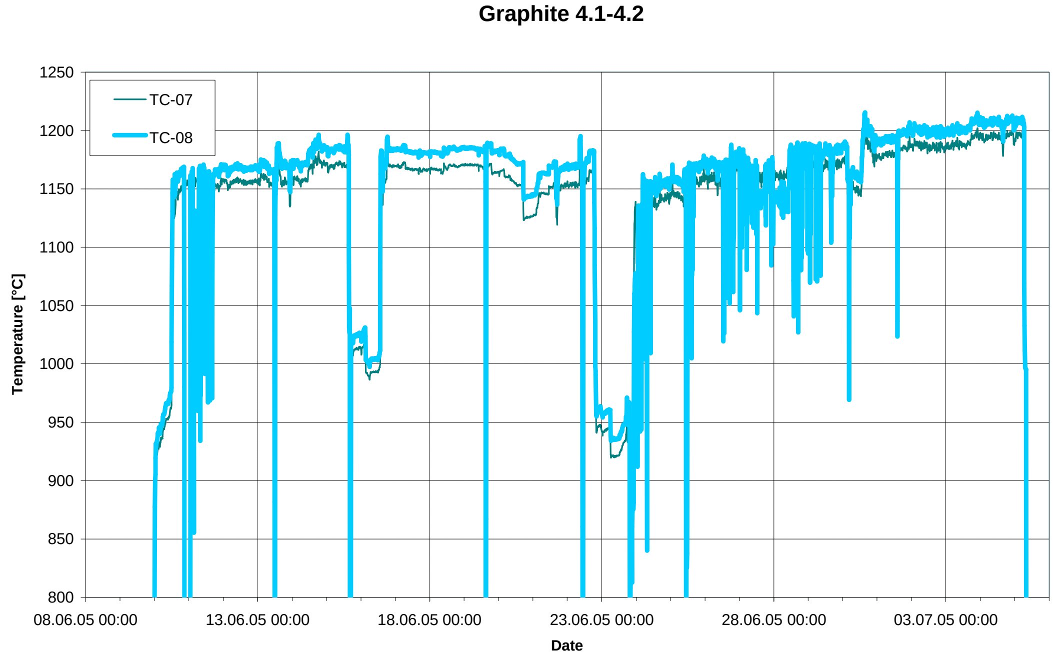


Figure 43: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

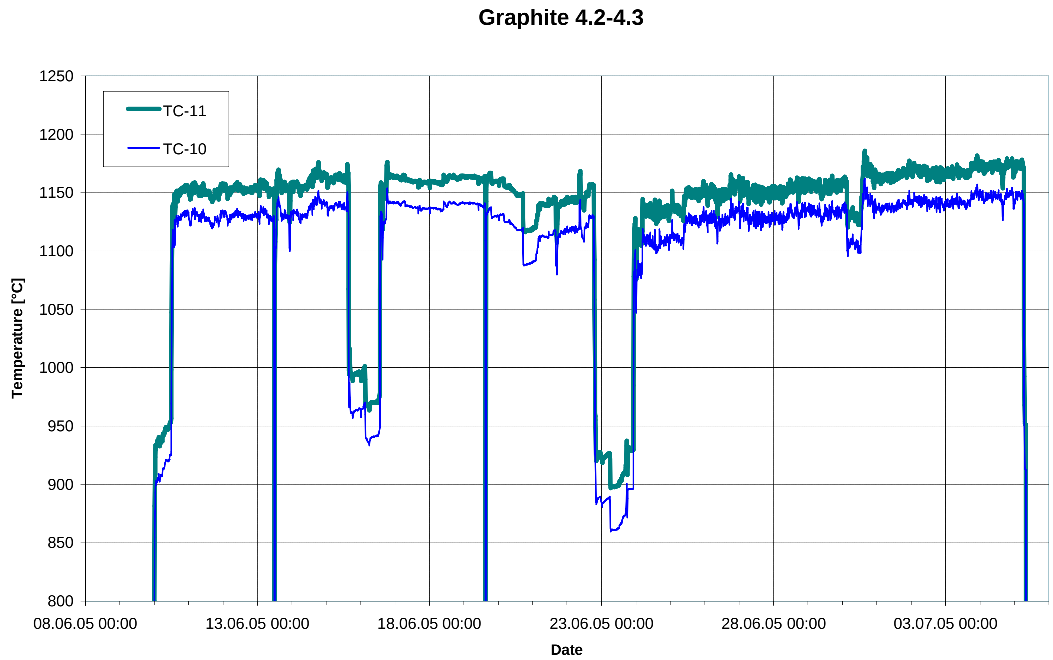


Figure 44: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

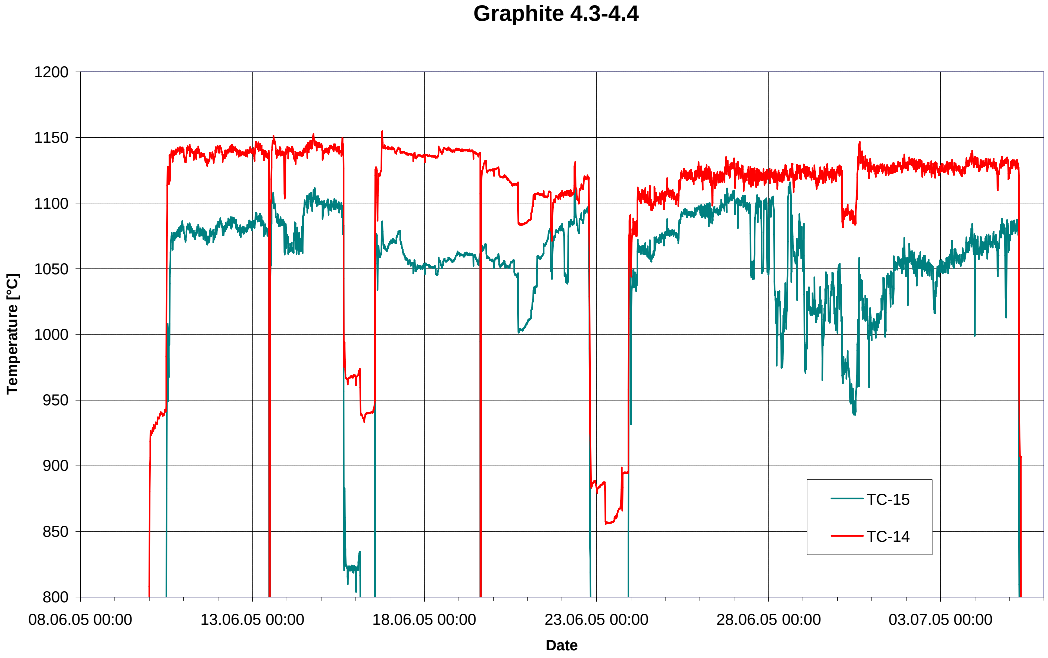


Figure 45: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

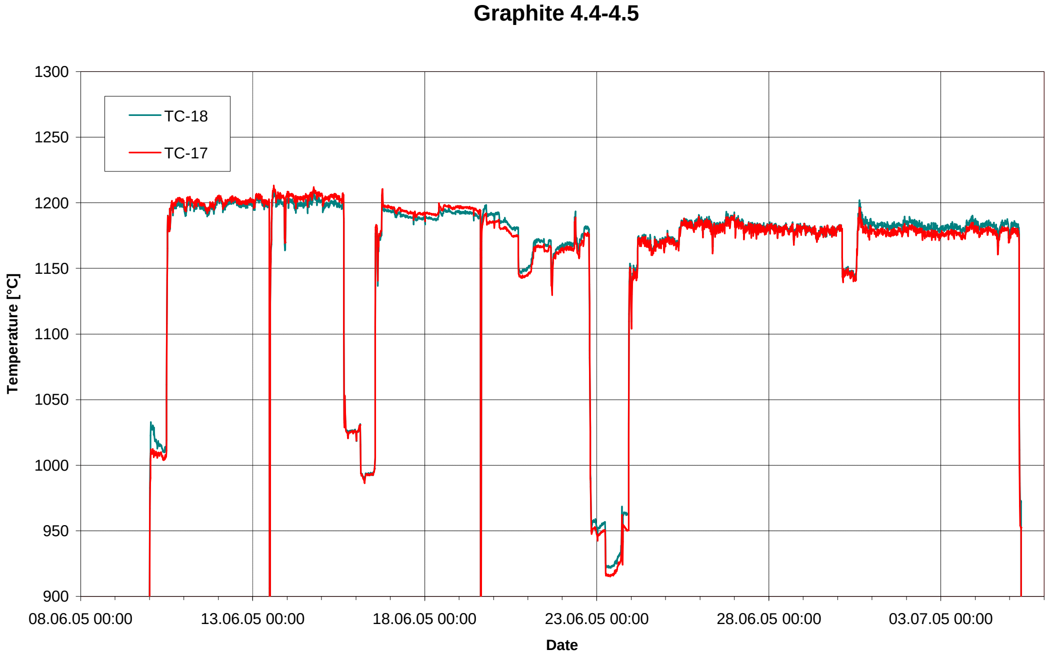


Figure 46: Temperatures graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

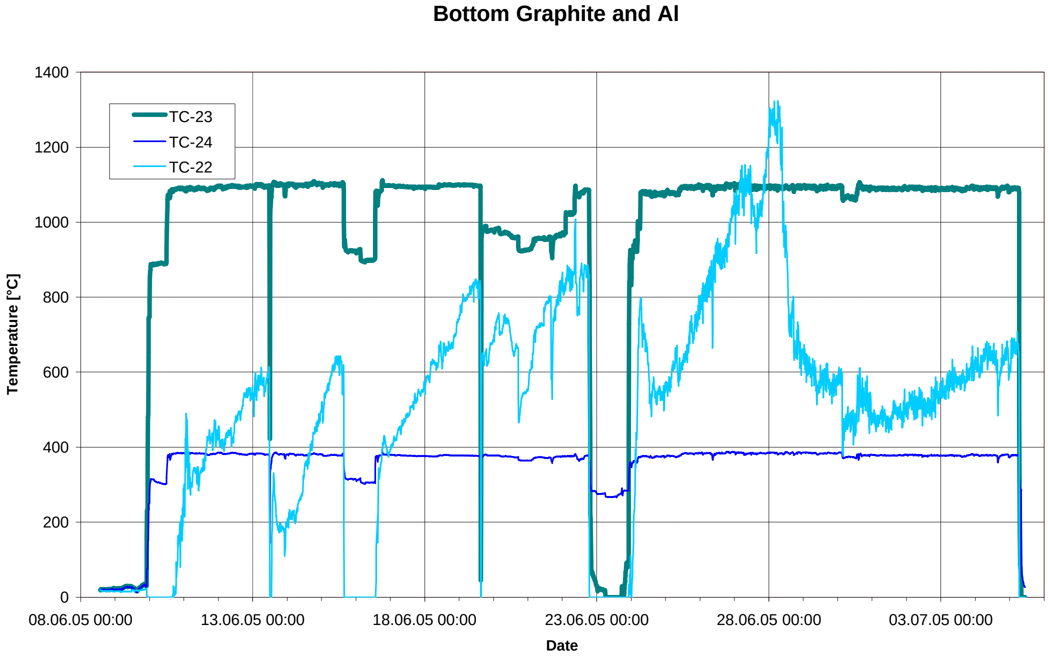


Figure 47: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
TC-01	4.7	4.1		Graphite
TC-02	800.7	816.2		
TC-03	736.2	751.5		
TC-04	1019.6	1036.4	1065	GLE4.1
TC-05	1017.6	1034.7		
TC-06	994.6	1012.1		
TC-07	1140.9	1161.8		Graphite
TC-08	1139.0	1156.6		
TC-09	72.2	72.9	1083	GLE4.2
TC-10	1104.8	1128.9		Graphite
TC-11	1129.9	1153.1		
TC-12	1021.8	1044.2	1082	GLE4.3
TC-13	1044.7	1068.3		
TC-14	1101.1	1126.6		Graphite
TC-15	1021.9	1064.3		
TC-16	1057.2	1079.2	1086	GLE4.4
TC-17	1159.1	1185.1		Graphite
TC-18	1160.4	1185.1		
TC-19	1115.5	1139.9	1069	GLE4.5
TC-20	995.7	1014.0		
TC-21	656.9	712.3		
TC-22	535.8	568.6		Graphite
TC-23	1012.5	1070.9		
TC-24	369.0	378.2		Al block

Table 14: Time averaged temperature readings during cycle 05-06

6.4 Temperatures during Cycle 05-07

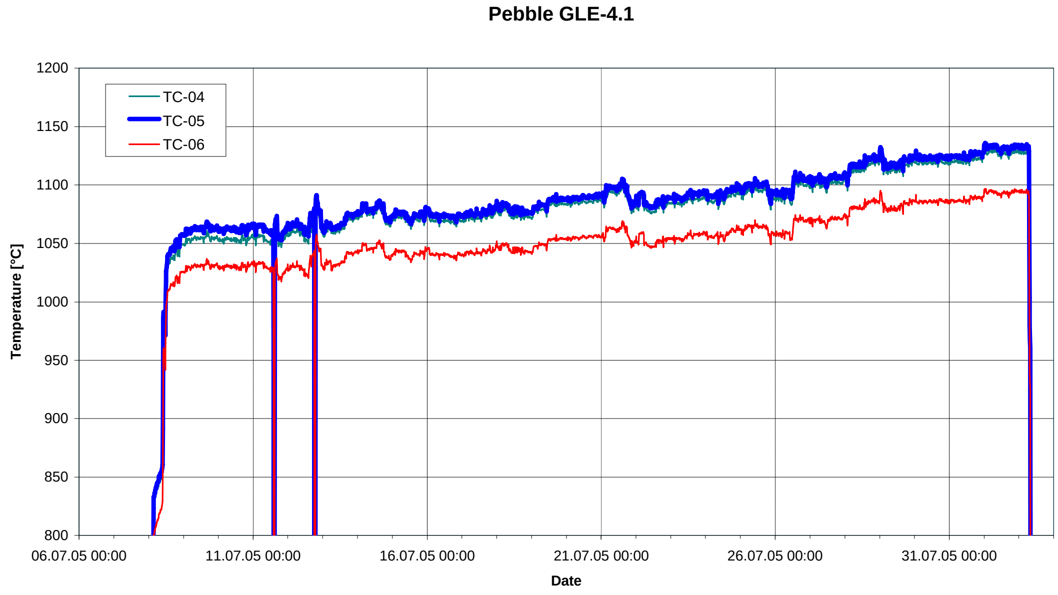


Figure 48: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

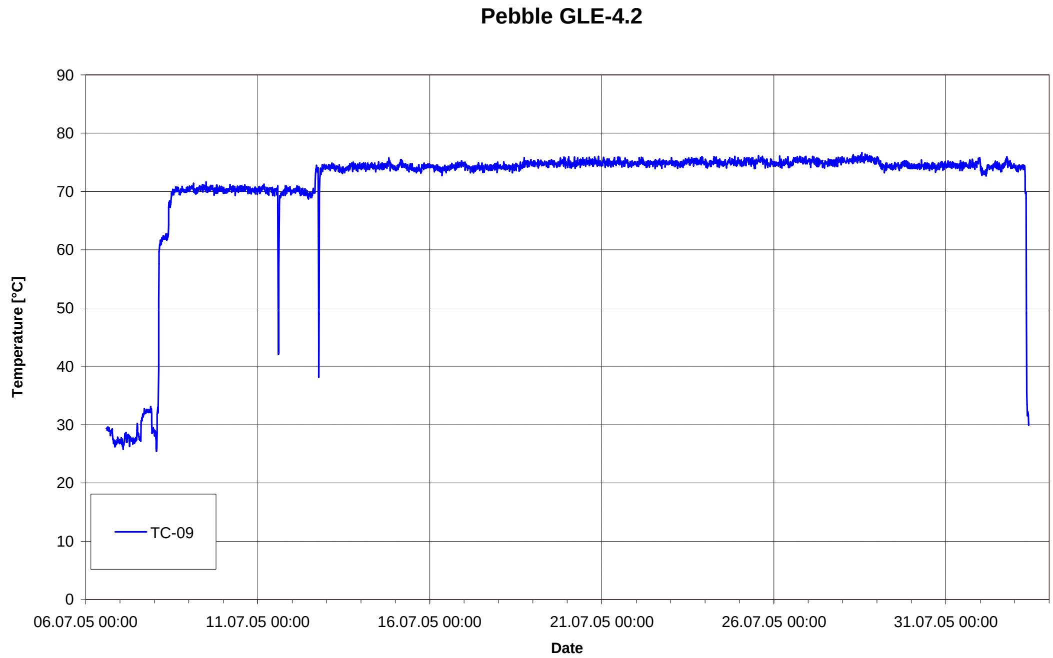


Figure 49: Temperature pebble GLE4.2 (TC-09)

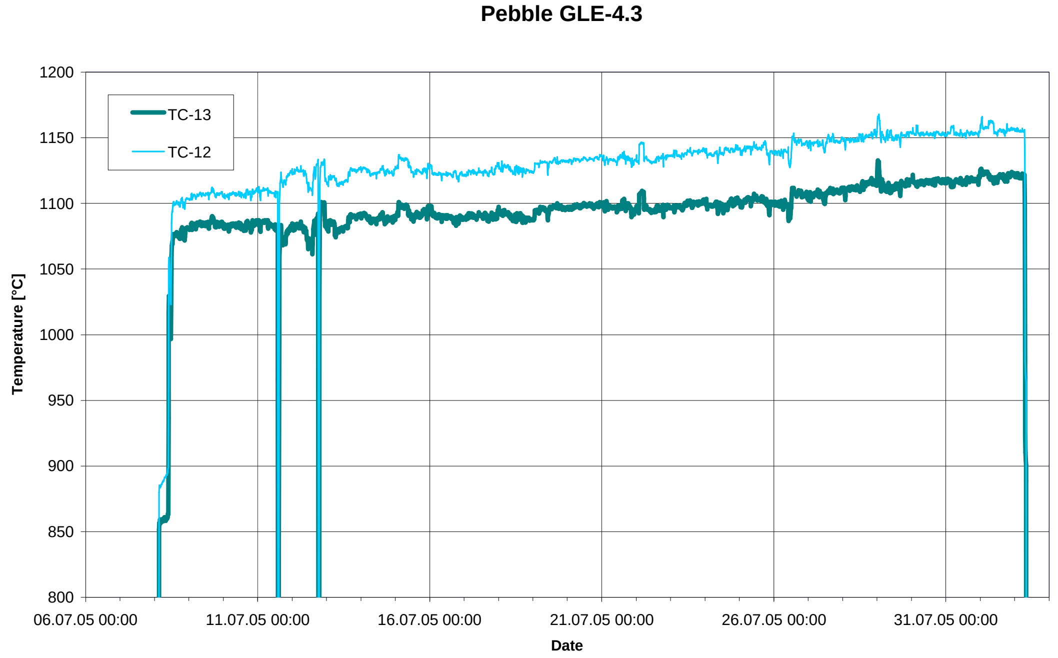


Figure 50: Temperatures pebble GLE4.3 (TC-12, TC-13)

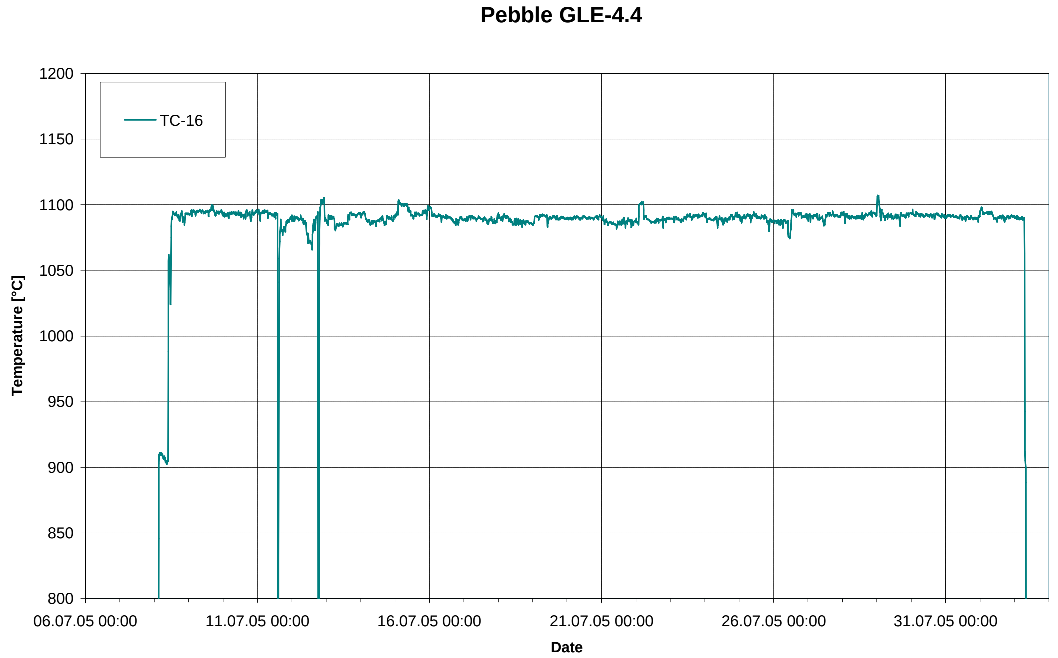


Figure 51: Temperature pebble GLE4.4 (TC-16)

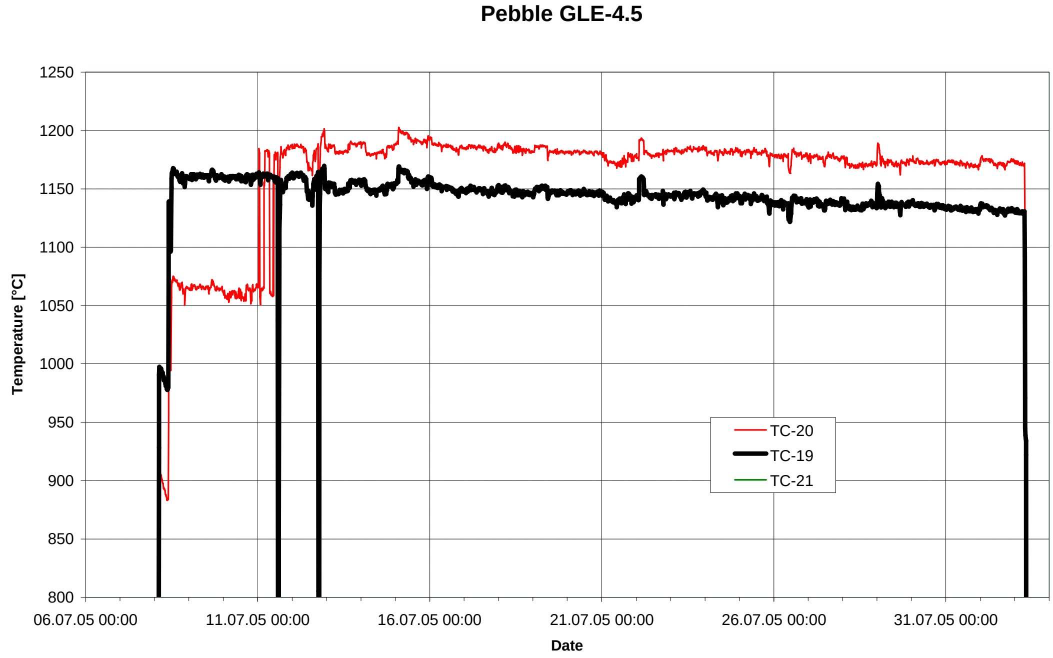


Figure 52: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

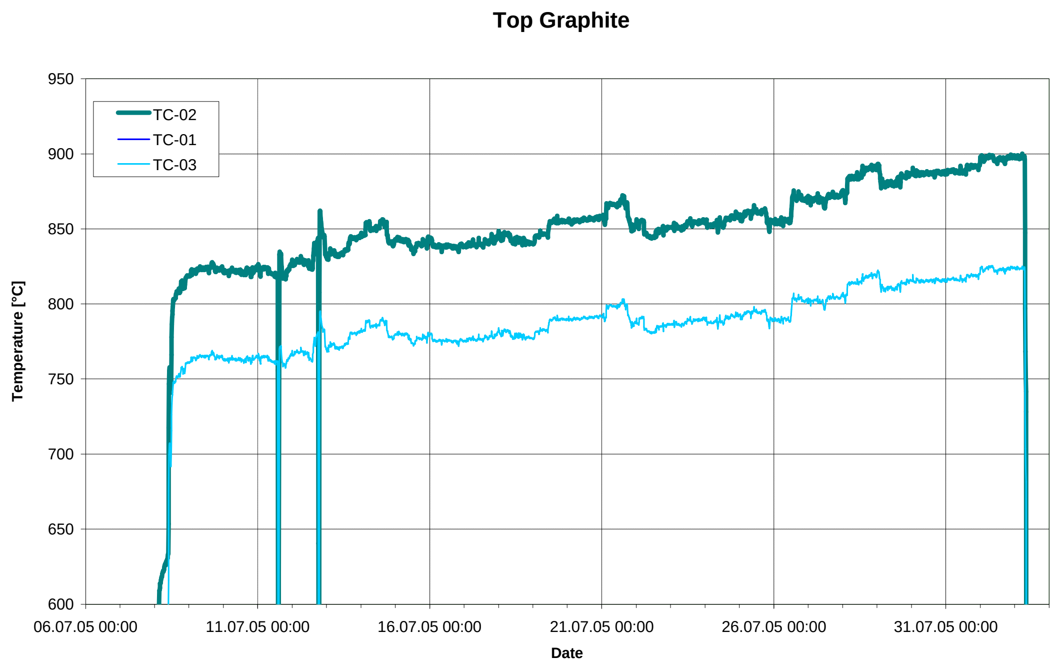


Figure 53: Temperatures top graphite (TC-01, TC-02, TC-03)

