sck cen mol

STUDIECENTRUM VOOR KERNENERGIE

CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

NDA MEASUREMENTS ON SPENT FUEL ASSEMBLIES AT TIHANGE 1 BY MEANS OF THE ION 1/FORK

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June 1986

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Summary. - This report describes field tests performed at Tihange 1 Nuclear Power Station on PWR spent fuel by means of the ION 1-FORK detector.
Two detector systems and three electronics systems were used to investigate the same fuel assemblies with various burn-ups and cooling times.
The purpose of the exercise was to test the performance of the instrument for as well inspection purposes as for fuel management. The results are presented and discussed.

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Samenvatting. - Dit rapport beschrijft experimenten die werden uitgevoerd aan de Nucleaire Centrale van Tihange 1 op PWR brandstof, met behulp van de ION-1-FORK detector.
Twee detectorsystemen en drie electronica systemen werden gebruikt bij het onderzoek van dezelfde brandstofelementen met verschillende burn-up en koeltijd.
Het doel van de oefening was de kwaliteiten van het instrument te testen voor zowel inspektie doeleinden als voor splijtstofbeheer. De resultaten zijn voorgesteld en besproken.

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Résumé. - Ce rapport décrit des expériences faites à la Centrale Nucléaire de Tihange 1 sur des assemblages PWR au moyen du détecteur ION-1-FORK.
Deux systèmes de détection et trois systèmes électroniques ont été utilisés pour examiner les mêmes assemblages de différents taux de combustion et temps de refroidissement.
Le but de cette exercice était de tester la performance de l'instrument pour des raisons d'inspection et de gestion matières. Les résultats sont présentés et discutés.

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ABSTRACT

This report describes field tests performed at Tihange 1 Nuclear Power Station on PWR spent fuel by means of the ION 1-FORK detector.

Two detector systems and three electronics systems were used to investigate the same fuel assemblies with various burn-ups and cooling times.

The purpose of the exercise was to test the performance of the instrument for as well inspection purposes as for fuel management. The results are presented and discussed.

ACKNOWLEDGEMENTS

We greatly appreciate the hospitality of the Tihange Nuclear Power Station that made this experiment possible. We would also like to express our appreciation to the operator's staff for the technical assistance in the manipulation of the irradiated fuel elements.

We also appreciate fruitful discussions with C. Beets.

The experiments were carried out from 6 to 10 may 1985.

TABLE OF CONTENTS

1. INTRODUCTION

The ever increasing use of nuclear fuel for electricity production in the world and the limited capacity of reprocessing possibilities, results in the short and long term storage of spent fuel assemblies. These assemblies represent problems from the safety point of view, for nuclear materials management and for safeguards.

Passive neutron and gross gamma assay of light water reactor spent fuel appears to be a quick and relatively easy way of determining burnup, cooling time and plutonium content from the operator's point of view and permits a verification of these values for the inspector.

With the aim of satisfying the needs of the operator and the demands of the inspectors, a field test of the equipment used at present by the EURATOM Inspectorate and by the IAEA for the verification of LWR fuel assemblies has been taken up in the Belgian Support Programme to the IAEA for safeguards implementation.

The ION 1-FORK detector is a Los Alamos concept and development that was already used for field tests in the past. However several modifications and improvements have been made on the basis of operational experience, and exercises of such size, with two different fork detectors and three electronics systems, combined several possibilities and also made an intercomparison between the different combinations possible.

2. DESCRIPTION OF THE INSTRUMENT

The ION 1-Fork detector was developed in the Los Alamos National Laboratory within the US Technical Support Programme to the IAEA.

The instrument is composed of a fork detector, a 10 m long pipe and an electronic unit, graphically represented in fig. 1 and 2.

The detector is made in polyethylene and composed of two identical cylindrical arms, each of them containing two fission chambers and one ionization chamber. The latter detects gamma rays, while the former (containing approxilately 150 mg ^{235}U each) detects as well thermal neutrons in the bare fission chamber as epithermal neutrons in the cadmium wrapped fission chamber. To make the radiation sensitive devices dismountable, the two arms (of diameter 7.5 cm) are screwed to a stainless stell backplate.

This mode of fabrication was choosen to make a complete water-tight setup which would be simple for decontamination.

The detector is connected to a stainless steel pipe of 4.45 cm diameter and 0.165 cm wall thickness.

This pipe has a twofold purpose namely to let the detector into the storage pool and assure the right positioning around the element, and to keep the system water-tight.

The signal transmission from the detectors to the electronics is achieved by coaxial cables inside the pipe.

The original concept of the ION 1 detection system was modified for the Euratom version in the sense that the standard preamplifier and connection box was replaced by a junction box and the AMPTEK system (integral preamplifier, amplifier-discriminator), that this device was shielded by about 3 cm of lead and housed in a small section of stainless steel piping that was branched in between the feed through flange of the Fork head and the rest of the support pipework.

The IAEA version was also equipped with an AMPTEK device but only 5 mm of lead shielding was used. The AMPTEK box was located together with an ORTEC H242B preamplifier in a 10 cm wide pipe section some 2 meters above the fork detection head. The two cadmium wrapped fission chambers were connected to that device the logic signal of which was led to the IAEA-ION 1-electronics and the analog signal of which was branched to the so called NIM electronics, composed of a fast amplifier, a discriminator and a counter. The whole setup is shown in fig. 3.

Originally the NIM electronics was foreseen to be used in conjunction with the H242B connected to the bare fission chambers. This preamplifier however, broke down after the fork was installed in the pool. Therefore, use was made of the NIM system to duplicate the AMPTEK discriminator. A comparison of the counting rates obtained with both systems would reveal a possible radiation induced change to the threshold of the AMPTEK A111 circuit.

3. EXPERIMENTAL SETUP

The operator's sliding support which is permanently attached to the bridge railing was modified to accommodate the Euratom detector system.

The IAEA system was attached to the wall of the storage pool.

Both fork systems were lowered into the pool using the operator's crane and attached to the respective mounting positions.

All measurements on fuel assemblies using the Euratom system were carried out by moving the FORK to the storage location of the assembly in the pool and measuring it as it was withdrawn from its storage position.

Concerning the IAEA setup, the assembly was completely taken out of its storage position and moved to the detector.

