EUR 5147 e
Part 1 of 2

COMMISSION OF THE EUROPEAN COMMUNITIES

THE FIRST JOINT 900°C HTR FUEL IRRADIATION EXPERIMENT IN THE HFR PETTEN PROJECT E 96-01

IRRADIATION HISTORY

by

H. RÖTTGER

1974

Joint Nuclear Research Centre
Petten Establishment - Netherlands

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During irradiation the R/B-value remained at 10^{-7} for Kr-85m and at $2.5.10^{-6}$ for Xe-133 which is relatively small.

Irradiation was terminated by a serious leakage of the irradiation device.

Visual inspection of the samples after dismantling showed that no monolayer or compact was broken.

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ABSTRACT

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THE FIRST JOINT 900°C HTR FUEL IRRADIATION EXPERIMENT IN THE HFR PETTEN PROJECT E 96-01

Irradiation History

1. Introduction

The general object of this irradiation project, which has been carried out in the framework of a joint BR2-HFR irradiation programme of Euratom, was to examine the behaviour of different HTR fuel samples, under realistic operating conditions, up to a fast fluence of 4.10^{21} cm^{-2} DNE [1]. The irradiation temperature of 900°C ± 50°C was imposed by the fact that in a HTR-power reactor most of the fuel will be operated in this range.

Irradiation started on 29th April 1971, and was terminated by a serious leakage in the inner and outer capsule on 28th September 1971.

A planned reloading of the sample carrier (inner capsule) into another outer capsule failed.

Dismantling of the irradiation device was carried out mainly in the hot cells (LSO) of the RCN at Petten, in March and April 1972.

The post irradiation examinations have been carried out in the p.i.e. cells of Euratom and RCN at Petten. The results are published in another report [9].

1) see 3.4

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2. Short experiment description

2.1 Fuel

The fuel, consisting of coated particles, was enclosed in a graphite matrix which had the geometrical form of monolayer compacts (coupons, Fig. 1) or annular compacts (Fig. 2) with the following dimensions:

Outer diameter : 22 mm
inner diameter : 12 mm
height : 2 mm (monolayer compacts= coupons)
10 and 14 mm (annular compacts) .

There were 124 coupons and 14 annular compacts distributed in the four graphite drums (Fig. 3) of the sample carrier according to a loading plan given in [1].
Some characteristics of the particles have been compiled in Table 1.

2.2 Irradiation rig [1]

The four above mentioned graphite drums (each of 125mm height) with the fuel samples were placed in a tubular stainless steel container (sample carrier or first containment, Figs. 4 and 6) which was surrounded by a second st. stl. container (Fig. 5). An additional Al-sleeve surrounded the whole assembly (Fig. 7) to reduce the water gap between the capsule and the filler element of the reactor core. The 0.2mm (cold) gas gap between the two st. stl. tubes was filled with a He-N2 mixture adjusted to get the required temperature of the fuel samples ($900^{\circ}C \pm 50^{\circ}C$).
Five small boxes, containing Ni-, Fe- and Co-foils for the determination of fast and thermal fluence values, were positioned in the graphite drums and can be seen in a x-ray picture of the sample carrier (Fig. 8).
16 Chromel-Alumel thermocouples have been placed throughout the rig in 8 sections. In each graphite box there were two Chromel-Alumel thermocouples positioned in two levels of the central graphite spine and two in the same levels of the external graphite tube (Figs. 8 and 9).

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By means of two small pipes (minitubes) leading to the first stainless steel container, the inner capsule could be purged.

2.3 Out-of-pile installation

The 16 Chromel-Alumel thermocouples as well as the small pipes had been connected to the existing EXOR-installation.
The temperatures were recorded continuously. One of the thermocouples was used in an alarm circuit to indicate an upper temperature limit.
By decompression of the inner capsule from 7 to 0.9 ata and collecting the He-gas in an evacuated 4l-tank the capsule was purged. Subsequently gas samples could be analysed by gaschromatographical and γ-spectrometrical methods for chemical impurities and fission gas products. The inner tube was pressurized with Helium supplied from an industrial bottle (total impurity level less than 0.0004%). A special purification system was not considered necessary.
With the existing EXOR-installation the $He+N_2$-gas mixture in the control gas gap between the inner and outer capsules could also be adjusted to get the required irradiation temperature.

3. Irradiation history

The irradiation started on 29th April, 1971 in Position E3 of the HFR, and was stopped after a total of 72.4 irradiation days by leakage of both containments on 28th September, 1971.
In January 1972 a reloading of the sample carrier into a new Refa-capsule failed so that further irradiation had to be abandoned.

3.1 Initial irradiation period

At the beginning of irradiation a slow reactor start, i.e. a step-wise increase of reactor power with more or less long intervals at constant power, was carried out. During the constant power period the inner capsule was purged several times, and the effluent subjected to gas analysis. In Table 2, one can find the results of gaschromatographic measurements during the first reactor start-up and the initial irradiation period.

The vertical temperature distributions during this time, measured with the thermocouples in the graphite spines (Fig. 9) are given in Table 4.

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The first R/B-values had been measured after 8 days and one received.

$R/B = 2.5.10^{-8}$ for Kr - 85m

$R/B = 5.4.10^{-7}$ for Xe - 133

$R/B = 4.7.10^{-9}$ for Xe - 135.

3.2 Normal operation

3.2.1 Temperatures

The behaviour of the capsule during the months May and June was very satisfactory. The vertical temperature distribution measured with the Chromel-Alumel thermocouples in the graphite spine of the boxes, showed that the irradiation temperature was within the limits, in the middle of each half cycle corresponding to a control rod position of 55cm,which may be regarded as ref. position. It must be mentioned that during this period the cycle length, normally about 12 days, was shortened due to special requirements of fuel element economy.

In Fig. 10 the vertical temperature distributions for the middle of each irradiation cycle have been presented. The gas mixture in the control gap ($He:N_2 = 1:9$) remained unchanged until the middle of June.

At this time, a continuous increase of the temperature indicated by thermocouple nr. 14 was observed, leading to a value of $1050^{0}C$. To reduce the temperature of the thermocouples passing through this part of the capsule, the percentage of the Helium in the control gap was increased to 50%.

A further change from 50% to 100% He was necessary soon after when the temperature again reached $1050^{o}C$.

These changes also caused the temperatures in the other graphite boxes to decrease and the required irradiation temperature could no longer be maintained (Fig. 11).

A continuous increase in temperature was likewise observed with thermocouple - nr.10 and later also with thermocouple nr.2. This continuous increase observed in function of irradiation time but under the same condition i.e. at equal control rod positions was caused by Pu-production and Pu-fission in the compacts with depleted uranium (0.4% U-235), which had a very high heavy metal loading

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(8 times more than the 3% enriched compacts) to give the same U-235 amount of 6.04mg/cm as for the other monolayers and compacts. In Fig. 8 one can recognize the depleted fuel compacts by the big number of coated particles. Their positions correspond with the positions of the thermocouples nr. 2, 4 and 10.

At the beginning of the 6th HFR-cycle, starting on 22nd June, 1971 it was possible to use again the 10% He-mixture due to a low control rod position. During this cycle a first irregularity in temperature behaviour of the capsule took place, after having carried out a normal gas sampling by pressure decrease in the inner capsule, when the temperature in the lower part of the capsule dropped suddenly by about 30degC (Fig. 12).
A small pressure decrease in the inner capsule had already been observed since end of May.
Two further temperature drops each of 30degC occured also on 29th June, 1971 (Fig. 13).
From this time the behaviour of the capsule was no longer satisfactory, and the required temperature could not be maintained in the lower part of the capsule.
After having modified the out-of-pile installation to satisfy the safety conditions (due to leakage of the inner capsule there existed only one containment), irradiation was restarted in September 1971 (8th HFR-cycle) but only with 100% Helium in the inner and outer capsule, and with no possibility to adjust the gas-mixture to get the required irradiation temperatures.
During this cycle the temperatures indicated by thermocouples nr. 2 and 10, caused by Pu-production and Pu-fission, again began to increase (Fig. 14).
On 29th September 1971 the outer capsule failed and irradiation had to be stopped and later to be abandoned, because a reloading of the sample carrier into another outer capsule failed.
Regarding Figs. 15 - 18 representing the temperatures, measured in the different boxes with the inner thermocouples as function of irradiation days, one can see that large deviations from the limits only appeared at the end of irradiation.

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This is in particular true for the boxes 2, 3 and 4. The temperature differences occurring during a cycle are caused by the vertical movement of the control rods, and cannot be avoided in a capsule with only one control gas gap over the whole length.

For all the temperatures given in the figures, it must be remembered, that the fuel temperature can be lower than the measured spine temperature [1], by up to 30degC.

3.2.2 Gas impurities

The inner capsule was filled with high purity industrial Helium. An additional gas purification was not used because the gas satisfied the conditions imposed:

$H_2O < 2$ vpm
$H_2 < 10$ vpm
$CO_2 < 10$ vpm
$CO < 10$ vpm

Some analyses carried out after the start-up period are given in Table 3.
The high impurity level of the last irradiation period, can be explained by the leakage between inner and outer containment, which allowed N_2 to enter the inner capsule.

Neutrography has shown that a certain amount of H_2O was also present in the outer capsule (Refa-capsule).
So it cannot be excluded that water vapour has entered the inner capsule.

3.2.3 Fission gas release

During irradiation the activity of Kr-85m, Xe-133 and Xe-135 of the gas in the rig has been measured several times. In Fig. 19 the measured ratio

$$\frac{R}{B} = \frac{\text{Release rate of a given isotope}}{\text{Birth rate of a given isotope}}$$

has been plotted as a function of the irradiation time. Table 5 gives the measured values as well as the date of sampling. It follows from these that the R/B-factor never exceeded 8.10^{-8} for Kr-85m, 2.10^{-6} for Xe-133 and $1.5.10^{-8}$ for Xe-135 during the irradiation time.

Some irregularities might originate from errors in quantitative sampling, and in γ-spectroscopy etc. To prevent gas impurities entering the inner capsule by the leakage, no gas sampling was carried out at the end of irradiation.

3.2.4 HFR operation data

The detailed HFR operational data during irradiation are given in the cycle reports [2, 3, 4, 5]. Two important curves of operation, namely HFR power vs time and control rod position vs time are presented in Figs. 20-23 for the cycles concerned.

3.3 Burn-up calculation

The theoretical burn-up in FIMA for different enrichments has been calculated with the PDC-Computer using the formula

$$\text{Fima } (\%) = 100 \left\{ E \frac{\sigma_{F5}}{\sigma_{A5}} \left(1 - e^{-\sigma_{A5}\phi t}\right) + (1-E) \frac{\sigma_{eff8} \cdot \sigma_{F9}}{\sigma_{A9} - \sigma_{eff8}} \left(\frac{1-e^{-\sigma_{eff_8}\phi t}}{\sigma_{eff8}} - \frac{1-e^{-\sigma_{A9}\phi t}}{\sigma_{A9}} \right) \right\}$$

with

$\sigma_{F\,5}$ = 580 barn = thermal fission cross section for U-235

$\sigma_{A\,5}$ = 690 barn = total thermal absorption cross section for U-235

σ_{eff8} = 19 barn = effective cross section for the production reaction U-238 → Pu-239

$\sigma_{F\,9}$ = 860 barn = thermal fission cross section for Pu-239

$\sigma_{A\,9}$ = 1250 barn = total thermal absorption cross section for Pu-239

E = enrichment of U-235 in %

ϕ = thermal neutron flux in $ncm^{-2}s^{-1}$

t = irradiation time in s

The results have been compiled in Tables 6 and 7.

The given formula can also be used for the U-Th-fuel by using the following cross-sections

$\sigma_{eff8} \rightarrow \sigma_{eff,Th}$ = 14 barn = effective cross section for the production reaction Th-232 → U-233

$\sigma_{F9} \rightarrow \sigma_{F,Th}$ = 572 barn = thermal fission cross section for U-233

$\sigma_{A9} \rightarrow \sigma_{A,Th}$ = 633 barn = total thermal absorption cross section for U-233

and regarding the U-238 atoms as Th-232 atoms - this of course is not correct. The n-figure of the U-Th fuel samples corresponds then to a Th - "enrichment" value of

$$E_{Th-232} = 13.6\% \ (n=6.22)$$

The so calculated burn-up values can be found in Table 7.

3.4 Fast and thermal neutron fluences [6]

The neutron dosimetry has been completed. The results are presented in Tables 8 and 9 and in Figs. 24a and 24b.

The difference between the "undisturbed" maximum fast neutron flux value [1] measured in the standard mock-up assembly[1] and the "disturbed" value measured in the experiment is of particular interest.

$$\emptyset \text{ fast, max. undist.} = 2.85.10^{14} cm^{-2} s^{-1}$$
$$\emptyset \text{ fast, max. dist.} = 1.91.10^{14} cm^{-2} s^{-1}$$

The fast neutron flux density of the HFR Petten is defined as the flux density of fission neutrons, which under the same conditions with the specified value for the average cross section for fission neutrons, would induce the same product activity in the detector material as the actual neutron spectrum in the irradiation position (E3).
Theoretical and experimental examinations have shown that the above defined equivalent fission flux given normally by the Neutron Metrology Group of the RCN-Petten as a result of their measurements, corresponds to the Dido-nickel flux which is often given in literature [7,8].

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1) The S-assembly consists of an aluminium inner plug of 46mm diameter covered with 2mm of st. stl. This 50mm diameter plug is placed in a 52.4mm diameterhole in the aluminium outer assembly.

4. Dismantling

The dismantling of the in-pile section of the rig was carried out in the hot cells (LSO) of the Reactor Centrum Nederland at Petten and started with the removal of the outer Al-sleeve. Visual inspection of the minitubes at the bottom of the Refa-capsule showed some damage (Fig.25) which could have caused the failure of the outer capsule (Refa). Fig. 26 shows also a fretted area caused by a vibrating minitube.

The next dismantling step was the Refa-capsule cutting to enable the sample carrier to be removed. The case of this operation indicated that a blocked sample carrier, could not explain the failed reloading operation.
Another explanation for the failed operation, namely blocking of the shield plug (see [1]) in the upper part of the Refa capsule, could not be checked.
Visual inspection of the sample carrier showed a more or less regular grey layer (Fig.27), which was analysed.
Apparently this layer consisted of stainless steel, coming perhaps from the centrering wire of 0.1mm diameter, which had been fixed before irradiation on the sample carrier and which could not be found after irradiation.
When the sample carrier was dipped into water and pressurized it showed no signs of leakage. The minitubes which connected with the inner capsule were disposed of, without first being tested, and it is unfortunately impossible to state precisely the origin of the leak.
By cutting off the end caps of the sample carrier, the graphite boxes, with the coupons and compacts were recovered (Fig.28).
The p.i.e. work was started immediately after dismantling with different γ-scans. Results will be discussed with other p.i.e. data in [9].

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Table 1. Characteristic data of the fuel samples (experiment E 96-1).