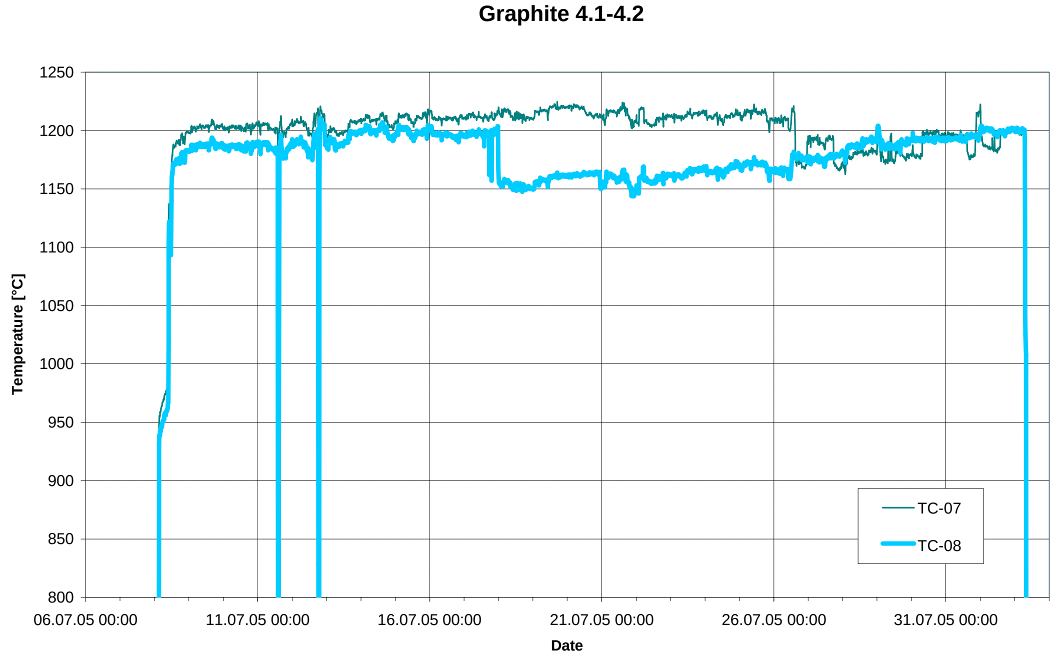


Figure 54: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

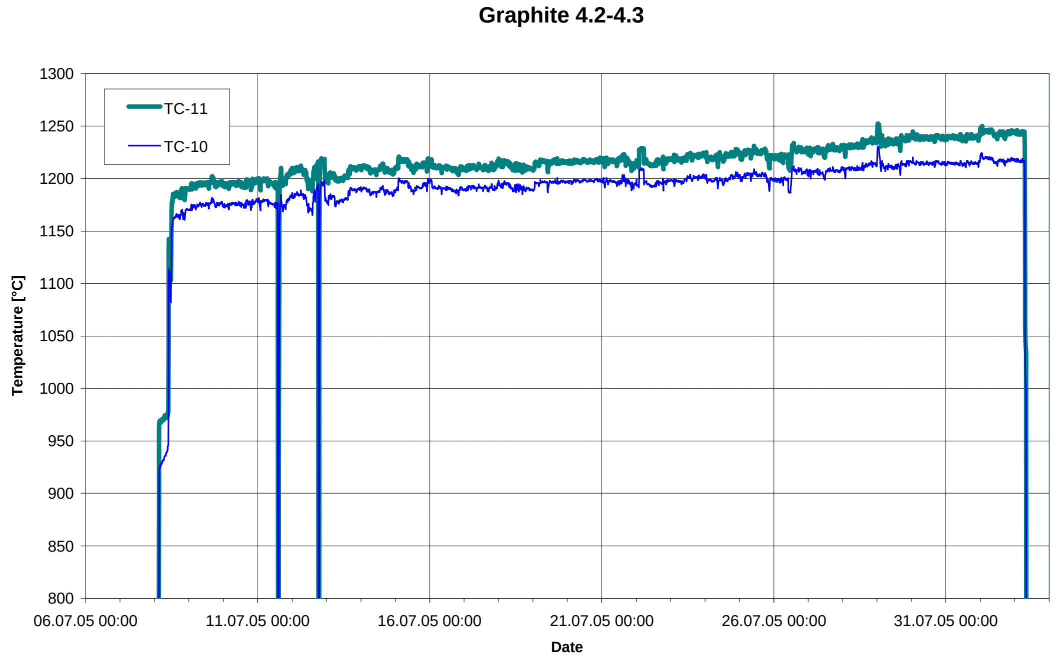


Figure 55: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

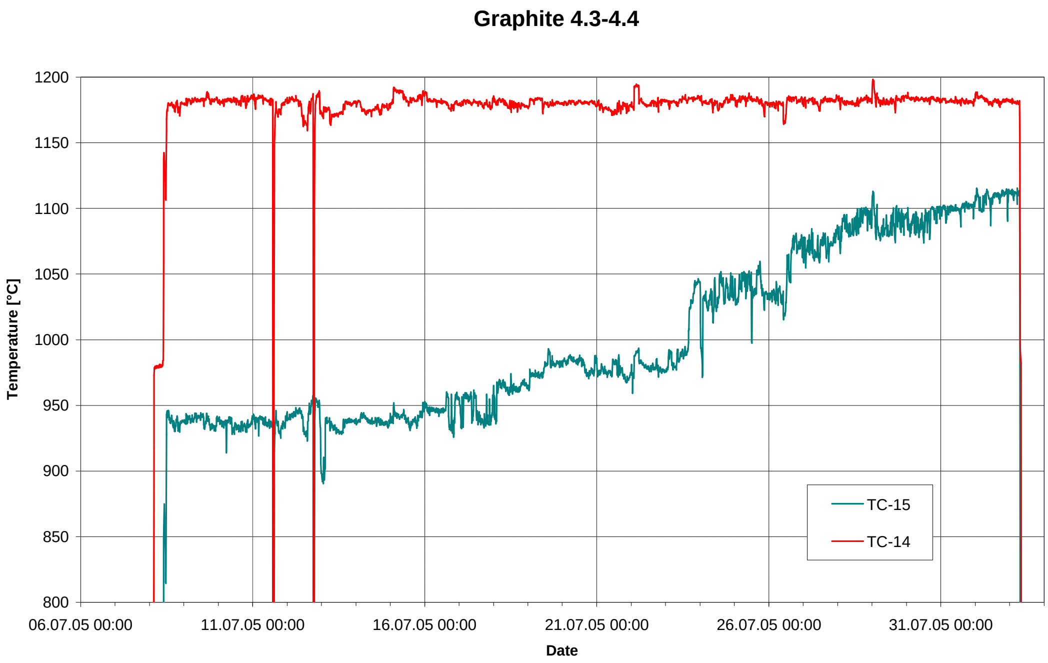


Figure 56: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

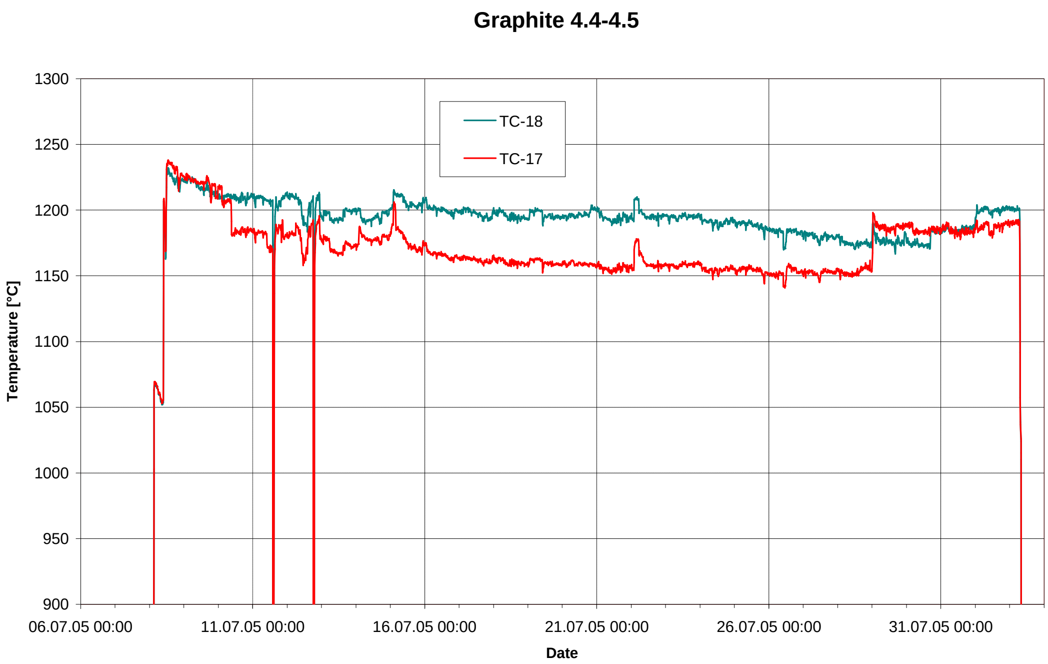


Figure 57: Temperatures graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

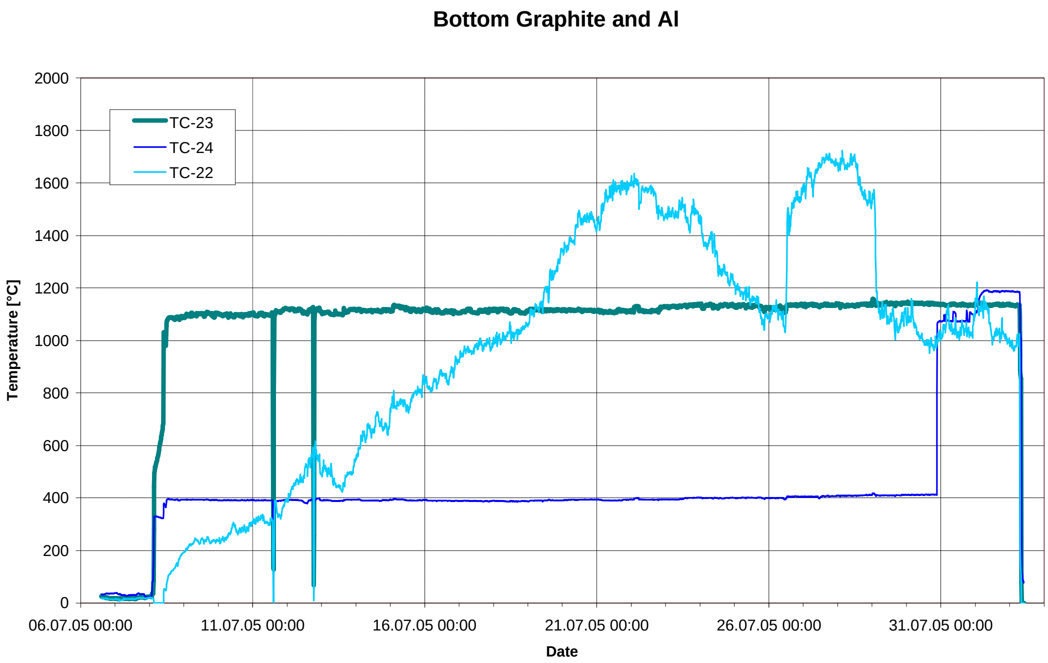


Figure 58: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
TC-01	1.3	1.3		Graphite
TC-02	834.8	834.8		
TC-03	773.2	773.2		
TC-04	1065.1	1065.1	1067	GLE4.1
TC-05	1071.4	1071.4		
TC-06	1037.3	1037.3		
TC-07	1200.5	1200.5		Graphite
TC-08	1181.5	1181.5		
TC-09	71.7	71.7	1087	GLE4.2
TC-10	1182.7	1182.7		Graphite
TC-11	1204.1	1204.1		
TC-12	1119.5	1119.5	1088	GLE4.3
TC-13	1085.2	1085.2		
TC-14	1177.7	1177.7		Graphite
TC-15	961.2	961.2		
TC-16	1087.4	1087.4	1091	GLE4.4
TC-17	1181.6	1181.6		Graphite
TC-18	1201.3	1201.3		
TC-19	1150.9	1150.9	1073	GLE4.5
TC-20	1143.3	1143.3		
TC-21	430.3	430.3		
TC-22	610.7	610.7		Graphite
TC-23	1108.8	1108.8		
TC-24	421.5	421.5		Al block

Table 15: Time averaged temperature readings during cycle 05-07

7 Fission Gas Release Measurements

In cycles 05-03 and 05-04 the fission gas release was measured according to the same procedure as previously:

1. **Depressurization:** approx. 18 hours before the gas sampling, the capsule is depressurized from 4.5 bar to close to atmospheric pressure.
2. **Purging:** A flow of 200 ml/min pure He is injected in the capsule and the gas is routed through the built-in charcoal filter and through the gas sampling vessel into the off-gas system. The temperature drops to its lowest possible value. Once the GM counters show low values (<70 mSv/h) after about 1 hour, the filter is bypassed. After 18 hours of stable conditions, we assume to obtain a steady-state R/B.
3. **Sampling:** The sampling vessel is removed and replaced. The noted data include date, time, ID of sampling vessel, He flow rate and gas pressure. The gas sample is analyzed in its vessel by gamma spectrometry.
4. **Temperature/Pressure Adjustment:** The rig is brought back to the desired temperature and is pressurized.

In cycles 05-06 and 05-07, a continuous He-Ne mixture flow (100 ml/min) was established. A simplified procedure could be used thanks to the modifications in the gas panel:

1. **Filter bypass:** Override the GM1 and GM3 alarms. Activate the filter bypass (close MV2.1, open MV2.2). Wait for at least one hour (at 100 ml/min total gas flow) until stable GM signals are reached.
2. **Sampling:** Override pressure alarm from Pt1.1 and close MV1 and MV2.3. Wait until the pressure at Pt1.2 is stable. Close V3.6 and V3.8, then remove sampling vessel. Place a new sampling vessel. Open V3.6, V3.8, MV1 and MV2.3. Arm all alarms.

To check the consistency with the previous method, the old method was simulated by injecting pure He into the rig and by lowering the pressure controller set-point to atmospheric pressure.

Evaluation of R/B:
From the measured concentration of 3 Kr and 2 Xe isotopes (statistical error 4 - 9%), the gas pressure and the He flow-rate, the release rate R can be determined.

The birth rate B is calculated using the nominal number of fissions on the date of sampling (neutronics error 10 - 15%) and the fission yield for the measured 5 isotopes.

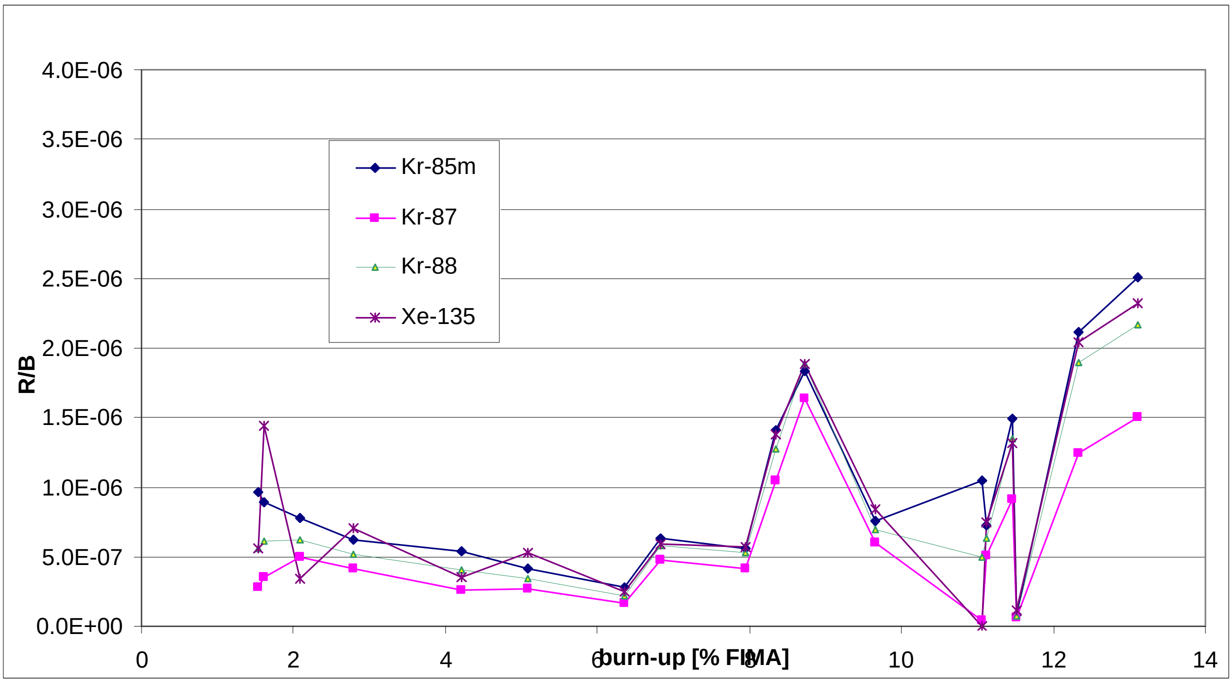


Figure 59: R/B measurements vs. burn-up

Overview gammaspectrometry measurements HFR-EU1bis gas samples.

	NRG	week	sample date	tank	flow	pressure	Kr-85m		Kr-87		Kr-88		Xe-133		Xe-135		Xe-133		Xe-135	
nr	code	nr		nr	[ml/min]	[bar rel]	[Bq/sample]		[Bq/sample]		[Bq/sample]		[Bq/sample]		[Bq/sample]		[Bq/sample]		[Bq/sample]	
																	not corrected for ingrow			
1	H4103	37	**10.09.04 13:56**	?	?	?							1.23E+00	39%			1.23E+00	39%		
2	H4104	38	**14.09.04 12:26**	2	?	?							1.48E+00	39%	1.39E+00	38%	1.48E+00	39%	1.39E+00	38%
3	H4109	40	**28.09.04 14:45**	1	?	?	1.40E+05	10%	2.48E+05	9%	2.94E+05	7%	6.13E+05	6%	1.80E+05	3%	6.19E+05	6%	1.94E+05	4%
4	H4110	40	**27.10.04 11:21**	2	?	?	1.10E+05	4%	2.96E+05	9%	3.23E+05	6%	1.72E+05	12%	4.30E+05	3%	1.74E+05	14%	4.34E+05	3%
5	H4111	41	**08.10.04 10:45**	7	?	?	5.77E+03	4%	2.49E+04	9%	1.94E+04	6%	2.11E+03	6%	6.24E+03	3%	2.11E+03	6%	6.24E+03	3%
6	H4112	42	**11.10.04 16:03**	1	?	?							1.18E+05	6%			1.18E+05	6%		
7	H4113	43	**18.10.04 16:00**	?	150	0.13	6.83E+03	5%	3.13E+04	9%	2.48E+04	9%	2.08E+04	6%	1.65E+04	3%	2.08E+04	6%	1.86E+04	3%
8	H4117	44	**25.10.04 15:40**	2	150	0.30	9.27E+04	4%	4.03E+05	9%	3.11E+05	7%	6.55E+05	6%	6.94E+05	4%	6.56E+05	6%	7.76E+05	3%
9	H4118	44	**25.10.04 12:15**	1	0	0.15	3.45E+03	5%	1.32E+04	14%	1.12E+04	8%	7.32E+04	6%	9.76E+03	3%	7.33E+04	6%	9.76E+03	3%
10	H4122	45	**01.11.04 15:05**	7	200	0.16	5.59E+03	5%	2.49E+04	9%	1.84E+04	9%	9.49E+03	6%	1.81E+04	3%	9.51E+03	6%	2.13E+04	3%
11	H4160	1	**06.01.05 11:05**	7	200	0.12	4.18E+03	4%	1.35E+04	9%	1.29E+04	4%	6.86E+03	6%	6.69E+03	4%	6.86E+03	6%	7.62E+03	3%
12	H5001	2	**12.01.05 11:23**	1	200	0.37	4.00E+04	5%	1.76E+05	9%	1.39E+05	5%	4.64E+05	7%	1.54E+06	6%	4.64E+05	7%	1.55E+06	4%
13	H5002	3	**19.01.05 10:55**	2	200	0.11	3.07E+03	4%	1.34E+04	9%	1.06E+04	4%	3.32E+03	6%	9.54E+03	4%	3.32E+03	6%	1.07E+04	3%
14	H5007	5	**01.02.05 11:07**	1	200	0.27	2.25E+04	4%	9.21E+04	9%	7.42E+04	6%	6.37E+06	6%	9.24E+04	4%	6.39E+06	6%	9.81E+04	5%
15	H5009	6	**09.02.05 14:56**	1	200	0.28	2.46E+04	5%	9.97E+04	9%	7.74E+04	8%	1.97E+06	6%	1.04E+05	3%	1.97E+06	6%	1.12E+05	6%
16	H5010	6	**09.02.05 14:33**	3	200	0.11	1.97E+03	4%	7.98E+03	9%	6.48E+03	4%	1.14E+03	6%	4.21E+03	3%	1.14E+03	6%	4.21E+03	3%
17	H5015	7	**16.02.05 13:51**	2	200	0.08	4.24E+03	4%	2.18E+04	9%	1.65E+04	4%	3.64E+03	6%	9.66E+03	4%	3.64E+03	6%	1.11E+04	3%
18	H5023	10	**08.03.05 09:58**	3	200	0.12	3.72E+03	4%	1.88E+04	9%	1.47E+04	4%	1.49E+03	7%	9.29E+03	4%	1.49E+03	7%	1.05E+04	3%
19	H5024	11	**15.03.05 10:35**	2	200	0.08	8.90E+03	10%	4.47E+04	9%	3.38E+04	4%	3.36E+03	6%	2.12E+04	5%	3.36E+03	6%	2.55E+04	3%
20	H5025	12	**21.03.05 10:05**	3	200	0.11	1.17E+04	4%	7.06E+04	9%	5.05E+04	6%	3.75E+03	10%	2.93E+04	4%	3.75E+03	10%	3.41E+04	7%
21	H5091	24	**15.06.05 15:25**	3	He80/Ne120	4.50	2.97E+04	4%	8.34E+03	8%	5.93E+04	4%	1.01E+04	6%	2.69E+02	34%	1.01E+04	6%	2.69E+02	34%
22	H5092	24	**16.06.05 13:11**	2	200 He	0.15	4.31E+03	6%	2.03E+04	7%	1.57E+04	7%	1.74E+03	6%	1.07E+04	3%	1.74E+03	6%	1.20E+04	3%
23	H5095	25	**22.06.05 14:29**	3	35He/65Ne	4.52	8.33E+04	4%	3.47E+05	9%	3.17E+05	4%	2.34E+04	6%	1.80E+05	3%	2.34E+04	6%	1.84E+05	3%
24	H5096	25	**23.06.05 13:31**	2	200 He	0.19	2.41E+03	5%	1.10E+04	9%	8.21E+03	5%	2.09E+03	7%	7.51E+03	4%	2.09E+03	7%	8.28E+03	3%
25	H5143	28	**12.07.05 13:54**	2	39He/61Ne	4.41	1.11E+05	4%	4.44E+05	5%	4.19E+05	4%	3.07E+04	6%	2.61E+05	3%	3.08E+04	6%	2.66E+05	3%
1	H5146	30	**27.07.05 11:10**	3	35He/65Ne	4.42	1.27E+05	6%	5.15E+05	8%	4.61E+05	8%	6.21E+04	6%	2.86E+05	9%	6.12E+04	6%	2.91E+05	7%

If Xe-133m and/or Xe-135m are measured, Xe-133 and/or Xe-135 are corrected for the ingrow from the mother nuclides
The uncorrected values are also given. Errors are 1 sigma statistical counting errors.

Table 16: Gamma spectrometry measurement data until end of cycle 05-07

28.09.04 14.45 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.45E+05		3373828915	100	33738289	10	5.6230E+06	4.43E+14	1.32E-02	9.61E-07
Kr-87	4578	2.85E+05		1882327501	100	18823275	10	3.1372E+06	4.43E+14	2.54E-02	2.79E-07
Kr-88	10080	3.53E+05		5133455202	100	51334552	10	8.5558E+06	4.43E+14	3.47E-02	5.56E-07
Xe-133	457056	6.47E+05		426626898722	100	4266268987	10	7.1104E+08	4.43E+14	6.62E-02	2.42E-05
Xe-135	33012	2.07E+05		9858633479	100	98586335	10	16431056	4.43E+14	6.58E-02	5.63E-07

29.09.04 14.25 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.34E+05		3117883273	100	31178833	10	5.1965E+06	4.42E+14	1.32E-02	8.91E-07
Kr-87	4578	3.58E+05		2364467527	100	23644675	10	3.9408E+06	4.42E+14	2.54E-02	3.51E-07
Kr-88	10080	3.90E+05		5671522745	100	56715227	10	9.4525E+06	4.42E+14	3.47E-02	6.16E-07
Xe-133	457056	1.90E+05		125284560676	100	1252845607	10	2.0881E+08	4.42E+14	6.62E-02	7.14E-06
Xe-135	33012	5.27E+05		25099033060	100	250990331	10	4.1832E+07	4.42E+14	6.58E-02	1.44E-06

08.10.04 10.45 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	5.77E+03		134255123	100	1342551	200	4.4752E+06	4.35E+14	1.32E-02	7.80E-07
Kr-87	4578	2.49E+04		164455982	100	1644560	200	5.4819E+06	4.35E+14	2.54E-02	4.96E-07
Kr-88	10080	1.94E+04		282121901	100	2821219	200	9.4041E+06	4.35E+14	3.47E-02	6.23E-07
Xe-133	457056	2.11E+03		1391318016	100	13913180	200	4.6377E+07	4.35E+14	6.62E-02	1.61E-06
Xe-135	33012	6.24E+03		297187792	100	2971878	200	9.9063E+06	4.35E+14	6.58E-02	3.46E-07

11.10.04 14.15 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Xe-133	457056	1.18E+05		77808306104	100	778083061	10	1.2968E+08	4.31E+14	6.62E-02	4.54E-06

18.10.04 16.00 h 0.13 bar

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	6.79E+03	1.13	157988264	100	1398126	150	3.4953E+06	4.24E+14	1.32E-02	6.24E-07
Kr-87	4578	3.03E+04	1.13	200121134	100	1770983	150	4.4275E+06	4.24E+14	2.54E-02	4.11E-07
Kr-88	10080	2.39E+04	1.13	347562548	100	3075775	150	7.6894E+06	4.24E+14	3.47E-02	5.22E-07
Xe-133	457056	2.07E+04	1.13	13649423189	100	120791356	150	3.0198E+08	4.24E+14	6.62E-02	1.07E-05
Xe-135	33012	1.86E+04	1.13	885848226	100	7839365	150	1.9598E+07	4.24E+14	6.58E-02	7.02E-07

25.10.04 12.15 h 0.15 bar **after 1 week of stagnance**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	3.45E+03	1.15	80273860	100	698034	0	0.0000E+00	4.24E+14	1.32E-02	0.00E+00
Kr-87	4578	1.32E+04	1.15	87181484	100	758100	0	0.0000E+00	4.24E+14	2.54E-02	0.00E+00
Kr-88	10080	1.12E+04	1.15	162874499	100	1416300	0	0.0000E+00	4.24E+14	3.47E-02	0.00E+00
Xe-133	457056	7.33E+04	1.15	48333464724	100	420290998	0	0.0000E+00	4.24E+14	6.62E-02	0.00E+00
Xe-135	33012	9.76E+03	1.15	464832187	100	4042019	0	0.0000E+00	4.24E+14	6.58E-02	0.00E+00

25.10.04 15.40 h 0.3 bar **after purging for 3:25 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	9.27E+04	1.30	2156923727	100	16591721	150	4.1479E+07	4.19E+14	1.32E-02	7.50E-06
Kr-87	4578	4.03E+05	1.30	2661677133	100	20474439	150	5.1186E+07	4.19E+14	2.54E-02	4.81E-06
Kr-88	10080	3.11E+05	1.30	4522675830	100	34789814	150	8.6975E+07	4.19E+14	3.47E-02	5.99E-06
Xe-133	457056	6.55E+05	1.30	431902038119	100	3322323370	150	8.3058E+09	4.19E+14	6.62E-02	3.00E-04
Xe-135	33012	7.51E+05	1.30	35767312766	100	275133175	150	6.8783E+08	4.19E+14	6.58E-02	2.50E-05

01.11.04 15.05 h 0.16 bar **after purging for 4:05 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	5.59E+03	1.16	130066922	100	1121267	200	3.7376E+06	4.12E+14	1.32E-02	6.87E-07
Kr-87	4578	2.49E+04	1.16	164455982	100	1417724	200	4.7257E+06	4.12E+14	2.54E-02	4.52E-07
Kr-88	10080	1.84E+04	1.16	267579535	100	2306720	200	7.6891E+06	4.12E+14	3.47E-02	5.38E-07
Xe-133	457056	9.49E+03	1.16	6257634110	100	53945122	200	1.7982E+08	4.12E+14	6.62E-02	6.59E-06
Xe-135	33012	1.81E+04	1.16	862035101	100	7431337	200	2.4771E+07	4.12E+14	6.58E-02	9.14E-07

Table 17: Spreadsheet table for the calculation of R/B values (1 of 3)

06.01.05 11.05 h 0.12 bar **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.18E+03	1.12	97259344	100	868387	200	2.8946E+06	4.03E+14	1.32E-02	5.44E-07
Kr-87	4578	1.35E+04	1.12	89162882	100	796097	200	2.6537E+06	4.03E+14	2.54E-02	2.59E-07
Kr-88	10080	1.29E+04	1.12	187596522	100	1674969	200	5.5832E+06	4.03E+14	3.47E-02	3.99E-07
Xe-133	457056	6.86E+03	1.12	4523432033	100	40387786	200	1.3463E+08	4.03E+14	6.62E-02	5.04E-06
Xe-135	33012	6.69E+03	1.12	318619604	100	2844818	200	9.4827E+06	4.03E+14	6.58E-02	3.57E-07

12.01.05 11:23 h 0.37 bar **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.00E+04	1.37	930711425	100	6793514	200	2.2645E+07	3.97E+14	1.32E-02	4.32E-06
Kr-87	4578	1.76E+05	1.37	1162419790	100	8484816	200	2.8283E+07	3.97E+14	2.54E-02	2.81E-06
Kr-88	10080	1.39E+05	1.37	2021388876	100	14754663	200	4.9182E+07	3.97E+14	3.47E-02	3.57E-06
Xe-133	457056	4.64E+05	1.37	305958085018	100	2233270694	200	7.4442E+09	3.97E+14	6.62E-02	2.83E-04
Xe-135	33012	1.54E+06	1.37	73344422982	100	535360752	200	1.7845E+09	3.97E+14	6.58E-02	6.84E-05

19.01.05 10:55 h (**after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	3.07E+03	1.11	71432102	100	643532	200	2.1451E+06	3.90E+14	1.32E-02	4.16E-07
Kr-87	4578	1.34E+04	1.11	88502416	100	797319	200	2.6577E+06	3.90E+14	2.54E-02	2.68E-07
Kr-88	10080	1.06E+04	1.11	154149080	100	1388730	200	4.6291E+06	3.90E+14	3.47E-02	3.42E-07
Xe-133	457056	3.32E+03	1.11	2189182850	100	19722368	200	6.5741E+07	3.90E+14	6.62E-02	2.54E-06
Xe-135	33012	9.54E+03	1.11	454354413	100	4093283	200	1.3644E+07	3.90E+14	6.58E-02	5.31E-07

01.02.05 11:07 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	2.25E+04	1.27	523525176	100	4122245	200	1.3741E+07	3.79E+14	1.32E-02	2.75E-06
Kr-87	4578	9.21E+04	1.27	608288992	100	4789677	200	1.5966E+07	3.79E+14	2.54E-02	1.66E-06
Kr-88	10080	7.42E+04	1.27	1079043558	100	8496406	200	2.8321E+07	3.79E+14	3.47E-02	2.15E-06
Xe-133	457056	6.37E+06	1.27	4200329744756	100	33073462557	200	1.1024E+11	3.79E+14	6.62E-02	4.39E-03
Xe-135	33012	9.24E+04	1.27	4400665379	100	34650908	200	1.1550E+08	3.79E+14	6.58E-02	4.63E-06

09.02.2005 14:33 PM Tank 3 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.97E+03	1.11	45837538	100	412951	200	1.3765E+06	3.72E+14	1.32E-02	2.80E-07
Kr-87	4578	7.98E+03	1.11	52705170	100	474821	200	1.5827E+06	3.72E+14	2.54E-02	1.68E-07
Kr-88	10080	6.48E+03	1.11	94234532	100	848960	200	2.8299E+06	3.72E+14	3.47E-02	2.19E-07
Xe-133	457056	1.14E+03	1.11	751707364	100	6772138	200	2.2574E+07	3.72E+14	6.62E-02	9.17E-07
Xe-135	33012	4.21E+03	1.11	200506507	100	1806365	200	6.0212E+06	3.72E+14	6.58E-02	2.46E-07

09.02.2005 14:56 PM Tank 1 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	2.46E+04	1.28	572387526	100	4471778	200	1.4906E+07	3.72E+14	1.32E-02	3.04E-06
Kr-87	4578	9.97E+04	1.28	658484392	100	5144409	200	1.7148E+07	3.72E+14	2.54E-02	1.82E-06
Kr-88	10080	7.74E+04	1.28	1125579129	100	8793587	200	2.9312E+07	3.72E+14	3.47E-02	2.27E-06
Xe-133	457056	1.97E+06	1.28	1299003076479	100	10148461535	200	3.3828E+10	3.72E+14	6.62E-02	1.37E-03
Xe-135	33012	1.04E+05	1.28	4953129864	100	38696327	200	1.2899E+08	3.72E+14	6.58E-02	5.27E-06