4. DESCRIPTION OF FUEL MATERIAL AND BOUNDARY CONDITIONS

a) The reactor no. 1 at Tihange was started up in 1975 and has an electrical power capacity of 870 MW (thermal power 2652 MW).

b) All the fuel assemblies are of the 15 x 15 matrix with 204 fuel rods per assembly.

c) The active length of an assembly is 3.66 m and the fuel cladding is made of zircalloy (Zr4).

d) The core consists of 157 fuel assemblies.

e) The fuel is uranium dioxide in the form of pellets.

f) The assemblies made available by the operator were of six different initial enrichments in ^{235}U varying from 1.95 % to 3.3 %.

g) The assemblies have declared average exposures (burn-ups) ranging from 9661 MWd/tU to 41167 MWd/tU.

h) The cooling time of the assemblies ranged from 36 to 3141 days.

i) The assemblies followed either 1, 2, 3 or 4 cycles in the reactor and all were continuous except for cycle combination Nos. 1, 2 (see fig. 4).

j) None of the assemblies measured contained gadolinium rods or have had fuel pins removed for post irradiation examination.

k) All the operator information on the fuel assemblies is given in table 1.

l) The irradiation histories relevant to the fuel cycles followed by the assemblies are shown in Fig. 4.

m) The boron concentration measured by the operator during the measurement campaign was 2075 p.p.m.

n) The temperature of the water in the pool at the storage rack level was 36°C.

TABLE 1 : Operator information of spent fuel

FUEL N°	ASS Id	N° OF CYCLES	EXPOSURE (MWd/tU)	IRRADIATION HISTORY	COOLING TIME (DAYS)	INTIAL ^{235}U ENRICHMENT (%)	TOTAL PLUTONIUM (kg)
1	A13	1	12493	1000	3141	1.95	2.525
2	A37	1	13093	1000	3141	1.95	2.592
3	A16	1	15475	1000	3141	1.95	2.873
4	B16	1	14105	1000	3141	2.55	2.797
5	B12	1	15401	1000	3141	2.55	2.948
6	C43	1	9661	1000	3141	3.10	1.930
7	C49	1	10452	1000	3141	3.10	2.051
8	C17	1	12156	1000	3141	3.10	2.296
9	C06	1	13828	1000	3141	3.10	2.508
10	C46	2	21689	1200	2671	3.10	3.307
11	C35	2	22143	1200	2671	3.10	3.339
12	C44	2	22246	1200	2671	3.10	3.353
13	H51	3	31175	5670	803	3.10	3.834
14	H44	3	34703	5670	803	3.10	4.037
15	H32	3	35916	5670	803	3.10	4.100
16	H12	4	41167	5678	431	3.10	4.336
17	D43	3	35124	2340	1852	3.20	4.423
18	E33	1	11695	3000	2307	3.30	2.194
19	G03	4	41016	4567	803	3.30	4.769
20	J11	2	17068	8900	36	3.30	2.656

5. MEASUREMENT RESULTS

Most of the measurements on the assemblies were made by both systems. The counting times used for the measurements were typically 100 seconds for the IAEA system and 60 seconds or 10000 counts in the neutron channel for the Euratom system.

The measurements made during the campaign were as follows :

a) Background

The Euratom FORK was suspended about 0.5 m above the top of the storage rack in the pool during all the measurements. The background at this level was typically between 1 and 4 relative gamma counts and 0.05 ± 0.03 neutrons per second. The IAEA FORK was always kept in the same position about 1 m above the level of the storage rack but in an area at the side of the pool away from the storage rack. The background at this location was typically zero neutrons and 0.03 relative gamma counts.

b) Axial Scans

Axial Scans were performed on 3 different assemblies as laid down in Ref. 1. The IAEA system measured up to 9 positions either side of the mid position of an assembly in steps of aproximately 20 cm. The Euratom system measured 10 positions along the length of an assembly of approximately 33 cm steps. The assemblies measured were Nos. A13, H44 and G03. The results are recorded in table 2. The positioning of the FORK detector around the assemblies during all measurements is described in Fig. 2. The relative positions of axial measurements for the two systems are shown in Fig. 5. The arrows in the figure indicate the positions chosen by the two systems for the single mid point measurements on all the other assemblies.

Table 2 : scanning of the assemblies A13, G03 and H44

Ass. Id	N° of meas.	EURATOM ION-1		IAEA ION-1		IAEA - NIM
		GAMMAS	NEUTRON COUNT RATE (n/s)	GAMMAS	NEUTRON COUNT RATE (n/s)	NEUTRON COUNT RATE (n/s)
A13	1	66.8	7.4			
	2	95.5	18.0	61.2	6.2	5.8
	3	100.0	27.0	80.3	12.7	11.9
	4	107.3	27.7	91.7	17.1	16.2
	5	101.1	29.5	94.7	23.7	22.5
	6	106.9	26.8	96.4	25.5	24.5
	7	102.0	28.5	99.2	22.4	21.4
	8	99.1	21.7	98.8	25.0	23.9
	9	87.7	17.5	96.9	25.9	25.1
	10	62.2	5.7	96.7	23.7	23.1
	11			95.9	23.3	22.3
	12			94.7	24.8	23.9
	13			92.4	22.3	21.3
	14			91.6	18.9	18.0
	15			84.2	16.4	15.7
	16			72.3	10.9	10.5
	17			56.8	4.1	3.6
	18					0.9
G03	1	985.8	680.0	514.0	167.0	168.3
	2	1213.0	1078.0	925.0	584.0	595.6
	3	1278.0	1255.0	1118.0	915.0	939.2
	4	1263.0	1206.0	1158.0	1002.0	1024.1
	5	1293.0	1291.0	1200.0	1126.0	1148.3
	6	1273.0	1241.0	1208.0	1137.0	1162.5
	7	1305.0	1335.0	1190.0	1097.0	1109.4
	8	1270.0	1235.0	1210.0	1145.0	1165.4
	9	1283.0	1261.0	1218.0	1178.0	1173.7
	10	935.0	581.0	1203.0	1134.0	1148.1
	11			1218.0	1176.0	1174.1
	12			1228.0	1195.0	1219.3
	13			1220.0	1173.0	1180.5
	14			1203.0	1139.0	1169.0
	15			1203.0	1150.0	1168.2
	16			1125.0	969.0	978.9
	17			910.0	577.0	579.1
	18			910.0	576.0	150.6

Table 2 : scanning of the assemblies A13, G03 and H44

Ass. Id	N° of meas.	EURATOM ION-1		IAEA ION-1		IAEA - NIM
		GAMMAS	NEUTRON COUNT RATE (n/s)	GAMMAS	NEUTRON COUNT RATE (n/s)	NEUTRON COUNT RATE (n/s)
H44	1	825.8	373.9	428.1	92.1	98.9
	2	993.3	597.3	760.0	311.1	333.6
	3	1036.0	677.8	915.0	489.6	526.0
	4	1018.0	663.4	947.5	556.1	596.7
	5	1033.0	689.9	985.0	601.2	646.7
	6	1018.0	674.8	990.0	609.5	656.5
	7	1041.0	701.6	970.0	602.2	647.7
	8	1016.0	682.8	990.0	617.1	662.6
	9	1016.0	656.1	990.0	622.0	671.3
	10	753.0	317.5	980.0	617.3	662.3
	11			985.0	625.9	669.8
	12			995.0	633.8	681.2
	13			1013.0	633.0	681.1
	14			980.0	625.8	671.7
	15			982.5	614.4	659.5
	16			915.0	515.8	552.3
	17			720.0	300.8	320.7
	18			361.9	70.3	74.4

c) Reproducibility

One fuel assembly, no. G03, was chosen for making repetitive measurements on. The assembly was measured 22 times by the IAEA system and 13 times by the Euratom system over the 3 days.