Kernel			coating	overall diameter in µm	fuel form and height in mm	partner
outer diameter in µm	porosity in %	enrichment of U-235 in % resp. n-number				
800	10-15	0.4, 3 and 9	PyC/SiC/ PyC	1100 to 1200	2mm coupons and 10mm annular compacts	Belgo-nucleaire
650 and 800 (nominal)	20 (nominal)	3.5 6 12	PyC/PyC/ SiC/PyC	932 to 1210 (measured)	2mm coupons and 14mm annular compacts	Dragon
500 to 630	8	89.42 n=6.22	PyC/PyC/ SiC/PyC	800 to 1000	2mm coupons	KFA Jülich

Table 2. Results of gaschromatographic analysis of the gas removed from the sample carrier during the initial irradiation period (experiment E 96-1).

time in hrs after first reactor start up	date and time of sampling	reactor power(MW)	H_2 vpm	O_2 vpm	N_2 vpm	CH_4 vpm	CO vpm	remarks
	26.4.1971	cold test	< 0.2	< 0.5	50-100	< 0.2	< 1	He - supply (H_2O:2.5vpm)
	27.4.1971	cold test	~0.5	~ 7	50-100	< 0.2	< 1	gas from capsule-41 tank
	28.4.1971	cold test	0.7	17	100	< 0.2	< 1	gas from capsule-41 tank
	29.4.1971	cold test	10	20	160	0.5	3	gas from capsule-41 tank
	29.4.1971,13,35h	10	1000	1-5	160	67	480	gas from capsule-41 tank
	"	20	300	6	52	96	700	gas from capsule-41 tank
	"	30	350	< 0.5	40	260	1000	gas from capsule-41 tank
	"	35	85	< 0.5	40	15	66	gas from capsule-41 tank
	"	40	100	< 0.5	~ 50	9	25	gas from capsule-41 tank
1	29.4.1971,20,45h	45	1500	~ 3	65	60	90	gas from capsule-41 tank (He-supply: 1.5 vpm H_2O)
4	29.4.1971,24,00h	45	2050	~3	84	~ 9	12	gas from capsule-41 tank (He-supply: 1.5 vpm H_2O)
13	30.4.1971,09.00h	45	206	~3	69	3	3	gas from capsule-41 tank (He-supply: 1.5 vpm H_2O)
25	30.4.1971,21.00h	45	118	~4	130	1.2	2.5	gas from capsule-41 tank (He-supply: 1.5 vpm H_2O)
48	1.5.1971,20.00h	45	45	< 1	200	0.3	< 1	gas from capsule-41 tank (He-supply: 1.5 vpm H_2O)
72	2.5.1971,20.00h	45	30	5	125	< 0.2	1.7	gas from capsule-41 tank (He-supply: 1.5 vpm H_2O)

Table 3. Results of gaschromatographic analysis of the gas removed from the sample carrier during irradiation (experiment E 96-1).

date of sampling	reactor power (MW)	H_2 vpm	O_2 vpm	N_2 vpm	CH_4 vpm	CO vpm	remarks
1.5.1971	45	45	< 1	200	0.3	< 1	
2.5.1971	45	30	5	125	< 0.2	1.7	
6.5.1971	45	43	11	-	-	2.7	
12.5.1971	45	20	3.8	> 400	-	-	
24.5.1971	45	45	31	too big	< 0.2	< 2.3	
27.5.1971	45	22	13	700	< 0.2	< 1	
17.6.1971	45	52	7.6	360	-	-	
25.6.1971	45	172	14	5000	0.6	6	
1.7.1971	45	70	15	0.5-1%	0.8	27	
2.7.1971	45	14	11	~ 50	-	-	
16.9.1971	45	33	-	-	0.7	11	
20.9.1971	45	8	-	> 1000	-	-	

Table 4. Vertical temperature distribution in the sample carrier measured during begin of irradiation with the thermocouples positioned in the graphite spines (cycle 71.04.1).

Reactor power in MW		45	45	45	45.16	44.90
% He in the He + N_2-mixture		100%	40%	8%	8%	8%
control rod position in cm					54.97	65.36
graphite box	thermocouple					
1	16	625	700	745	775	880
	14	770	850	898	931	1035
2	12	740	835	880	900	935
	10	775	875	926	935	950
3	8	750	850	891	893	875
	6	758	855	900	893	865
4	4	784	875	915	903	855
	2	750	840	881	870	825
date of measurement		29.4.71	29.4.71	29.4.71	30.4.71	6.5.71
hour of measurement		19.25h	19.30h	20.45h	04.00	20.00

Table 5. Measured resp. calculated fission gas release factor R/B (experiment E 96-1).

Date and time of sampling	R/B for		
	Kr - 85 m in 10^{-8}	Xe-133 in 10^{-6}	Xe-135 in 10^{-8}
6.5.1971 23.12h	2.47	0.54	0.47
12.5.1971 14.35h	3.7	1.28	0.72
18.5.1971 15.06h	6.24	2.12	1.47
24.5.1971 14.45h	3.82	1.43	0.85
7.6.1971 16.38h	7.1	2.43	1.62
17.6.1971 16.15h	4.74	1.98	1.11
1.7.1971 10.48h	5.81	0.32	1.43

ıble 6. Burn-up in FIMA as function of irradiation days for fuel with different enrichment ($\phi_{th.,max} = 2.37.10^{14}$ cm^{-2}s^{-1}; $\sigma_{eff.} = 19$ barn)

Irradiation days	Fima in %			
	enrichment 3%	enrichment 6%	enrichment 9%	enrichment 12%
5	0.18	0.35	0.52	0.70
10	0.36	0.69	1.03	1.36
15	0.55	1.03	1.51	1.99
20	0.73	1.35	1.97	2.59
25	0.92	1.66	2.41	3.16
30	1.11	1.97	2.83	3.70
35	1.29	2.27	3.24	4.21
40	1.48	2.55	3.63	4.71
45	1.66	2.83	4.00	5.17
50	1.84	3.10	4.36	5.62
55	2.02	3.36	4.70	6.05
60	2.20	3.61	5.03	6.45
65	2.37	3.86	5.35	6.84
2.4 70	2.55	4.10	5.65	7.21
lays 75	2.72	4.33	5.95	7.56
80	2.89	4.56	6.23	7.90
85	3.05	4.78	6.50	8.22
90	3.22	4.99	6.76	8.53
95	3.38	5.20	7.01	8.83
100	3.54	5.40	7.26	9.12
105	3.70	5.60	7.49	9.39
110	3.86	5.79	7.72	9.65
115	4.01	5.98	7.94	9.91
120	4.17	6.16	8.16	10.15
125	4.32	6.34	8.36	10.38
130	4.47	6.52	8.56	10.61
135	4.62	6.69	8.76	10.83
140	4.76	6.86	8.95	11.04
145	4.91	7.02	9.13	11.25
150	5.05	7.18	9.31	11.45
155	5.19	7.34	9.49	11.64
160	5.34	7.50	9.66	11.83
165	5.48	7.65	9.83	12.01
170	5.61	7.80	10.00	12.19
175	5.75	7.95	10.16	12.36
180	5.89	8.10	10.31	12.53
185	6.02	8.25	10.47	12.69
190	6.16	8.39	10.62	12.85
195	6.29	8.53	10.77	13.01
200	6.42	8.67	10.92	13.16
205	6.55	8.81	11.06	13.31
210	6.68	8.94	11.20	13.46
215	6.81	9.08	11.34	13.61
220	6.94	9.21	11.48	13.75
225	7.07	9.34	11.62	13.89
230	7.20	9.47	11.75	14.03
235	7.32	9.60	11.88	14.16
240	7.45	9.73	12.01	14.30
245	7.58	9.86	12.14	14.43
250	7.70	9.99	12.27	14.56

Table 7. Burn-up in FIMA as function of irradiation days for fuel with different enrichment
($\phi_{th.,max}$ = $2.37.10^{14}$ $cm^{-2}s^{-1}$;
$\sigma_{eff.}$ = barn for U-fuel and 14 barn for U-Th-fuel)

Irradiation days	FIMA in %		
	enrichment 0.4%	enrichment 3.5%	enrichment 13.6%
5	0.03	0.21	0.78
10	0.08	0.42	1.52
15	0.13	0.63	2.21
20	0.20	0.84	2.87
25	0.27	1.04	3.48
30	0.36	1.25	4.06
35	0.45	1.45	4.61
40	0.54	1.65	5.13
45	0.64	1.85	5.62
50	0.75	2.05	6.09
55	0.86	2.24	6.52
60	0.97	2.43	6.94
65	1.08	2.62	7.34
72.4 days → 70	1.20	2.81	7.71
75	1.32	2.99	8.07
80	1.44	3.17	8.41
85	1.56	3.34	8.73
90	1.68	3.51	9.04
95	1.81	3.69	9.34
100	1.93	3.85	9.62
105	2.06	4.02	9.89
110	2.19	4.18	10.15
115	2.31	4.34	10.40
120	2.44	4.50	10.64
125	2.57	4.66	10.87
130	2.69	4.81	11.09
135	2.82	4.96	11.31
140	2.95	5.11	11.51
145	3.08	5.26	11.71
150	3.21	5.41	11.91
155	3.33	5.55	12.09
160	3.46	5.70	12.28
165	3.59	5.84	12.45
170	3.72	5.98	12.62
175	3.84	6.12	12.79
180	3.97	6.26	12.95
185	4.10	6.39	13.11
190	4.22	6.53	13.27
195	4.35	6.66	13.42
200	4.47	6.80	13.57
205	4.60	6.93	13.72
210	4.73	7.06	13.86
215	4.85	7.19	14.00
220	4.98	7.32	14.14
225	5.10	7.45	14.27
230	5.22	7.58	14.41
235	5.35	7.70	14.54
240	5.47	7.83	14.67
245	5.60	7.96	14.80
250	5.72	8.08	14.92

Table 8. Measured vertical thermal and fast neutron fluences in 10^{20} cm^{-2}-experiment E 96-1, HFR position E 3 —. Ref. [6].

distance above centerline reactor core in mm	φ thermal	φ fast	
	$^{59}Co(n,\gamma)^{60}Co$	$^{58}Ni(n,p)^{58}Co$	$^{54}Fe(n,p)^{54}Mn$
+ 210	6.22	6.18	6.07
+ 85	11.69	10.34	9.05 [1]
- 40	14.85	11.95	12.67
- 165	13.08	10.11	11.56
- 290	9.03	6.18	6.45

Table 9. Cycle-avaraged vertical thermal and fast neutron flux densities in 10^{14} cm^{-2}s^{-1} calculated with the values of Table 8-experiment E 96-1, HFR-position E 3—, Ref. [6].

distance above centerline reactor core (in mm)	Φ thermal	Φ fast	
	$^{59}Co(n,\gamma)^{60}Co$	$^{58}Ni(n,p)^{58}Co$	$^{54}Fe(n,p)^{54}Mn$
+ 210	1.001	0.988	0.969
+ 85	1.868	1.651	1.446 [1]
- 40	2.370	1.909	2.025
- 165	2.090	1.615	1.847
- 290	1.442	0.986	1.031

1) This value is too low, which might be caused by the fact that the quartz foil encapsulation was broken and part of the ^{54}Mn activity can be evaporated.

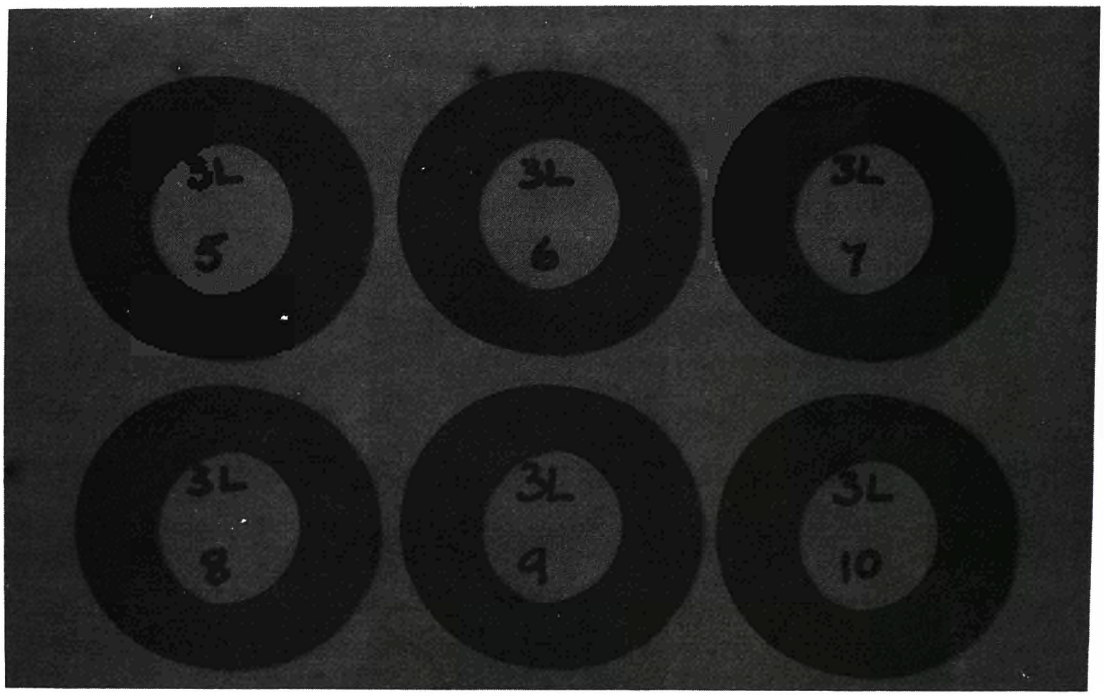

Fig. 1 Fuel samples – monolayer compact (coupon)
Outer diameter: 22 mm
Inner diameter: 12 mm
Height: 2 mm

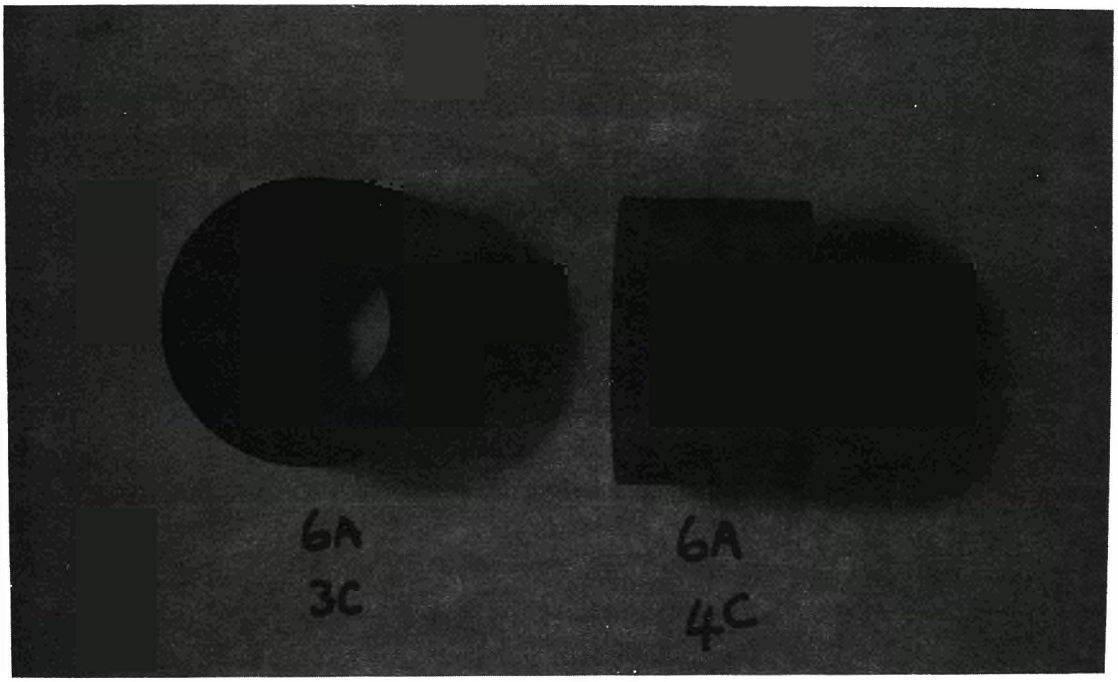

Fig. 2 Fuel sample – annular compact
Outer diameter: 22 mm
Inner diameter : 12 mm
Height: 10 resp. 14 mm