16.02.2005 13:51 PM Tank 2 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.24E+03	1.08	98655411	100	913476	200	3.0449E+06	3.65E+14	1.32E-02	6.32E-07
Kr-87	4578	2.18E+04	1.08	143981542	100	1333162	200	4.4439E+06	3.65E+14	2.54E-02	4.80E-07
Kr-88	10080	1.65E+04	1.08	239949039	100	2221750	200	7.4058E+06	3.65E+14	3.47E-02	5.85E-07
Xe-133	457056	3.64E+03	1.08	2400188426	100	22223967	200	7.4080E+07	3.65E+14	6.62E-02	3.07E-06
Xe-135	33012	9.66E+03	1.08	460069562	100	4259903	200	1.4200E+07	3.65E+14	6.58E-02	5.91E-07

08.03.05 09:58 Tank 3 **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	3.72E+03	1.12	86556163	100	772823	200	2.5761E+06	3.48E+14	1.32E-02	5.60E-07
Kr-87	4578	1.88E+04	1.12	124167568	100	1108639	200	3.6955E+06	3.48E+14	2.54E-02	4.17E-07
Kr-88	10080	1.47E+04	1.12	213772780	100	1908686	200	6.3623E+06	3.48E+14	3.47E-02	5.26E-07
Xe-133	457056	1.49E+03	1.12	982494713	100	8772274	200	2.9241E+07	3.48E+14	6.62E-02	1.27E-06
Xe-135	33012	9.29E+03	1.12	442447850	100	3950427	200	1.3168E+07	3.48E+14	6.58E-02	5.74E-07

Table 18: Spreadsheet table for the calculation of R/B values (2 of 3)

15.03.05 10:35 Tank 2 after purging for 18 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	8.90E+03	1.08	207083292	100	1917438	200	6.3915E+06	3.43E+14	1.32E-02	1.41E-06
Kr-87	4578	4.47E+04	1.08	295228208	100	2733595	200	9.1120E+06	3.43E+14	2.54E-02	1.05E-06
Kr-88	10080	3.38E+04	1.08	491531971	100	4551222	200	1.5171E+07	3.43E+14	3.47E-02	1.28E-06
Xe-133	457056	3.36E+03	1.08	2215558547	100	20514431	200	6.8381E+07	3.43E+14	6.62E-02	3.01E-06
Xe-135	33012	2.12E+04	1.08	1009676472	100	9348856	200	3.1163E+07	3.43E+14	6.58E-02	1.38E-06

21.03.05 10:05 Tank 3 after purging for 18 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.17E+04	1.11	272233092	100	2452550	200	8.1752E+06	3.37E+14	1.32E-02	1.84E-06
Kr-87	4578	7.06E+04	1.11	466288848	100	4200800	200	1.4003E+07	3.37E+14	2.54E-02	1.63E-06
Kr-88	10080	5.05E+04	1.11	734389484	100	6616121	200	2.2054E+07	3.37E+14	3.47E-02	1.88E-06
Xe-133	457056	3.75E+03	1.11	2472721592	100	22276771	200	7.4256E+07	3.37E+14	6.62E-02	3.32E-06
Xe-135	33012	2.93E+04	1.11	1395449087	100	12571613	200	4.1905E+07	3.37E+14	6.58E-02	1.89E-06

07.04.05 10:21 Tank 2 after purging for 18 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.63E+03	1.11	107729847	100	970539	200	3.2351E+06	3.24E+14	1.32E-02	7.56E-07
Kr-87	4578	2.50E+04	1.11	165116447	100	1487536	200	4.9585E+06	3.24E+14	2.54E-02	6.03E-07
Kr-88	10080	1.79E+04	1.11	260308352	100	2345120	200	7.8171E+06	3.24E+14	3.47E-02	6.95E-07
Xe-133	457056	2.68E+03	1.11	1767171698	100	15920466	200	5.3068E+07	3.24E+14	6.62E-02	2.47E-06
Xe-135	33012	1.25E+04	1.11	595328109	100	5363316	200	1.7878E+07	3.24E+14	6.58E-02	8.39E-07

15.06.05 15:25 Tank 3 TC16=1090C 80 ml/min He 120 ml/min Ne

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	2.97E+04	5.50	691053233	100	1256460	200	4.1882E+06	3.04E+14	1.32E-02	1.04E-06
Kr-87	4578	8.34E+03	5.50	55082847	100	100151	200	3.3384E+05	3.04E+14	2.54E-02	4.33E-08
Kr-88	10080	5.93E+04	5.50	862362305	100	1567931	200	5.2264E+06	3.04E+14	3.47E-02	4.96E-07
Xe-133	457056	1.01E+04	5.50	6659863489	100	12108843	200	4.0363E+07	3.04E+14	6.62E-02	2.01E-06
Xe-135	33012	2.69E+02	5.50	12811461	100	23294	200	7.7645E+04	3.04E+14	6.58E-02	3.89E-09

16.06.05 13:11 Tank 2 TC16=900C 200 ml/min He

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.31E+03	1.15	100284156	100	872036	200	2.9068E+06	3.03E+14	1.32E-02	7.27E-07
Kr-87	4578	2.03E+04	1.15	134074555	100	1165866	200	3.8862E+06	3.03E+14	2.54E-02	5.05E-07
Kr-88	10080	1.57E+04	1.15	228315146	100	1985349	200	6.6178E+06	3.03E+14	3.47E-02	6.30E-07
Xe-133	457056	1.74E+03	1.15	1147342819	100	9976894	200	3.3256E+07	3.03E+14	6.62E-02	1.66E-06
Xe-135	33012	1.07E+04	1.15	509600861	100	4431312	200	1.4771E+07	3.03E+14	6.58E-02	7.41E-07

22.06.05 14:29 Tank 3 TC16=1078C 35 ml/min He 65 ml/min Ne relatively unstable temperatures

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	8.33E+04	5.52	1938206542	100	3511244	100	5.8521E+06	2.98E+14	1.32E-02	1.49E-06
Kr-87	4578	3.47E+05	5.52	2291816290	100	4151841	100	6.9197E+06	2.98E+14	2.54E-02	9.14E-07
Kr-88	10080	3.17E+05	5.52	4609930026	100	8351323	100	1.3919E+07	2.98E+14	3.47E-02	1.35E-06
Xe-133	457056	2.34E+04	5.52	15429782736	100	27952505	100	4.6588E+07	2.98E+14	6.62E-02	2.36E-06
Xe-135	33012	1.80E+05	5.52	8572724764	100	15530298	100	2.5884E+07	2.98E+14	6.58E-02	1.32E-06

23.06.05 13:31 Tank 2 TC16=790C 200 ml/min He

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	2.41E+03	5.52	56075363	100	101586	200	3.3862E+05	2.97E+14	1.32E-02	8.63E-08
Kr-87	4578	1.10E+04	5.52	72651237	100	131615	200	4.3872E+05	2.97E+14	2.54E-02	5.81E-08
Kr-88	10080	8.21E+03	5.52	119392825	100	216291	200	7.2097E+05	2.97E+14	3.47E-02	6.99E-08
Xe-133	457056	2.09E+03	5.52	1378130167	100	2496613	200	8.3220E+06	2.97E+14	6.62E-02	4.23E-07
Xe-135	33012	7.51E+03	5.52	357673128	100	647959	200	2.1599E+06	2.97E+14	6.58E-02	1.10E-07

12.07.05 13:54 Tank 2 TC16=1070C 39 ml/min He + 61 ml/min Ne

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.11E+05	5.41	2582724204	100	4773982	100	7.9566E+06	2.85E+14	1.32E-02	2.11E-06
Kr-87	4578	4.44E+05	5.41	2932468106	100	5420459	100	9.0341E+06	2.85E+14	2.54E-02	1.25E-06
Kr-88	10080	4.19E+05	5.41	6093251359	100	11262942	100	1.8772E+07	2.85E+14	3.47E-02	1.90E-06
Xe-133	457056	3.07E+04	5.41	20243347435	100	37418387	100	6.2364E+07	2.85E+14	6.62E-02	3.30E-06
Xe-135	33012	2.61E+05	5.41	12430450908	100	22976804	100	3.8295E+07	2.85E+14	6.58E-02	2.04E-06

27.07.05 11:10 Tank 3 TC16=1085C 35 ml/min He + 65 ml/min Ne

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.27E+05	5.42	2955008774	100	5452046	100	9.0867E+06	2.74E+14	1.32E-02	2.51E-06
Kr-87	4578	5.15E+05	5.42	3401398817	100	6275644	100	1.0459E+07	2.74E+14	2.54E-02	1.50E-06
Kr-88	10080	4.61E+05	5.42	6704030732	100	12369060	100	2.0615E+07	2.74E+14	3.47E-02	2.17E-06
Xe-133	457056	6.21E+04	5.42	40948269568	100	75550313	100	1.2592E+08	2.74E+14	6.62E-02	6.94E-06
Xe-135	33012	2.86E+05	5.42	13621107125	100	25131194	100	4.1885E+07	2.74E+14	6.58E-02	2.32E-06

Table 19: Spreadsheet table for the calculation of R/B values (3 of 3)

8 Data Analysis and Interpretation

8.1 Temperature profiles

In Figure 60, the average temperature readings during high temperature operation are plotted for all 8 reactor cycles performed so far. It can be seen that the temperatures of pebbles GLE4.3 and GLE4.4 are reasonably close to each other and show only little deviation from the target temperatures, in particular since the gas panel modification just before cycle 05-06. TC16 on GLE4.4 is the reference thermocouple for the temperature adjustment. Data for GLE4.2 are available only for the first 2 cycles and would have to be recalculated for the other cycles from the operational neighboring thermocouples. Due to its position at the lower end of the sample holder and the strong expected neutron flux buckling in this area (to be confirmed by post-irradiation analysis of gamma scan wire), the temperature gradient along the surface of GLE4.5 is high and of the order of 200 K.

In conclusion, three out of five fuel pebbles (GLE4.2, 4.3 and 4.4) have been irradiated so far with sufficient precision at the desired target temperatures.

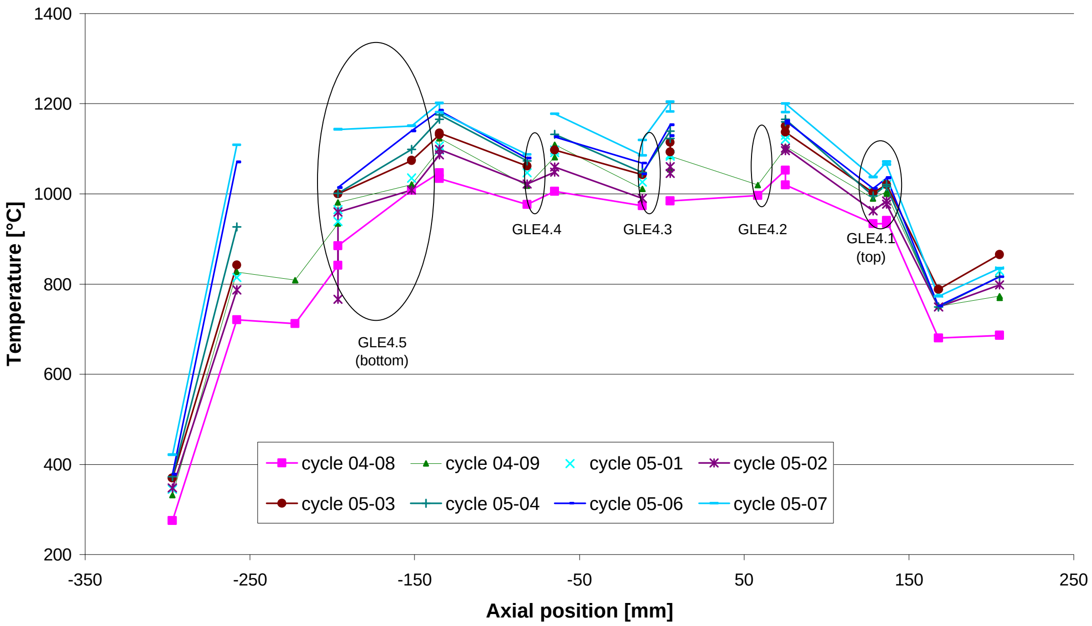


Figure 60: Average temperatures during high temperature operation

8.2 Fission gas release

From Figure 59 it can be concluded that the release of fission gases tends to increase as from the burn-up of approx. 10% FIMA. This tendency has yet to be confirmed by further measurements including at the coldest possible temperature under irradiation.

The quality of the R/B measurement (steady-state R/B) can be verified by checking that there is little or no temperature dependence on the fission gas transport.

In [7], we find the expression for R/B as follows:

$$\frac{R}{B} = 3\sqrt{\frac{D'}{l}}$$

with:

R: Fission gas release rate

B: Fission gas birth rate

D': apparent fission gas diffusivity, temperature dependent $D' = D'_0 \exp\left[\frac{-Q}{RT}\right]$

$l = \frac{\ln 2}{T_{½}}$ with $T_{1/2}$ half life of concerned isotope

At constant temperature T, we can then derive:

$$\ln\frac{R}{B} = const. - n \ln l$$

with

n < 0.2 for graphite contamination

0.2 < n < 0.3 observed in previous irradiations

n > 0.5 in case of particle bursts

For Xe-135, the thermal neutron absorption cross section is rather high (2.65×10^6 barn), so that some of the produced Xe-135 disappears due to neutron absorption before it can diffuse out of the pebble. Therefore, its λ has to be corrected: $l_{eff} = l_{Xe-135} + s_a \Phi_{th}$

with $\sigma_a = 2.65\times10^6$ barn = 2.65×10^{-22} m^2

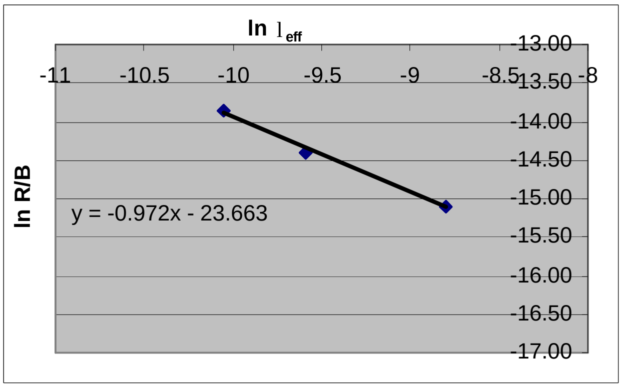
$\Phi_{th} \approx 10^{18}$ m^{-2} s^{-1}

Consequently, when plotting the individual ln R/B values from a given measurement against ln λ or ln λ_{eff}, the result should be a straight line with the negative inclination n.

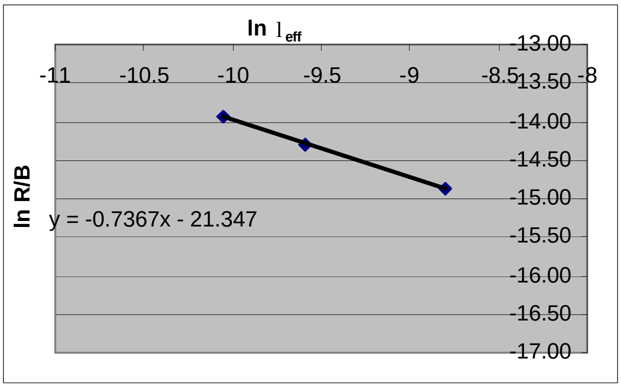
isotope	half life [s]	λ [s^{-1}]	λ_{eff} [s^{-1}]
Kr-85m	16128	4.30E-05	4.30E-05
Kr-87	4578	1.51E-04	1.51E-04
Kr-88	10080	6.88E-05	6.88E-05
Xe-135	33012	2.10E-05	2.86E-04

Table 20: Half-lives and λ_{eff} for measured isotopes

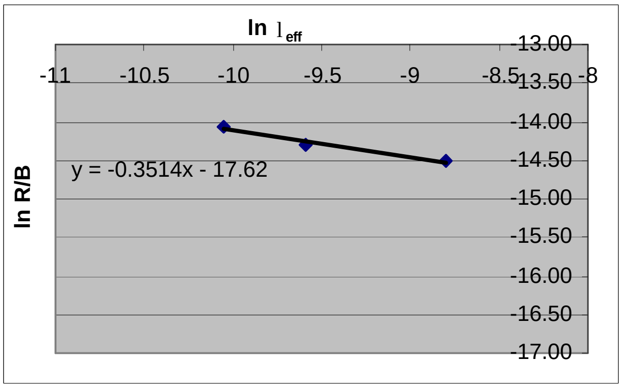
Unfortunately, some inconsistencies remained with this approach. Therefore, in a first step, only the analysis of the three measured Kr isotopes is reported here, for which the curve fits yielded reasonably straight lines.



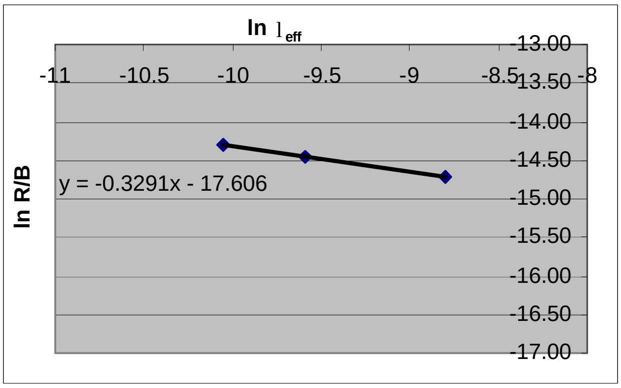
Measurement date 20040928



Measurement date 20040929



Measurement date 20041008



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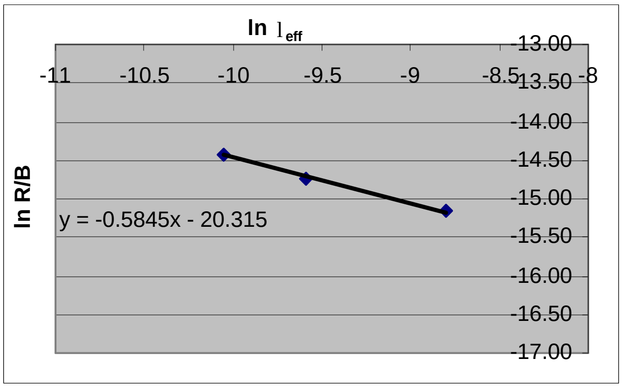
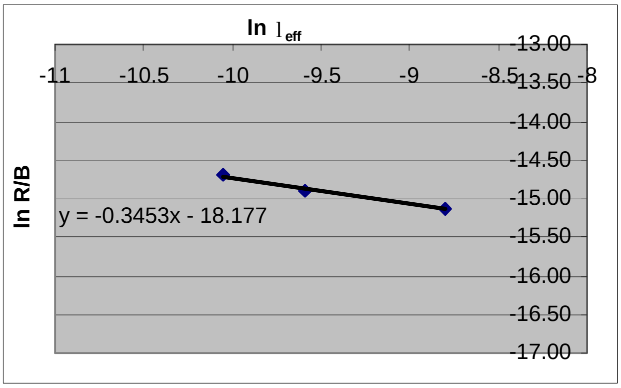
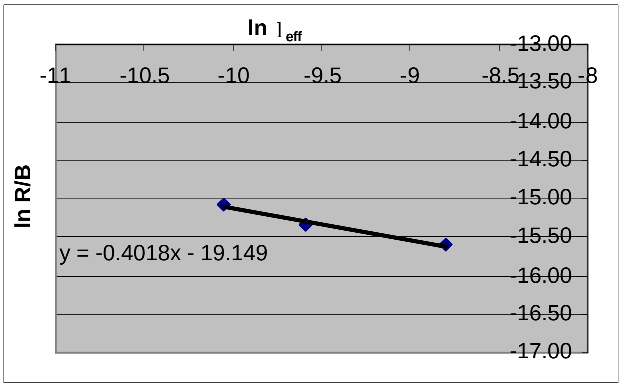


Measurement date 20050106

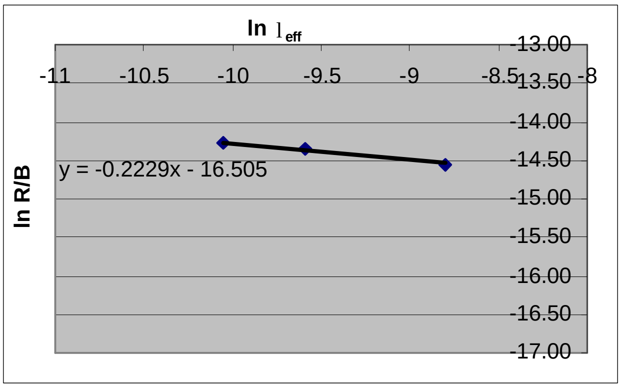


Measurement date 20050119

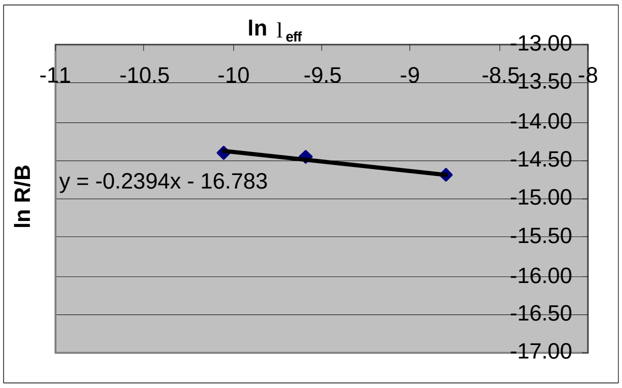
Figure 61: ln R/B vs. ln λ_{eff} plots for Kr gas release measurements (part 1/3)



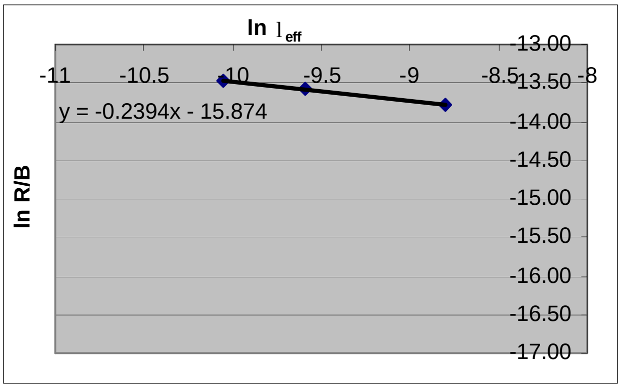
Measurement date 20050209



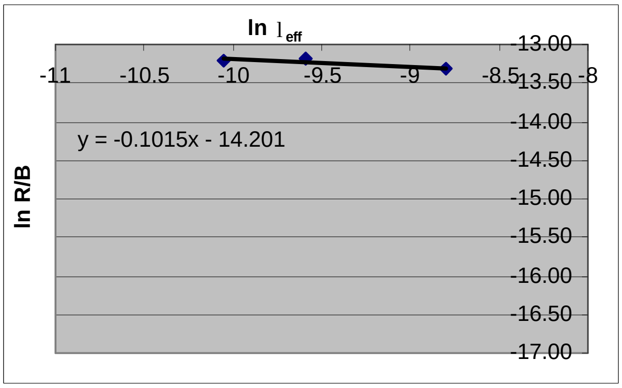
Measurement date 20050216



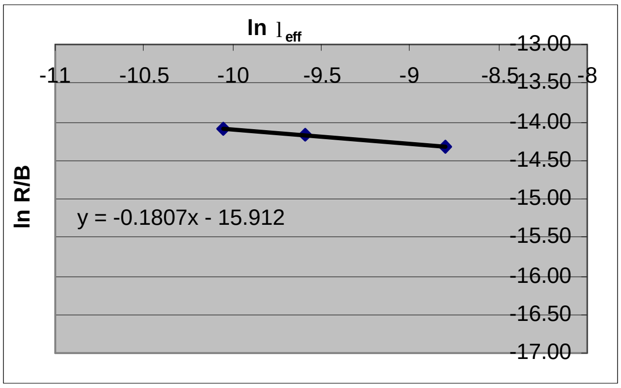
Measurement date 20050308



Measurement date 20050315

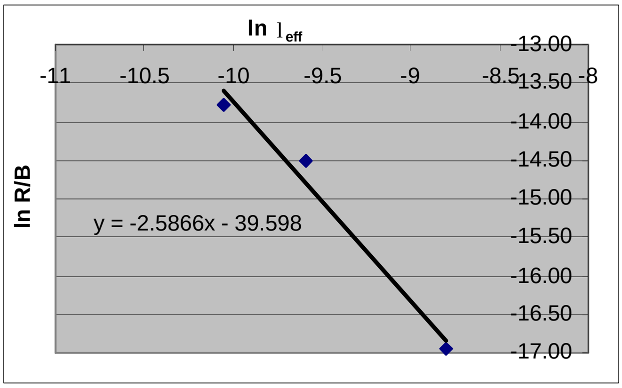


Measurement date 20050321

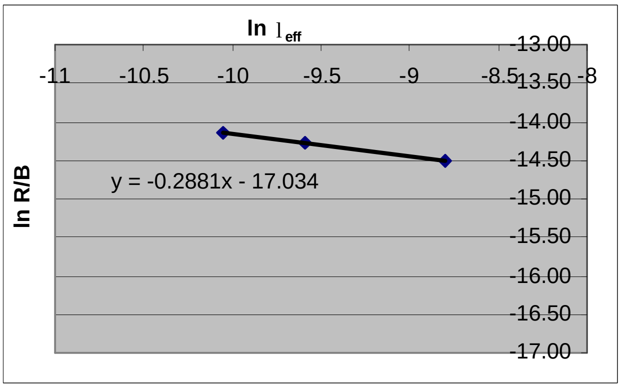


Measurement date 20050407

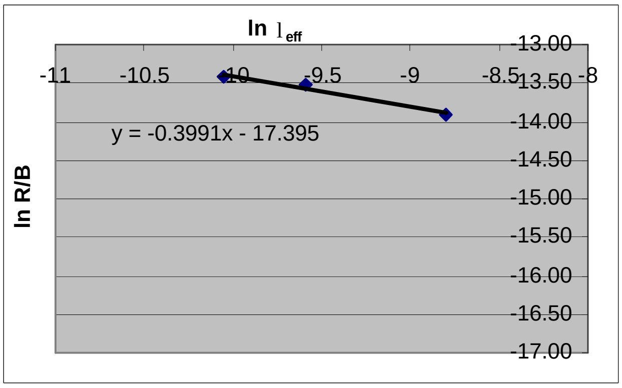
Figure 62: ln R/B vs. ln λ_{eff} plots for Kr gas release measurements (part 2/3)



Measurement date 20050615



Measurement date 20050616



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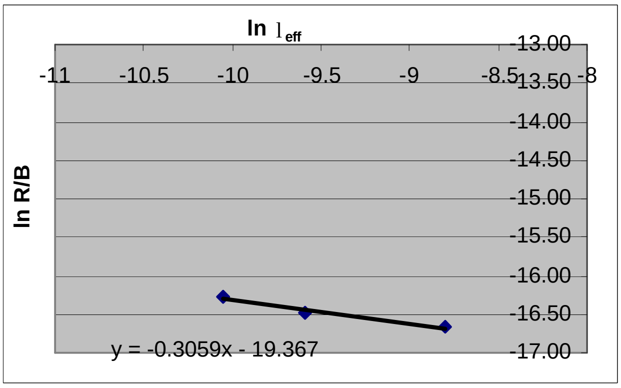
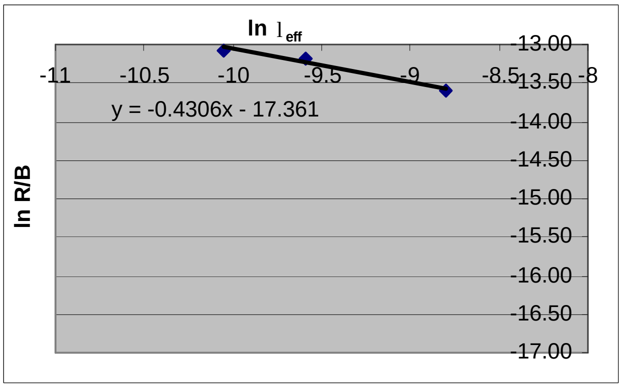
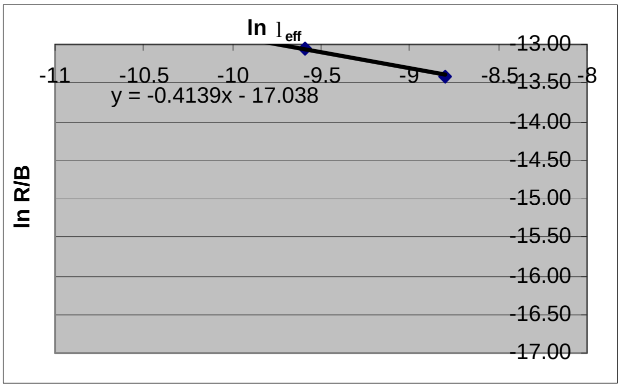


Measurement date 20050623



Measurement date 20050712



Measurement date 20050725

Figure 63: ln R/B vs. ln λ_{eff} plots for Kr gas release measurements (part 3/3)

Measurement date	inclination n in ln R/B vs. ln λ_{eff} plots $\ln\frac{R}{B} = const. - n \ln l$	Comments
20040928	***0.9720***	very low gas flow rate
20040929	***0.7367***	very low gas flow rate
20041008	0.3514	
20041018	0.3291	
20050106	***0.5845***	
20050119	0.3453	
20050209	0.4018	
20050216	0.2229	
20050308	0.2394	
20050315	0.2394	
20050321	0.1015	
20050407	0.1807	
20050615	***2.5866***	insufficient purging? temperature fluctuations
20050616	0.2881	
20050622	0.3991	
20050623	0.3059	
20050712	0.4306	
20050725	0.4139	

Table 21: Inclination n of straight fits in ln R/B vs. ln λ_{eff} plots

From Table 21 it can be concluded that only in 4 measurements, the inclination was > 0.5, which, however, may have its reason in the timing of the gas measurement, which proved very sensitive to even small temperature fluctuations.