Another check was made comparing the normalized neutron and gamma emission rate, measured independently for the same assemblies with two systems in mid point position.

d) Mid point measurement

Measurements were made at the mid point position on all 20 assemblies using the Euratom system and the IAEA systems.

All the measurement results are recorded in table 3.

Table 3 : Measurement data

Fuel N°	Ass Id	EURATOM ION-1		IAEA ION-1		IAEA - NIM
		GAMMAS	NEUTORN COUNT RATE (n/s)	GAMMAS	NEUTRON COUNT RATE (n/s)	NEUTRON COUNT RATE (n/s)
1	A13	105.7	27.09	96.7	23.88	22.80
2	A37	111.0	29.88	103.1	28.60	27.71
3	A16	141.2	62.36	130.5	59.33	61.38
4	B16	122.8	28.71	114.7	27.62	26.98
5	B12	133.1	36.85	125.2	35.31	35.63
6	C43	79.7	7.14	73.4	5.96	6.12
7	C49	87.3	7.64	79.1	7.37	7.59
8	C17	104.9	13.50	92.2	12.28	11.96
9	C06	116.9	19.91	109.1	17.57	17.95
10	C46	197.6	83.53	192.5	88.13	85.95
11	C35	201.4	91.18	187.5	82.52	89.93
12	C44	206.6	102.44	189.7	92.28	95.05
13	H51	904.1	486.90	846.3	422.10	454.27
14	H44	1012.8	670.73	982.5	620.80	666.98
15	H32	1056.0	773.23	997.5	700.65	750.97
16	H12	1915.0	1413.00	1815.0	1269.33	1379.89
17	D43	495.9	620.60	459.7	575.30	600.66
18	E33	104.0	6.76	89.0	5.76	6.12
19	G03	1267.1	1247.85	1219.0	1164.00	1149.22
20	J11	-	194.30	-	139.40	-

6. DATA EVALUATION

A. Axial Scans

The reasons for measuring the fuel assemblies at various positions along their axial length are the following.

a) Establish that a flat region along the burn-up profile exists.

b) As a result of the scan the mid position can be chosen for the single point measurements on all the other assemblies.

c) Investigate the characteristics associated with the relative build-ups of fission products and actinides along the axis of an assembly.

A programme written for the EPSON HX20 was used for the evaluation of the scan data. The neutron and gamma results for each assembly as measured using the three electronic systems were used to produce axial profiles. The profiles are shown in Figs. 6, 7 and 8. The neutron and gamma results are normalised to values at the axial position giving the most efficient neutron response.

As can be seen from the plots the gamma data varies relatively linearly with burn-up as compared to the neutron production. The relative build-ups of the fission products and actinides along the axis of an assembly are uniform as can also be seen in Figs. 6, 7 and 8. The correlation between the gamma and neutron data takes the form of a power function.

The data was fitted to a linear function by taking logarithms. The fitted function was

$\text{Log } N = \text{Log } a + b \text{ Log } \gamma$ where N = Neutrons

γ = gamma

n is number of data pairs, a and b are constants, r^2 is coefficient of determination. The results of the combination of measurements are given in Table 4.

Table 4

Fuel Assembly	Declared burn-up (MWd/tU)	No. of cycles	Measurement system	Fitting Parameters			
				a	b	r^2	n
A13	12493	1	Euratom	-10.59	2.99	0.982	10
			IAEA (ION-1)	-11.39	3.19	0.982	15
			IAEA (NIM)	-11.16	3.13	0.983	16
G03	41016	4	Euratom	-10.19	2.42	0.999	10
			IAEA (ION-1)	-10.97	2.54	0.999	19
			IAEA (NIM)	-10.40	2.46	0.994	18
H44	34703	3	Euratom	-11.04	2.53	0.996	10
			IAEA (ION-1)	- 8.87	2.22	0.998	18
			IAEA (NIM)	- 8.86	2.23	0.999	18

The coefficient b is assumed to be a characteristic constant for a given type of fuel assembly and reactor but more research has to be made in this field.

The gamma response is approximately linearly related to the burn-up. The gamma results can therefore be used to estimate the ratio between the average burn-up along the axial length of the assembly (as declared by the operator) and the expected burn-up at the mid position, to be used for the measurement on all the assemblies. This was carried out and the ratios for the combination of measurements are shown in Talbe 5.

Table 5

Assembly No.	Ratio of declared burn-up (MID/Average)		
	Euratom	IAEA (ION-1)	IAEA (NIM)
A13	1.15	1.10	1.10
G03	1.05	1.10	1.10
H44	1.04	1.11	1.11

A better estimate was possible using the IAEA data as many more measurement points were taken, 18 as opposed to 10 for the Euratom system. The ratio of 1.10 was therefore considered for subsequent evaluation of the single, mid point data on all the assemblies.

B. Reproducibility

Assembly no. G03 was measured several times during the measurement campaign. The results over the 3 days are graphically represented in Figs. 9 and 10. Both measurement systems proved to be very stable over the campaign. The IAEA ION-1 system suggested to give slightly better reproducibility over the Euratom system considering that the IAEA system was in a fixed position during the measurements ,as was not the case for the Euratom system.

The average results with the absolute and relative standard deviations are given in Table 6 for the systems.

Table 6

Measurement system	$\bar{N}$	σN	$(\frac{\sigma N}{N})$ x 100	$\bar{\gamma}$	$\sigma\gamma$	$(\frac{\sigma\gamma}{\gamma})$ x 100	n
Euratom ION-1	1246.5	15.4	1.23	1267.5	11.4	0.90	13
IAEA ION-1	1149.2	13.4	1.17	1212.5	9.8	0.81	22
IAEA NIM	1197.0	42.6	3.55	-	-	-	14

The results, of all neutron and gamma measurements made on all the assemblies at the respective mid point positions (table 3), show that both FORK systems were consistent over all the measurements.

C. Mid Point Neutron Data

The standard procedure for neutron data evaluation is to correlate the neutron responses against the respective declared burn-up of the assemblies. For PWR fuel assemblies with exposures greater than 15000 MWd/tU the principal neutron sources are ^{242}Cm and ^{244}Cm. If the assemblies have been cooled longer than 2 years the majority of the neutrons originate from the ^{244}Cm. The neutron response is therefore normally assumed to be ^{244}Cm and the neutron data in Table 3 are corrected for decay to the date of discharge of the assembly.

The error analysis of the ION-1 for the neutron data is based on counting statistics and is therefore much lower than the error found due to the scatter. An error of 2.5 % (2σ from reproducibility measurements) was attributed to all the neutron data for purpose of data evaluation. The declared average burn-up values were increased by 10 % to account for the expected burn-up at the mid position and a 5 % error uncertainty attributed to them.