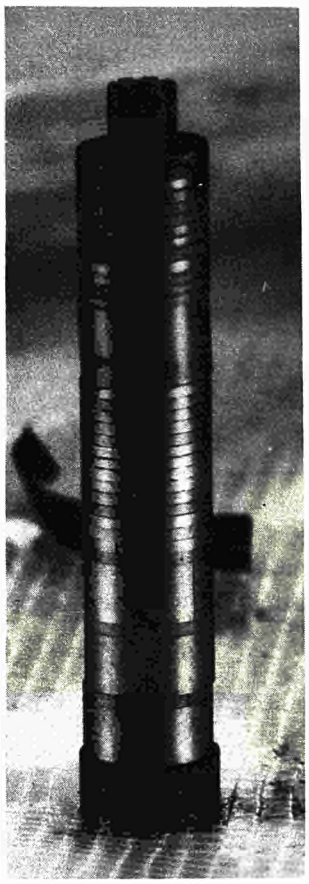

Fig. 3 One of the four graphite boxes (only graphite spine but without graphite sleeve) with monolayer and annular compacts before final assembling.

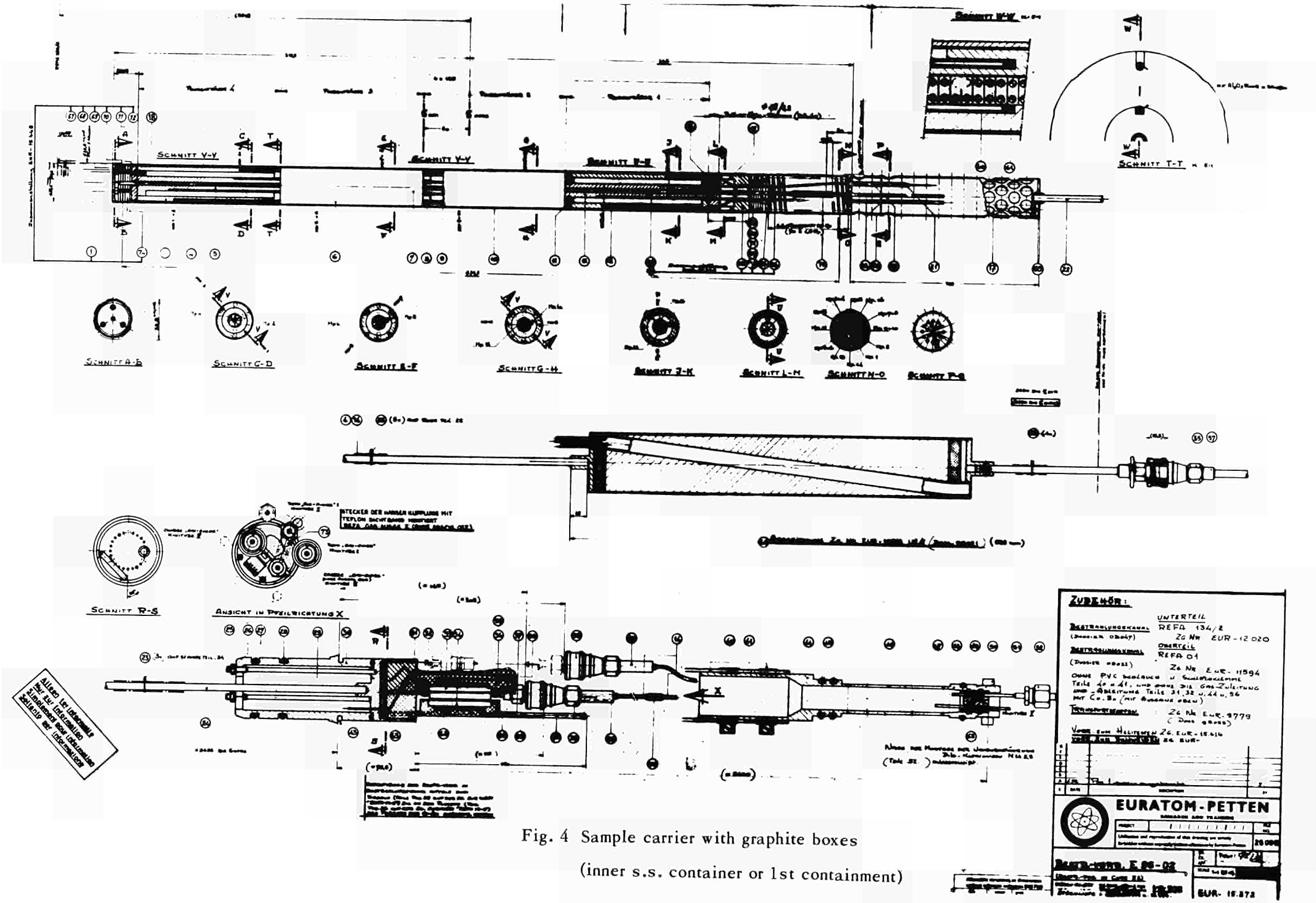

Fig. 4 Sample carrier with graphite boxes

(inner s.s. container or 1st containment)

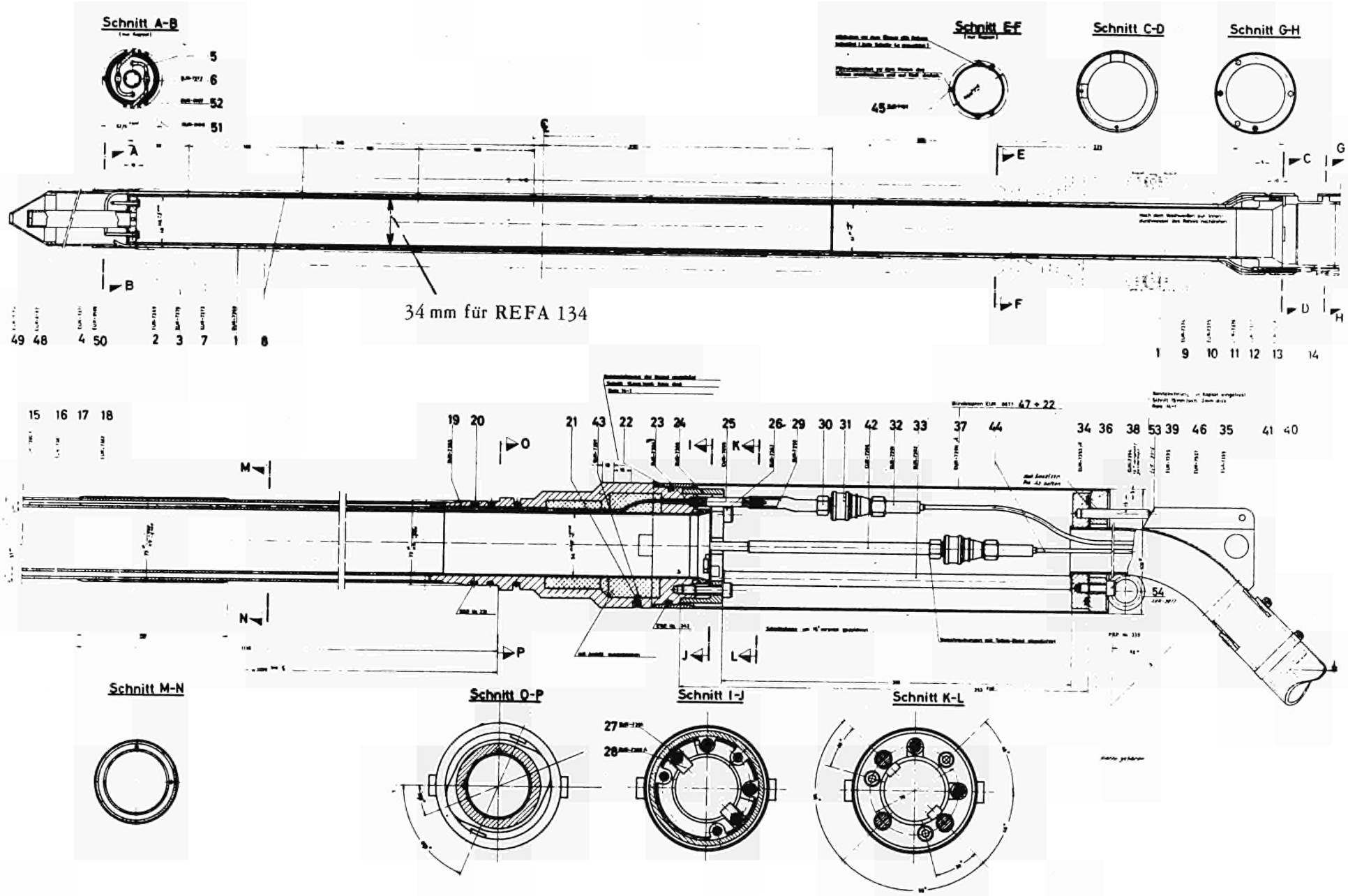

Fig. 5 Refa-capsule (outer st.stl. container or 2nd containment)

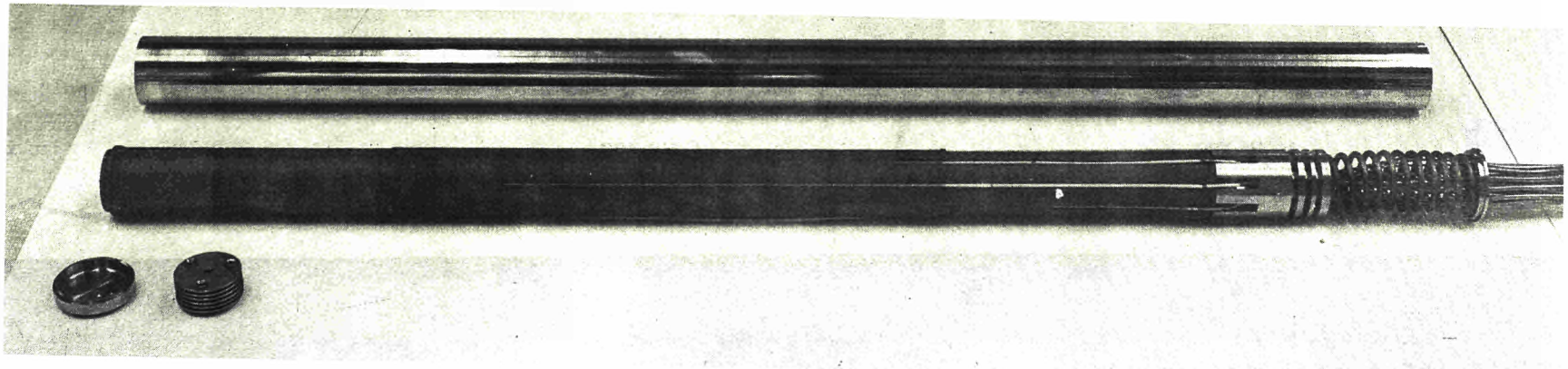

Fig. 6 Sample carrier. Graphite-boxes assembled with st.stl. tube, end caps and heat shield not yet assembled