9 References

[1] M. A. Fütterer, HFR-EU1bis: Irradiation Progress Report, Cycles 04-08, 04-09, 05-01, 05-02, rev. B, Technical Memorandum HFR/05/4806, D(05)5821, 2 September 2005.

[2] M. A. Fütterer, H. Lohner, R. Conrad, K. Bakker, S. de Groot, C. M. Sciolla, HFR-EU1bis: Irradiation of High Temperature Reactor Fuel Pebbles at VHTR Conditions in the HFR Petten, rev. D, Technical Memorandum HFR/03/4757, D(04)11197, 8 November 2004.

[3] C. M. Sciolla, HFR TEDDI post-cycle output, Cycle 05-03, NRG technical report 25138/05.65928/I, 25 March 2005.

[4] C. M. Sciolla, HFR TEDDI post-cycle output, Cycle 05-04, NRG technical report 25138/05.66561/I, 26 April 2005.

[5] C. M. Sciolla, HFR TEDDI post-cycle output, Cycle 05-06, NRG technical report 25138/05.67842/I, 5 July 2005.

[6] C. M. Sciolla, HFR TEDDI post-cycle output, Cycle 05-07, NRG technical report 25138/05.XXXXX/I, to be issued.

[7] Fuel performance and fission product behaviour in gas cooled reactors, IAEA TECDOC-978, ISSN 1011-4289, November 1997.

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EUROPEAN COMMISSION
Directorate General Joint Research Centre
Institute for Energy - HFR Unit

7 December 2005
D(05)27415

TECHNICAL MEMORANDUM
HFR / 05 / 4815

HFR-EU1bis: Irradiation Progress Report

Cycles 05-08, 05-09

Project n° 337.2

rev. A

Michael A. Fütterer

	For the authors	Verified by	Approved by Unit Head
Name	M. A. Fütterer	F. Scaffidi-Argentina	R. May
Date	7.12.05	08.12.2005	8/12/2005
Signature	M. Fütterer	F. Scaffidi-Argentina	[illegible]

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Revision	Date	Description
A	07.12.05	initial release
B		
C		

Abstract

This is the third progress report of the HTR fuel pebble irradiation experiment HFR-EU1bis combining the results of the last two irradiation cycles. The two earlier issued reports [1], [2] covered the first 8 reactor cycles.

The irradiation had started on 9 September 2004 and was interrupted for 2 reactor cycles. Due to scheduled reactor maintenance and for a gas panel modification, the irradiation was paused again during cycle 05-05. In agreement with the HTR-F/F1 project coordinator, the experiment was finished after 10 reactor cycles in the end of cycle 05-09 on 18 October 2005.

This document contains the history of the irradiation including significant special events, nuclear data as well as temperature and fission gas release measurements. The results of the post-irradiation neutron radiographs are also provided which clarified the location of the gas leak between 1st and 2nd containment since the 2nd irradiation cycle.

Some preliminary attempts were made to analyze and interpret the information obtained so far.

Further reports will contain a summary of the irradiation, the correction of the burn-up and some more detailed analysis of the experimental results.

Further data is available to the HTR-F/F1 partners on request.

Table of Contents

1 Irradiation History

27.08.05 23:10 start cycle 05-08 **4 scrams** **3 gas samples taken** **20.09.05 08:00 end cycle 05-08**
22.09.05 17:30 start cycle 05-09 **1 scram** **2 gas samples taken** **18.10.05 08:00 end cycle 05-09**

1.1 Special Events

A nitrogen leak from the boa and Y piece appeared in the beginning of cycle 05-09 (rig head containment) and could not be completely fixed during the reactor cycle. For several days, the 1st and 2nd containments were isolated (no purge gas flow) and the pressure was lowered. In case of additional failure of the dual O-ring seal between the rig head and the 2nd containment, nitrogen could have entered into the 1st and 2nd containment and thus increase the fuel temperature in an uncontrolled manner. To avoid this type of incident, the pressure in the 1st and 2nd containments was lowered from 5.4 bar abs to 2.3 bar abs (rig head containment pressure) but the purge gas flow of 100 ml/min was maintained and the rig head containment pressure was adjusted on a regular basis.

1.2 Modifications of Installation

A funnel with connection to the HFR off-gas system was placed under water above the leaking Y piece of the boa to avoid potentially contaminated gas to escape into the reactor hall. No contamination was released from the boa.

2 Nuclear Data

The information in this section is extracted from post-cycle nuclear calculations of the HFR core.

2.1 Fluxes, fluences and other data cycle 05-08

Cycle 05-08, position G3, **orientation North**, data from [4]

	flux start-up initial [10^{18} $m^{-2}s^{-1}$]	flux start-up equilibrium [10^{18} $m^{-2}s^{-1}$]	flux end of cycle [10^{18} $m^{-2}s^{-1}$]	fluence [10^{25} m^{-2}]
F_1 [1)]	0.803	0.808	0.792	0.153
F_2 [1)]	1.314	1.321	1.294	0.251
F_3 [1)]	1.613	1.626	1.604	0.310
F_4 [1)]	1.087	1.081	1.137	0.213
F_{Fe}	1.266	1.275	1.249	0.242
F_{Co}	0.938	0.936	0.971	0.183
$F_{E > 1\ MeV}$	1.010	1.016	0.996	0.193
$F_{E > 0.1\ MeV}$	1.999	2.011	1.970	0.382

[1)] energy groups with boundaries: $14.918\times10^6 - 1.353\times10^6 - 0.0674\times10^6 - 0.683 - 0$ eV

Table 1: Neutron fluxes and fluences cycle 05-08

full power days	22.19
dpa (stainless steel)	0.297
gamma heating in small graphite samples [W/g]	4.795 initial start-up 4.833 start-up equilibrium 4.896 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

Table 2: Nuclear characteristics for cycle 05-08

2.2 Fluxes, fluences and other data cycle 05-09

Cycle 05-09, position G3, **orientation South**, data from [5]

	flux start-up initial $[10^{18}\ m^{-2}s^{-1}]$	flux start-up equilibrium $[10^{18}\ m^{-2}s^{-1}]$	flux end of cycle $[10^{18}\ m^{-2}s^{-1}]$	fluence $[10^{25}\ m^{-2}]$
F_1 1)	0.781	0.788	0.775	0.173
F_2 1)	1.283	1.294	1.271	0.284
F_3 1)	1.532	1.549	1.535	0.341
F_4 1)	1.030	1.028	1.096	0.235
F_{Fe}	1.232	1.243	1.223	0.273
F_{Co}	0.890	0.891	0.934	0.202
$F_{E > 1\ MeV}$	0.983	0.992	0.976	0.218
$F_{E > 0.1\ MeV}$	1.949	1.966	1.933	0.431

1) energy groups with boundaries: $14.918\times10^6 – 1.353\times10^6 – 0.0674\times10^6 – 0.683 – 0$ eV

Table 3: Neutron fluxes and fluences cycle 05-09

full power days	25.6
dpa (stainless steel)	0.335
gamma heating in small graphite samples [W/g]	4.652 initial start-up 4.713 start-up equilibrium 4.812 end of cycle
axial shape factor fast fluence	1.270
axial shape factor thermal fluence	1.230

Table 4: Nuclear characteristics for cycle 05-09

2.3 Analysis of nuclear data

From Table 1 through Table 4 the following can be concluded:

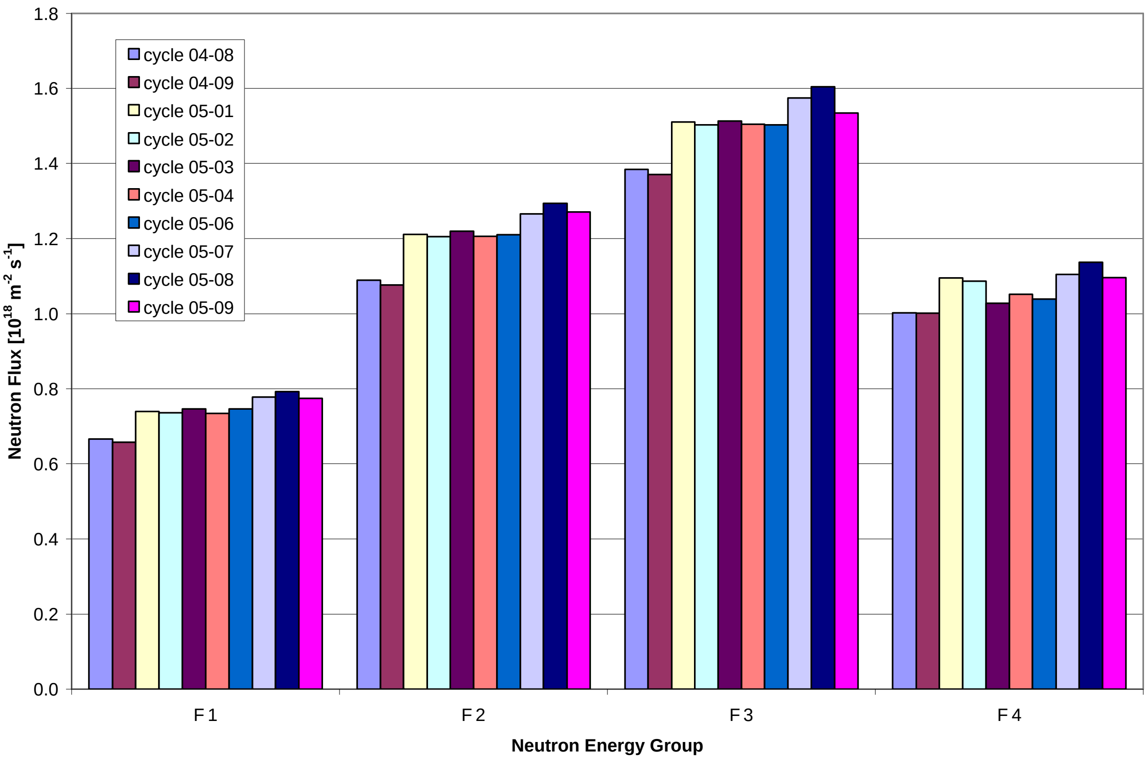
The nuclear data of this set of two reactor cycles turned out to vary much less than in the first two irradiation cycles that are responsible for the relatively large overall flux variation. Between the last two cycles, the fluxes varied only slightly while the fluences varied significantly due to the shorter cycle length of cycle 05-08.

According to these calculations, the attained thermal and fast fluence would be 2.23×10^{25} m^{-2} and 3.98×10^{25} m^{-2} respectively accumulated during 249.44 equivalent full power days. The values and axial profiles for fluence and spectrum will be verified during PIE through the analysis of gamma scan wires and neutron detector sets.

Cycle	efpd	F_1 [1)]	F_2	F_3	F_4	$Fluence_4$	$Fluence_{E > 0.1\ MeV}$
	[days]	EOC [10^{18} $m^{-2}s^{-1}$]				[10^{25} m^{-2}]	
04-08	24.97	0.666	1.089	1.384	1.002	0.209	0.357
04-09	24.72	0.658	1.076	1.371	1.001	0.207	0.350
05-01	25.99	0.740	1.211	1.511	1.095	0.24	0.419
05-02	25.67	0.736	1.205	1.503	1.087	0.234	0.410
05-03	25.29	0.746	1.220	1.513	1.028	0.220	0.411
05-04	25.67	0.735	1.206	1.505	1.052	0.226	0.408
05-06	24.26	0.746	1.210	1.503	1.039	0.211	0.389
05-07	25.19	0.778	1.266	1.575	1.105	0.233	0.424
05-08	22.19	0.792	1.294	1.604	1.137	0.213	0.382
05-09	25.60	0.775	1.271	1.535	1.096	0.235	0.431
total	249.55					2.23	3.98
variation between 05-08 and 05-09	15.37%	2.19%	1.81%	4.50%	3.74%	10.33%	12.83%
variation during entire irradiation	17.12%	20.36%	20.26%	16.99%	13.59%	15.94%	23.14%

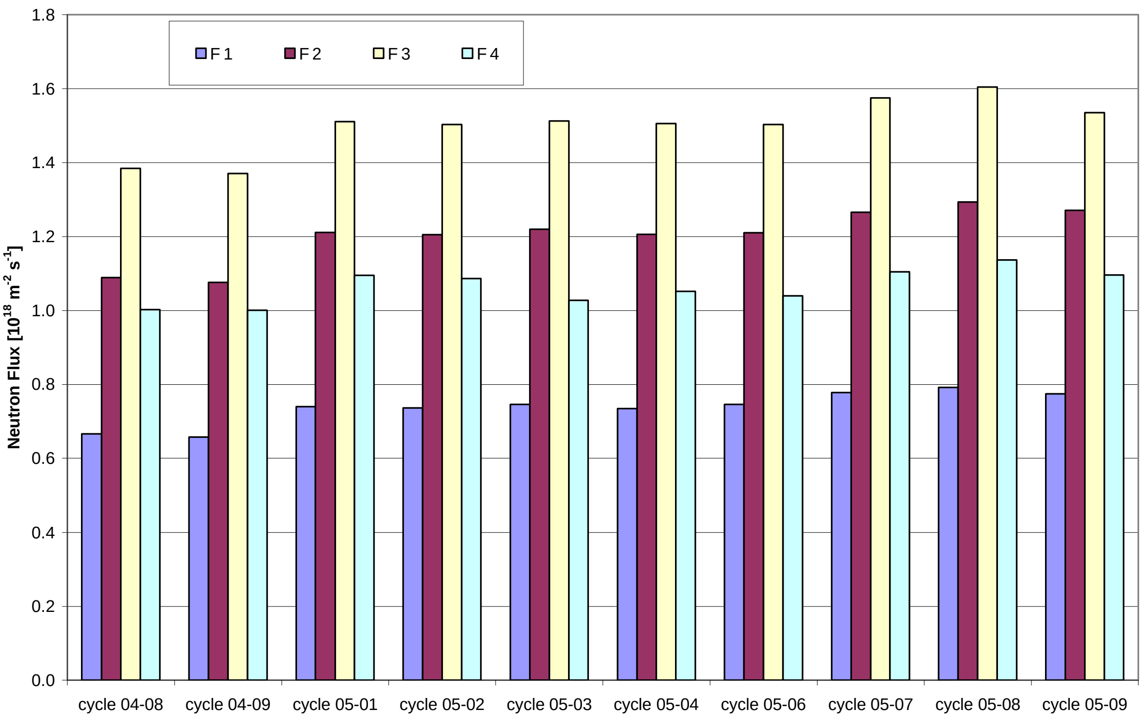
[1)]energy groups with boundaries: $14.918 \times 10^6 - 1.353 \times 10^6 - 0.0674 \times 10^6 - 0.683 - 0$ eV

Table 5: Comparison of fluxes and fluences



Energy groups with boundaries: $14.918\times10^6 - 1.353\times10^6 - 0.0674\times10^6 - 0.683 - 0$ eV

Figure 1: Comparison of neutron fluxes per reactor cycle



Energy groups with boundaries: $14.918\times10^6 - 1.353\times10^6 - 0.0674\times10^6 - 0.683 - 0$ eV

Figure 2: Comparison of neutron fluxes per energy group

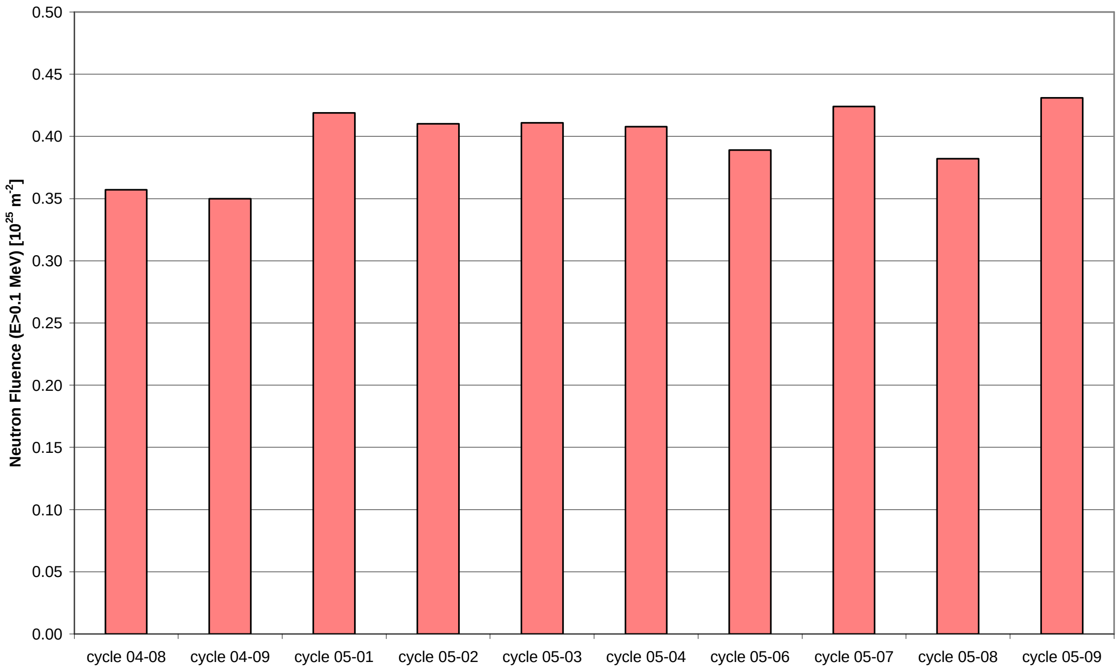


Figure 3: Comparison of fast fluences (E > 0.1 MeV) per reactor cycle

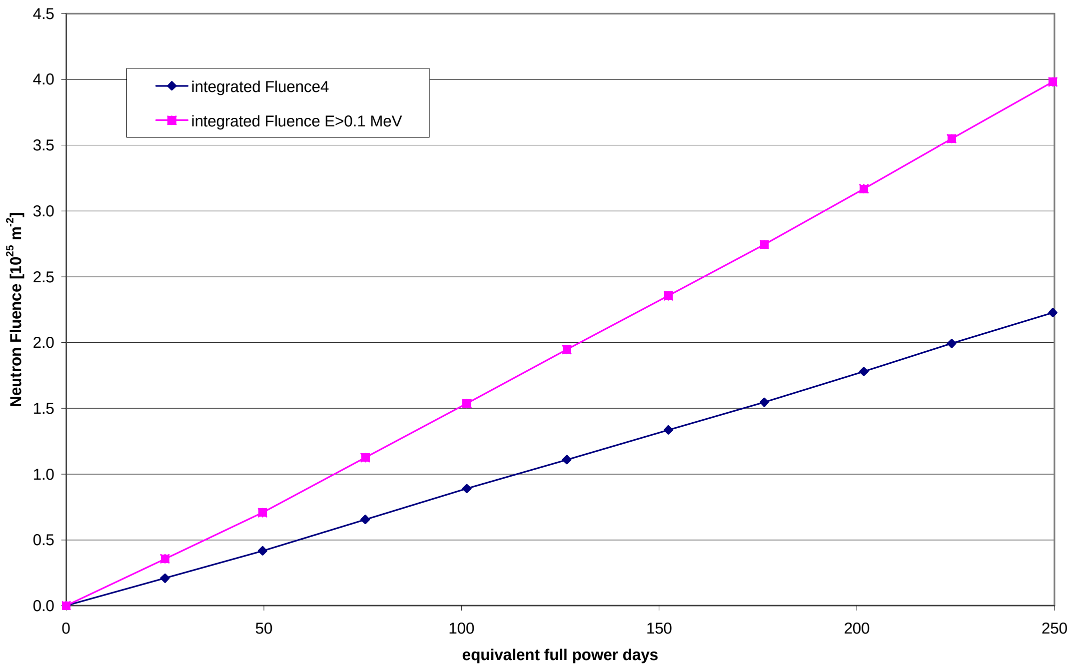


Figure 4: Incremental increase in fast (upper curve) and thermal fluence per reactor cycle

3 Reactor Power and Control Rod Positions

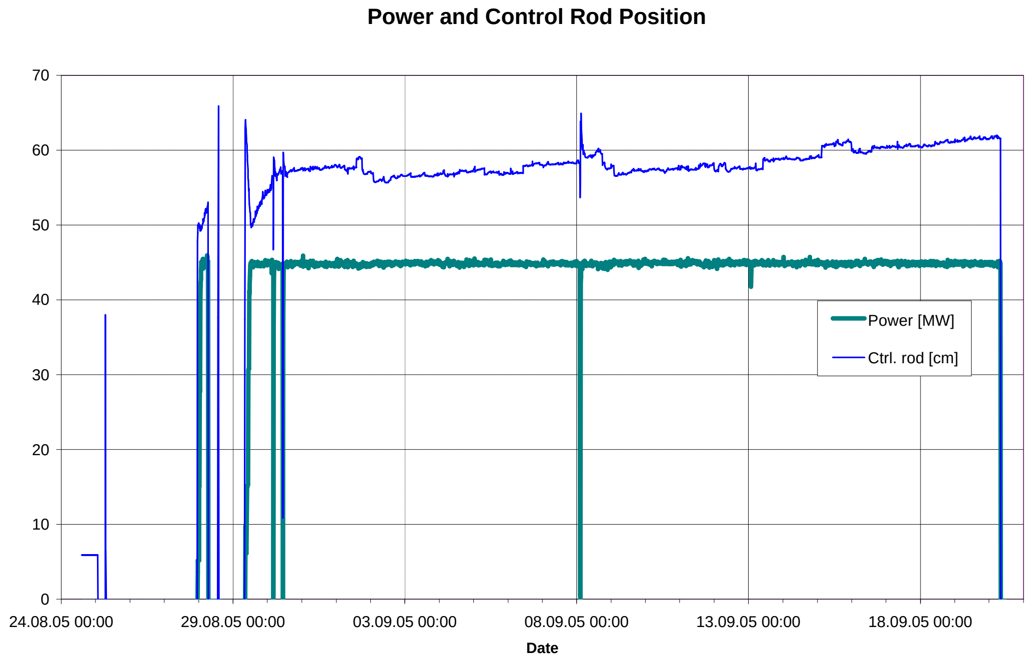


Figure 5: Reactor Power/Control Rod position cycle 05-08

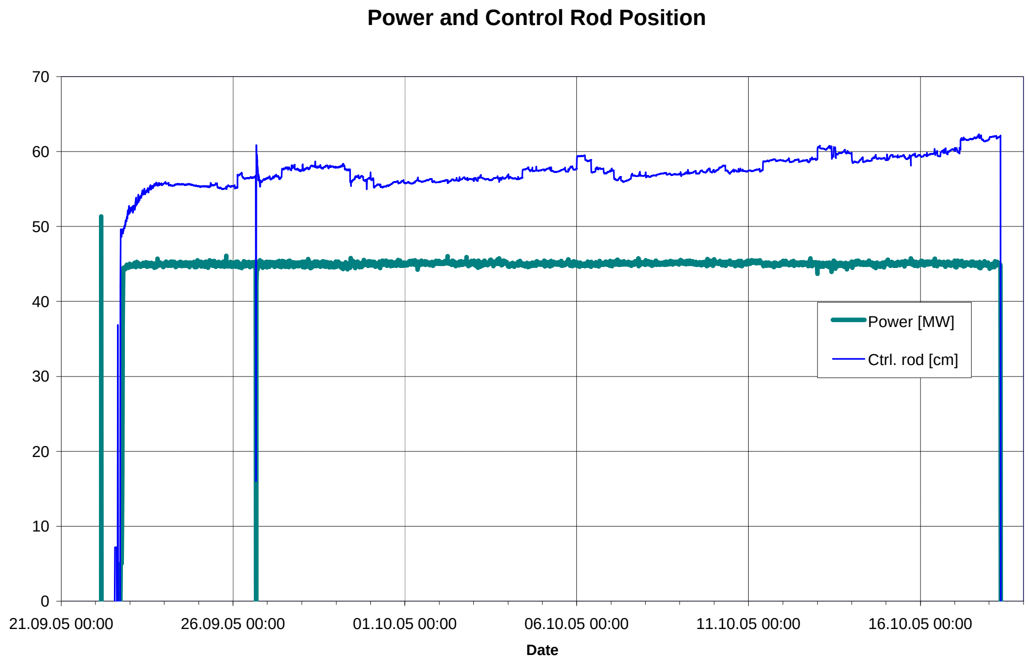


Figure 6: Reactor Power/Control Rod position cycle 05-09

4 Vertical Displacement Unit (VDU) Position

The VDU was not used since the beginning of the irradiation and was held in the lowest possible position. The very small measured differences are artifacts related to the data acquisition system.

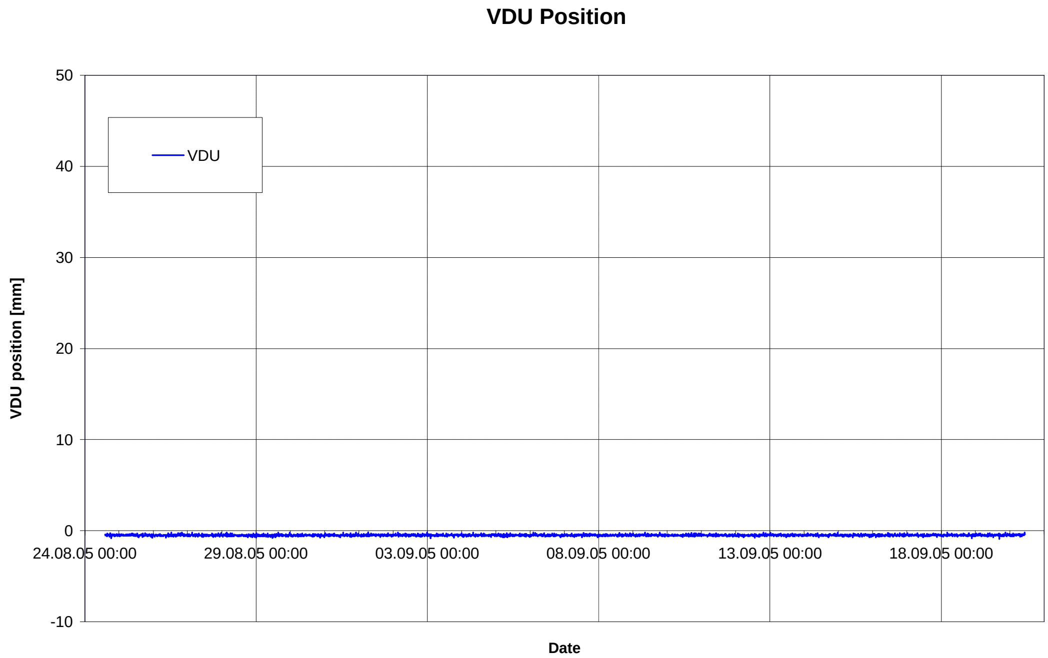


Figure 7: VDU position cycle 05-08

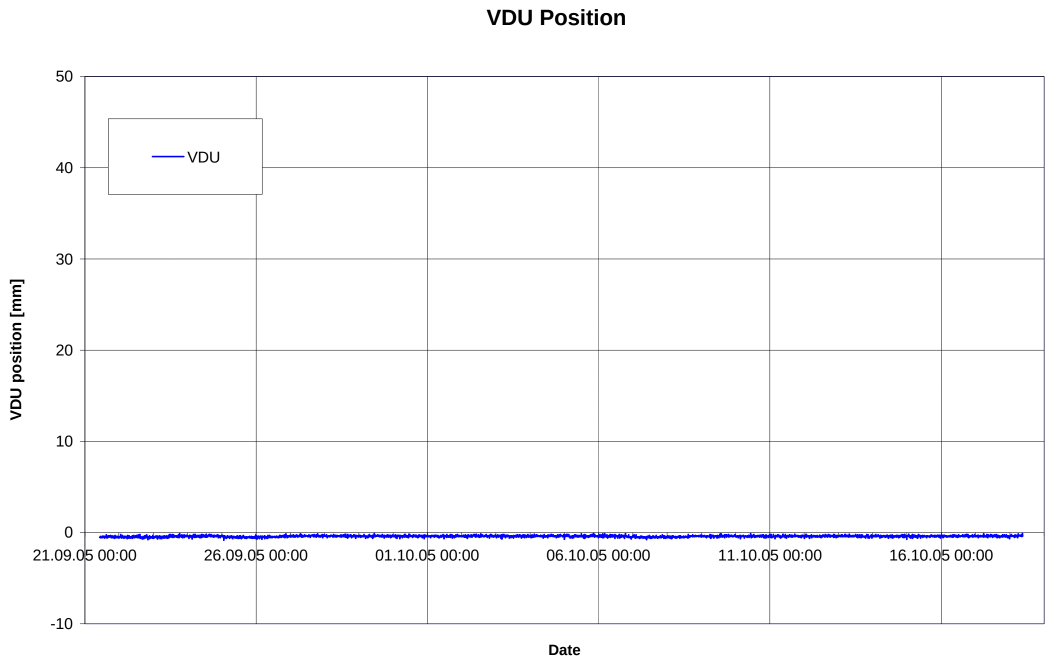


Figure 8: VDU position cycle 05-09

5 Counter Readings in Gas Panel (GM1 and GM3)

The Geiger-Müller counter readings of the two counters in the gas panel (GM1 and GM3) are at background level (3 V) when the gas is stagnant. Higher activities are only measured during purging (4 V) and in particular when activating the filter bypass (8 V stabilized), generally before taking a gas sample. These values are somewhat higher than observed in previous cycles.