The data was fitted to a weighted least-squares routine (Deming technique ref.3) to the function

$R = aE^b$ where R is corrected neutron count rate
E is the operator declared exposure (+ 10 %)
and a and b are constants.

The resulting coefficients using the two FORK heads and three electronic systems are given in table 7a for 20 data points where available and in table 7b for the 19 data points in all cases; the correlations are shown in fig. 11a, b for 20 data points and 11c, d, e for 19 data points.

Table 7a

COEFFICIENTS	EURATOM ION-1	IAEA ION-1
a	5.86 E-13	4.51 E-13
b	3.302	3.317
σa	1.25 E-12	8.18 E-13
σb	0.215	0.182
Cov ab	-2.69 E-13	-1.48 E-13
r^2	0.99	0.99

Table 7b

COEFFICIENTS	EURATOM ION-1	IAEA ION-1	IAEA NIM
a	3.55 E-13	3.18 E-13	2.01 E-13
b	3.344	3.347	3.395
σa	5.25 E-13	4.83 E-13	2.96 E-13
σb	0.148	0.152	0.147
Cov ab	-7.74 E-14	-7.32 E-14	-4.36 E-14
r^2	0.99	0.99	0.99

The results of using the coefficients in the inverse of the fitted functions to predict the exposures are given in tables 8a and 8b, for 20 data points where available, resp. 19 data points (element J11 has been omitted).

Table 8a

Fuel n°	Ass. Id.	Initial Enrich. % ^{235}U	Declared exposure (MWd/tU)	Calculated exposure from fitted functions		Residuals % of declared exposures	
				EUR ION-1	IAEA ION-1	EUR ION-1	IAEA ION-1
1	A13	1.95	13742	15218	15146	10.75	10.22
2	A37	1.95	14402	15676	15993	8.85	11.05
3	A16	1.95	17023	19589	19928	15.08	17.07
4	B16	2.55	15516	15488	15826	- 0.18	2.00
5	B12	2.55	16941	16704	17042	- 1.40	0.60
6	C43	3.10	10627	10159	9966	- 3.90	- 6.21
7	C49	3.10	11497	10371	10625	- 9.78	- 7.58
8	C17	3.10	13372	12324	12395	- 7.83	- 7.30
9	C06	3.10	15211	13861	13808	- 8.87	- 9.22
10	C46	3.10	23858	21085	22121	-11.62	- 7.27
11	C35	3.10	24357	21652	21687	-11.10	-10.96
12	C44	3.10	24471	22429	22430	- 8.34	- 8.33
13	H51	3.10	34293	33895	33441	- 1.15	- 2.48
14	H44	3.10	38173	37349	37566	- 2.15	- 1.59
15	H32	3.10	39508	38993	38961	- 1.30	- 1.38
16	H12	3.10	45284	46250	46055	2.14	1.71
17	D43	3.20	38636	37721	37956	- 2.36	- 1.76
18	E33	3.30	12865	9733	9611	-24.34	-25.20
19	G03	3.30	45118	45075	45404	- 0.09	0.64
20	J11	3.30	18775	25045	23373	33.40	24.50

Table 8b

Fuel n°	Ass. Id.	Initial Enrich. % ^{235}U	Declared exposure (MWd/tU)	Calculated exposure from fitted functions			Residuals % of declared exposures		
				EUR ION-1	IAEA ION-1	IAEA NIM	EUR ION-1	IAEA ION-1	IAEA NIM
1	A13	1.95	13742	15641	15440	15190	13.82	12.36	10.54
2	A37	1.95	14402	16105	16295	16104	11.83	13.15	11.82
3	A16	1.95	17023	20069	20265	20355	17.90	19.05	19.58
4	B16	2.55	15516	15915	16126	15977	2.58	3.94	2.98
5	B12	2.55	16941	17147	17354	17342	1.23	2.44	2.37
6	C43	3.10	10627	10496	10197	10322	- 1.23	- 4.04	- 2.86
7	C49	3.10	11497	10711	10865	10997	- 6.82	- 5.49	- 4.35
8	C17	3.10	13372	12701	12658	12572	- 5.01	- 5.34	- 5.98
9	C06	3.10	15211	14263	14087	14170	- 6.22	- 7.38	- 6.84
10	C46	3.10	23858	21581	22475	22152	- 9.54	- 5.79	- 7.14
11	C35	3.10	24357	22154	22037	22450	- 9.04	- 9.52	- 7.83
12	C44	3.10	24471	22939	22786	22819	- 6.25	- 6.88	- 6.75
13	H51	3.10	34293	34485	33852	34150	0.56	- 1.28	- 0.41
14	H44	3.10	38173	37951	37987	38240	- 0.58	- 0.48	0.18
15	H32	3.10	39508	39600	39386	39600	0.24	- 0.30	0.24
16	H12	3.10	45284	46869	46488	46826	3.50	2.66	3.41
17	D43	3.20	38636	38325	38378	38304	- 0.80	- 0.66	- 0.85
18	E33	3.30	12865	10060	9836	10061	-21.80	-23.54	-21.79
19	G03	3.30	45118	45694	45836	44888	1.28	1.60	- 0.51

In this consistency check, most of the predicted values are within 10 % of the declared values. Two parameters influence the large spread in the data. The first being the contribution of ^{242}Cm which can clearly be seen in the case of the short cooled assembly No. J11 (measurement No. 20). There is also a contribution from ^{242}Cm and the Plutonium isotopes for the low burn-up assemblies (lower than 15000 MWd/tU). The second parameter is the different initial enrichments amongst the fuel assemblies. Neutron emission increases with decreasing initial enrichment (ref. 2).

The operator-declared values of plutonium can also be correlated against the neutron response. A weighted least-squares fitting was applied similar to that for the burn-up as follows.

$N = aP^b$ where N is corrected neutrons rate (n/s)
P is total plutonium (kg)

a and b are constants.

The coefficients that were obtained for the different measurement systems are given in Tables 9a and 9b.

Table 9a

COEFFICIENTS	EURATOM ION-1	IAEA ION-1
a	1.719 E-1	1.374 E-1
b	5.873	5.963
σa	1.136 E-1	7.316 E-2
σb	0.579	0.466
Cov ab	-6.393 E-2	-3.320 E-2
r^2	0.86	0.88

Table 9b

COEFFICIENTS	EURATOM ION-1	IAEA ION-1	IAEA NIM
a	1.121 E-1	9.804 E-2	9.438 E-2
b	6.130	6.160	6.228
σa	3.674 E-2	3.053 E-2	3.064 E-2
σb	0.285	0.268	0.282
Cov ab	-1.019 E-2	-7.961 E-3	-8.413 E-3
r^2	0.86	0.88	0.84

The correlation between total Plutonium and Neutron response is shown in Fig. 12a, b, c, d, e.