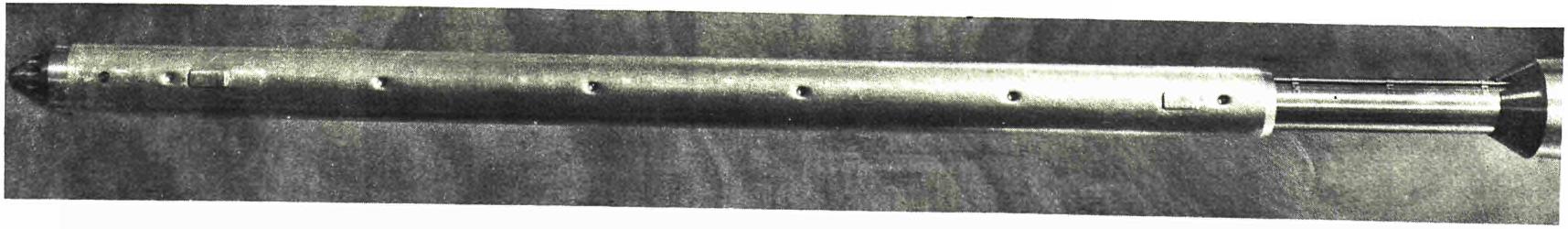

Fig. 7 Irradiation-rig. In-pile section assembled with Al-thimble

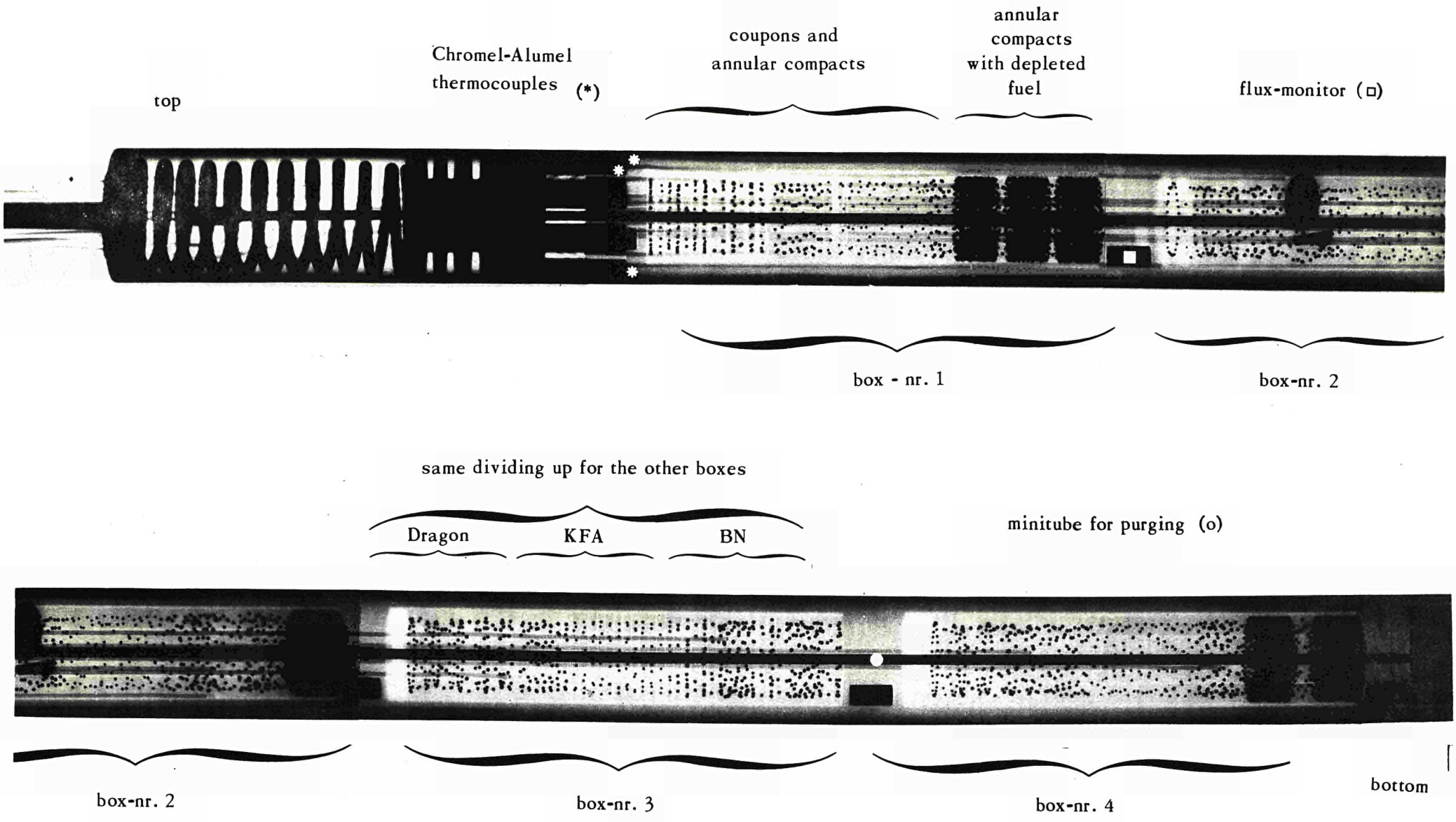

Fig. 8 Panoramic x-ray of 900°C HFR-rig (E96 – 1) before irradiation

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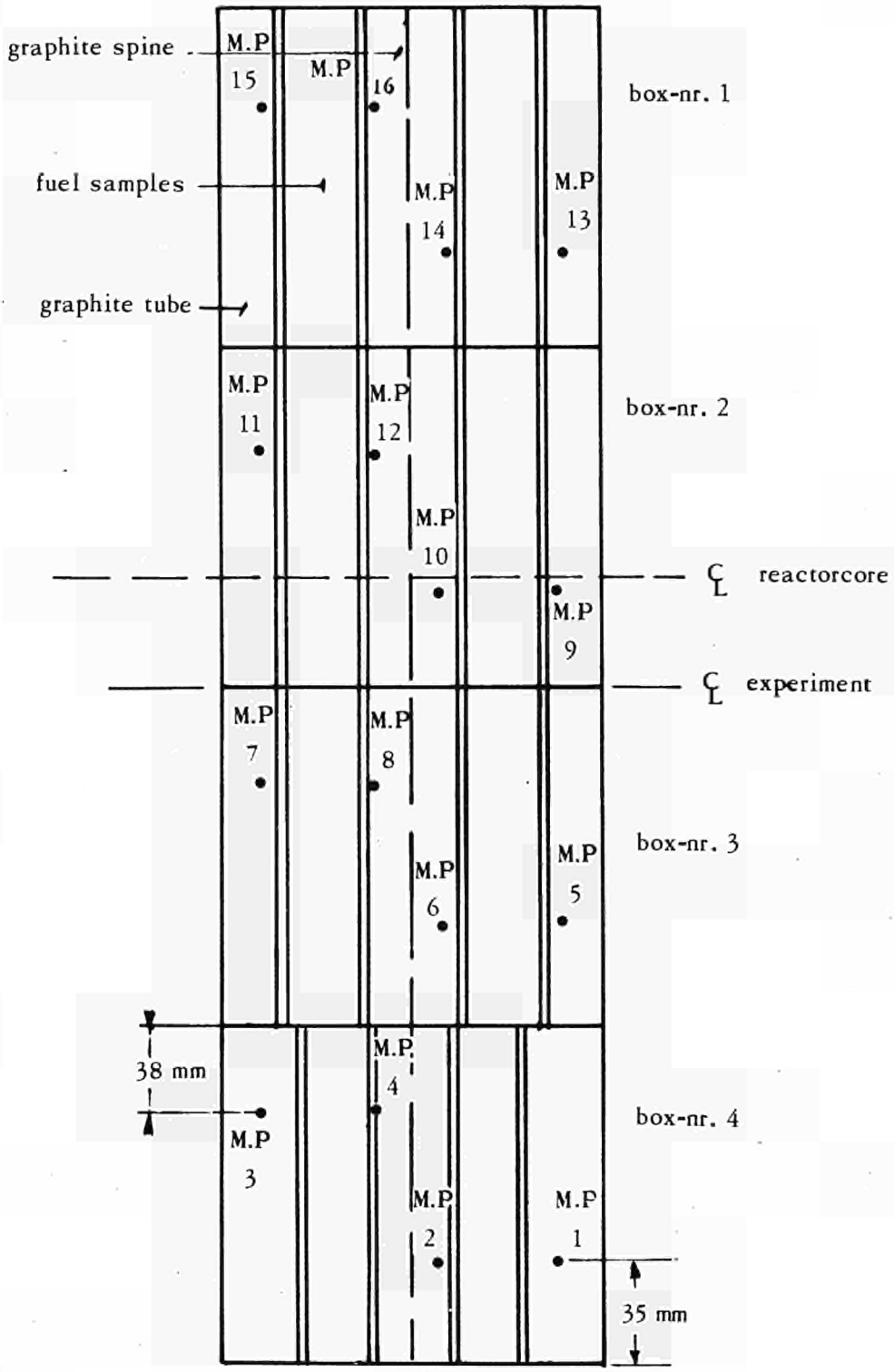

Fig. 9 Positions of the thermocouples nr. 1–16 in the graphite boxes (M.P. = measuring point)

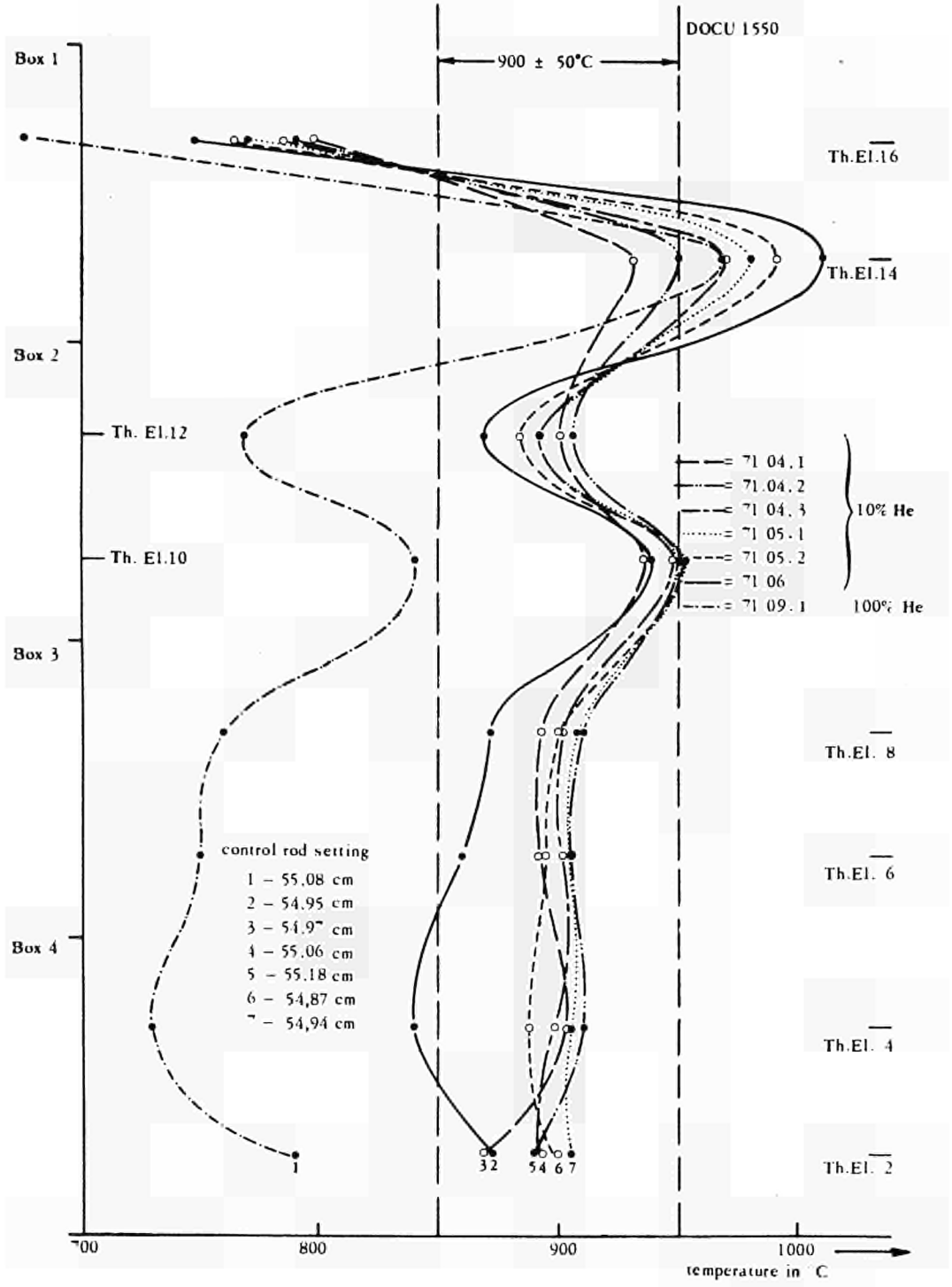

Fig. 10 Vertical temperature distribution measured with the inner thermocouples at mid-cycle (control rod setting about 55 cm) of each irradiation cycle. Gas mixture in outer capsule: 90% N_2 + 10% He (cycle 71.09.1 only 100% He).

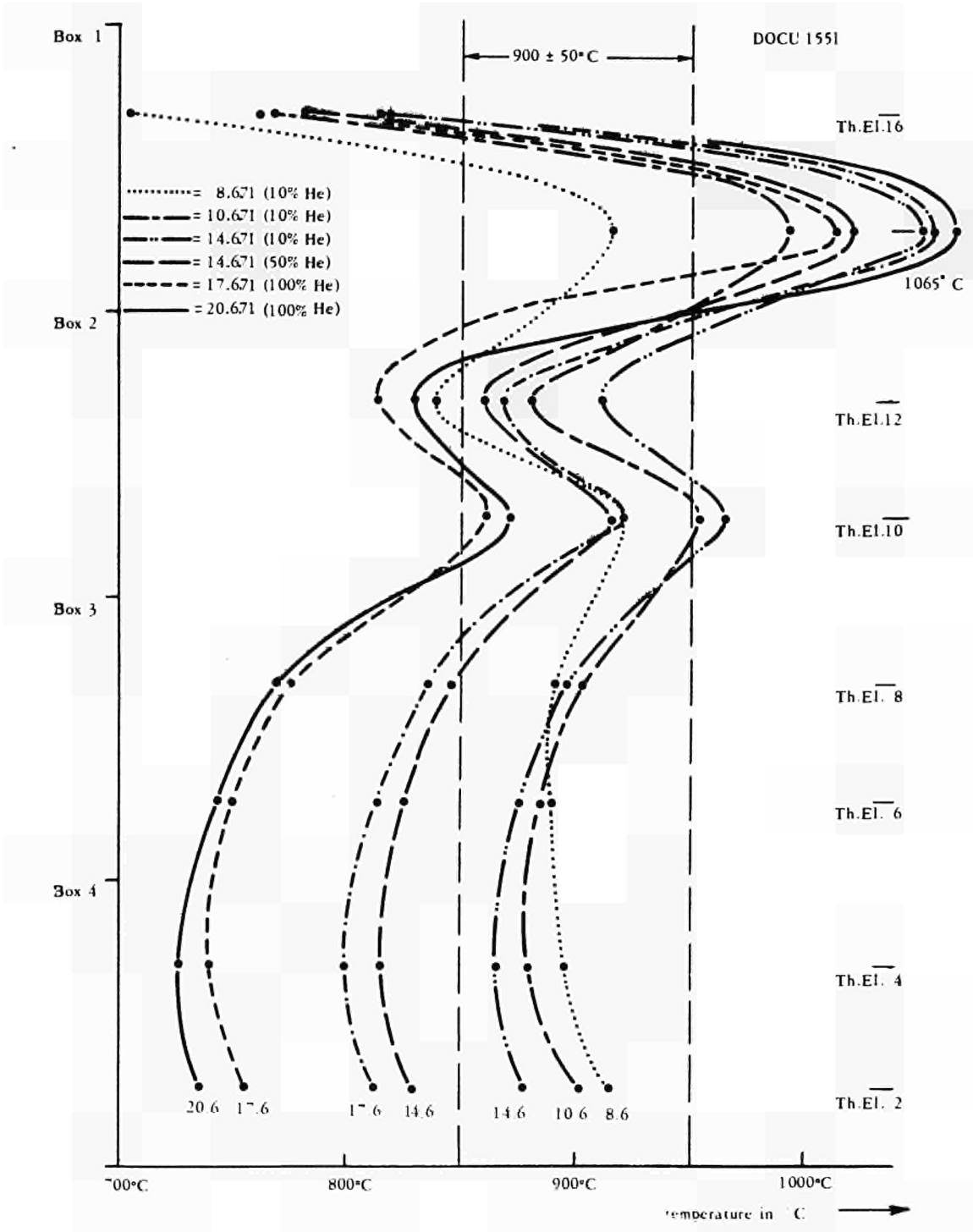

Fig. 11 Vertical temperature distribution measured with the inner thermocouples during the HFR-cycle 71.05.2. Gas mixture in outer capsule in parentheses .