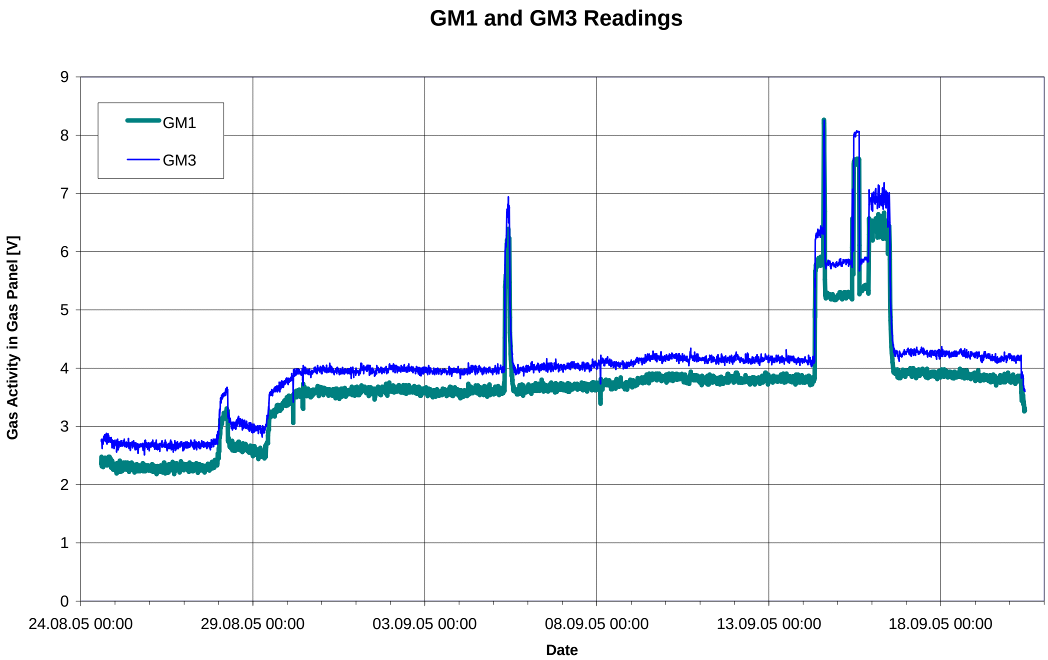


Figure 9: GM1 and GM3 readings cycle 05-08

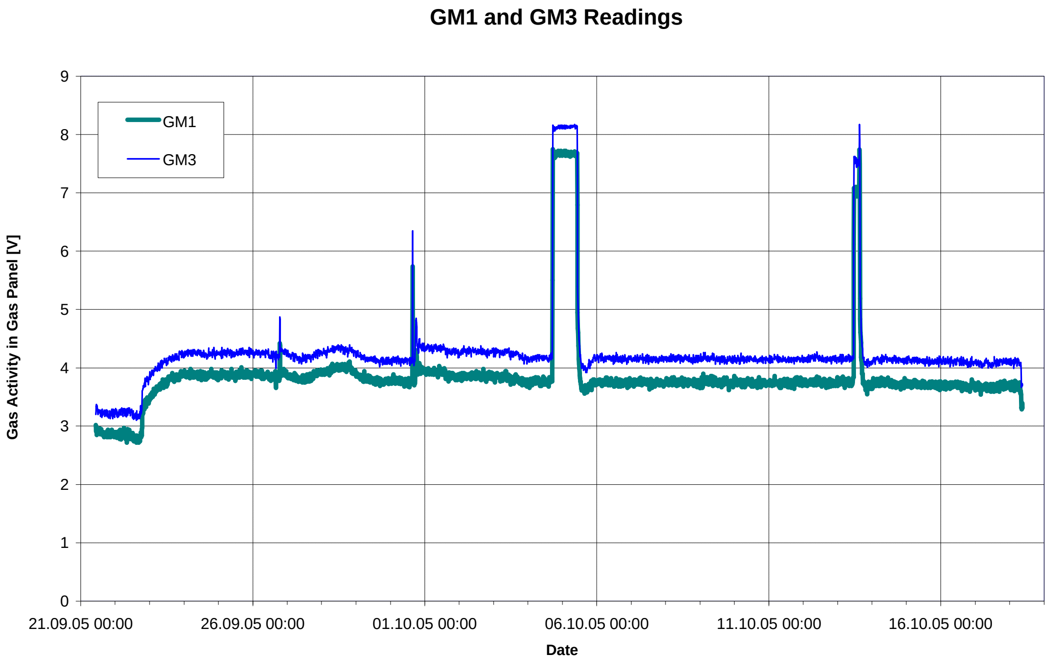


Figure 10: GM1 and GM3 readings cycle 05-09

6 Temperature Measurements

After the first 4 cycles, **6** out of 24 thermocouples provided no or wrong information, only one of those failed (TC-09) has no backup.

Contrary to what was written earlier, the TC-12 values seem to be physical all through the irradiation. In return, TC-21 showed values that are seemingly too low and erratic. In cycle 05-07, TC-24 was lost.

In cycle 05-09 TC-5 was lost. In the last two cycles, several temperature measurements behaved awkwardly.

Location	TC #	
1 Graphite	**1**, 2, 3	TC-01 no contact since 29.12.2004
GLE4.1	4, **5**, 6	wrong values as of 23.09.2005
Graphite between GLE4.1 and GLE4.2	7, **8**	TC-08 sometimes erratic values since beginning
GLE4.2	**9**	TC-09 erroneous value since 29.12.2004
Graphite between GLE4.2 and GLE4.3	10, 11	
GLE4.3	**12**, 13	TC-12 too low since beginning, returned to correct values from cycle 05-04 onwards
Graphite between GLE4.3 and GLE4.4	14, **15**	TC-15 slipped? values too low since 17.02.2005
GLE4.4	16	
Graphite between GLE4.4 and GLE4.5	17, 18	
GLE4.5	19, 20, **21**	TC-21 values too low and erratic since 05-03
Graphite between GLE4.5 and Al block	**22**, 23	TC-22 no contact or erroneous values since 29.12.2004
Aluminum Block	**24**	TC-24 erroneous value since 30.07.2005

Table 6: Location of thermocouples, malfunction is indicated in **bold red**

TC nr	axial position [mm]	radial position [mm]	cycle 04-08	cycle 04-09	cycle 05-01	cycle 05-02	cycle 05-03	cycle 05-04	cycle 05-06	cycle 05-07	cycle 05-08	cycle 05-09
1	205	18.50	**687.0**	**769.6**	~~2.1~~	~~3.3~~	~~0.2~~	~~2.0~~	~~3.9~~	~~2.8~~	~~5.9~~	~~0.7~~
2	205	18.50	**686.0**	**773.4**	**840.6**	**798.5**	**869.1**	**826.5**	**819.8**	**851.8**	**831.2**	**874.5**
3	168	18.50	**680.7**	**751.2**	**790.3**	**748.9**	**792.4**	**758.4**	**754.3**	**786.7**	**764.7**	**803.2**
4	136.524	5.01	**941.3**	**1000.2**	**1029.9**	**977.5**	**1023.5**	**1030.9**	**1039.4**	**1081.8**	**1064.6**	**1108.3**
5	136.524	5.01	**934.3**	**1004.8**	**1029.3**	**984.6**	**1023.4**	**1036.1**	**1037.4**	**1086.7**	**1063.9**	~~120.3~~
6	128.208	18.21	**934.4**	**990.1**	**1014.1**	**962.7**	**1005.1**	**1009.6**	**1014.4**	**1052.1**	**1031.5**	**1072.5**
7	75	5.00	**1020.3**	**1105.3**	**1130.0**	**1101.6**	**1141.1**	**1178.8**	**1164.0**	**1199.1**	~~1062.0~~	~~1167.0~~
8	75	5.00	~~1052.5~~	**1101.5**	~~1140.2~~	~~1096.3~~	~~1153.5~~	**1173.2**	~~1162.0~~	~~1176.9~~	~~1127.8~~	~~1059.1~~
9	58.2085	18.21	**996.7**	**1020.0**	~~70.5~~	~~68.5~~	~~70.6~~	~~71.3~~	~~73.0~~	~~73.8~~	~~75.3~~	~~52.4~~
10	5	5.00	**984.7**	**1084.1**	**1097.3**	**1046.0**	**1097.4**	**1127.7**	**1129.4**	**1192.5**	**1151.3**	**1170.8**
11	5	5.00	**984.9**	**1054.6**	**1095.0**	**1060.5**	**1118.4**	**1146.1**	**1153.6**	**1213.8**	**1191.0**	**1212.0**
12	-11.7915	18.21	**868.2**	**998.2**	**997.9**	**948.4**	**1007.8**	**1053.0**	**1045.2**	**1129.6**	**1088.8**	**1159.2**
13	-11.7915	18.21	**973.8**	**1011.2**	**1037.4**	**990.5**	**1047.4**	**1051.1**	**1067.9**	**1094.0**	**1082.6**	~~1138.2~~
14	-65	5.00	**1006.0**	**1109.2**	**1102.7**	**1060.0**	**1101.9**	**1132.3**	**1124.7**	**1176.9**	**1134.6**	**1167.7**
15	-65	5.00	**1006.1**	**1081.9**	**1108.7**	~~1048.4~~	~~973.5~~	~~1014.1~~	~~1061.8~~	~~997.0~~	~~974.1~~	~~981.3~~
16	-81.7915	18.21	**976.7**	**1018.1**	**1057.8**	**1021.7**	**1066.6**	**1071.7**	**1079.2**	**1087.0**	**1094.4**	**1104.8**
17	-135	5.00	**1033.9**	**1123.6**	**1115.6**	**1099.3**	**1140.5**	**1172.8**	**1182.4**	1168.3	1145.7	~~1170.1~~
18	-135	5.00	**1047.2**	**1098.6**	**1105.1**	**1087.1**	**1136.3**	**1165.2**	**1183.1**	**1191.4**	**1145.3**	**1165.0**
19	-151.792	18.21	**1007.8**	**1021.0**	**1041.7**	**1009.0**	**1079.4**	**1098.5**	**1139.2**	**1142.4**	**1133.6**	**1158.6**
20	-196.524	5.01	**885.0**	**981.2**	**973.2**	**960.1**	**1006.0**	**999.3**	1018.3	1163.3	1103.7	1128.1
21	-196.524	5.01	**842.1**	**934.4**	**945.3**	~~766.5~~	~~631.4~~	~~493.1~~	~~724.9~~	~~407.0~~	~~502.4~~	~~698.6~~
22	-222.5	18.50	**712.4**	**808.9**	~~-354.9~~	~~0.4~~	~~0.0~~	~~141.7~~	~~600.6~~	~~1004.9~~	~~138.5~~	~~987.0~~
23	-258	18.50	**721.1**	**826.7**	**823.0**	**787.5**	**848.2**	**962.0**	**1072.9**	**1116.1**	**1062.0**	**1147.0**
24	-297	0.00	**275.5**	**332.3**	**348.2**	**347.8**	**372.0**	**370.8**	**378.4**	~~467.7~~	~~714.5~~	~~730.3~~
			TC8 occasional drop-outs	TC8 ok	TC1, TC9, TC22 failed permanently, TC8 occasional drop-outs	TC15 failed on 16.02.2005, TC21 failed on 15.02.05, TC8 occasional drop-outs	TC8 occasional drop-outs	TC8 ok	TC8 occasional drop-outs, TC20 increased by 100 K between 28.06.-30.06.05 (moved and moved back)	TC8 dropped >50K on 18.07.05, then moves slowly back upwards. TC17 increases > 50K on 29.07.05, TC20 increases > 100K on 11.07.2005, TC24 failed on 30.07.05 (increased 600K)	TC8 strong drop-outs in first half of cycle, TC13 decreases 30K on 16.09.05, TC17 decreases slowly, TC20 decreases slowly all along cycle	TC5 failed since BOC, TC7 unexplained jumps, TC8 drop-outs for 3 days, TC13 too low then recovers;TC17 unreliable; TC20 moved?

Table 7: History of thermocouple behavior

In Table 7, the behavior of all 24 thermocouples was analyzed to obtain an idea about the reliability of the obtained data. The red lines indicate temperature measurements at pebble surfaces. Yellow boxes with strikethrough numbers indicate suspicious behavior of the concerned thermocouple and thus potentially unreliable data.

Figure 11 summarizes the axial temperature profile of the irradiation. The encircled measurement points concern the fuel pebbles.

Figure 12 shows the evolution of these average temperatures with time. The most striking observation is that the temperature read by TC-23 situated in the bottom graphite block has abnormally increased from the 5th irradiation cycle on as if the insulation gap between the lowermost graphite half shell and this bottom graphite block had gradually disappeared. It will be an objective of the post-irradiation neutron radiograph to clarify this behavior.

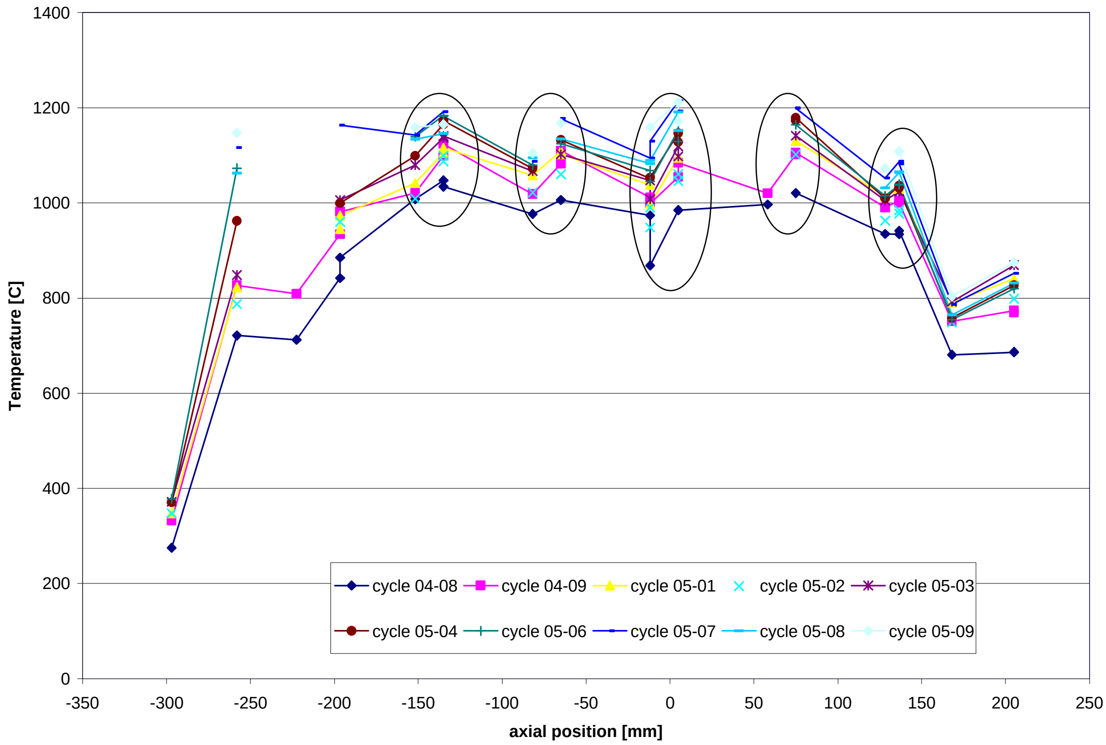


Figure 11: Average temperatures in irradiation rig for all 10 irradiation cycles

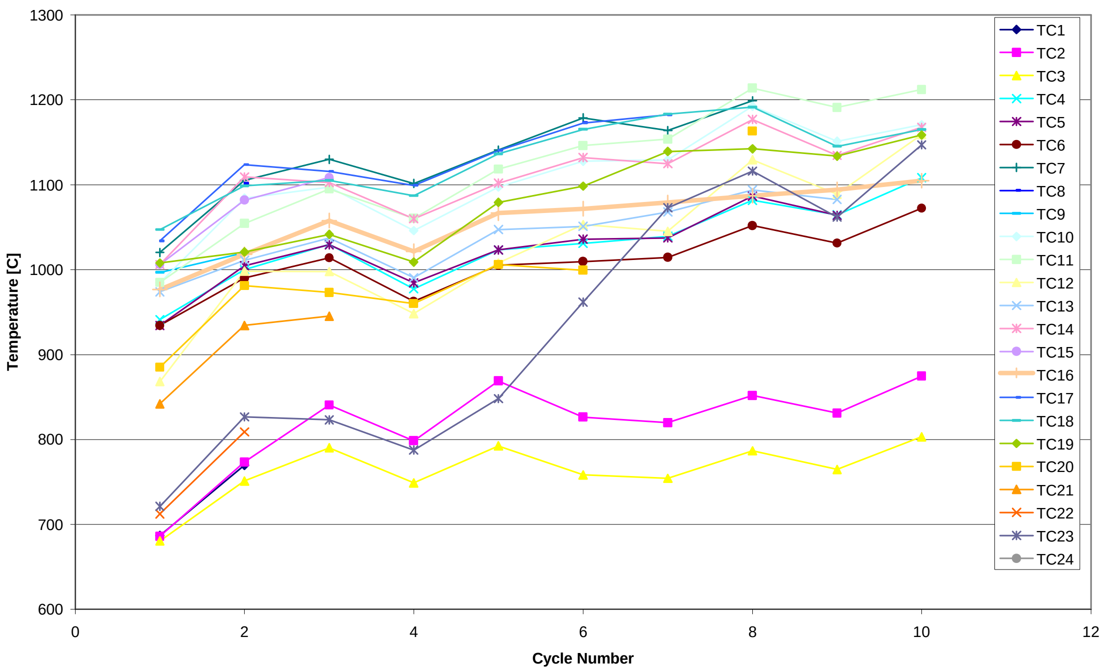


Figure 12: Evolution of average temperatures during irradiation

Table 8 shows the calculated surface temperatures of the 5 pebbles that would keep their central temperatures constant at 1250°C [1].

	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	3948	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 8: Predicted power and temperature evolution per pebble and required gas mixture per cycle; *: cycles 13 and 14 require pure N_2 in 1st containment

6.1 Temperatures during Cycle 05-08

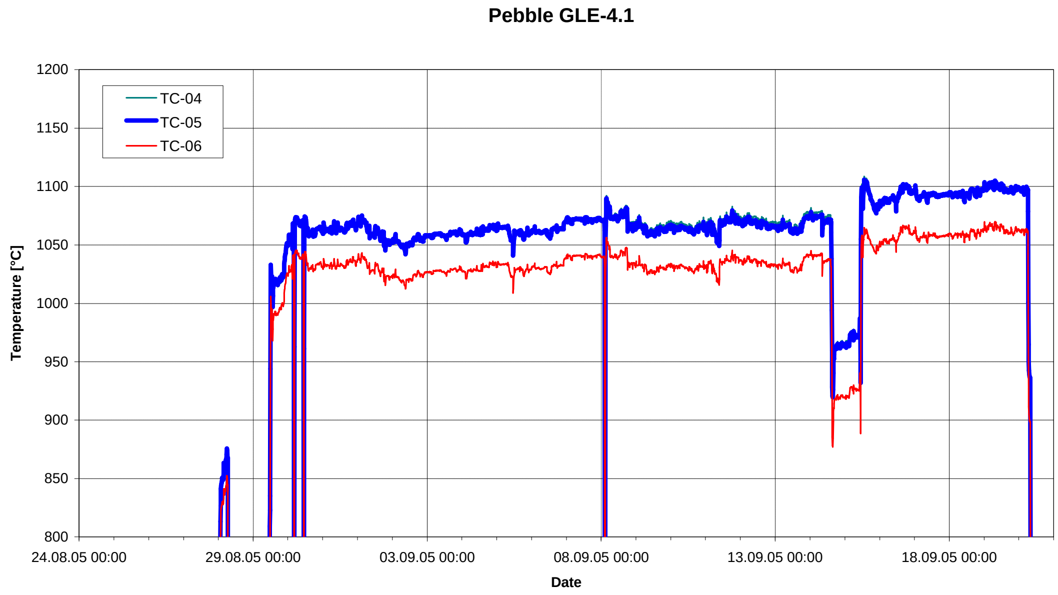


Figure 13: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

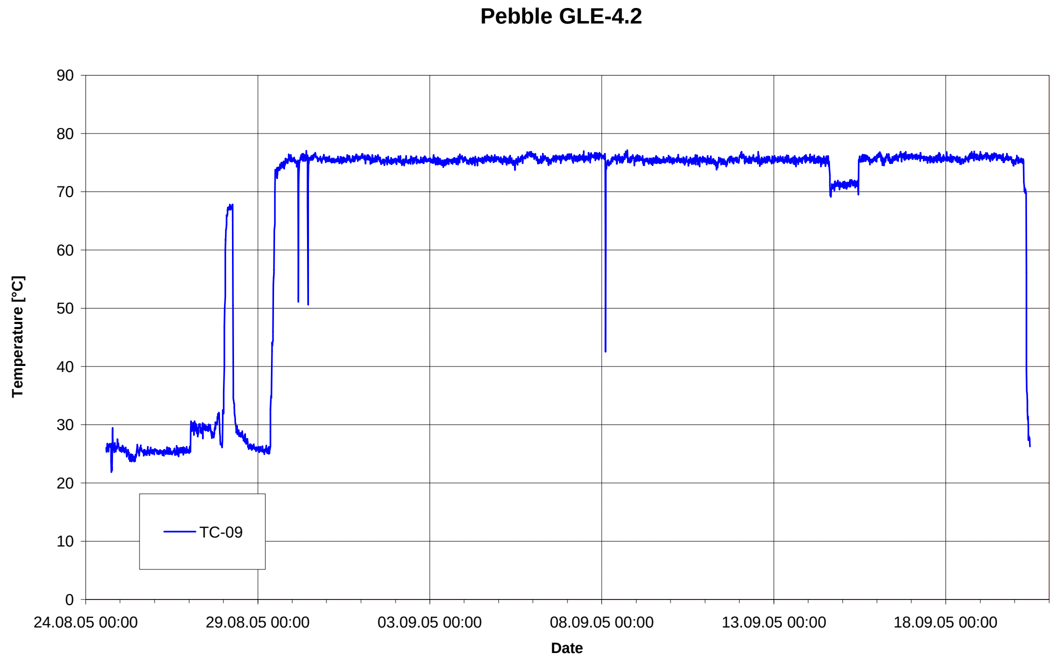


Figure 14: Temperature pebble GLE4.2 (TC-09)

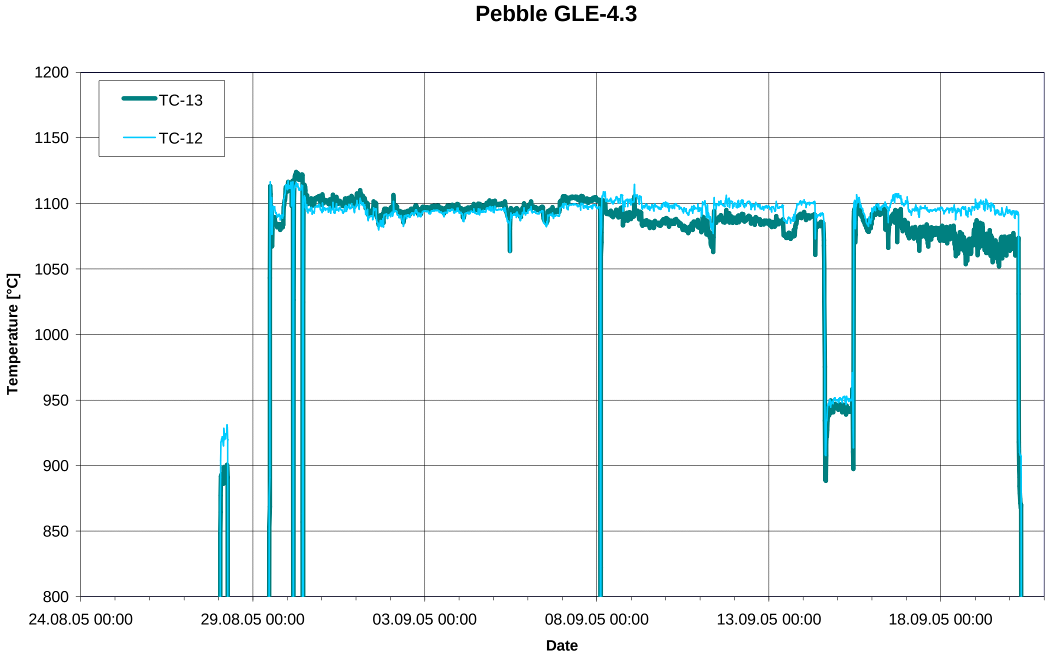


Figure 15: Temperatures pebble GLE4.3 (TC-12, TC-13)

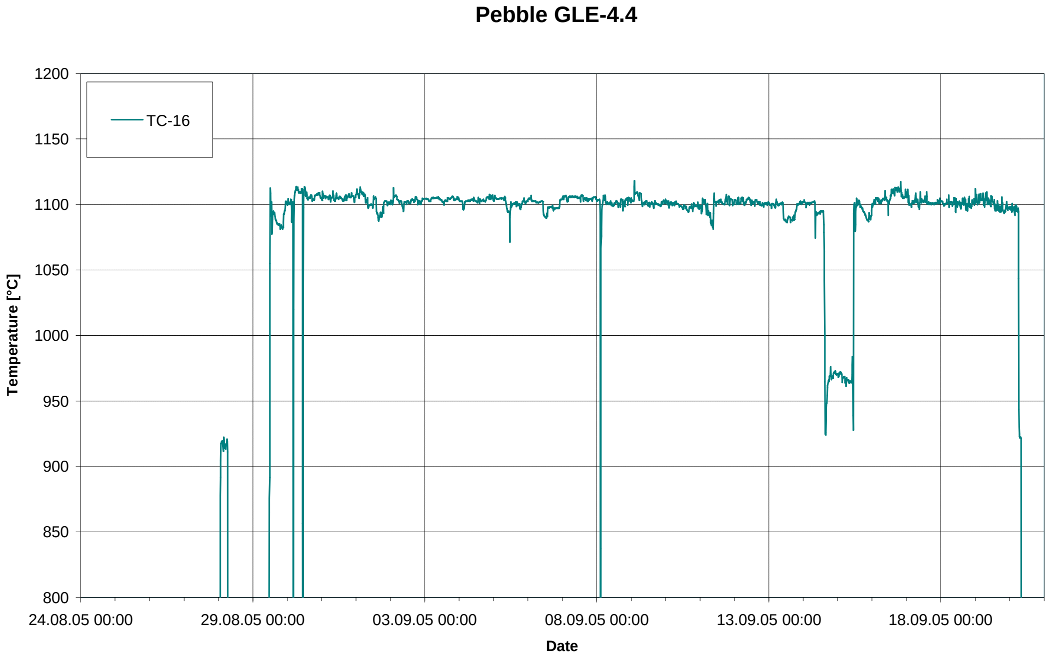


Figure 16: Temperature pebble GLE4.4 (TC-16)

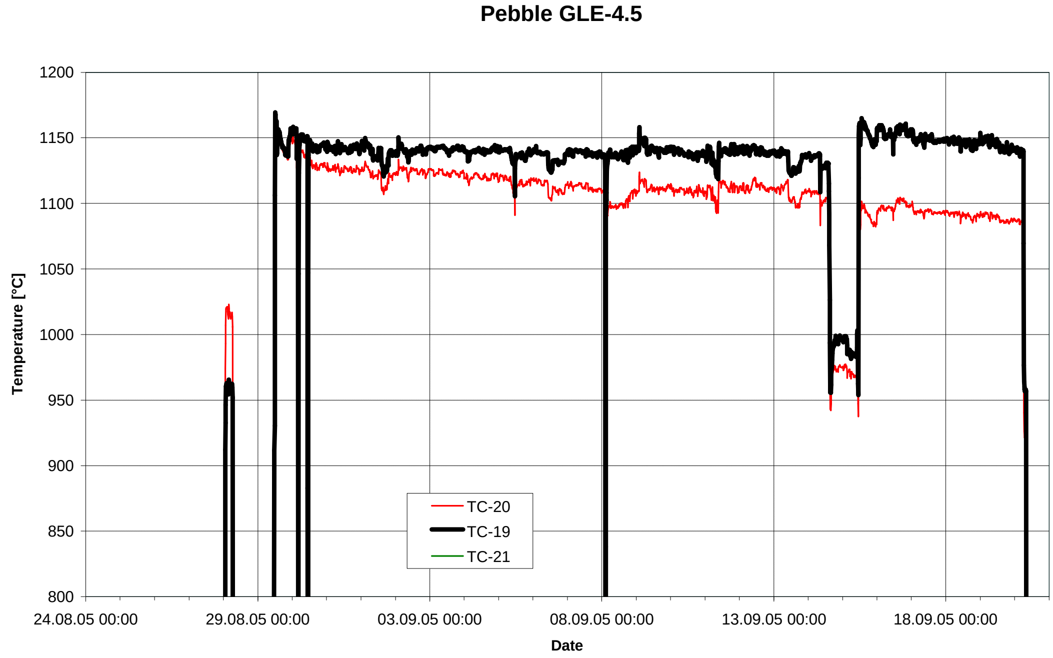


Figure 17: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

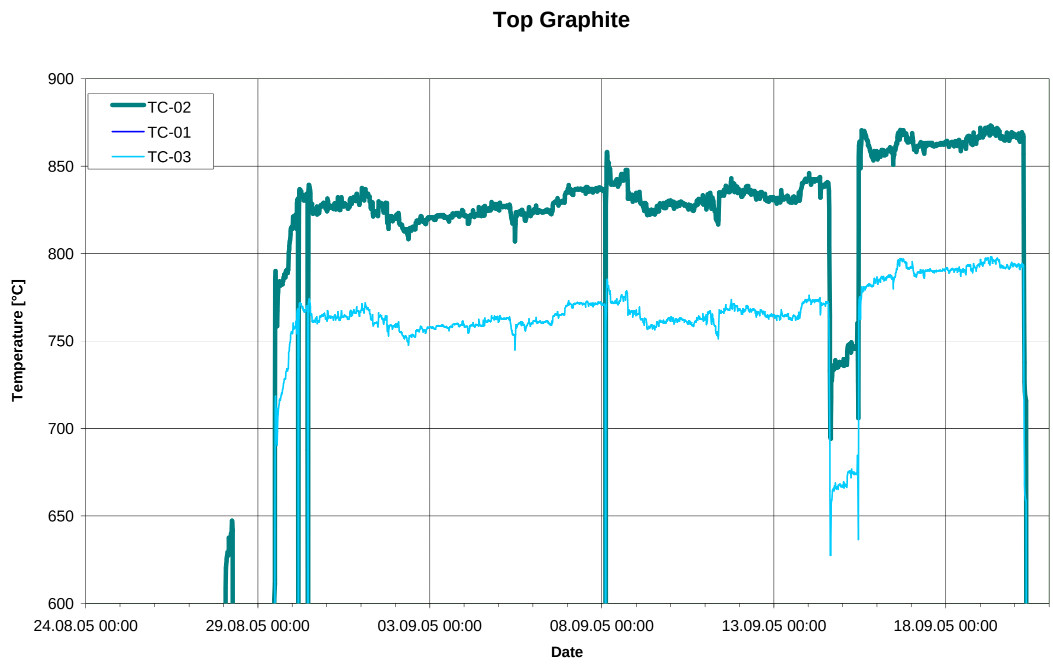


Figure 18: Temperatures top graphite (TC-01, TC-02, TC-03)