The neutron responses were re-introduced into the fitted functions to obtain the predicted values of total plutonium. The results are given in Tables 10a and 10b.

Table 10a

Fuel n°	Ass. Id.	Initial Enrich. % ^{235}U	Declared Total Plutonium (kg)	Calculated Pu-content from fitted functions		Residuals % of declared Pu-content	
				EUR ION-1	IAEA ION-1	EUR ION-1	IAEA ION-1
1	A13	1.95	2.525	2.504	2.510	- 0.84	- 0.59
2	A37	1.95	2.592	2.546	2.587	- 1.78	- 0.19
3	A16	1.95	2.873	2.885	2.924	0.44	1.77
4	B16	2.55	2.797	2.528	2.572	- 9.60	- 8.04
5	B12	2.55	2.948	2.638	2.680	-10.50	- 9.08
6	C43	3.10	1.930	1.995	1.989	3.36	3.04
7	C49	3.10	2.051	2.018	2.061	- 1.60	0.48
8	C17	3.10	2.296	2.224	2.245	- 3.15	- 2.21
9	C06	3.10	2.508	2.376	2.384	- 5.27	- 4.94
10	C46	3.10	3.307	3.007	3.099	- 9.03	- 6.27
11	C35	3.10	3.339	3.053	3.065	- 8.57	- 8.21
12	C44	3.10	3.353	3.114	3.123	- 7.13	- 6.87
13	H51	3.10	3.834	3.927	3.900	2.44	1.71
14	H44	3.10	4.037	4.147	4.160	2.74	3.06
15	H32	3.10	4.100	4.249	4.245	3.64	3.55
16	H12	3.10	4.336	4.677	4.660	7.87	7.47
17	D43	3.20	4.423	4.171	4.184	- 5.70	- 5.39
18	E33	3.30	2.194	1.947	1.949	-11.24	-11.17
19	G03	3.30	4.769	4.610	4.623	- 3.30	- 3.06
20	J11*	3.30	2.656	3.313	3.195	24.74	20.30

* Very short cooled assembly (High contribution from ^{242}Cm)

Table 10b

Fuel n°	Ass. Id.	Initial Enrich. % ^{235}U	Declared Total Plutonium (kg)	Calculated Pu-content from fitted functions			Residuals % of declared Pu-content		
				EUR ION-1	IAEA ION-1	IAEA NIM	EUR ION-1	IAEA ION-1	IAEA NIM
1	A13	1.95	2.525	2.583	2.570	2.543	2.31	1.79	0.72
2	A37	1.95	2.592	2.625	2.646	2.625	1.27	2.11	1.29
3	A16	1.95	2.873	2.959	2.979	2.983	3.01	3.71	3.83
4	B16	2.55	2.797	2.608	2.632	2.614	- 6.76	- 5.91	- 6.53
5	B12	2.55	2.948	2.716	2.739	2.734	- 7.86	- 7.10	- 7.27
6	C43	3.10	1.930	2.078	2.051	2.060	7.67	6.30	6.75
7	C49	3.10	2.051	2.101	2.123	2.132	2.45	3.54	3.98
8	C17	3.10	2.296	2.306	2.307	2.294	0.43	0.49	- 0.09
9	C06	3.10	2.508	2.456	2.455	2.449	- 2.05	- 2.50	- 2.37
10	C46	3.10	3.307	3.079	3.152	3.124	- 6.86	- 4.66	- 5.51
11	C35	3.10	3.339	3.123	3.118	3.147	- 6.45	- 6.61	- 5.76
12	C44	3.10	3.353	3.183	3.175	3.175	- 5.06	- 5.30	- 5.32
13	H51	3.10	3.834	3.976	3.937	3.955	3.71	2.70	3.16
14	H44	3.10	4.037	4.189	4.192	4.206	3.78	3.83	4.20
15	H32	3.10	4.100	4.288	4.275	4.287	4.58	4.27	4.57
16	H12	3.10	4.336	4.701	4.678	4.697	8.41	7.89	8.34
17	D43	3.20	4.423	4.212	4.215	4.210	- 4.77	- 4.70	- 4.80
18	E33	3.30	2.194	2.030	2.012	2.032	- 7.45	- 8.30	- 7.40
19	G03	3.30	4.769	4.636	4.642	4.590	- 2.79	- 2.66	- 3.74

As can be seen from the results the errors between the predicted and the declared plutonium are generally lower than those shown in Tables 8a and 8b for exposure. For a small range in Plutonium concentration the ^{244}Cm concentration changes by several orders of magnitude thus large variations in the measured neutron count rates result in relatively small variations in plutonium concentration. The short cooled assembly J11 however is a very noticeable outlier due to the large contribution from ^{242}Cm.

The errors in the plutonium and burn-up correlations against the neutron response are still very large. The achievable errors are normally in the region of ± 3 to 5 %.

Up until now there has not been the possibility to account for the ^{242}Cm and other plutonium isotopic contributions to the total neutron emission of spent fuel assemblies. This is especially the case for interrupted cycles and unusual power histories.

A programme developed for the HP85 computer (within a research contract between the IAEA and the Nuclear Power Plant Research Institute Jaslovskê Bohunice (CSSR)) for the WWER/440 light water reactor is used to correct the data.

The characteristics of the USSR-designed WWER/440 Reactor are as follows :

- Electrical power = 440 MW
- Thermal power = 1375 MW
- No. of Fuel Assemblies in core = 349
- No. of Fuel rods in an assembly = 126
- Active length of an assembly = 2.5 m
- Initial Enrichments of fuel are 1.6, 2.4, 3.6 % ^{235}U
- Fuel in UO_2 pellets
- Cladding is zircalloy

The comparison of this reactor to Tihange 1 is not perfect but it is expected that the ^{244}Cm factors produced would be of the same order. There is an ISPO task underway for the creation of such a programme specifically for the Westinghouse design reactors. The irradiation history concerning power days and non power and cooling days as in Fig. 4 are used as input to the programme. By using different power ratings the contribution of ^{244}Cm can be calculated for different burn-ups related to the initial enrichments of the WWER/440 reactor fuel.

A normalization of the initial enrichments to an arbitrary reference value of 3.1 % has been made with the same programme.

From the output, factors for the ^{244}Cm contribution were calculated for the 20 assemblies measured at Tihange. These factors are given in Table 11a and 11b as well as the normalization values. The factors were applied to the neutron data and the correlation against the burn-up was remade as previously explained. The resulting coefficients are given in Table 12. Again the corrected neutron response was used with the fitted functions to predict the burn-ups. The results are listed in Tables 11a and 11b and the correlation is graphically given in Fig. 13a, b and fig. 13c, d, e.