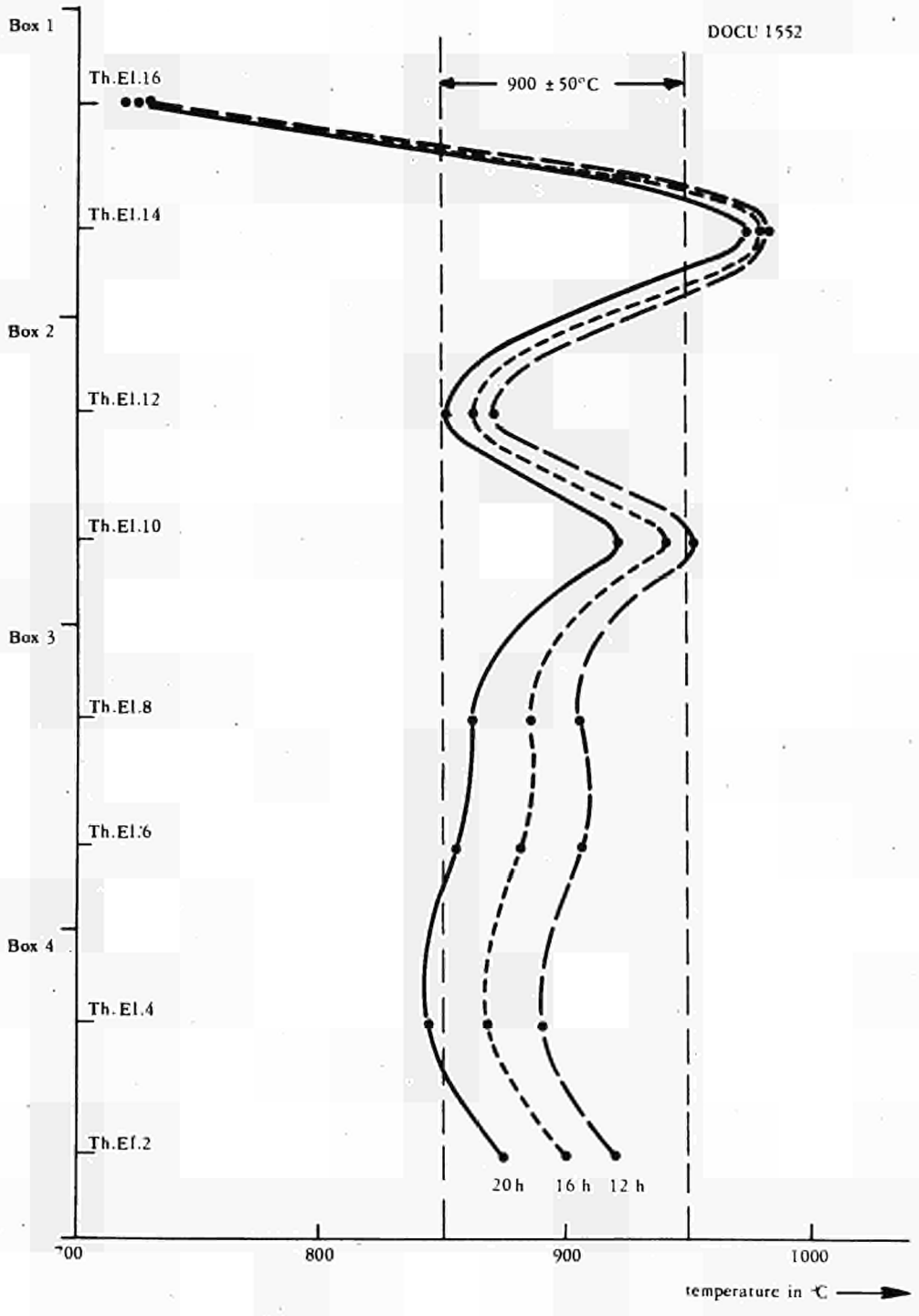

Fig. 12 Vertical temperature distribution measured with the inner thermocouples on June 26th,1971, indicating an anormal behaviour of the capsule (see 3.2.1)

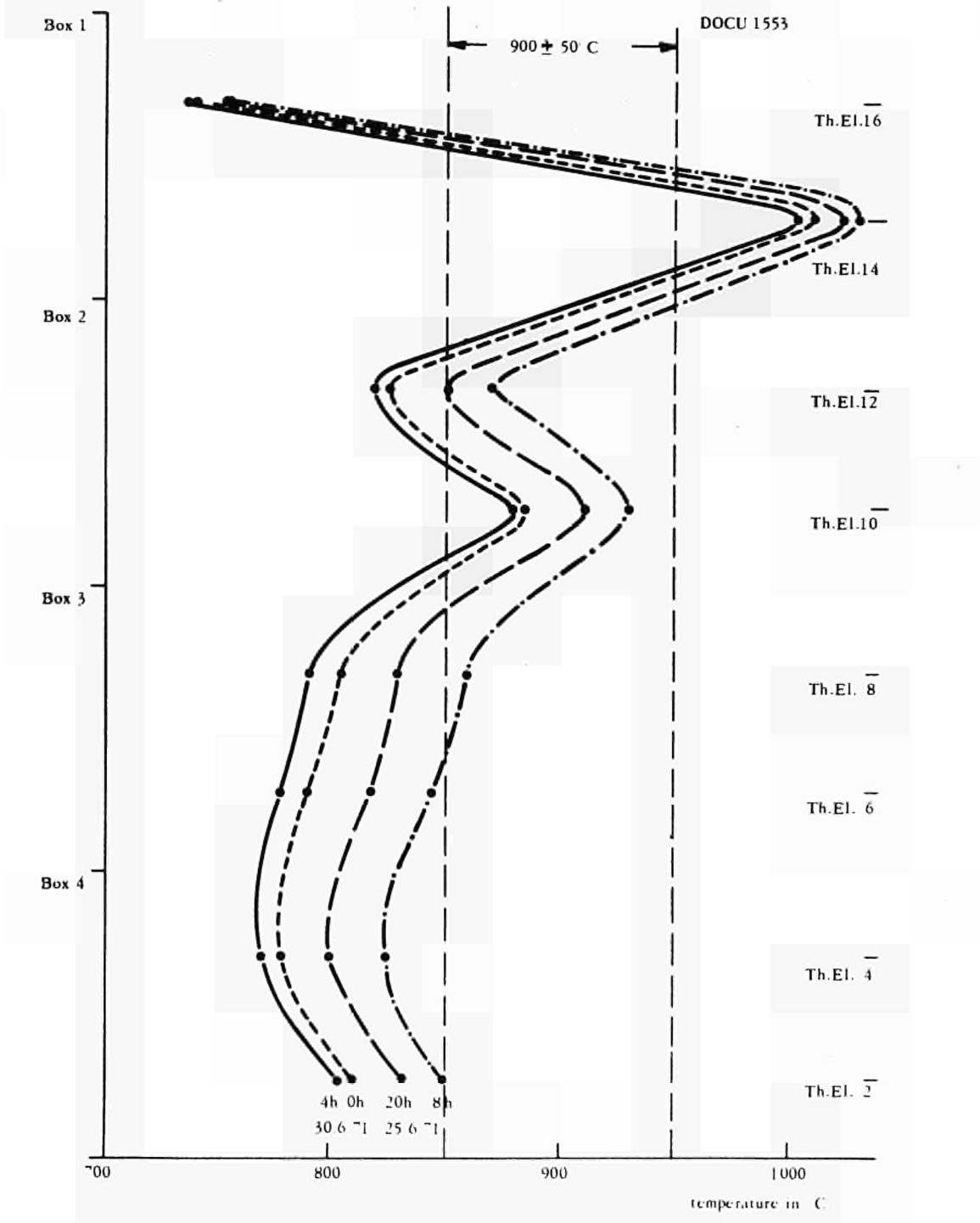

Fig. 13 Vertical temperature distribution measured with the inner thermocouples on June 29th and 30th, 1971, indicating an anormal behaviour of the capsule (see 3.2.1)

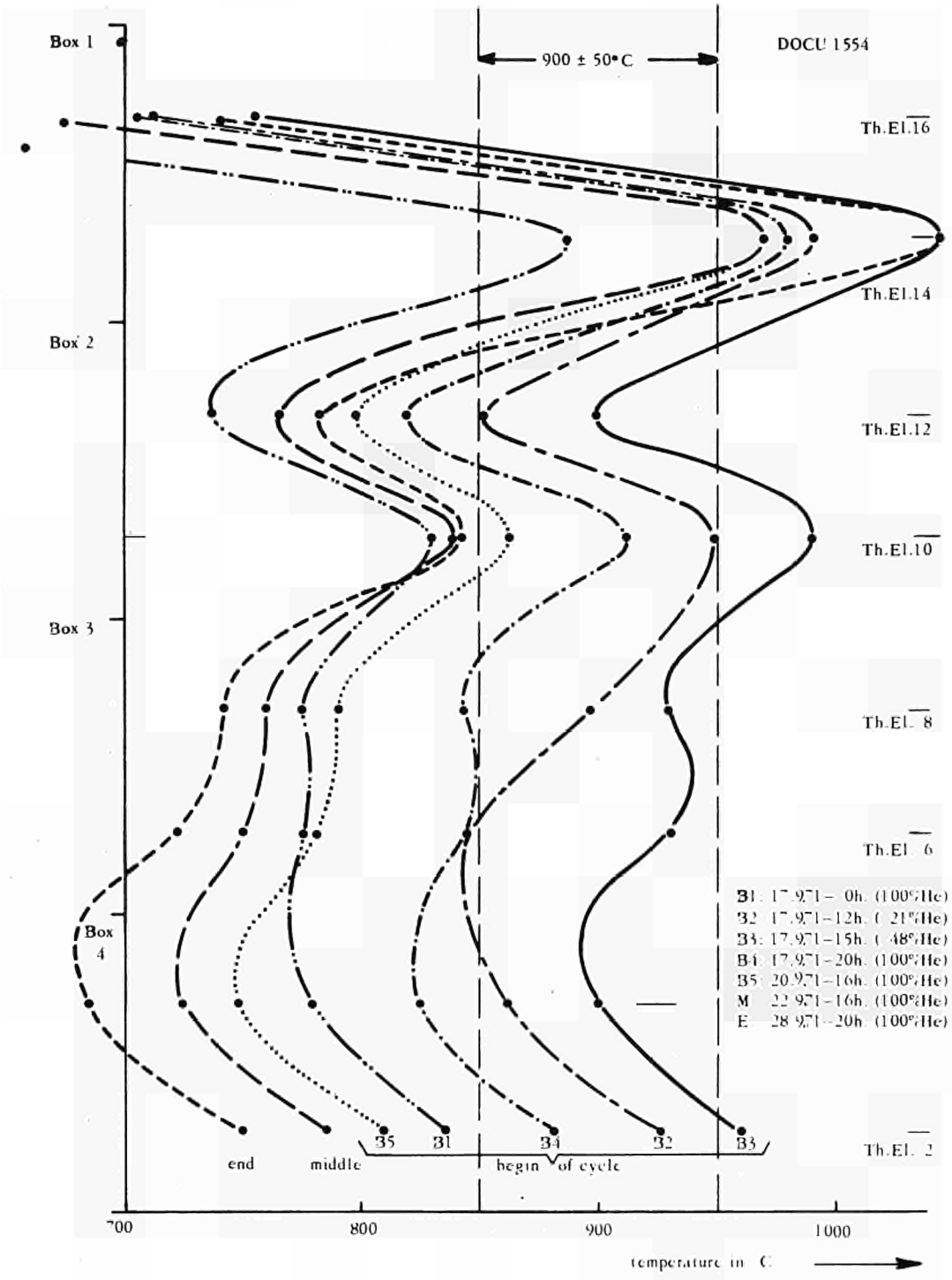

Fig. 14 Vertical temperature distribution measured with the inner thermocouples during the last irradiation cycle (September 1971, HFR-cycle 71.09.1)

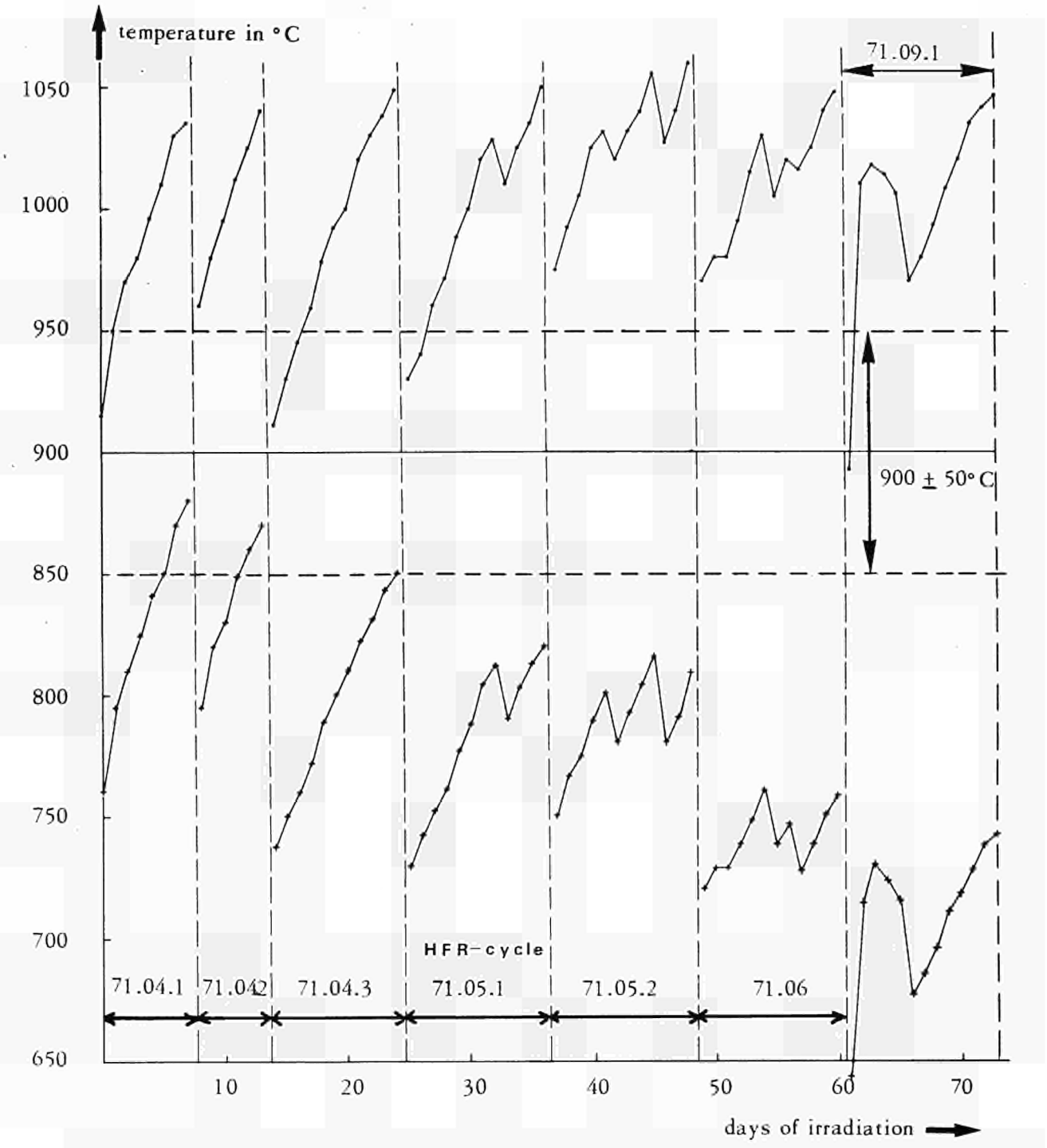

Fig. 15 Graphite-box-nr. 1: Temperatures measured with the thermocouples nr. 14 and 16 (see Fig. 9) as a function of the irradiation days
• = measured with the thermocouple nr. 14
+ = measured with the thermocouple nr. 16