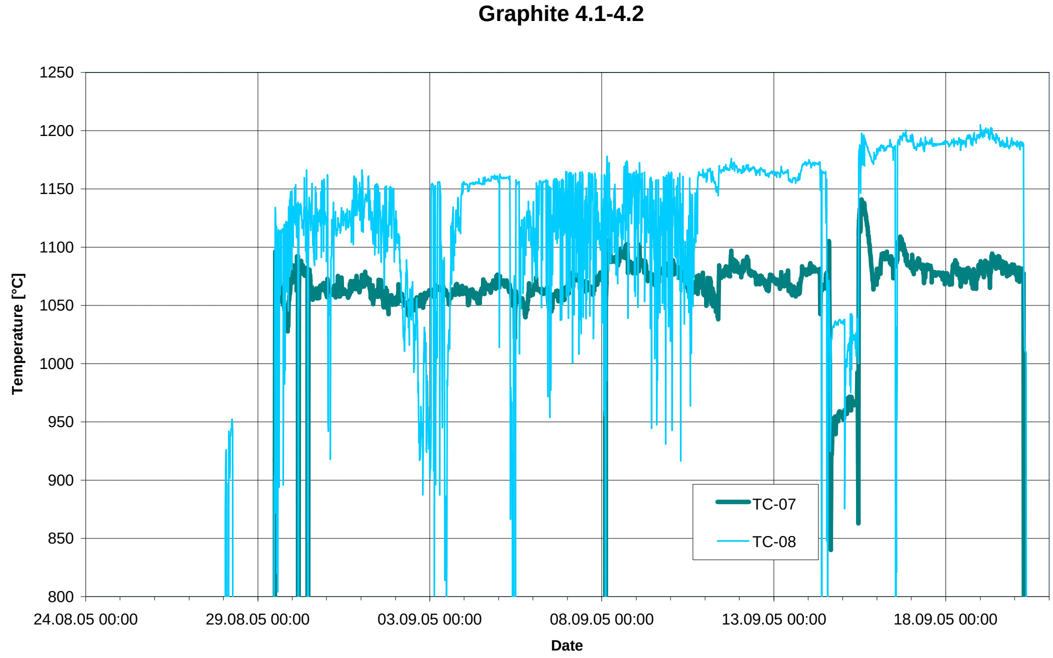


Figure 19: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

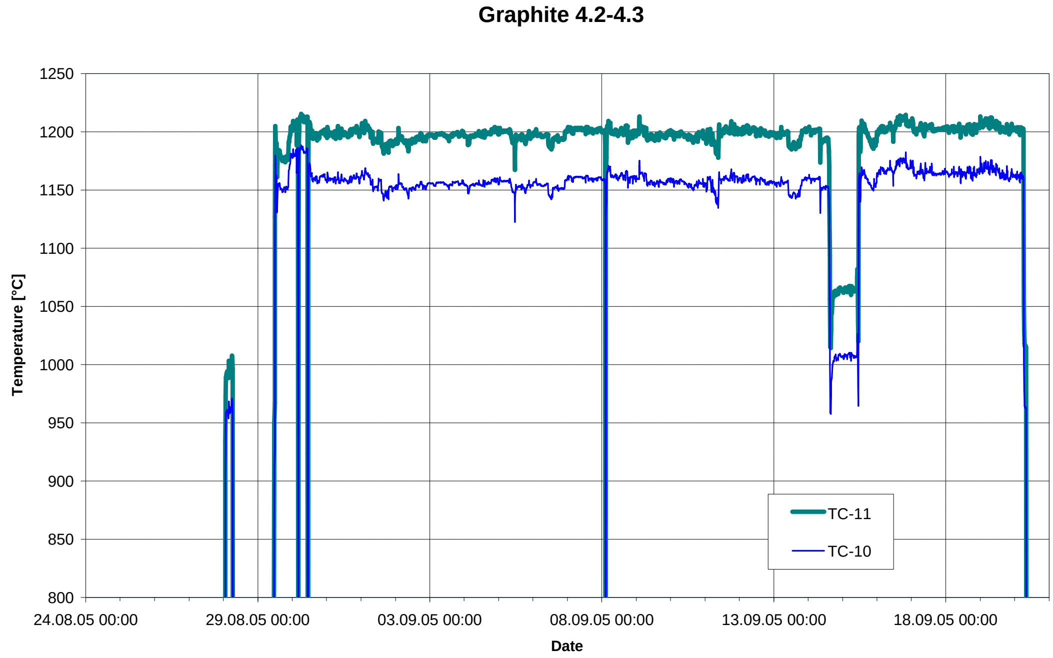


Figure 20: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

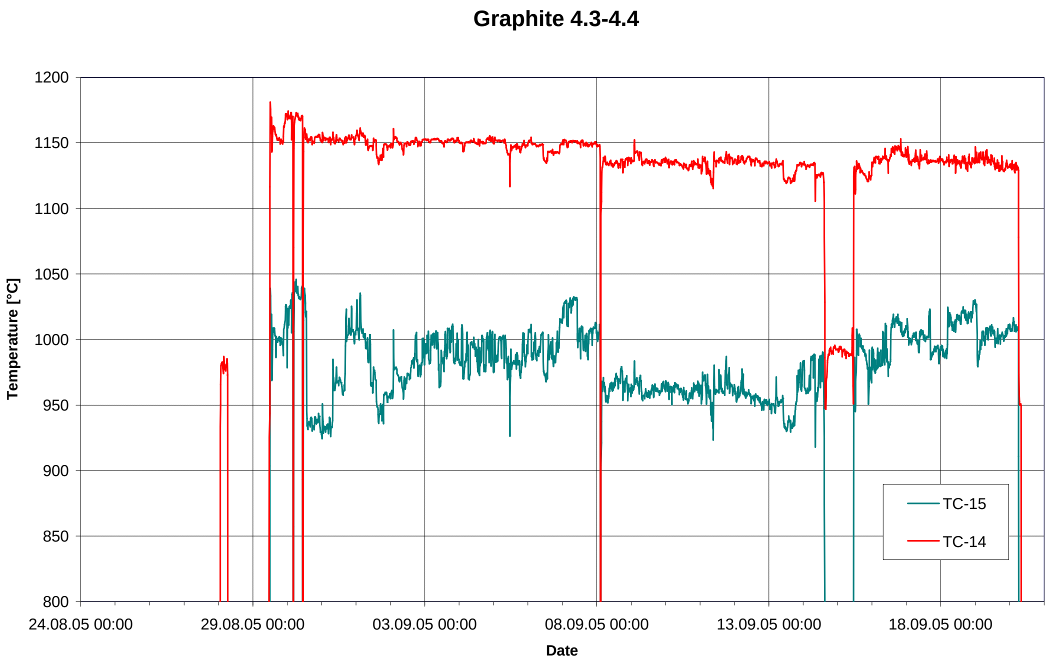


Figure 21: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

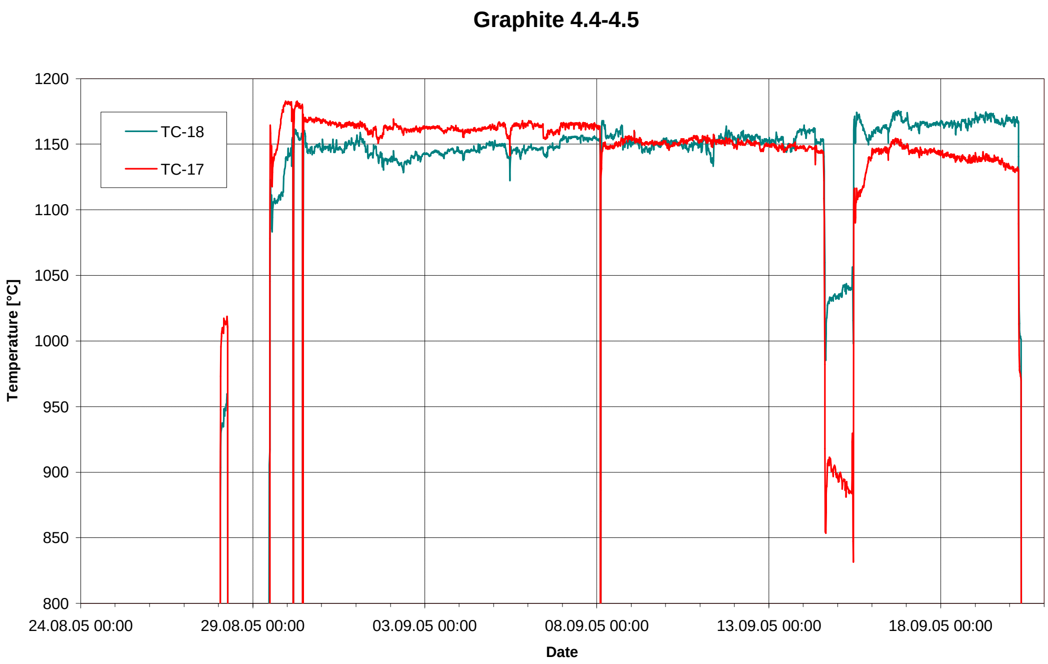


Figure 22: Temperature graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

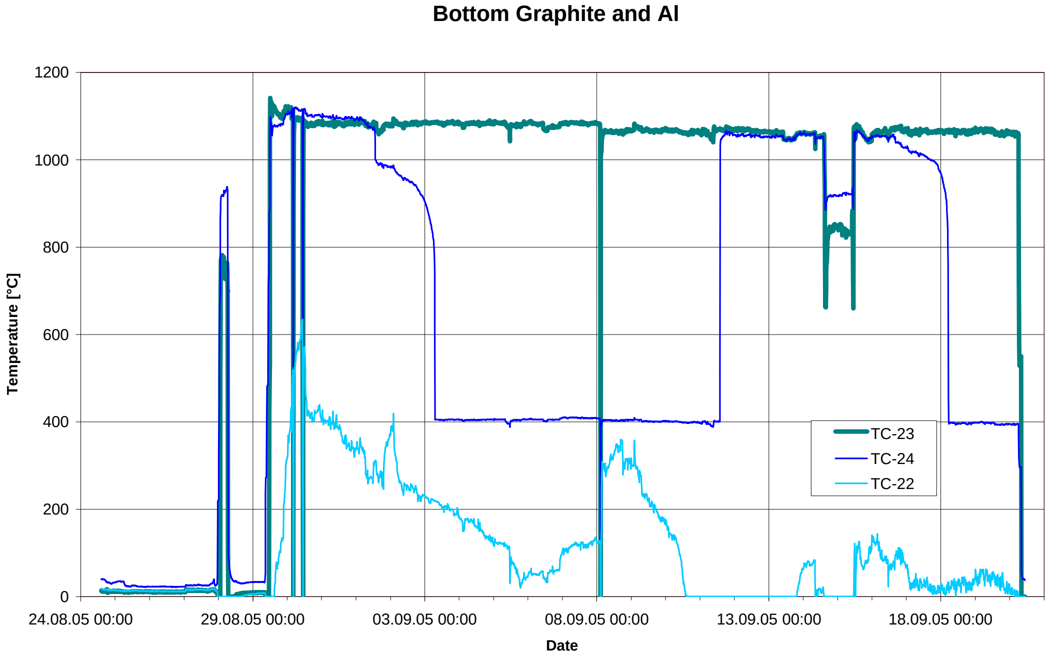


Figure 23: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
~~TC-01~~	~~5.9~~	~~5.9~~		Graphite
TC-02	831.0	831.2		
TC-03	764.0	764.7		
TC-04	1065.2	1064.6	1076	GLE4.1
TC-05	1064.5	1063.9		
TC-06	1031.5	1031.5		
TC-07	~~1063.7~~	~~1062.0~~		Graphite
TC-08	~~1128.1~~	~~1127.8~~		
TC-09	~~75.3~~	~~75.3~~	1099	GLE4.2
TC-10	1151.0	1151.3		Graphite
TC-11	1191.3	1191.0		
TC-12	1088.5	1088.8	1101	GLE4.3
TC-13	1082.3	1082.6		
TC-14	1134.3	1134.6		Graphite
TC-15	~~970.5~~	~~974.1~~		
TC-16	1094.3	1094.4	1103	GLE4.4
TC-17	1141.6	1145.7		Graphite
TC-18	1145.8	1145.3		
TC-19	1133.5	1133.6	1083	GLE4.5
TC-20	1103.8	1103.7		
TC-21	~~495.5~~	~~502.4~~		
TC-22	~~134.3~~	~~138.5~~		Graphite
TC-23	1059.8	1062.0		
TC-24	~~730.1~~	~~714.5~~		Al block

Table 9: Time averaged temperature readings during cycle 05-08

6.2 Temperatures during Cycle 05-09

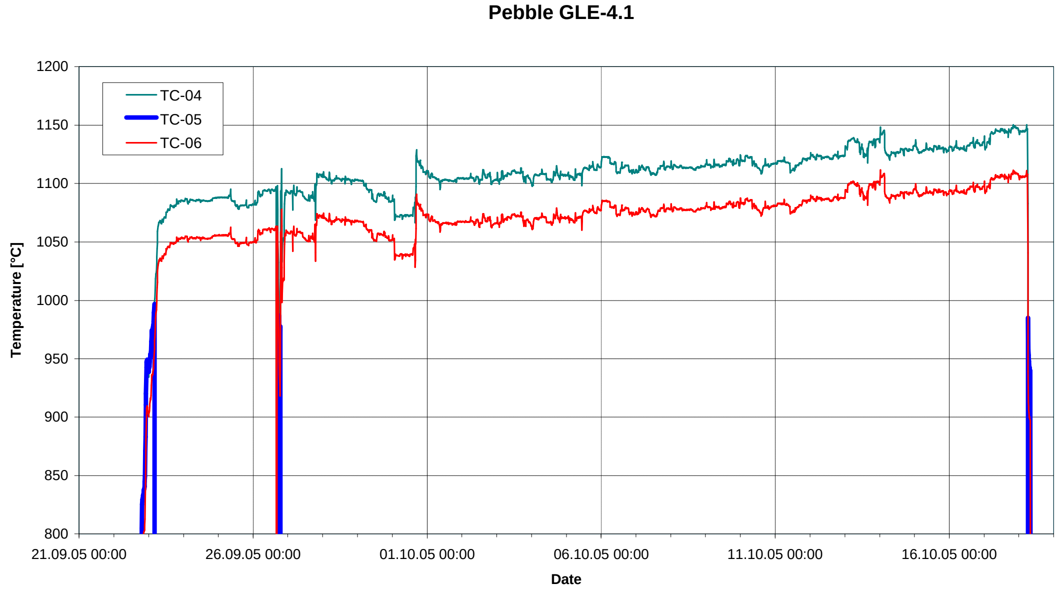


Figure 24: Temperatures pebble GLE4.1 (TC-04, TC-05, TC-06)

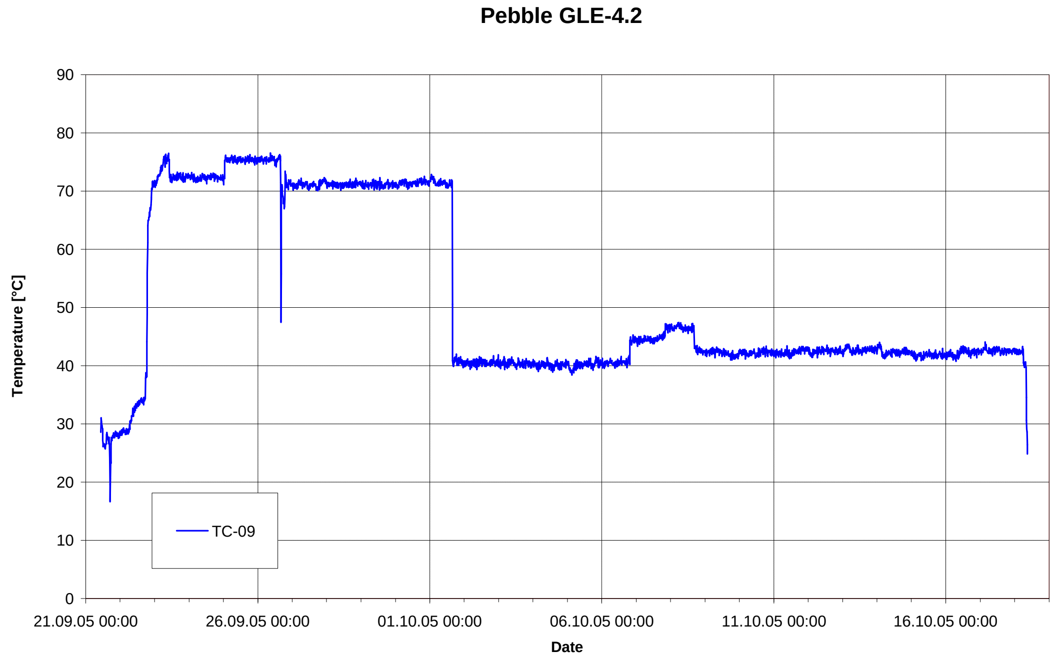


Figure 25: Temperature pebble GLE4.2 (TC-09)

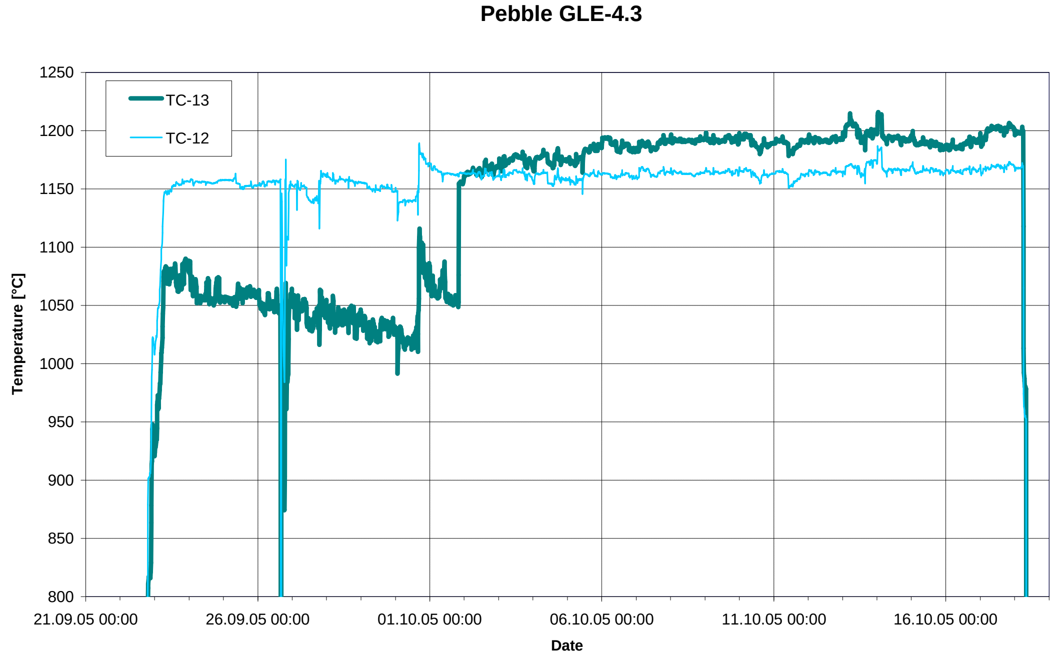


Figure 26: Temperatures pebble GLE4.3 (TC-12, TC-13)

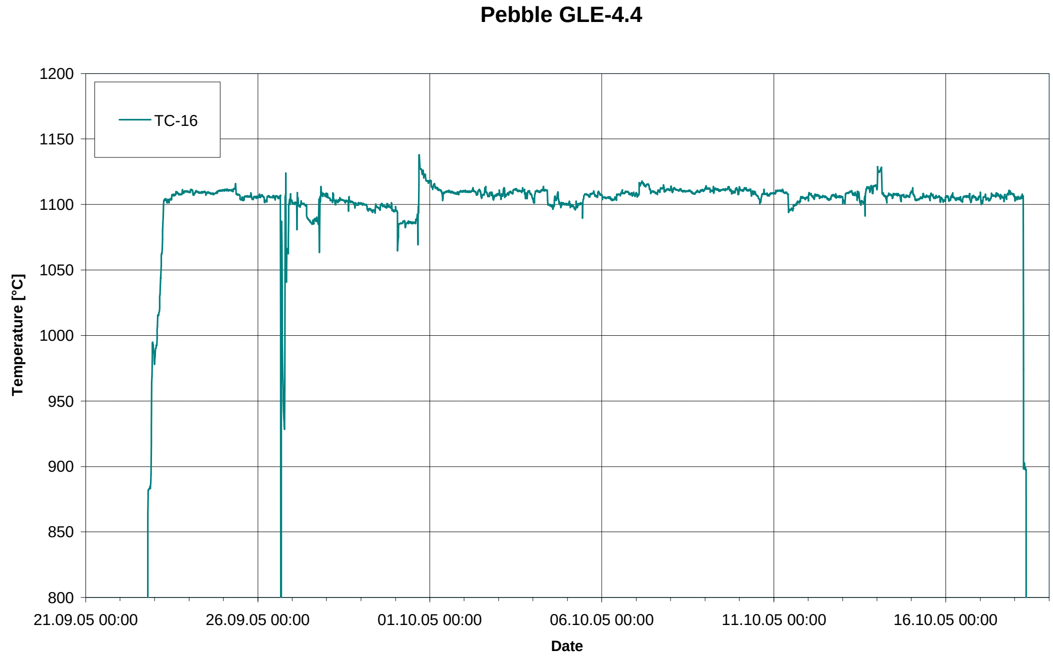


Figure 27: Temperature pebble GLE4.4 (TC-16)

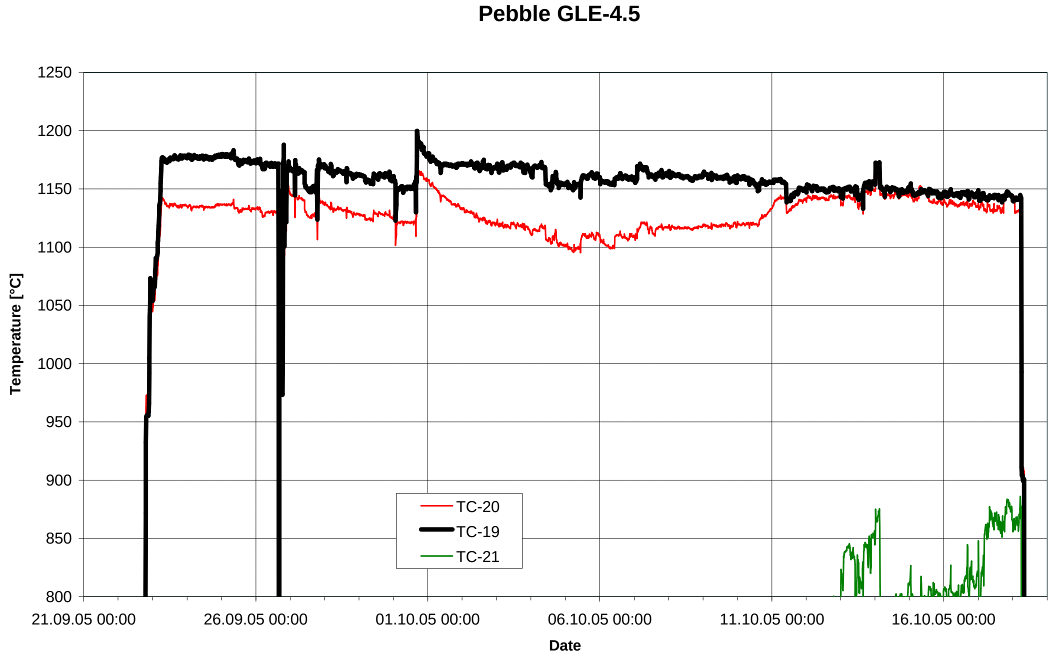


Figure 28: Temperatures pebble GLE4.5 (TC-19, TC-20, TC-21)

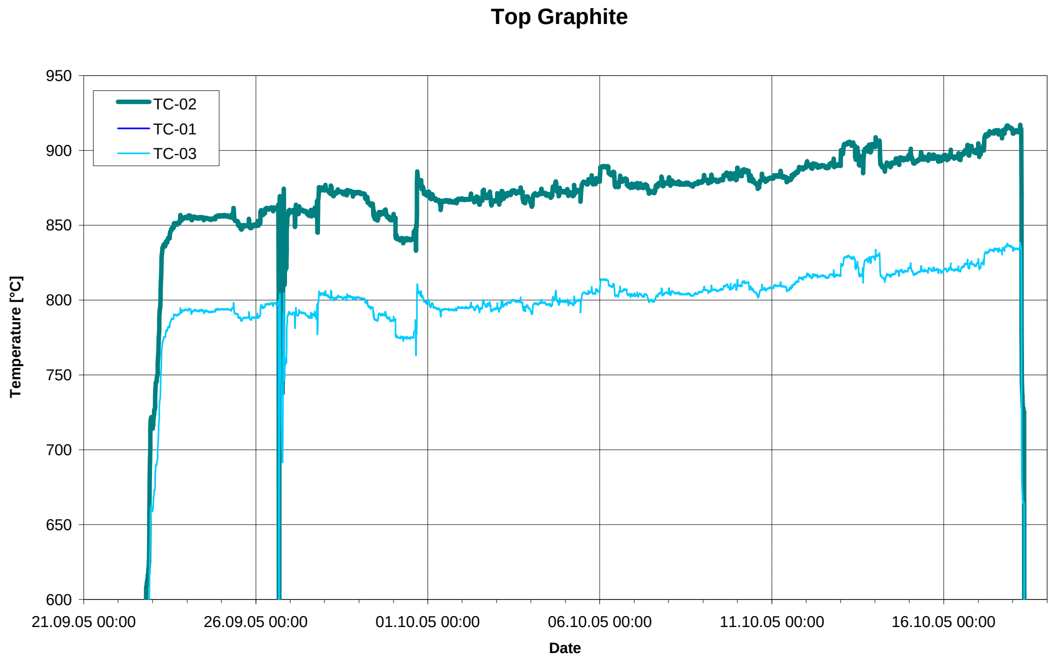


Figure 29: Temperatures top graphite (TC-01, TC-02, TC-03)

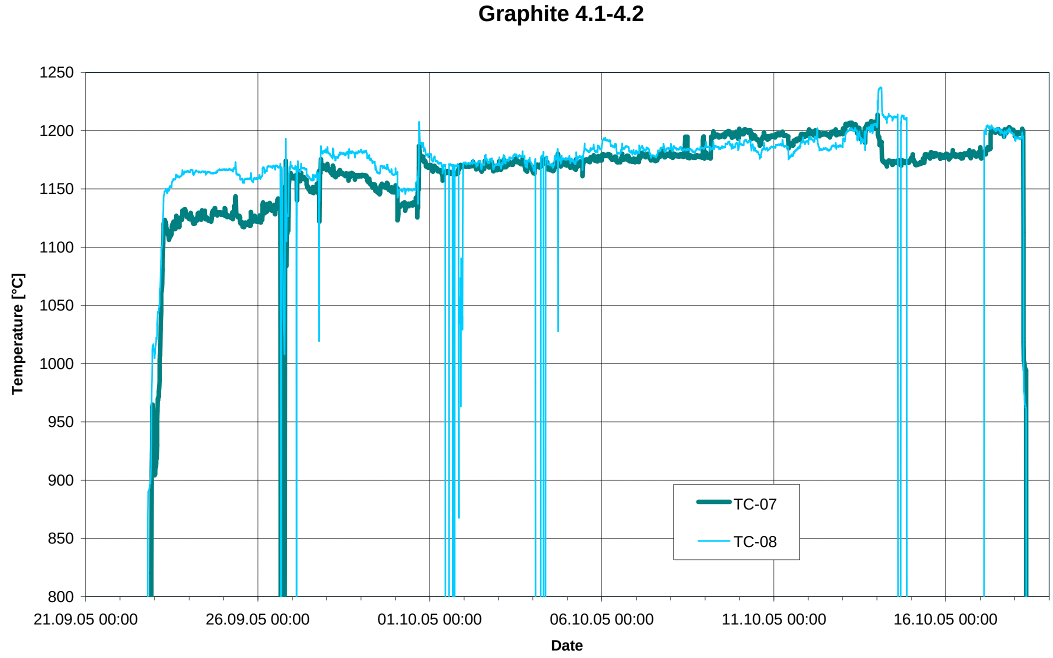


Figure 30: Temperatures graphite between GLE4.1 and GLE4.2 (TC-07, TC-08)