Table 11a

Fuel N°	Ass. Id	Initial enrich. % ^{235}U	Factor for ^{244}Cm yields	Factor for init. enrichm.	Declared* exposures MWd/tU	Calculated exposure from fitting using		Residuals % of declared exposures	
						EUR ION-1	IAEA ION-1	EUR ION-1	IAEA ION-1
1	A13	1.95	0.79	0.37	13742	13247	13186	- 3.60	- 4.04
2	A37	1.95	0.82	0.39	14402	13810	14036	- 4.10	- 2.54
3	A16	1.95	0.90	0.40	17023	17030	17269	0.05	1.45
4	B16	2.55	0.86	0.70	15516	15841	16115	2.10	3.86
5	B12	2.55	0.89	0.73	16941	17221	17494	1.66	3.27
6	C43	3.10	0.59	1.00	10627	10778	10588	1.43	- 0.36
7	C49	3.10	0.66	1.00	11497	11351	11570	- 1.27	0.64
8	C17	3.10	0.77	1.00	13372	13685	13730	2.34	2.68
9	C06	3.10	0.85	1.00	15211	15571	15492	2.37	1.85
10	C46	3.10	0.94	1.00	23858	23067	23989	- 3.31	0.55
11	C35	3.10	0.95	1.00	24357	23655	23650	- 2.88	- 2.90
12	C44	3.10	0.96	1.00	24471	24374	24337	- 0.39	- 0.54
13	H51	3.10	0.95	1.00	34293	34515	34078	0.65	- 0.62
14	H44	3.10	0.97	1.00	38173	37577	37715	- 1.56	- 1.19
15	H32	3.10	0.97	1.00	39508	39078	39004	- 1.08	- 1.27
16	H12	3.10	0.90	1.00	45284	44935	44725	- 0.77	- 1.23
17	D43	3.20	0.98	1.07	38636	38660	38814	0.07	0.47
18	E33	3.30	0.67	1.20	12865	11700	11552	- 9.05	-10.20
19	G03	3.30	0.97	1.13	45118	45488	45712	0.82	1.32
20	J11	3.30	0.29	1.18	18775	21112	19898	12.45	5.99

* The declared exposures given by the operator are average burn-up values. The figures tabulated are those of the operator multiplied by a factor of 1.1 in order to represent the burn-up at the mid region of the assemblies.

Table 11b

Fuel N°	Ass. Id	Initial enrich. % ^{235}U	Factor for ^{244}Cm yields	Factor for init. enrichm.	Declared* exposures MWd/tU	Calculated exposure from fitting using			Residuals % of declared exposures		
						EUR ION-1	IAEA ION-1	IAEA NIM	EUR ION-1	IAEA ION-1	IAEA NIM
1	A13	1.95	0.79	0.37	13742	13375	13243	13076	- 2.67	- 3.63	- 4.84
2	A37	1.95	0.82	0.39	14402	13941	14095	13959	- 3.20	- 2.13	- 3.07
3	A16	1.95	0.90	0.40	17023	17177	17335	17416	0.91	1.84	2.31
4	B16	2.55	0.86	0.70	15516	15983	16178	16030	3.01	4.27	3.32
5	B12	2.55	0.89	0.73	16941	17369	17560	17529	2.53	3.66	3.48
6	C43	3.10	0.59	1.00	10627	10891	10638	10720	2.49	0.11	0.88
7	C49	3.10	0.66	1.00	11497	11467	11623	11710	- 0.25	1.10	1.86
8	C17	3.10	0.77	1.00	13372	13815	13788	13677	3.31	3.12	2.28
9	C06	3.10	0.85	1.00	15211	15711	15555	15597	3.29	2.26	2.54
10	C46	3.10	0.94	1.00	23858	23237	24066	23859	- 2.60	0.88	0.01
11	C35	3.10	0.95	1.00	24357	23827	23726	24075	- 2.17	- 2.58	- 1.15
12	C44	3.10	0.96	1.00	24471	24548	24414	24414	- 0.32	- 0.23	- 0.23
13	H51	3.10	0.95	1.00	34293	34714	34165	34425	1.23	- 0.37	0.39
14	H44	3.10	0.97	1.00	38173	37781	37805	38036	- 1.02	- 0.96	- 0.35
15	H32	3.10	0.97	1.00	39508	39284	39094	39504	- 0.56	- 1.04	0.00
16	H12	3.10	0.90	1.00	45284	45146	44817	45145	- 0.30	- 1.03	- 0.30
17	D43	3.20	0.98	1.07	38636	38865	38904	38848	0.60	0.70	0.55
18	E33	3.30	0.67	1.20	12865	11819	11605	11784	- 8.13	- 9.79	- 8.40
19	G03	3.30	0.97	1.13	45118	45699	45803	45019	1.29	1.52	- 0.21

* The declared exposures given by the operator are average burn-up values. The figures tabulated are those of the operator multiplied by a factor of 1.1 in order to represent the burn-up at the mid region of the assemblies.

Table 12

COEFFICIENTS	EURATOM ION-1	IAEA ION-1	IAEA NIM
a	3.46 E-14	3.52 E-14	2.64 E-14
b	3.563	3.553	3.585
σa	5.47 E-14	6.02 E-14	4.34 E-14
σb	0.159	0.172	0.165
Cov ab	-8.66 E-15	-1.03 E-14	-7.14 E-15
r^2	0.9982	0.9978	0.9974

As can be seen from the results the contributions from ^{242}Cm and the isotopes have been corrected for and the effect of initial enrichment of the fuel has been highlighted.

It is expected to obtain better results if the data is evaluated taking one enrichment. The results for measurements of fuel of 3.1 % is taken as an example. The resulting fitting coefficients are given in table 13a.

Table 13a

COEFFICIENTS	EURATOM ION-1	IAEA ION-1	IAEA NIM
a	2.19 E-15	1.83 E-15	1.14 E-15
b	3.824	3.832	3.883
σa	9.31 E-16	5.67 E-16	2.48 E-16
σb	4.24 E-2	3.08 E-2	2.17 E-2
Cov ab	-3.94 E-17	-1.74 E-17	-5.37 E-18
r^2	0.9966	0.9988	0.9981

A comparison between the predicted and the declared values of burn-up are given in Table 13b and the correlation is shown graphically in Fig. 14a, b, c.

Table 13b

Fuel N°	Ass. Id	Declared* exposures MWd/tU	Calculated exposure from fitting using			Residuals % of declared exposures		
			EUR ION-1	IAEA ION-1	IAEA NIM	EUR ION-1	IAEA ION-1	IAEA NIM
6	C43	10627	10683	10458	10528	0.53	- 1.59	- 0.93
7	C49	11497	11260	11447	11519	- 2.05	- 0.43	0.20
8	C17	13372	13619	13628	13491	1.85	1.92	0.90
9	C06	15211	15530	15413	15422	2.10	1.33	1.39
10	C46	23858	23161	24064	23650	- 2.92	0.87	- 0.87
11	C35	24357	23762	23718	23991	- 2.44	- 2.62	- 1.50
12	C44	24471	24496	24419	24335	0.11	- 0.21	- 0.55
13	H51	34293	34895	34413	34527	1.76	0.35	0.69
14	H44	38173	38046	38159	38217	- 0.33	- 0.03	0.12
15	H32	39508	39592	39488	39505	0.22	- 0.05	0.00
16	H12	45284	45634	45398	45500	0.78	0.26	0.48

The difference between the predicted and operator declared values of burn-up is not greater than ± 3 %.