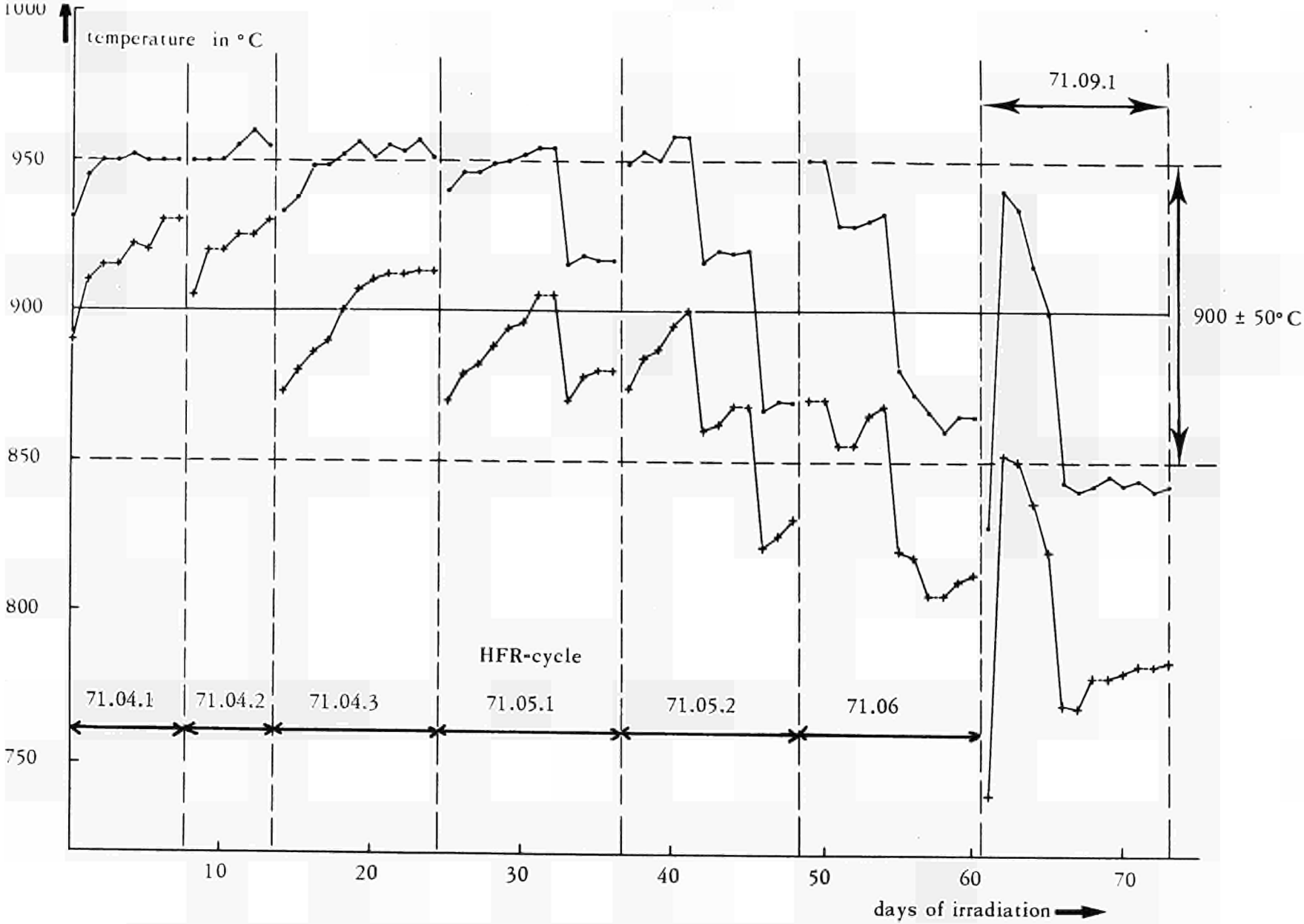

Fig. 16 Graphite-box-nr. 2: Temperatures measured with the thermocouples nr. 10 and 12 (see Fig. 9) as a function of the irradiation days
• = measured with the thermocouple nr. 10
+ = measured with the thermocouple nr. 12

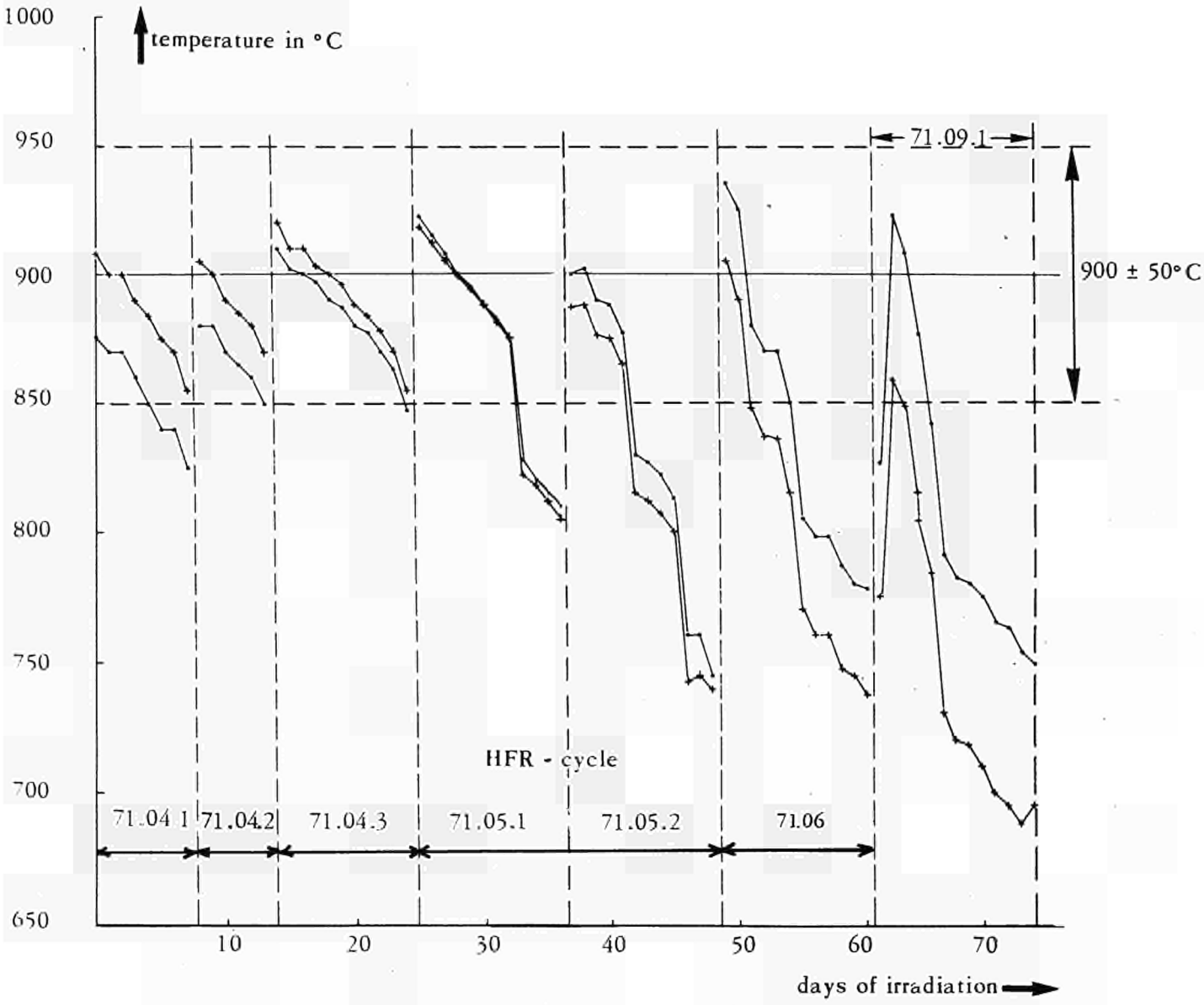

Fig. 17 Graphite-box-nr. 3: Temperatures measured with the thermocouples nr. 6 and 8 (see Fig. 9) as a function of the irradiation days
• = measured with the thermocouple nr. 6
+ = measured with the thermocouple nr. 8

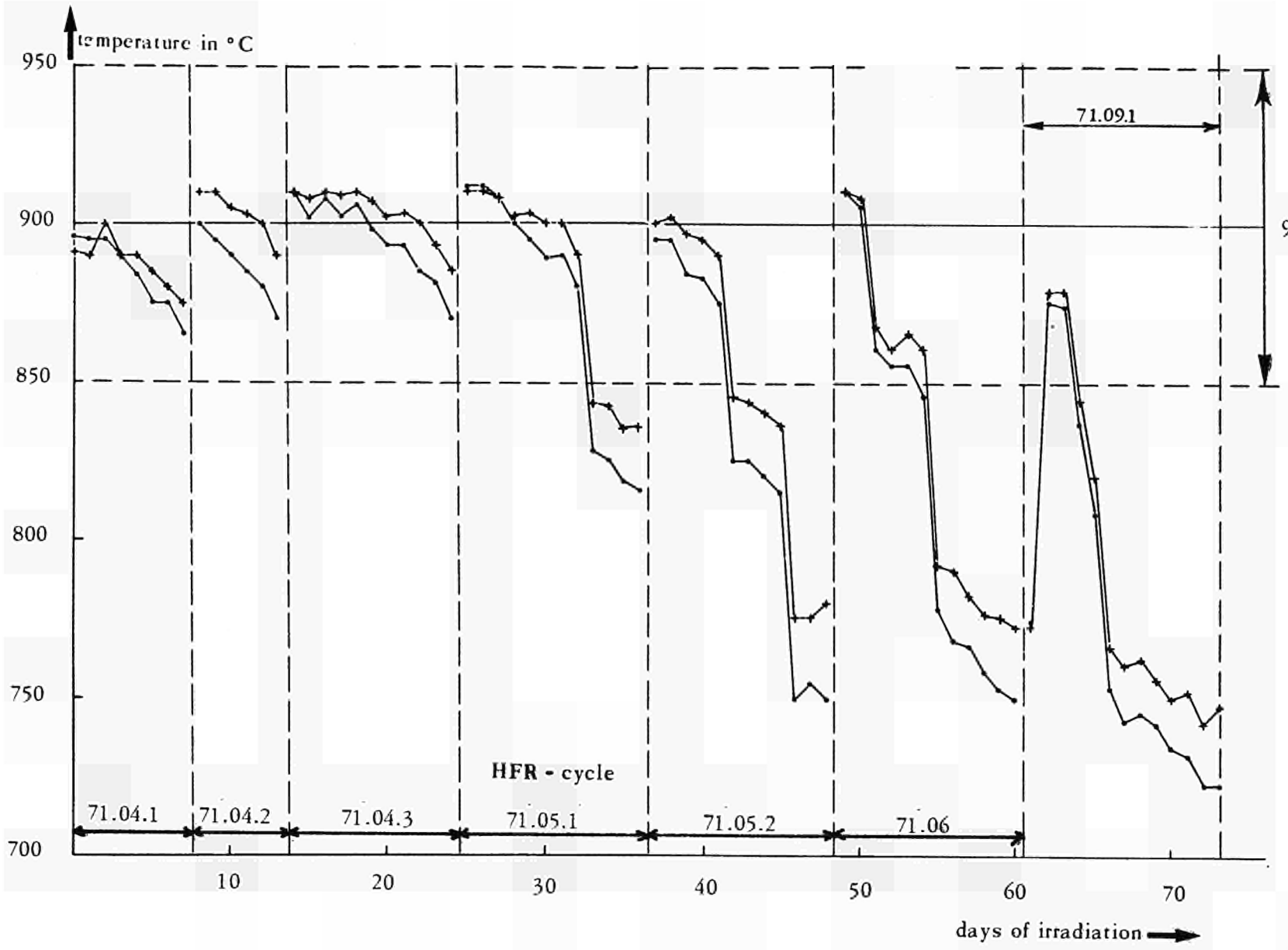

Fig. 18 Graphite-box-nr. 4 : Temperatures measured with the thermocouples nr. 2 and 4 (see Fig. 9) as a function of the irradiation days