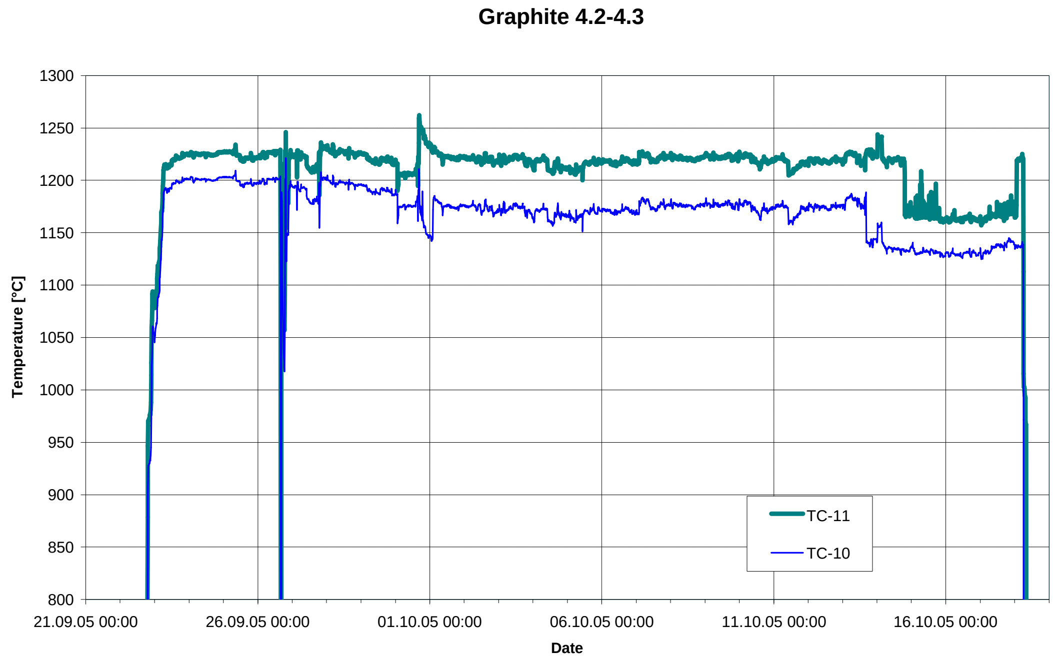


Figure 31: Temperatures graphite between GLE4.2 and GLE4.3 (TC-11, TC-12)

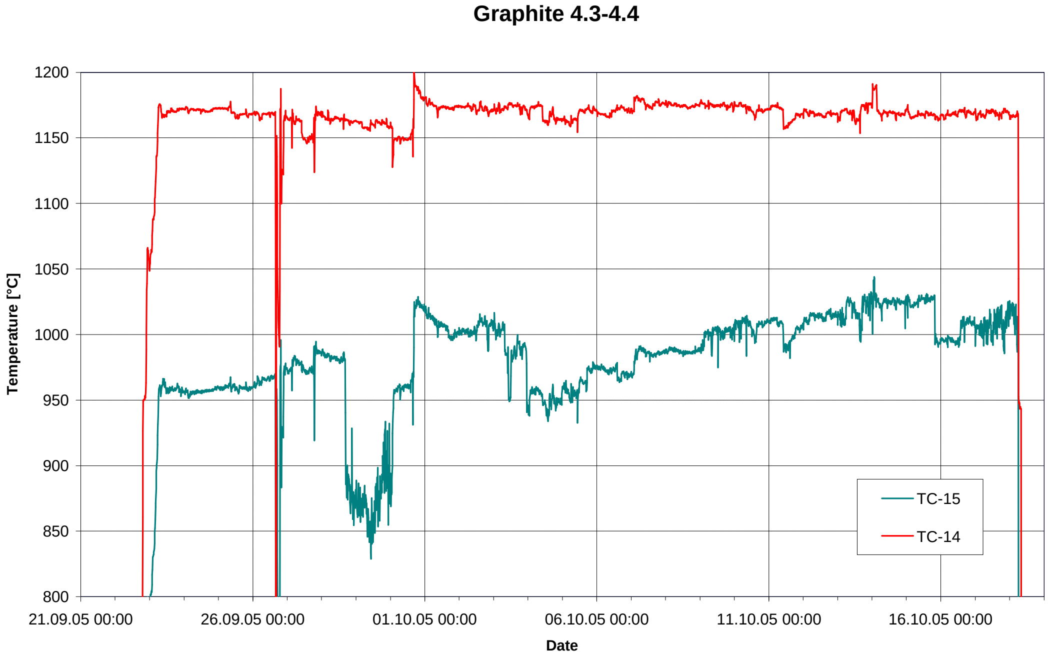


Figure 32: Temperatures graphite between GLE4.3 and GLE4.4 (TC-14, TC-15)

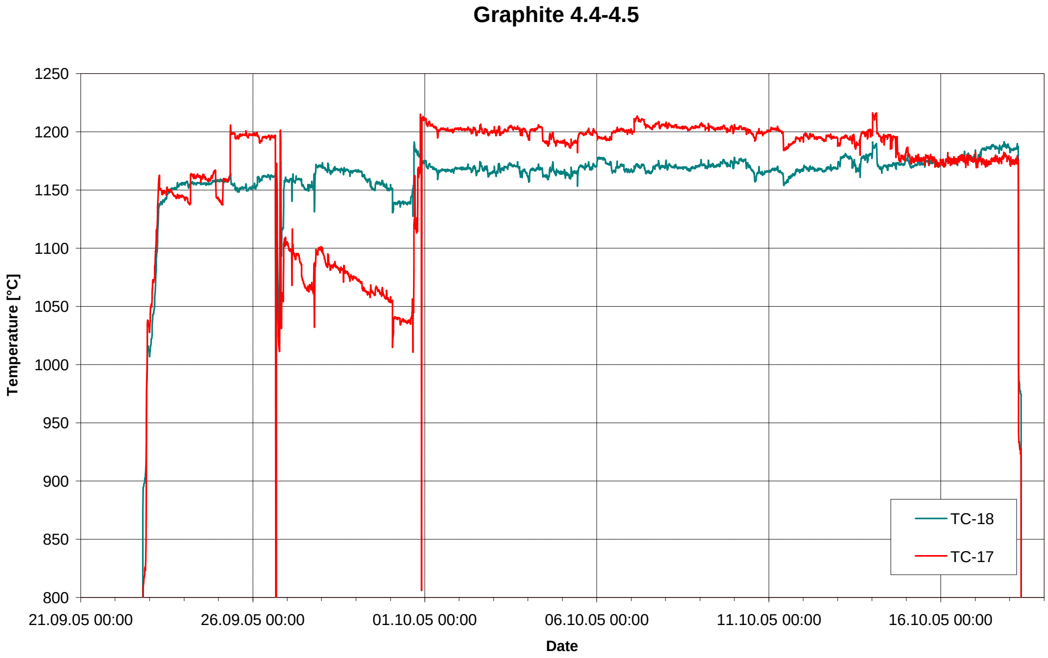


Figure 33: Temperatures graphite between GLE4.4 and GLE4.5 (TC-17, TC-18)

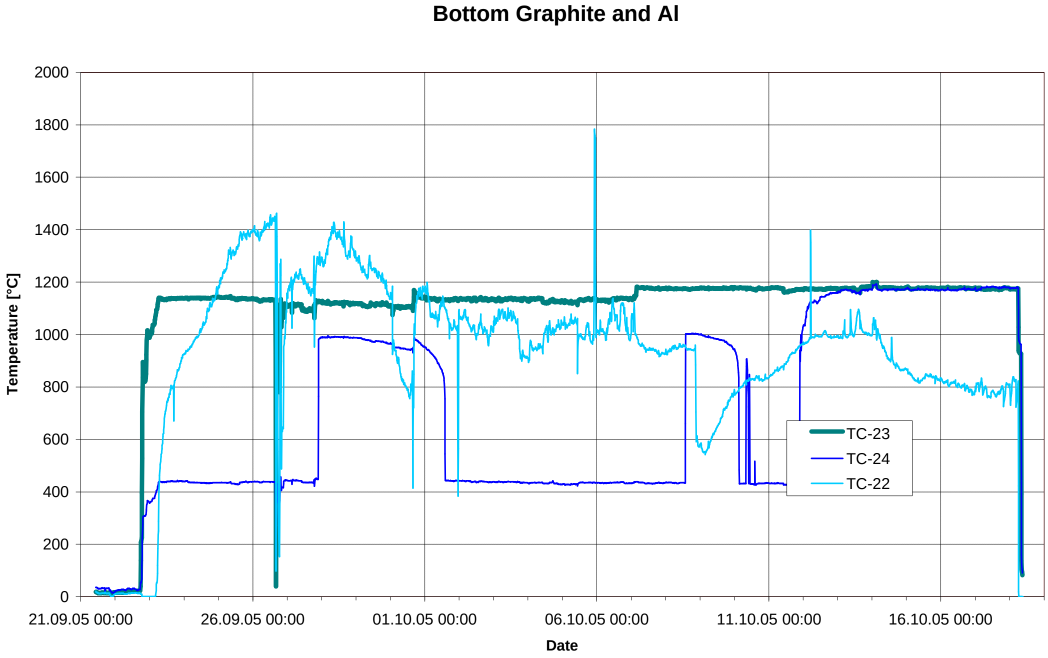


Figure 34: Temperatures bottom graphite and aluminum disc (TC-22, TC-23, TC-24)

TC number	Average temperature during full power operation [°C]	Average temperature during high temperature operation [°C]	Target temperature [°C]	Location
~~TC-01~~	~~0.9~~	~~0.7~~		Graphite
TC-02	872.0	874.5		
TC-03	800.9	803.2		
TC-04	1105.6	1108.3	1079	GLE4.1
TC-05	~~131.1~~	~~120.3~~		
TC-06	1069.8	1072.5		
~~TC-07~~	~~1162.6~~	~~1167.0~~		Graphite
TC-08	~~1057.9~~	~~1059.1~~		
TC-09	~~52.5~~	~~52.4~~	1104	GLE4.2
TC-10	1167.4	1170.8		Graphite
TC-11	1209.5	1212.0		
TC-12	1156.5	1159.2	1108	GLE4.3
~~TC-13~~	~~1135.1~~	~~1138.2~~		
TC-14	1165.4	1167.7		Graphite
~~TC-15~~	~~977.7~~	~~981.3~~		
TC-16	1102.4	1104.8	1109	GLE4.4
~~TC-17~~	~~1167.1~~	~~1170.1~~		Graphite
TC-18	1162.4	1165.0		
TC-19	1156.3	1158.6	1088	GLE4.5
TC-20	1126.3	1128.1		
~~TC-21~~	~~692.3~~	~~698.6~~		
~~TC-22~~	~~973.4~~	~~987.0~~		Graphite
TC-23	1144.1	1147.0		
~~TC-24~~	~~727.0~~	~~730.3~~		Al block

Table 10: Time averaged temperature readings during cycle 05-09

7 Fission Gas Release Measurements

In cycles 05-08 and 05-09 the fission gas release was measured according to the same procedure as since cycle 05-07:

A continuous gas flow (100 ml/min) was maintained throughout the cycles and the He/Ne mixture was adjusted to attain the target temperature of TC-16 as the reference thermocouple. A simplified gas sampling procedure could be used thanks to the earlier modifications in the gas panel:

1. **Filter bypass:** Override the GM1 and GM3 alarms. Activate the filter bypass (close MV2.1, open MV2.2). Wait for at least one hour (at 100 ml/min total gas flow) until stable GM signals are reached.
2. **Sampling:** Override pressure alarm from Pt1.1 and close MV1 and MV2.3. Wait until the pressure at Pt1.2 is stable. Close V3.6 and V3.8, then remove sampling vessel. Place a new sampling vessel. Open V3.6, V3.8, MV1 and MV2.3. Arm all alarms.

Evaluation of R/B:
From the measured concentration of 3 Kr and 2 Xe isotopes (statistical error 4 - 9%), the gas pressure and the He flow-rate, the release rate R can be determined.

The birth rate B is calculated using the nominal number of fissions on the date of sampling (neutronics error 10 - 15%) and the fission yield for the measured 5 isotopes.

The burn-up is the one pre-calculated for the experiment. Later adjustments will be made once the analysis of the burn-up measurements of the pebbles, the gamma scan wires and the fluence detectors are available.

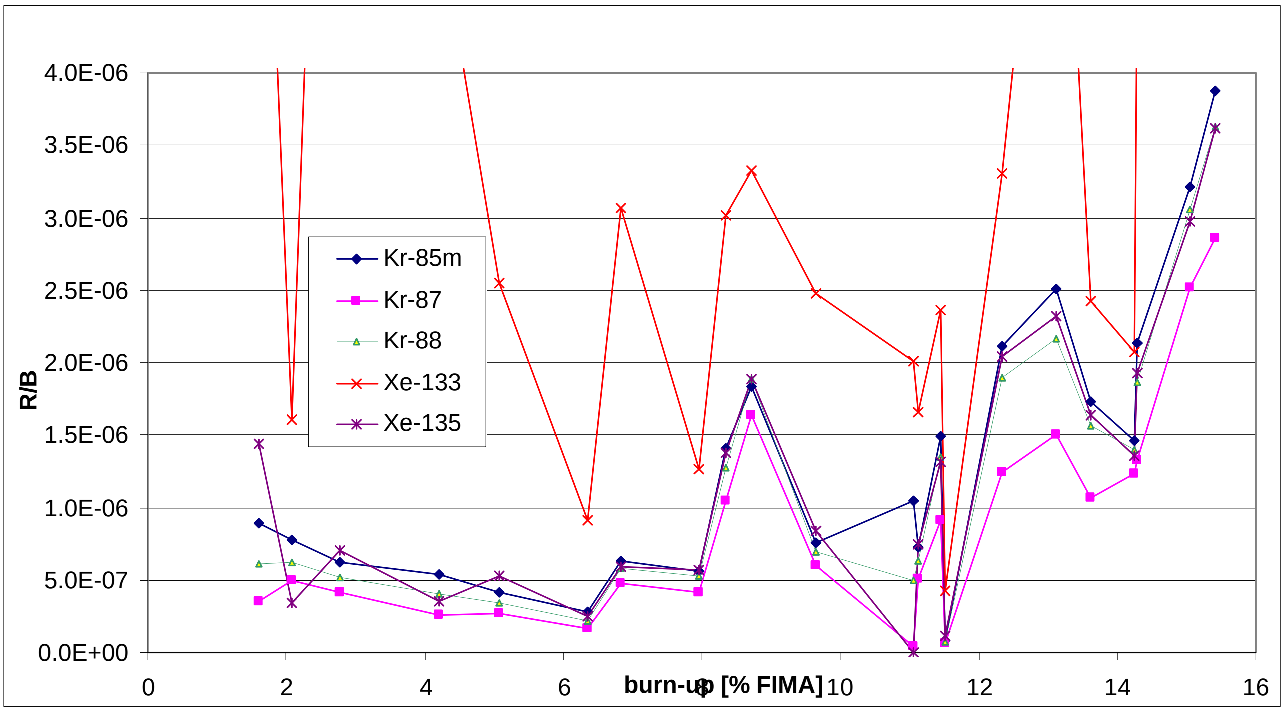


Figure 35: R/B measurements vs. burn-up (linear view)

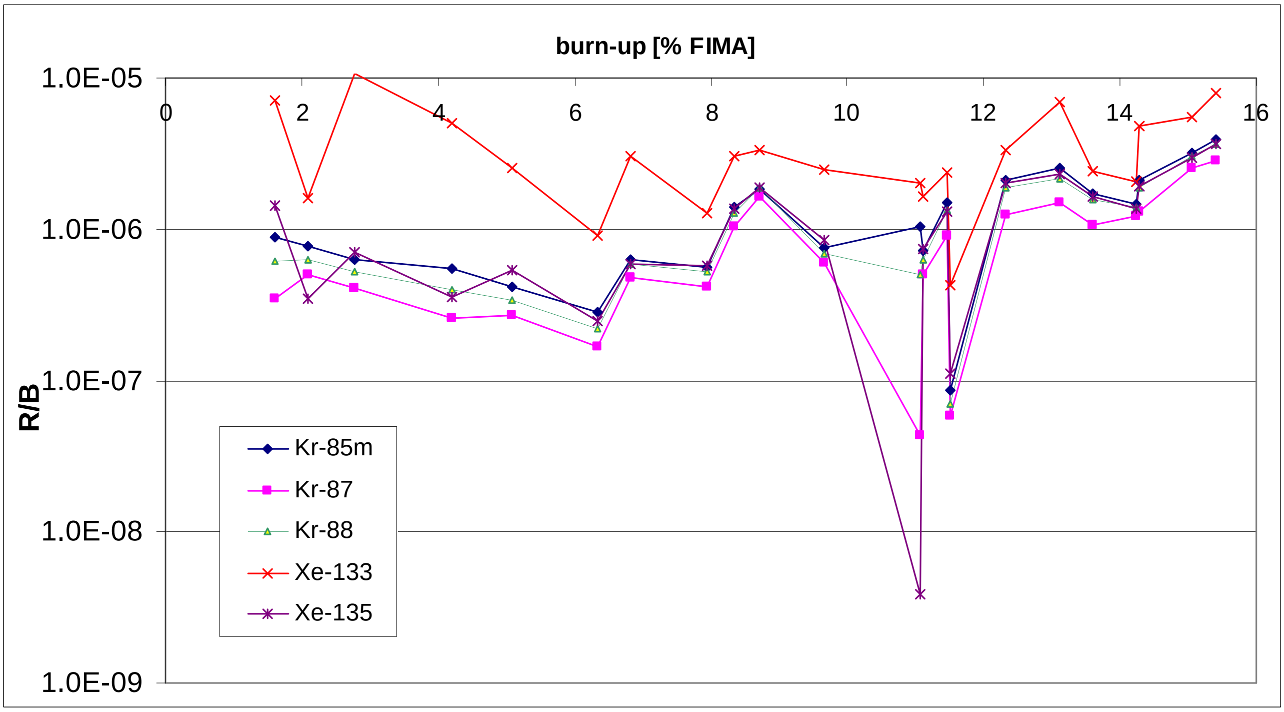
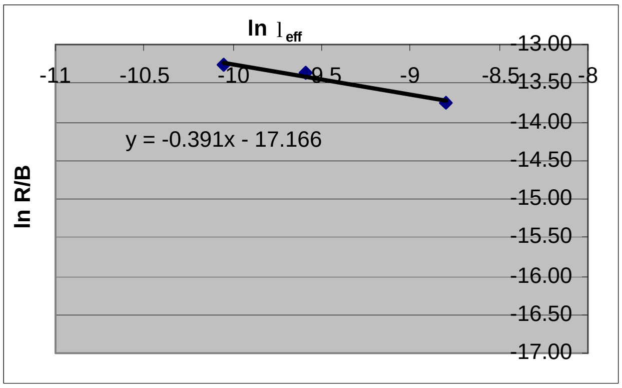
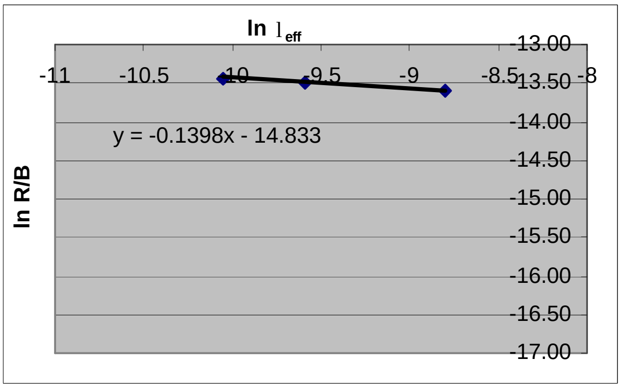


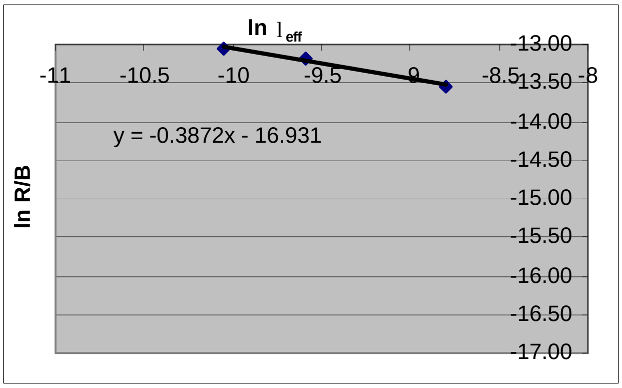
Figure 36: R/B measurements vs. burn-up (logarithmic view)



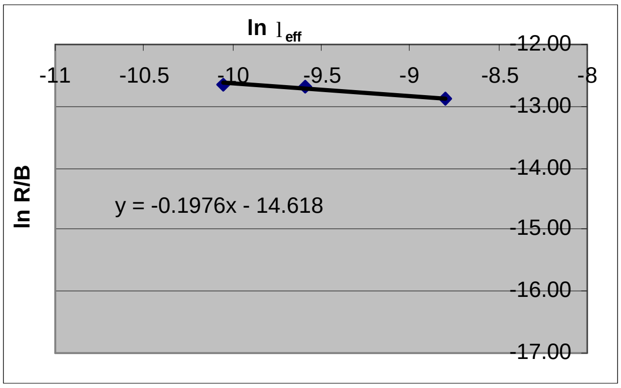
Measurement date 20050905



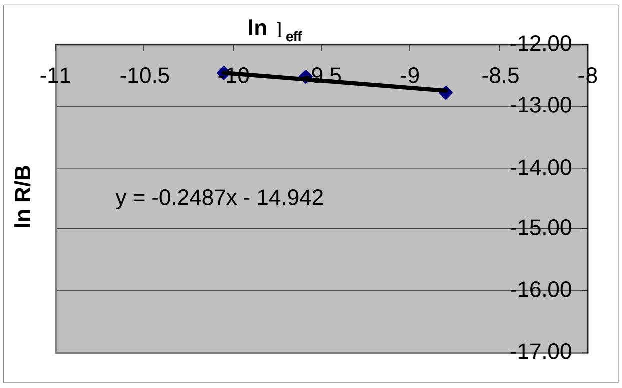
Measurement date 20050915



Measurement date 20050916



Measurement date 20051005



Measurement date 20051013

Figure 37: ln R/B vs. ln λ_{eff} plots for Kr gas release measurements

Measurement date	inclination n in ln R/B vs. ln λ_{eff} plots $\ln\frac{R}{B} = const. - n\ln l$	Comments
20050905	0.391	TC-16 = 1094°C, 5.4 bar abs
20050915	0.1398	TC-16 = 965°C, 1.09 bar abs
20050916	0.3872	TC-16 = 1102°C, 5.51 bar abs
20051005	0.1976	TC-16 = 1100°C, 2.33 bar abs
20051013	0.2487	TC-16 = 1108°C, 2.34 bar abs

Table 11: Inclination n of straight fits in ln R/B vs. ln λ_{eff} plots

As explained in [2], the value of the inclination n is an indicator for the quality of the gas measurement and provides hints about the fission gas release mechanisms.

From Figure 37 it can be deduced that the three points are reasonably well in line and consistent with earlier measurements.

Overview gammaspectrometry measurements HFR-EU1bis gas samples.

nr	NRG code	week nr	sample date	tank nr	flow [ml/min]	pressure [bar rel]	Kr-85m [Bq/sample]		Kr-87 [Bq/sample]		Kr-88 [Bq/sample]		Xe-133 [Bq/sample]		Xe-135 [Bq/sample]		Xe-133 [Bq/sample]		Xe-135 [Bq/sample]	
																	not corrected for ingrow			
1	H4103	37	**10.09.04 13:56**	?	?	?							1.23E+00	39%			1.23E+00	39%		
2	H4104	38	**14.09.04 12:26**	2	?	?							1.48E+00	39%	1.39E+00	38%	1.48E+00	39%	1.39E+00	38%
3	H4109	40	**28.09.04 14:45**	1	?	?	1.40E+05	10%	2.48E+05	9%	2.94E+05	7%	6.13E+05	6%	1.80E+05	3%	6.19E+05	6%	1.94E+05	4%
4	H4110	40	**27.10.04 11:21**	2	?	?	1.10E+05	4%	2.96E+05	9%	3.23E+05	6%	1.72E+05	12%	4.30E+05	3%	1.74E+05	14%	4.34E+05	3%
5	H4111	41	**08.10.04 10:45**	7	?	?	5.77E+03	4%	2.49E+04	9%	1.94E+04	6%	2.11E+03	6%	6.24E+03	3%	2.11E+03	6%	6.24E+03	3%
6	H4112	42	**11.10.04 16:03**	1	?	?							1.18E+05	6%			1.18E+05	6%		
7	H4113	43	**18.10.04 16:00**	?	150	0.13	6.83E+03	5%	3.13E+04	9%	2.48E+04	9%	2.08E+04	6%	1.65E+04	3%	2.08E+04	6%	1.86E+04	3%
8	H4117	44	**25.10.04 15:40**	2	150	0.30	9.27E+04	4%	4.03E+05	9%	3.11E+05	7%	6.55E+05	6%	6.94E+05	4%	6.56E+05	6%	7.76E+05	3%
9	H4118	44	**25.10.04 12:15**	1	0	0.15	3.45E+03	5%	1.32E+04	14%	1.12E+04	8%	7.32E+04	6%	9.76E+03	3%	7.33E+04	6%	9.76E+03	3%
10	H4122	45	**01.11.04 15:05**	7	200	0.16	5.59E+03	5%	2.49E+04	9%	1.84E+04	9%	9.49E+03	6%	1.81E+04	3%	9.51E+03	6%	2.13E+04	3%
11	H4160	1	**06.01.05 11:05**	7	200	0.12	4.18E+03	4%	1.35E+04	9%	1.29E+04	4%	6.86E+03	6%	6.69E+03	4%	6.86E+03	6%	7.62E+03	3%
12	H5001	2	**12.01.05 11:23**	1	200	0.37	4.00E+04	5%	1.76E+05	9%	1.39E+05	5%	4.64E+05	7%	1.54E+06	6%	4.64E+05	7%	1.55E+06	4%
13	H5002	3	**19.01.05 10:55**	2	200	0.11	3.07E+03	4%	1.34E+04	9%	1.06E+04	4%	3.32E+03	6%	9.54E+03	4%	3.32E+03	6%	1.07E+04	3%
14	H5007	5	**01.02.05 11:07**	1	200	0.27	2.25E+04	4%	9.21E+04	9%	7.42E+04	6%	6.37E+06	6%	9.24E+04	4%	6.39E+06	6%	9.81E+04	5%
15	H5009	6	**09.02.05 14:56**	1	200	0.28	2.46E+04	5%	9.97E+04	9%	7.74E+04	8%	1.97E+06	6%	1.04E+05	3%	1.97E+06	6%	1.12E+05	6%
16	H5010	6	**09.02.05 14:33**	3	200	0.11	1.97E+03	4%	7.98E+03	9%	6.48E+03	4%	1.14E+03	6%	4.21E+03	3%	1.14E+03	6%	4.21E+03	3%
17	H5015	7	**16.02.05 13:51**	2	200	0.08	4.24E+03	4%	2.18E+04	9%	1.65E+04	4%	3.64E+03	6%	9.66E+03	4%	3.64E+03	6%	1.11E+04	3%
18	H5023	10	**08.03.05 09:58**	3	200	0.12	3.72E+03	4%	1.88E+04	9%	1.47E+04	4%	1.49E+03	7%	9.29E+03	4%	1.49E+03	7%	1.05E+04	3%
19	H5024	11	**15.03.05 10:35**	2	200	0.08	8.90E+03	10%	4.47E+04	9%	3.38E+04	4%	3.36E+03	6%	2.12E+04	5%	3.36E+03	6%	2.55E+04	3%
20	H5025	12	**21.03.05 10:05**	3	200	0.11	1.17E+04	4%	7.06E+04	9%	5.05E+04	6%	3.75E+03	10%	2.93E+04	4%	3.75E+03	10%	3.41E+04	7%
21	H5091	24	**15.06.05 15:25**	3	He80/Ne120	4.50	2.97E+04	4%	8.34E+03	8%	5.93E+04	4%	1.01E+04	6%	2.69E+02	34%	1.01E+04	6%	2.69E+02	34%
22	H5092	24	**16.06.05 13:11**	2	200 He	0.15	4.31E+03	6%	2.03E+04	7%	1.57E+04	7%	1.74E+03	6%	1.07E+04	3%	1.74E+03	6%	1.20E+04	3%
23	H5095	25	**22.06.05 14:29**	3	35He/65Ne	4.52	8.33E+04	4%	3.47E+05	9%	3.17E+05	4%	2.34E+04	6%	1.80E+05	3%	2.34E+04	6%	1.84E+05	3%
24	H5096	25	**23.06.05 13:31**	2	200 He	0.19	2.41E+03	5%	1.10E+04	9%	8.21E+03	5%	2.09E+03	7%	7.51E+03	4%	2.09E+03	7%	8.28E+03	3%
25	H5143	28	**12.07.05 13:54**	2	39He/61Ne	4.41	1.11E+05	4%	4.44E+05	5%	4.19E+05	4%	3.07E+04	6%	2.61E+05	3%	3.08E+04	6%	2.66E+05	3%
1	H5146	30	**27.07.05 11:10**	3	35He/65Ne	4.42	1.27E+05	6%	5.15E+05	8%	4.61E+05	8%	6.21E+04	6%	2.86E+05	9%	6.12E+04	6%	2.91E+05	7%
2	H5151	36	**05.09.05 11:08**	2	47He/53Ne	4.40	8.48E+04	4%	3.56E+05	5%	3.23E+05	6%	2.10E+04	6%	1.96E+05	3%	2.10E+04	6%	2.00E+05	3%
3	H5152	37	**15.09.05 10:00**	2	100He	0.09	1.40E+04	4%	7.98E+04	5%	5.61E+04	6%	3.51E+03	6%	3.17E+04	4%	3.51E+03	6%	3.50E+04	3%
4	H5154	37	**16.09.05 11:05**	3	40He/60Ne	4.51	1.03E+05	4%	4.32E+05	5%	3.83E+05	6%	4.07E+04	6%	2.26E+05	3%	4.07E+04	6%	2.32E+05	3%
5	H5162	40	**05.10.05 10:26**	2	26He/74Ne	1.33	6.25E+04	5%	3.33E+05	5%	2.50E+05	6%	1.90E+04	6%	1.41E+05	3%	1.86E+04	6%	1.52E+05	3%
6	H5165	41	**13.10.05 15:30**	3	22He/78Ne	1.34	7.41E+04	4%	3.70E+05	5%	2.92E+05	6%	2.69E+04	6%	1.69E+05	3%	2.64E+04	6%	1.77E+05	3%

If Xe-133m and/or Xe-135m are measured, Xe-133 and/or Xe-135 are corrected for the ingrow from the mother nuclides
The uncorrected values are also given. Errors are 1 sigma statistical counting errors.