Similar to previous calculations, the correlation between neutron data and Pu-content is established.

The fitting parameters are given in tables 14a and 14b for all assembles resp. without the short cooling time assembly.

Table 14a

COEFFICIENTS	EURATOM ION-1	IAEA ION-1
a	1.72 E-1	1.37 E-1
b	5.87	5.96
σa	1.14 E-1	7.32 E-2
σb	5.79 E-1	4.66 E-1
Cov ab	-6.39 E-2	-3.32 E-2
r^2	0.8641	0.8778

Table 14b

COEFFICIENTS	EURATOM ION-1	IAEA ION-1	IAEA NIM
a	1.12 E-1	9.90 E-2	9.44 E-2
b	6.13	6.16	6.23
σa	3.67 E-2	3.05 E-2	3.06 E-2
σb	2.85 E-1	2.68 E-1	2.82 E-1
Cov ab	-1.02 E-2	-7.96 E-3	-8.41 E-3
r^2	0.8623	0.8751	0.8419

The calculated Pu-contents are given in tables 15a and 15b.

Table 15a

Fuel n°	Ass. Id.	Declared Total (kg)	Calculated Pu-content from fitted functions		Residuals % of declared Pu-content	
			EUR ION-1	IAEA ION-1	EUR ION-1	IAEA ION-1
1	A13	2.525	2.299	2.303	- 8.93	- 8.78
2	A37	2.592	2.355	2.386	- 9.14	- 7.93
3	A16	2.873	2.655	2.685	- 7.57	- 6.53
4	B16	2.797	2.547	2.581	- 8.92	- 7.70
5	B12	2.948	2.672	2.705	- 9.35	- 8.24
6	C43	1.930	2.043	2.033	5.88	5.33
7	C49	2.051	2.105	2.138	2.63	4.25
8	C17	2.296	2.343	2.357	2.04	2.65
9	C06	2.508	2.522	2.524	0.58	0.65
10	C46	3.306	3.159	3.237	- 4.44	- 2.08
11	C35	3.339	3.205	3.211	- 4.01	- 3.82
12	C44	3.353	3.260	3.264	- 2.67	- 2.65
13	H51	3.834	3.979	3.953	3.79	3.11
14	H44	4.037	4.177	4.188	3.48	3.74
15	H32	4.100	4.272	4.269	4.21	4.11
16	H12	4.336	4.633	4.614	6.85	6.42
17	D43	4.423	4.246	4.257	- 4.00	- 3.76
18	E33	2.194	2.142	2.136	- 2.38	- 2.64
19	G03	4.769	4.660	4.672	- 2.27	- 2.03
20	J11	2.656	3.003	2.911	13.06	9.59

Table 15b

Fuel n°	Ass. Id.	Declared Total (kg)	Calculated Pu-content from fitted functions			Residuals % of declared Pu-content		
			EUR ION-1	IAEA ION-1	IAEA NIM	EUR ION-1	IAEA ION-1	IAEA NIM
1	A13	2.525	2.334	2.326	2.306	- 7.55	- 7.87	- 8.68
2	A37	2.592	2.390	2.409	2.392	- 7.81	- 7.04	- 7.70
3	A16	2.873	2.689	2.707	2.711	- 6.41	- 5.76	- 5.64
4	B16	2.797	2.581	2.604	2.587	- 7.70	- 6.90	- 7.51
5	B12	2.948	2.706	2.727	2.721	- 8.22	- 7.49	- 7.71
6	C43	1.930	2.078	2.056	2.061	7.69	6.54	6.79
7	C49	2.051	2.140	2.161	2.166	4.34	5.38	5.63
8	C17	2.296	2.377	2.308	2.365	3.55	3.65	3.01
9	C06	2.508	2.557	2.547	2.547	1.94	1.56	1.56
10	C46	3.306	3.189	3.257	3.229	- 3.52	- 1.48	- 2.33
11	C35	3.339	3.235	3.231	3.255	- 3.11	- 3.23	- 2.52
12	C44	3.353	3.290	3.283	3.280	- 1.88	- 2.07	- 2.16
13	H51	3.834	4.002	3.968	3.983	4.38	3.50	3.89
14	H44	4.037	4.198	4.201	4.214	3.98	4.07	4.38
15	H32	4.100	4.291	4.281	4.292	4.67	4.42	4.68
16	H12	4.336	4.647	4.624	4.642	7.17	6.64	7.06
17	D43	4.423	4.265	4.269	4.264	- 3.56	- 3.47	- 3.59
18	E33	2.194	2.177	2.159	2.174	- 0.79	- 1.58	- 0.90
19	G03	4.769	4.674	4.681	4.634	- 1.98	- 1.84	- 2.82

The fitting parameters limited to initial enrichment 3.1 % are given in table 16.

Table 16

COEFFICIENTS	EURATOM ION-1	IAEA ION-1	IAEA NIM
a	1.18 E-1	1.04 E-1	9.92 E-2
b	6.17	6.20	6.28
σa	4.91 E-2	3.97 E-2	3.97 E-2
σb	3.59 E-1	3.30 E-1	3.46 E-1
Cov ab	-1.71 E-2	-1.27 E-2	-1.34 E-2
r^2	0.8810	0.8898	0.8841

The calculated values are given in table 17.

Fuel n°	Ass. Id.	Declared exposure (kg)	Calculated Pu-content from fitted functions			Residuals % of declared Pu-content		
			EUR ION-1	IAEA ION-1	IAEA NIM	EUR ION-1	IAEA ION-1	IAEA NIM
6	C43	1.930	2.005	1.983	1.989	3.89	2.77	3.07
7	C49	2.051	2.065	2.087	2.092	0.69	1.74	2.02
8	C17	2.296	2.298	2.301	2.287	0.09	0.23	- 0.41
9	C06	2.508	2.474	2.446	2.465	- 1.36	- 1.68	- 1.71
10	C46	3.306	3.096	3.166	3.134	- 6.33	- 4.23	- 5.19
11	C35	3.339	3.141	3.140	3.160	- 5.92	- 5.94	- 5.37
12	C44	3.353	3.195	3.192	3.185	- 4.69	- 4.79	- 5.01
13	H51	3.834	3.898	3.870	3.877	1.67	0.95	1.12
14	H44	4.037	4.092	4.101	4.104	1.37	1.59	1.67
15	H32	4.100	4.185	4.181	4.181	2.07	1.97	1.99
16	H12	4.336	4.537	4.521	4.527	4.63	4.27	4.40

D. Mid Point Gamma Data

The gamma data shown on Table 3, are divided by the respective operator declared values of exposure. The ratio of gamma/exposure is then plotted against cooling time. The data has been fitted with a least squares method (Deming) on the HP85 to a function of the form

$G = aT^b$ where G = Gamma/exposure
(exposure is in GWd/tU)
and T = cooling time days

The result of the fitted functions are given in Table 18.