• = measured with the thermocouple nr. 2

+ = measured with the thermocouple nr. 4

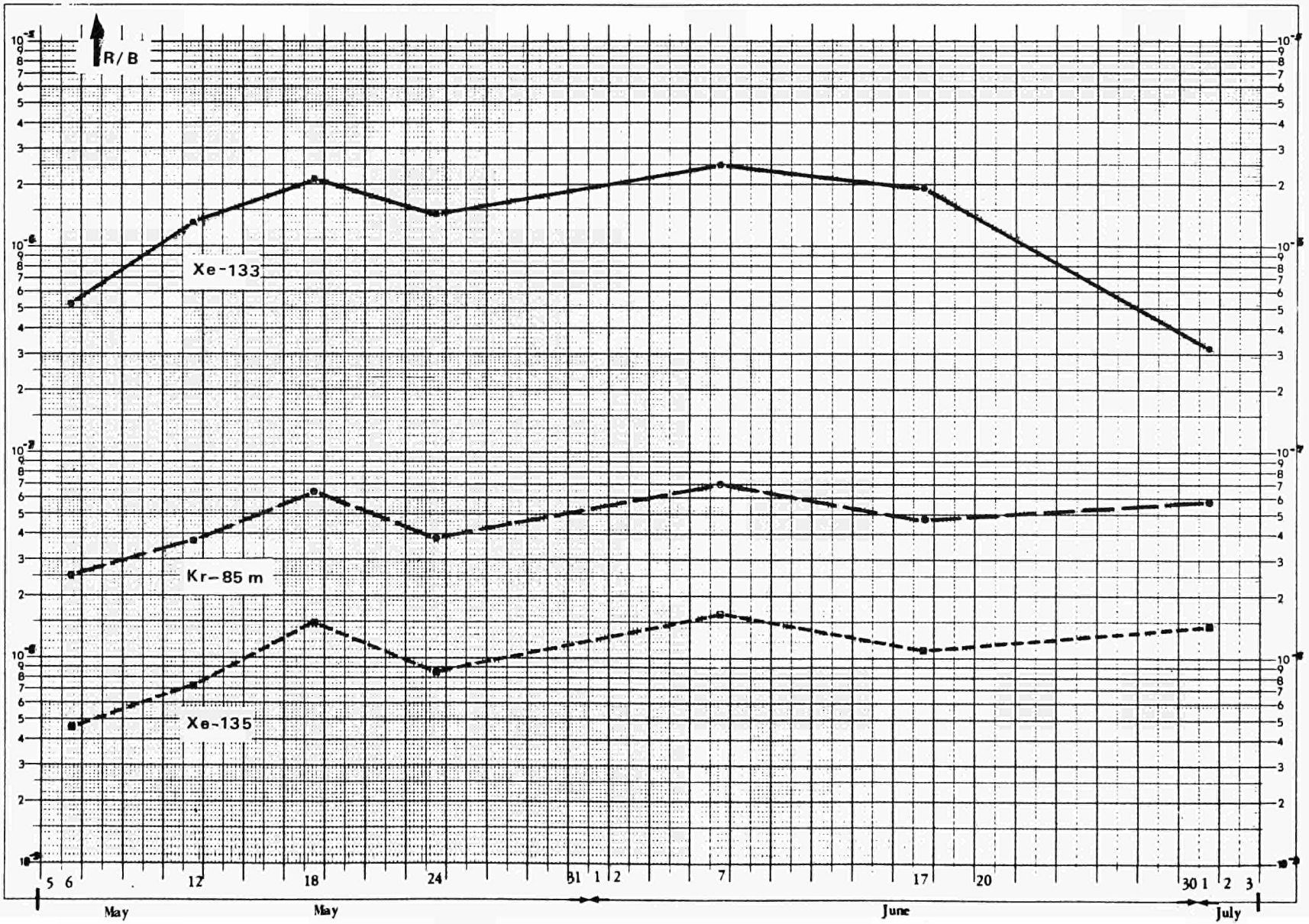

Fig. 19 R/B–values in function of irradiation time

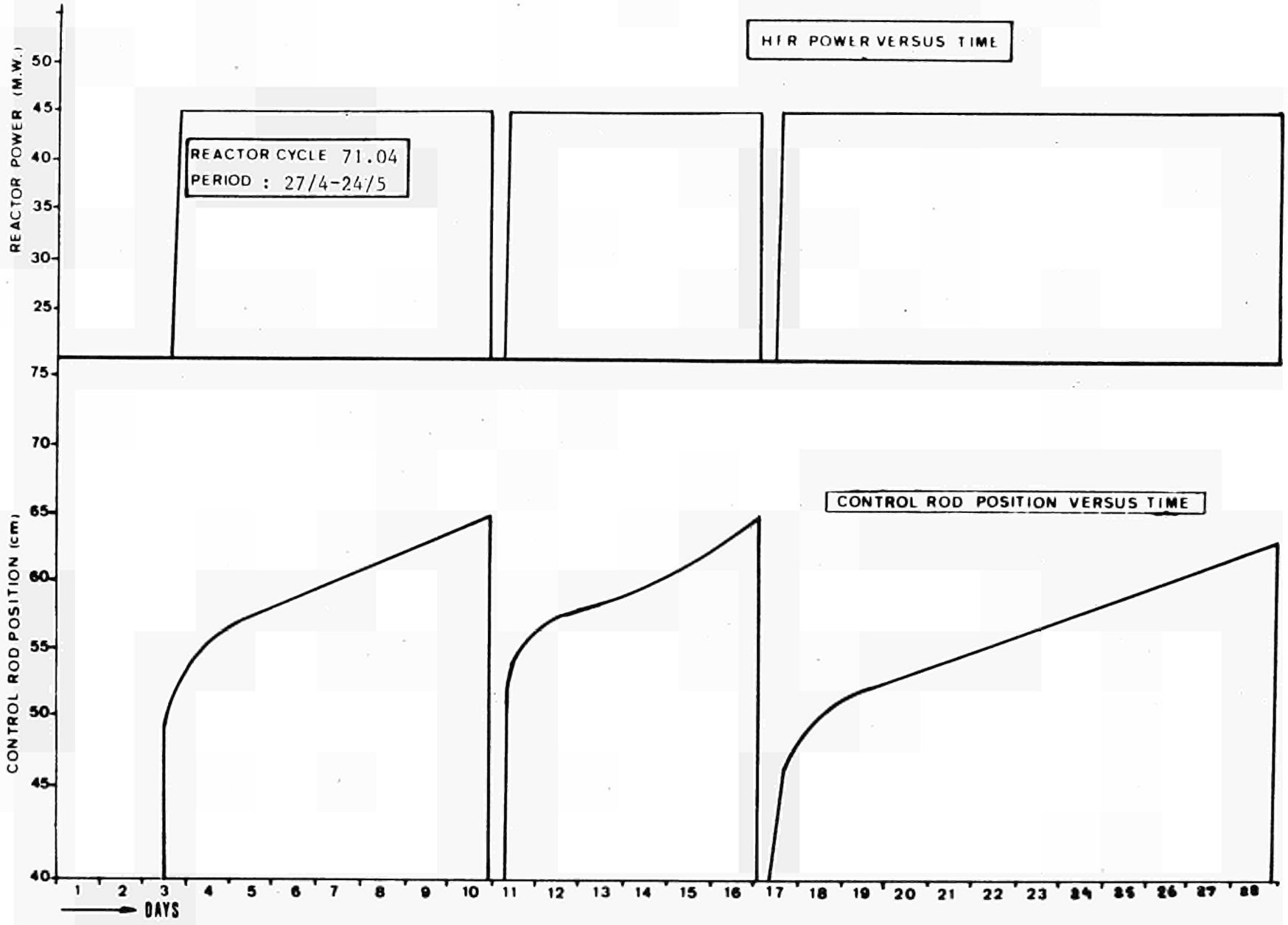

Fig. 20 HFR power and control rod position vs. time. HFR-cycle 71.04

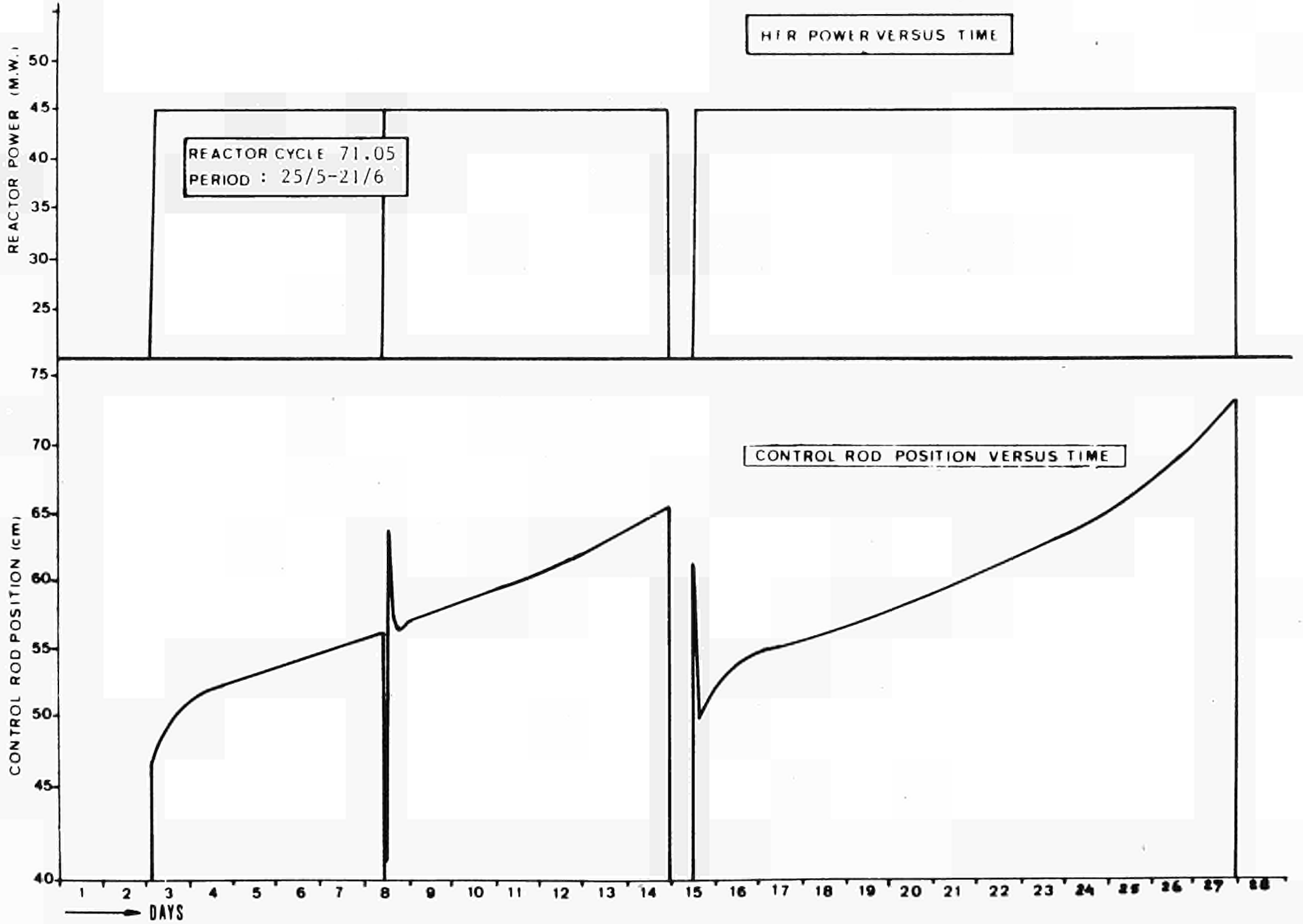

Fig. 21 HFR power and control rod position vs. time. HFR-cycle 71.05

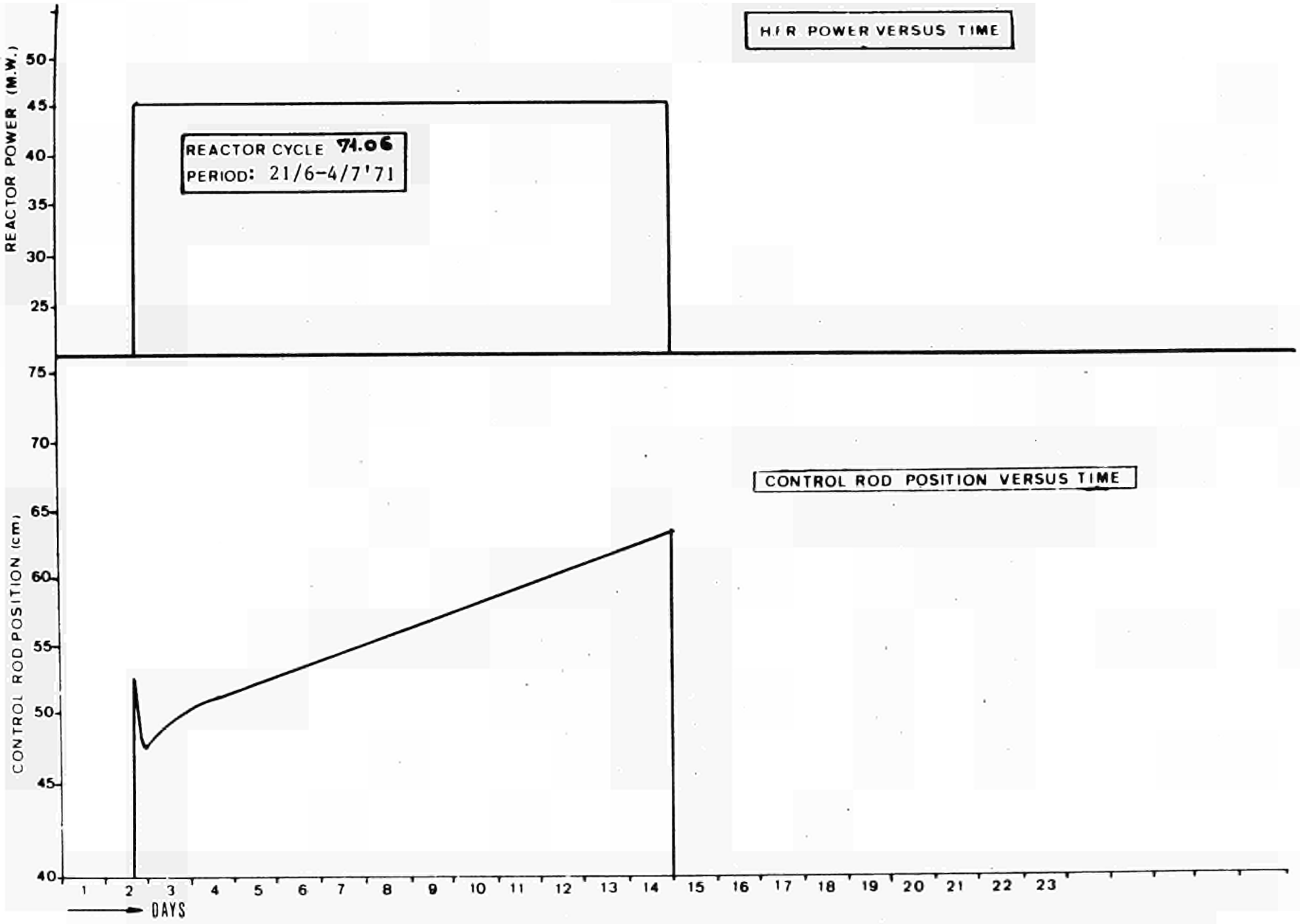

Fig. 22 HFR power and control rod position vs. time. HFR-cycle 71.06

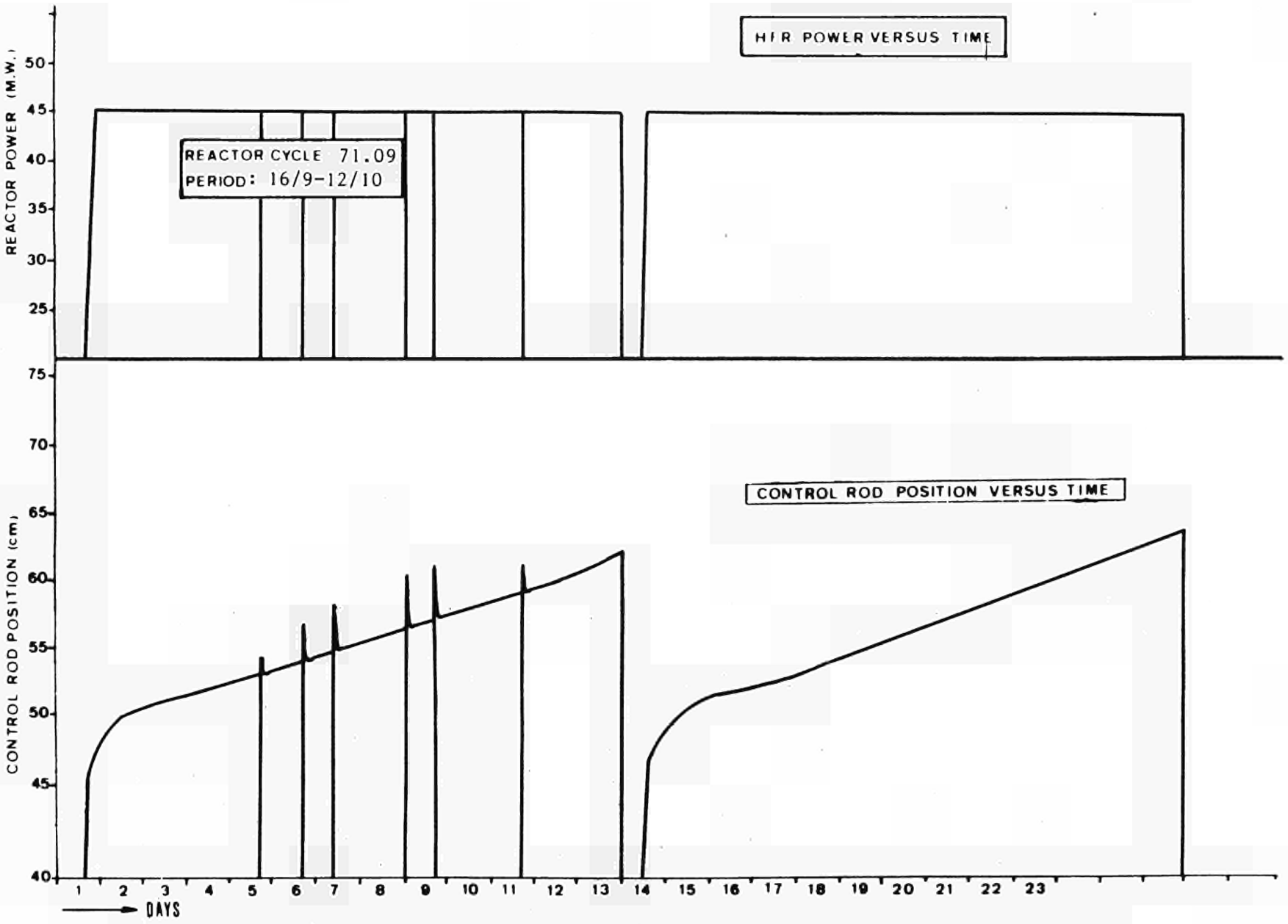

Fig. 23 HFR power and control rod position vs. time. HFR-cycle 71.09

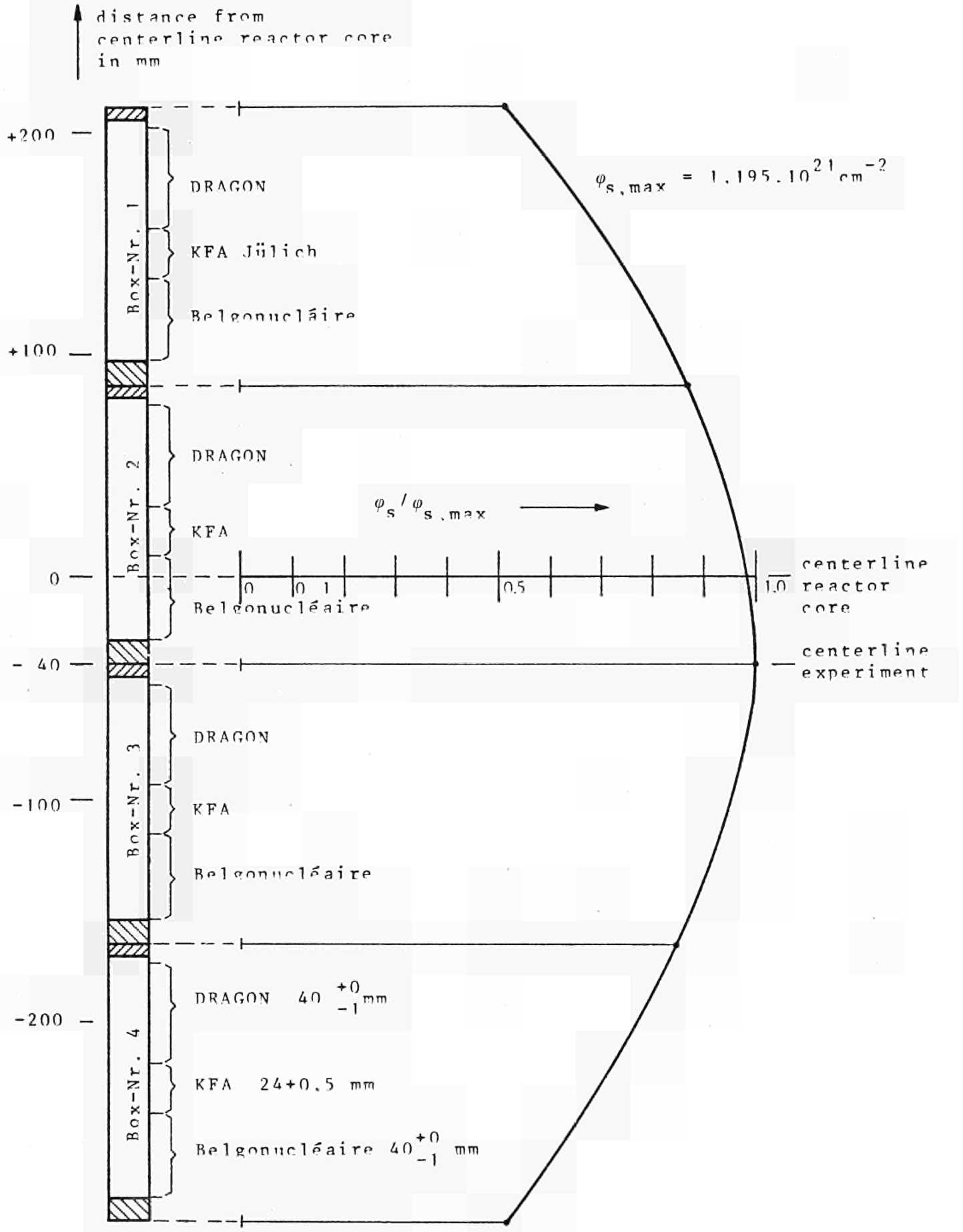

Fig. 24a Relative vertical fast fluence distribution $\varphi_s/\varphi_{s,max}$ ——— in position E3 after 72.4 days of irradiation [Ref. 6]