Table 12: Gamma spectrometry measurement data for the entire irradiation

28.09.04 14.45 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.45E+05		3373828915	100	33738289	10	5.6230E+06	4.43E+14	1.32E-02	9.61E-07
Kr-87	4578	2.85E+05		1882327501	100	18823275	10	3.1372E+06	4.43E+14	2.54E-02	2.79E-07
Kr-88	10080	3.53E+05		5133455202	100	51334552	10	8.5558E+06	4.43E+14	3.47E-02	5.56E-07
Xe-133	457056	6.47E+05		426626898722	100	4266268987	10	7.1104E+08	4.43E+14	6.62E-02	2.42E-05
Xe-135	33012	2.07E+05		9858633479	100	98586335	10	16431056	4.43E+14	6.58E-02	5.63E-07

29.09.04 14.25 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.34E+05		3117883273	100	31178833	10	5.1965E+06	4.42E+14	1.32E-02	8.91E-07
Kr-87	4578	3.58E+05		2364467527	100	23644675	10	3.9408E+06	4.42E+14	2.54E-02	3.51E-07
Kr-88	10080	3.90E+05		5671522745	100	56715227	10	9.4525E+06	4.42E+14	3.47E-02	6.16E-07
Xe-133	457056	1.90E+05		125284560676	100	1252845607	10	2.0881E+08	4.42E+14	6.62E-02	7.14E-06
Xe-135	33012	5.27E+05		25099033060	100	250990331	10	4.1832E+07	4.42E+14	6.58E-02	1.44E-06

08.10.04 10.45 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	5.77E+03		134255123	100	1342551	200	4.4752E+06	4.35E+14	1.32E-02	7.80E-07
Kr-87	4578	2.49E+04		164455982	100	1644560	200	5.4819E+06	4.35E+14	2.54E-02	4.96E-07
Kr-88	10080	1.94E+04		282121901	100	2821219	200	9.4041E+06	4.35E+14	3.47E-02	6.23E-07
Xe-133	457056	2.11E+03		1391318016	100	13913180	200	4.6377E+07	4.35E+14	6.62E-02	1.61E-06
Xe-135	33012	6.24E+03		297187792	100	2971878	200	9.9063E+06	4.35E+14	6.58E-02	3.46E-07

11.10.04 14.15 h

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/cm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Xe-133	457056	1.18E+05		77808306104	100	778083061	10	1.2968E+08	4.31E+14	6.62E-02	4.54E-06

18.10.04 16.00 h 0.13 bar

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	6.79E+03	1.13	157988264	100	1398126	150	3.4953E+06	4.24E+14	1.32E-02	6.24E-07
Kr-87	4578	3.03E+04	1.13	200121134	100	1770983	150	4.4275E+06	4.24E+14	2.54E-02	4.11E-07
Kr-88	10080	2.39E+04	1.13	347562548	100	3075775	150	7.6894E+06	4.24E+14	3.47E-02	5.22E-07
Xe-133	457056	2.07E+04	1.13	13649423189	100	120791356	150	3.0198E+08	4.24E+14	6.62E-02	1.07E-05
Xe-135	33012	1.86E+04	1.13	885848226	100	7839365	150	1.9598E+07	4.24E+14	6.58E-02	7.02E-07

25.10.04 12.15 h 0.15 bar **after 1 week of stagnance**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	3.45E+03	1.15	80273860	100	698034	0	0.0000E+00	4.24E+14	1.32E-02	0.00E+00
Kr-87	4578	1.32E+04	1.15	87181484	100	758100	0	0.0000E+00	4.24E+14	2.54E-02	0.00E+00
Kr-88	10080	1.12E+04	1.15	162874499	100	1416300	0	0.0000E+00	4.24E+14	3.47E-02	0.00E+00
Xe-133	457056	7.33E+04	1.15	48333464724	100	420290998	0	0.0000E+00	4.24E+14	6.62E-02	0.00E+00
Xe-135	33012	9.76E+03	1.15	464832187	100	4042019	0	0.0000E+00	4.24E+14	6.58E-02	0.00E+00

25.10.04 15.40 h 0.3 bar **after purging for 3:25 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	9.27E+04	1.30	2156923727	100	16591721	150	4.1479E+07	4.19E+14	1.32E-02	7.50E-06
Kr-87	4578	4.03E+05	1.30	2661677133	100	20474439	150	5.1186E+07	4.19E+14	2.54E-02	4.81E-06
Kr-88	10080	3.11E+05	1.30	4522675830	100	34789814	150	8.6975E+07	4.19E+14	3.47E-02	5.99E-06
Xe-133	457056	6.55E+05	1.30	431902038119	100	3322323370	150	8.3058E+09	4.19E+14	6.62E-02	3.00E-04
Xe-135	33012	7.51E+05	1.30	35767312766	100	275133175	150	6.8783E+08	4.19E+14	6.58E-02	2.50E-05

01.11.04 15.05 h 0.16 bar **after purging for 4:05 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	5.59E+03	1.16	130066922	100	1121267	200	3.7376E+06	4.12E+14	1.32E-02	6.87E-07
Kr-87	4578	2.49E+04	1.16	164455982	100	1417724	200	4.7257E+06	4.12E+14	2.54E-02	4.52E-07
Kr-88	10080	1.84E+04	1.16	267579535	100	2306720	200	7.6891E+06	4.12E+14	3.47E-02	5.38E-07
Xe-133	457056	9.49E+03	1.16	6257634110	100	53945122	200	1.7982E+08	4.12E+14	6.62E-02	6.59E-06
Xe-135	33012	1.81E+04	1.16	862035101	100	7431337	200	2.4771E+07	4.12E+14	6.58E-02	9.14E-07

06.01.05 11.05 h 0.12 bar **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.18E+03	1.12	97259344	100	868387	200	2.8946E+06	4.03E+14	1.32E-02	5.44E-07
Kr-87	4578	1.35E+04	1.12	89162882	100	796097	200	2.6537E+06	4.03E+14	2.54E-02	2.59E-07
Kr-88	10080	1.29E+04	1.12	187596522	100	1674969	200	5.5832E+06	4.03E+14	3.47E-02	3.99E-07
Xe-133	457056	6.86E+03	1.12	4523432033	100	40387786	200	1.3463E+08	4.03E+14	6.62E-02	5.04E-06
Xe-135	33012	6.69E+03	1.12	318619604	100	2844818	200	9.4827E+06	4.03E+14	6.58E-02	3.57E-07

12.01.05 11:23 h 0.37 bar **after purging for 18 hours**

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.00E+04	1.37	930711425	100	6793514	200	2.2645E+07	3.97E+14	1.32E-02	4.32E-06
Kr-87	4578	1.76E+05	1.37	1162419790	100	8484816	200	2.8283E+07	3.97E+14	2.54E-02	2.81E-06

Table 13: Spreadsheet table for the calculation of R/B values (1 of 2)

08.03.05 09:58 Tank 3 after purging for 18 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	3.72E+03	1.12	86556163	100	772823	200	2.5761E+06	3.48E+14	1.32E-02	5.60E-07
Kr-87	4578	1.88E+04	1.12	124167568	100	1108639	200	3.6955E+06	3.48E+14	2.54E-02	4.17E-07
Kr-88	10080	1.47E+04	1.12	213772780	100	1908686	200	6.3623E+06	3.48E+14	3.47E-02	5.26E-07
Xe-133	457056	1.49E+03	1.12	982494713	100	8772274	200	2.9241E+07	3.48E+14	6.62E-02	1.27E-06
Xe-135	33012	9.29E+03	1.12	442447850	100	3950427	200	1.3168E+07	3.48E+14	6.58E-02	5.74E-07

15.03.05 10:35 Tank 2 after purging for 18 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	8.90E+03	1.08	207083292	100	1917438	200	6.3915E+06	3.43E+14	1.32E-02	1.41E-06
Kr-87	4578	4.47E+04	1.08	295228208	100	2733595	200	9.1120E+06	3.43E+14	2.54E-02	1.05E-06
Kr-88	10080	3.38E+04	1.08	491531971	100	4551222	200	1.5171E+07	3.43E+14	3.47E-02	1.28E-06
Xe-133	457056	3.36E+03	1.08	2215558547	100	20514431	200	6.8381E+07	3.43E+14	6.62E-02	3.01E-06
Xe-135	33012	2.12E+04	1.08	1009676472	100	9348856	200	3.1163E+07	3.43E+14	6.58E-02	1.38E-06

21.03.05 10:05 Tank 3 after purging for 18 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.17E+04	1.11	272233092	100	2452550	200	8.1752E+06	3.37E+14	1.32E-02	1.84E-06
Kr-87	4578	7.06E+04	1.11	466288848	100	4200800	200	1.4003E+07	3.37E+14	2.54E-02	1.63E-06
Kr-88	10080	5.05E+04	1.11	734389484	100	6616121	200	2.2054E+07	3.37E+14	3.47E-02	1.88E-06
Xe-133	457056	3.75E+03	1.11	2472721592	100	22276771	200	7.4256E+07	3.37E+14	6.62E-02	3.32E-06
Xe-135	33012	2.93E+04	1.11	1395449087	100	12571613	200	4.1905E+07	3.37E+14	6.58E-02	1.89E-06

07.04.05 10:21 Tank 2 after purging for 18 hours

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.63E+03	1.11	107729847	100	970539	200	3.2351E+06	3.24E+14	1.32E-02	7.56E-07
Kr-87	4578	2.50E+04	1.11	165116447	100	1487536	200	4.9585E+06	3.24E+14	2.54E-02	6.03E-07
Kr-88	10080	1.79E+04	1.11	260308352	100	2345120	200	7.8171E+06	3.24E+14	3.47E-02	6.95E-07
Xe-133	457056	2.68E+03	1.11	1767171698	100	15920466	200	5.3068E+07	3.24E+14	6.62E-02	2.47E-06
Xe-135	33012	1.25E+04	1.11	595328109	100	5363316	200	1.7878E+07	3.24E+14	6.58E-02	8.39E-07

15.06.05 15:25 Tank 3 TC16=1090C 80 ml/min He 120 ml/min Ne

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	2.97E+04	5.50	691053233	100	1256460	200	4.1882E+06	3.04E+14	1.32E-02	1.04E-06
Kr-87	4578	8.34E+03	5.50	55082847	100	100151	200	3.3384E+05	3.04E+14	2.54E-02	4.33E-08
Kr-88	10080	5.93E+04	5.50	862362305	100	1567931	200	5.2264E+06	3.04E+14	3.47E-02	4.96E-07
Xe-133	457056	1.01E+04	5.50	6659863489	100	12108843	200	4.0363E+07	3.04E+14	6.62E-02	2.01E-06
Xe-135	33012	2.69E+02	5.50	12811461	100	23294	200	7.7645E+04	3.04E+14	6.58E-02	3.89E-09

16.06.05 13:11 Tank 2 TC16=900C 200 ml/min He

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	4.31E+03	1.15	100284156	100	872036	200	2.9068E+06	3.03E+14	1.32E-02	7.27E-07
Kr-87	4578	2.03E+04	1.15	134074555	100	1165866	200	3.8862E+06	3.03E+14	2.54E-02	5.05E-07
Kr-88	10080	1.57E+04	1.15	228315146	100	1985349	200	6.6178E+06	3.03E+14	3.47E-02	6.30E-07
Xe-133	457056	1.74E+03	1.15	1147342819	100	9976894	200	3.3256E+07	3.03E+14	6.62E-02	1.66E-06
Xe-135	33012	1.07E+04	1.15	509600861	100	4431312	200	1.4771E+07	3.03E+14	6.58E-02	7.41E-07

22.06.05 14:29 Tank 3 TC16=1078C 35 ml/min He 65 ml/min Ne relatively unstable temperatures

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	8.33E+04	5.52	1938206542	100	3511244	100	5.8521E+06	2.98E+14	1.32E-02	1.49E-06
Kr-87	4578	3.47E+05	5.52	2291816290	100	4151841	100	6.9197E+06	2.98E+14	2.54E-02	9.14E-07
Kr-88	10080	3.17E+05	5.52	4609930026	100	8351323	100	1.3919E+07	2.98E+14	3.47E-02	1.35E-06
Xe-133	457056	2.34E+04	5.52	15429782736	100	27952505	100	4.6588E+07	2.98E+14	6.62E-02	2.36E-06
Xe-135	33012	1.80E+05	5.52	8572724764	100	15530298	100	2.5884E+07	2.98E+14	6.58E-02	1.32E-06

23.06.05 13:31 Tank 2 TC16=790C 200 ml/min He

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	2.41E+03	5.52	56075363	100	101586	200	3.3862E+05	2.97E+14	1.32E-02	8.63E-08
Kr-87	4578	1.10E+04	5.52	72651237	100	131615	200	4.3872E+05	2.97E+14	2.54E-02	5.81E-08
Kr-88	10080	8.21E+03	5.52	119392825	100	216291	200	7.2097E+05	2.97E+14	3.47E-02	6.99E-08
Xe-133	457056	2.09E+03	5.52	1378130167	100	2496613	200	8.3220E+06	2.97E+14	6.62E-02	4.23E-07
Xe-135	33012	7.51E+03	5.52	357673128	100	647959	200	2.1599E+06	2.97E+14	6.58E-02	1.10E-07

12.07.05 13:54 Tank 2 TC16=1070C 39 ml/min He + 61 ml/min Ne

Isotope	T 1/2 [s]	Activity [Bq]	abs. p [bar]	Atoms [at]	V sampl vessel [cm3]	Conc. [at/Ncm3]	gas flow [cm3/min]	Release [at/s]	fissions/s	yield at/fission	R/B
Kr-85m	16128	1.11E+05	5.41	2582724204	100	4773982	100	7.9566E+06	2.85E+14	1.32E-02	2.11E-06
Kr-87	4578	4.44E+05	5.41	2932468106	100	5420459	100	9.0341E+06	2.85E+14	2.54E-02	1.25E-06
Kr-88	10080	4.19E+05	5.41	6093251359	100	11262942	100	1.8772E+07	2.85E+14	3.47E-02	1.90E-06
Xe-133	457056	3.07E+04	5.41	20243347435	100	37418387	100	6.2364E+07	2.85E+14	6.62E-02	3.30E-06
Xe-135	33012	2.61E+05	5.41	12430450908	100	22976804	100	3.8295E+07	2.85E+14	6.58E-02	2.04E-06

Table 14: Spreadsheet table for the calculation of R/B values (2 of 2)

8 Post-Irradiation Neutron Radiographs

The HFR-EU1bis capsule was neutron-radiographed four times after the irradiation [6]:

1. normal position 0°
2. normal position 90°
3. lifted position 0°
4. lifted position 90°.

The latter two exposures were taken to focus on the bottom of the capsule where the leak between the 1st and 2nd containment was suspected.

With image enhancement techniques, it could be confirmed that the gas feed line for the 2nd containment that runs all across the 1st containment has melted on a length of > 6 cm between the level of the lowest pebbles GLE4.5 and GLE4.4 (cf. **Error! Reference source not found.**, **Error! Reference source not found.**). This means that in the beginning of the second irradiation cycle this AISI 316L steel tube has seen a temperature >1380°C. The weld between this gas line and the lower end cap was, however, intact as shown by comparison of pre-irradiation X-ray and post-irradiation neutron radiograph (cf. Figure 40).

It must be concluded that the measured temperature spike during the incident in the beginning of the 2nd irradiation cycle (cf. Figure 38) had been chopped off by data compression before this data could be recovered from DACOS. Some analytical work will be invested into reconstructing the temperature spike and thus calculate the real temperature and duration that the fuel has seen during this incident.

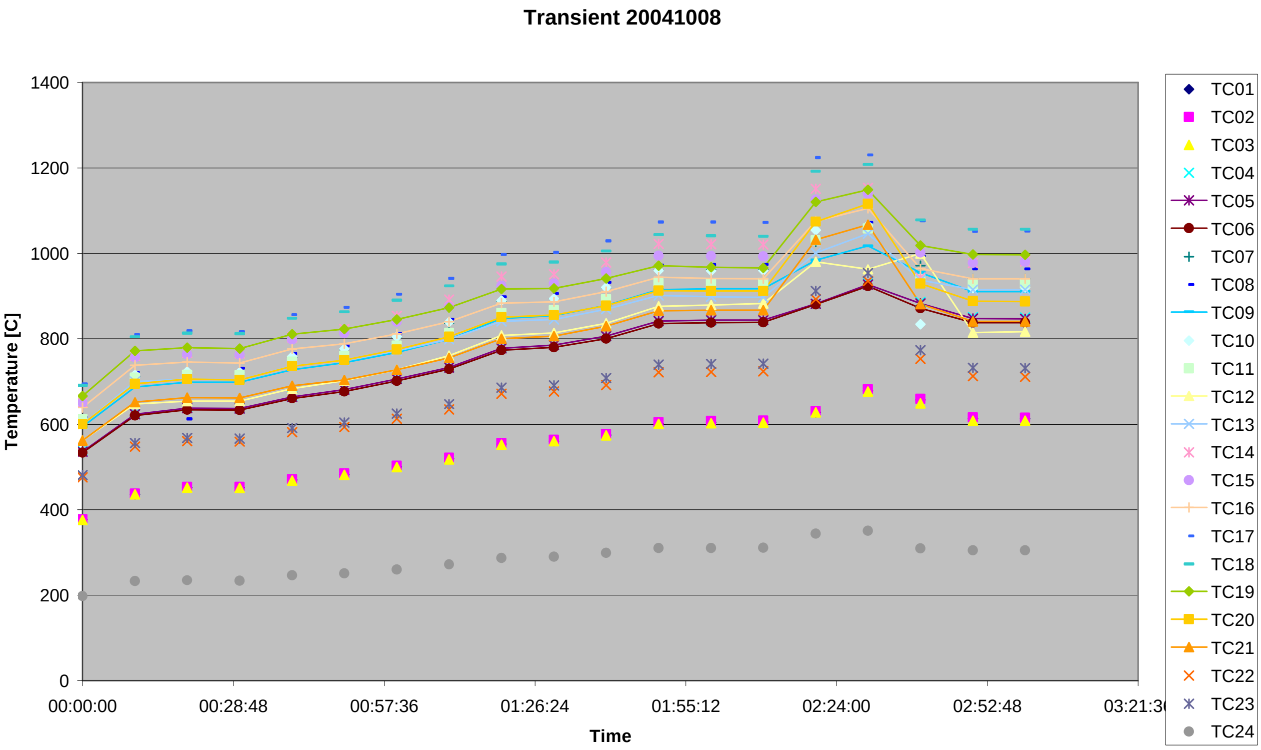


Figure 38: Temperature plot during incident on 20041004 cycle 04-09

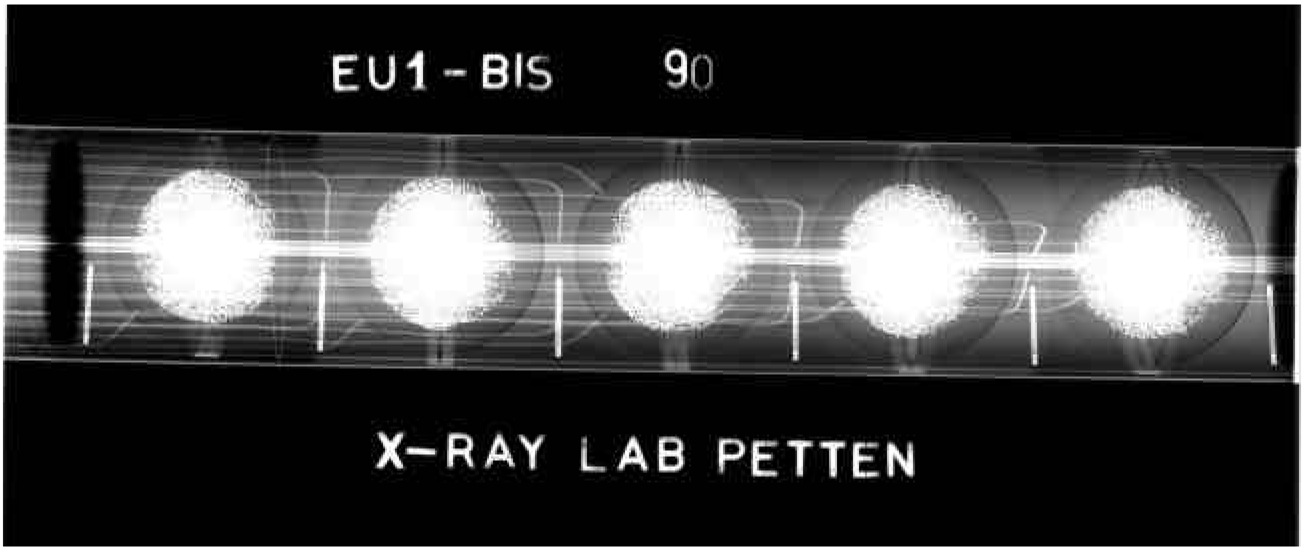


Figure 39: Pre-Irradiation X-ray of HFR-EU1bis sample holder

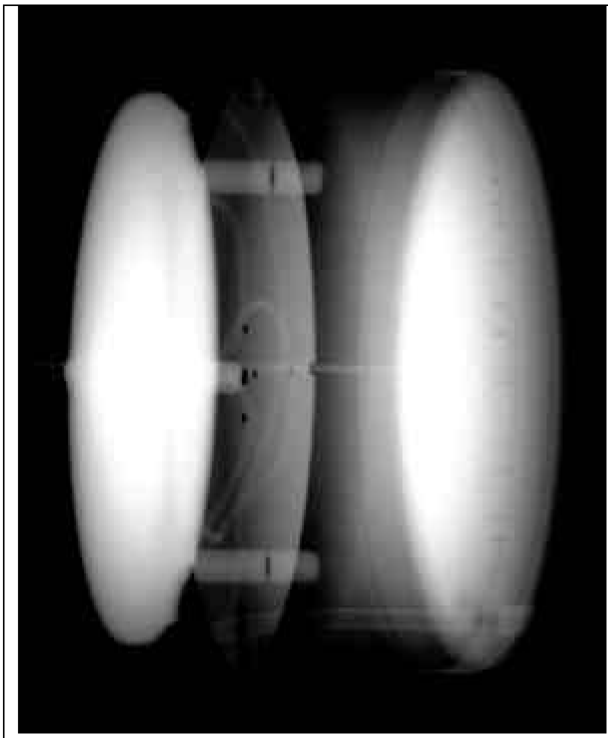
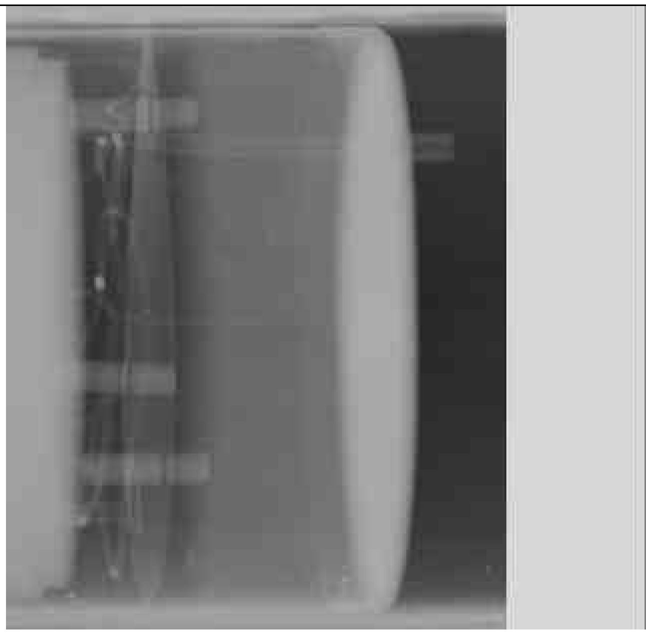
	
Pre-Irradiation X-ray of sample holder bottom	Post-irradiation neutron radiography of sample holder bottom

Figure 40: Bottom of sample holder showing intact 2nd containment gas feed outlet

Damaged minitube

↓ ↓

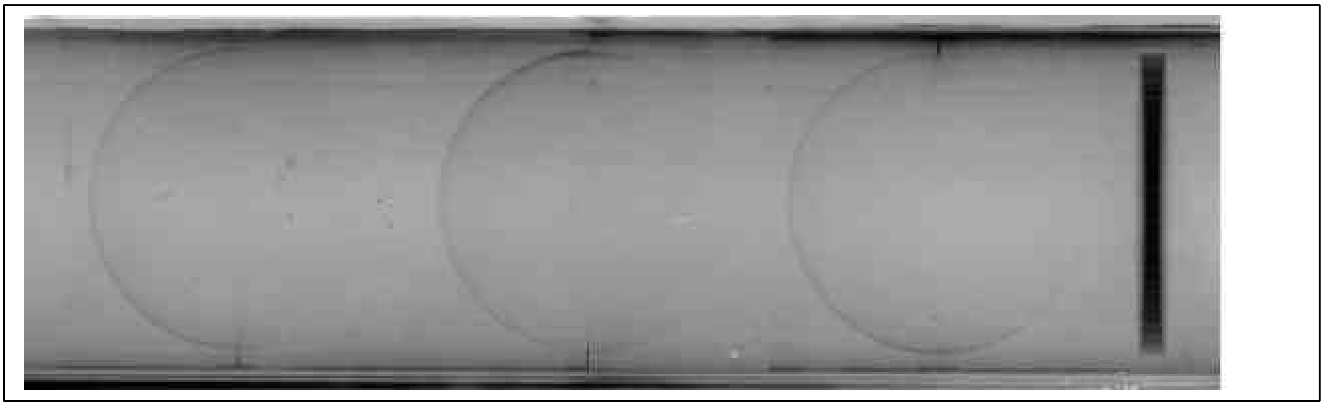
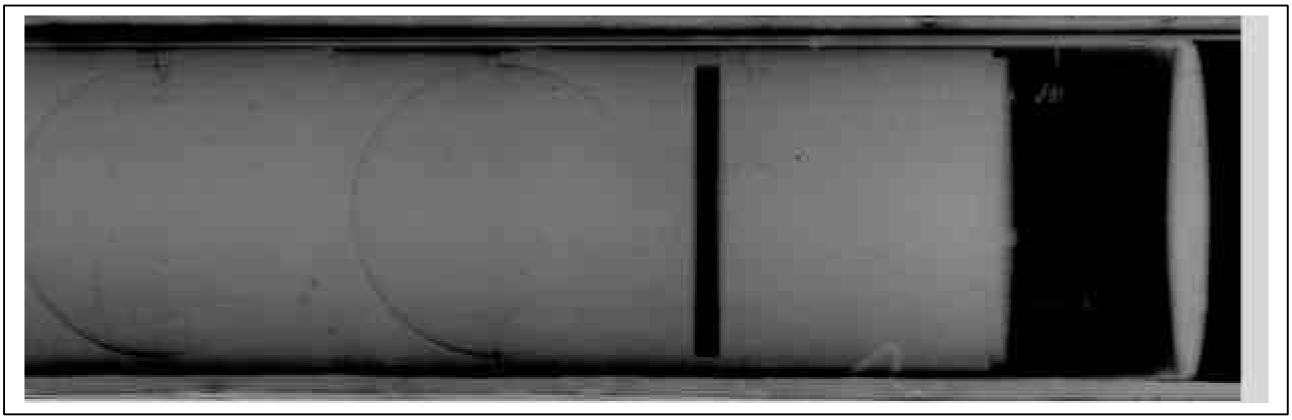


Figure 41: Post-Irradiation neutron radiograph of HFR-EU1bis sample holder, 3 lower pebbles



↑ ↑

Damaged minitube

Figure 42: Post-Irradiation neutron radiograph of HFR-EU1bis sample holder, 2 lower pebbles and end cap

9 References

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[2] M. A. Fütterer, HFR-EU1bis: Irradiation Progress Report, Cycles 05-03, 05-04, 05-06, 05-07, rev. B, Technical Memorandum HFR/05/4812, D(05)19257, 1 November 2005.

[3] M. A. Fütterer, H. Lohner, R. Conrad, K. Bakker, S. de Groot, C. M. Sciolla, HFR-EU1bis: Irradiation of High Temperature Reactor Fuel Pebbles at VHTR Conditions in the HFR Petten, Design and Safety Report, rev. D, Technical Memorandum HFR/03/4757, D(04)11197, 8 November 2004.

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[6] L. Metten, Analysis of neutron radiographs of HFR-EU1bis, JRC-IE technical note, hfr/lm/lm/0512.036, D(05)31615, 6 December 2005.

10 List of Figures

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