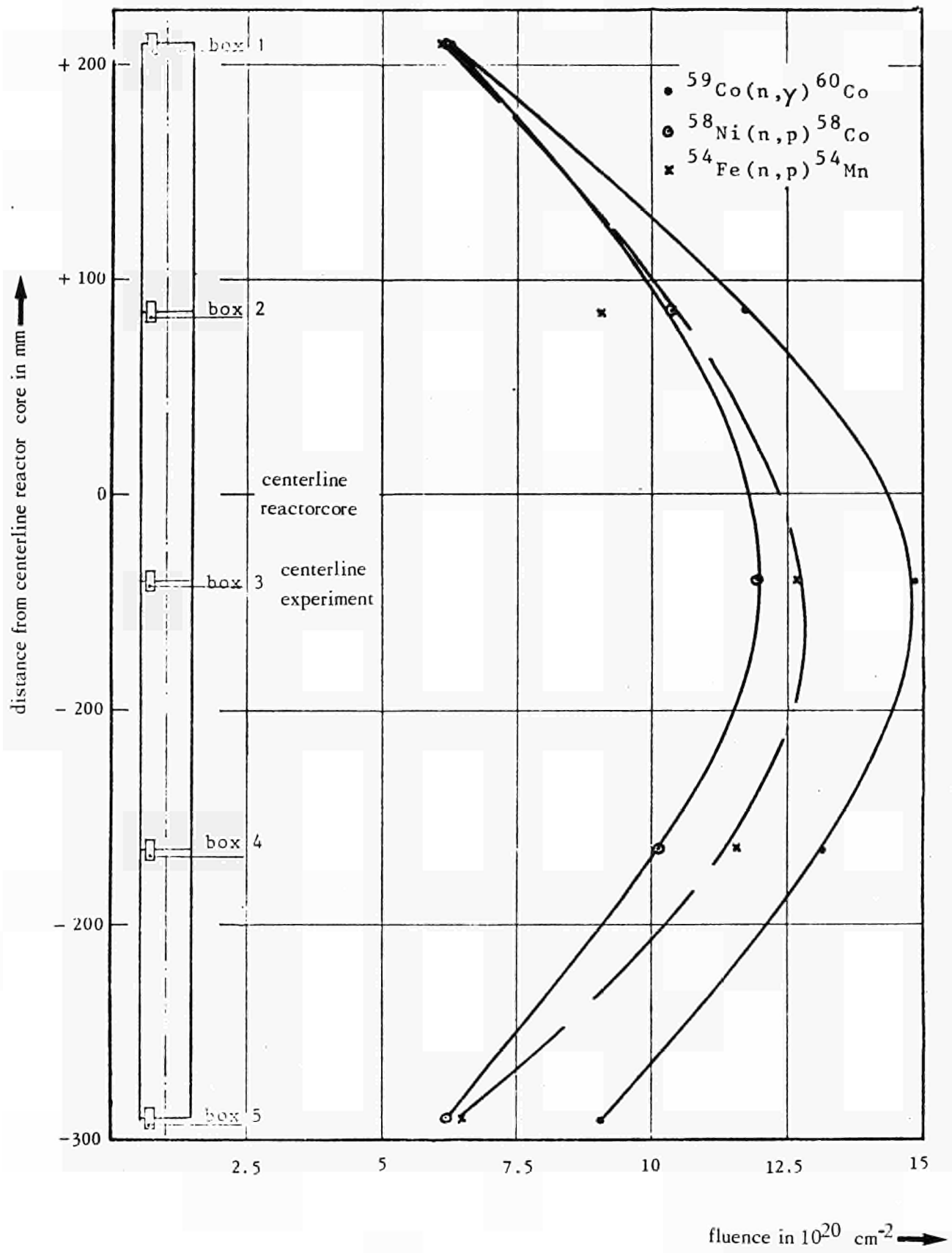

Fig. 24b Vertical thermal and fast fluence distributions measured in experiment E96-1, HFR-position E3, [Ref. 6]

Fig. 25 Bent parts of the minitubes at the bottom of the capsule after removal of the Al-sleeve

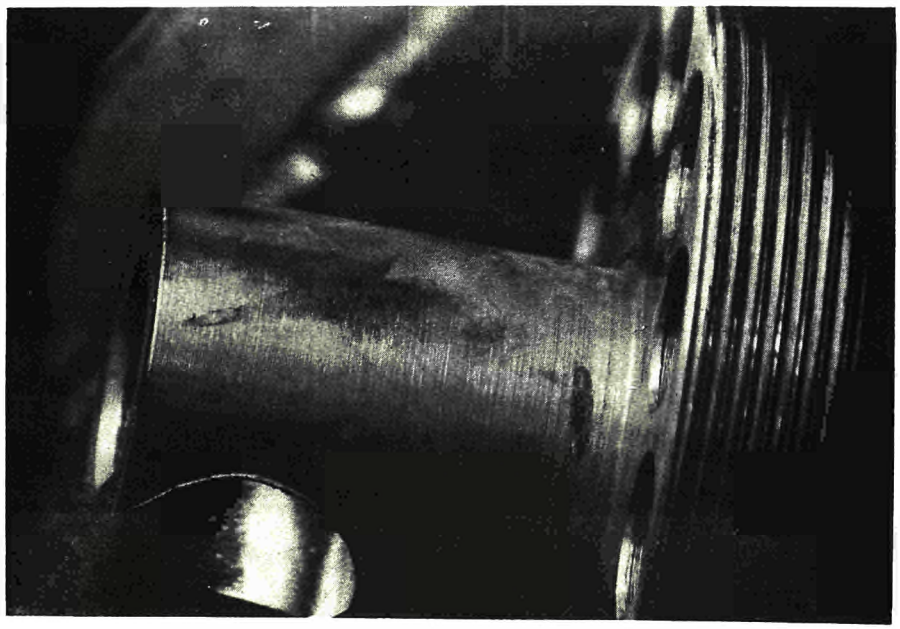

Fig. 26 Frebbing on the outer endplug caused by the bent part of a minitube and by vibration.

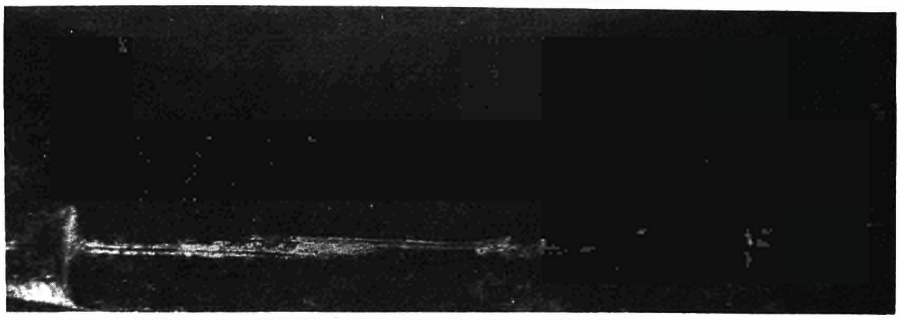

Fig. 27 Partial view. Outer surface of the sample carrier with irregular grey layer

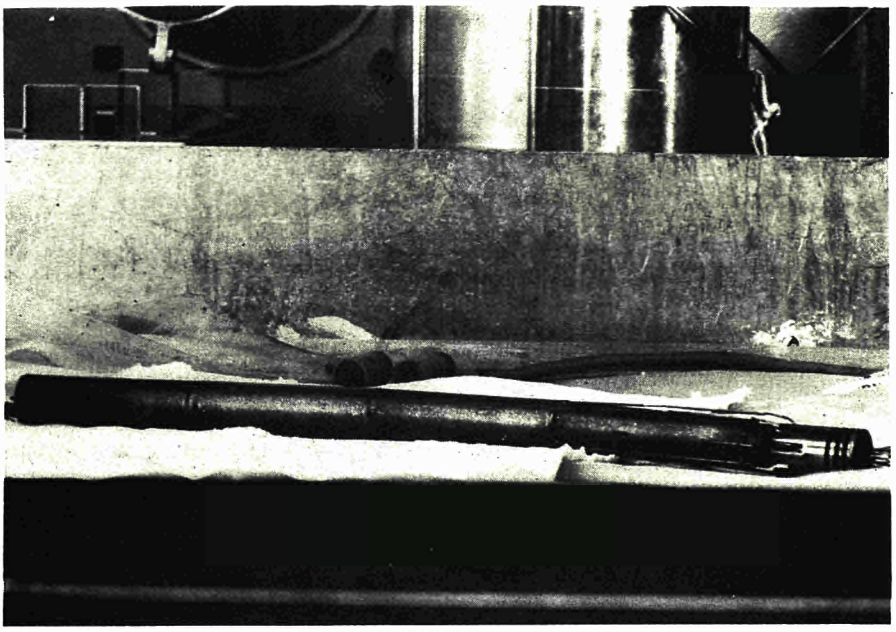

Fig. 28 Recovered graphite boxes without stainless steel tube.

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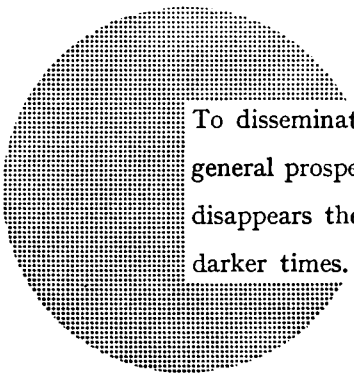

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Alfred Nobel

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