Table 18

COEFFICIENTS	EURATOM ION-1	IAEA ION-1
a	9.44 E+03	9.81 E+03
b	-8.69 E-01	-8.83 E-01
σa	1.35 E+03	1.68 E+03
σb	2.13 E-02	2.55 E-02
Cov ab	-2.87 E+01	-4.28 E+01
r^2	0.9906	0.9872

The correlation is shown graphically is Fig. 15a, b. The values of the ratios where then reintroduced into the fitted functions to produce the predicted values of cooling times. The results are compared against the declared values in Table 19.

Table 19

Fuel n°	Ass. Id.	Declared cooling time (d)	Calculated cooling time from fitted functions		Residuals % of declared cooling time	
			EUR ION-1	IAEA ION-1	EUR ION-1	IAEA ION-1
1	A13	3141	3222	3269	2.59	4.08
2	A37	3141	3213	3208	2.31	2.14
3	A16	3141	2955	2968	- 5.91	- 5.51
4	B16	3141	3116	3092	- 0.79	- 1.56
5	B12	3141	3145	3092	0.13	- 1.56
6	C43	3141	3317	3337	5.60	6.26
7	C49	3141	3271	3352	4.15	6.73
8	C17	3141	3149	3347	0.27	6.57
9	C06	3141	3227	3199	2.73	1.84
10	C46	2671	2959	2798	10.79	4.76
11	C35	2671	2963	2952	10.93	10.52
12	C44	2671	2893	2928	8.32	9.64
13	H51	803	780	789	- 2.81	- 1.73
14	H44	803	775	758	- 3.50	- 5.60
15	H32	803	768	769	- 4.34	- 4.21
16	H12	431	453	456	5.10	5.73
17	D43	1852	1787	1803	- 3.51	- 2.65
18	E33	2307	3043	3332	31.93	44.45
19	G03	803	726	712	- 9.63	-11.30
20	J11	36	-	-	-	-

An apparent outlier from the results is assembly E33. This is a low burn-up and relatively long cooled assembly. This assembly was a one cycle assembly but was in the reactor less time than the other one cycle assemblies as can be seen from fig. 4. The ^{137}Cs build up was not so high and therefore it shows up as a longer cooled assembly from the results in comparison to the others.

7. CONCLUSIONS

The neutron and gamma measurements made on the 20 assemblies at Tihange 1 were used successfully to :

a) Demonstrate that the assemblies had radiation characteristics typical for PWR spent fuel assemblies.

b) Verify that the operator declared information for the assemblies was consistent.

- The test on the new AMPTEK device was successfull. The device was able to facilitate measurements on spent fuel with as short as 36 days cooling time. The results indicate that a high gamma flux does not contribute to the recorded neutron pulses whereas the old system could not discriminate against them at such a high level of activity.
- The measurements show that the IAEA and Euratom systems gave similar results which were reproducible over the measurment campaign.
- There was no significant difference in the quality of the measurement results whether the ION-1/FORK system is used attached to the bridge or permanently fixed to the side of the pool.
- The results indicate the importance of performing a more detailed axial scan than previously suggested by the LANL.

If data on spent fuel from different reactors is to be compared in the future, the ratio between the operator's declared average burn-up and that at the mid position is important.

- The dependance on the initial enrichment of the fuel has been noticeable from the results.
- The use of the reactor physics code BUNECO was important to evaluate the relative contribution of ^{244}Cm for assemblies carrying different power histories. The development of such a programme to suit a Westinghouse type reactor will be a useful aid to the data evaluation procedure in the future.
- Calibrations must be either made for each initial enrichment of fuel or further work must be carried out to produce factors that could normalise the ^{244}Cm contribution for different enrichments.
- When results from destructive analysis can be evaluated the measurements data for the 11 assemblies with initial enrichments of 3.1 % could be considered for use as a calibration curve.

REFERENCES

1. Draft User Manual For ION-1/FORK (Internal Note F/4 RSc/ec 596/84).

2. A Non-destructive Measurement System for Spent Light-Water Reactor Fuel Assemblies (H. WUERZ, IAEA-SM-260/30).

3. W.E. DEMING
   Statistical Adjustment of Data
   John WILEY & Sons (New York)
   (1948)

LIST OF FIGURES

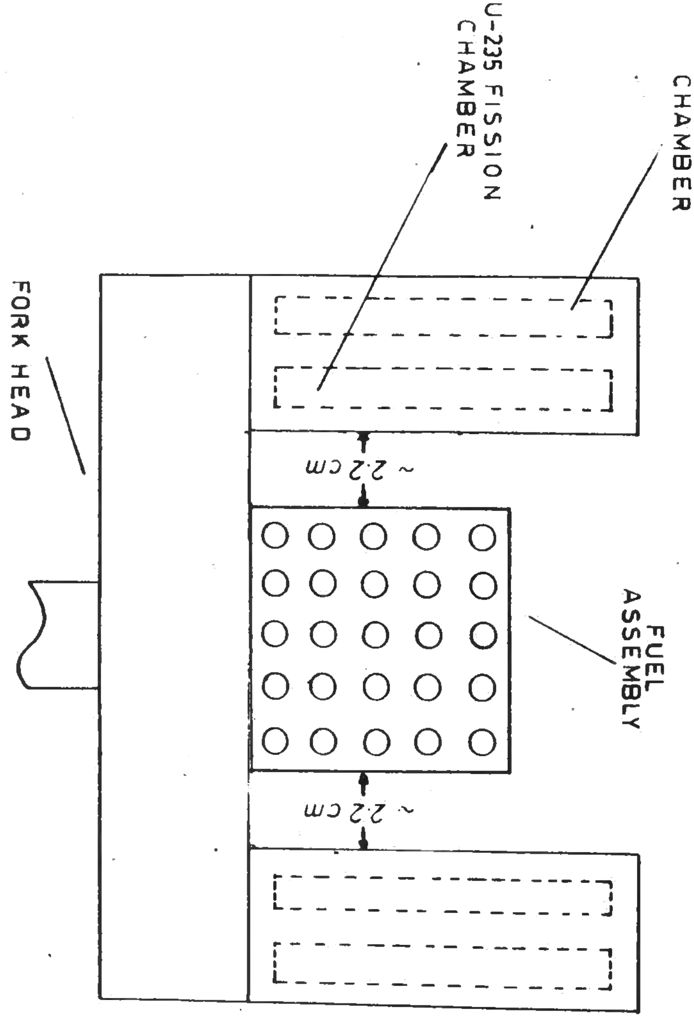


Fig.2.

VIEW OF POSITION OF ASSEMBLY WITH RESPECT TO FORK

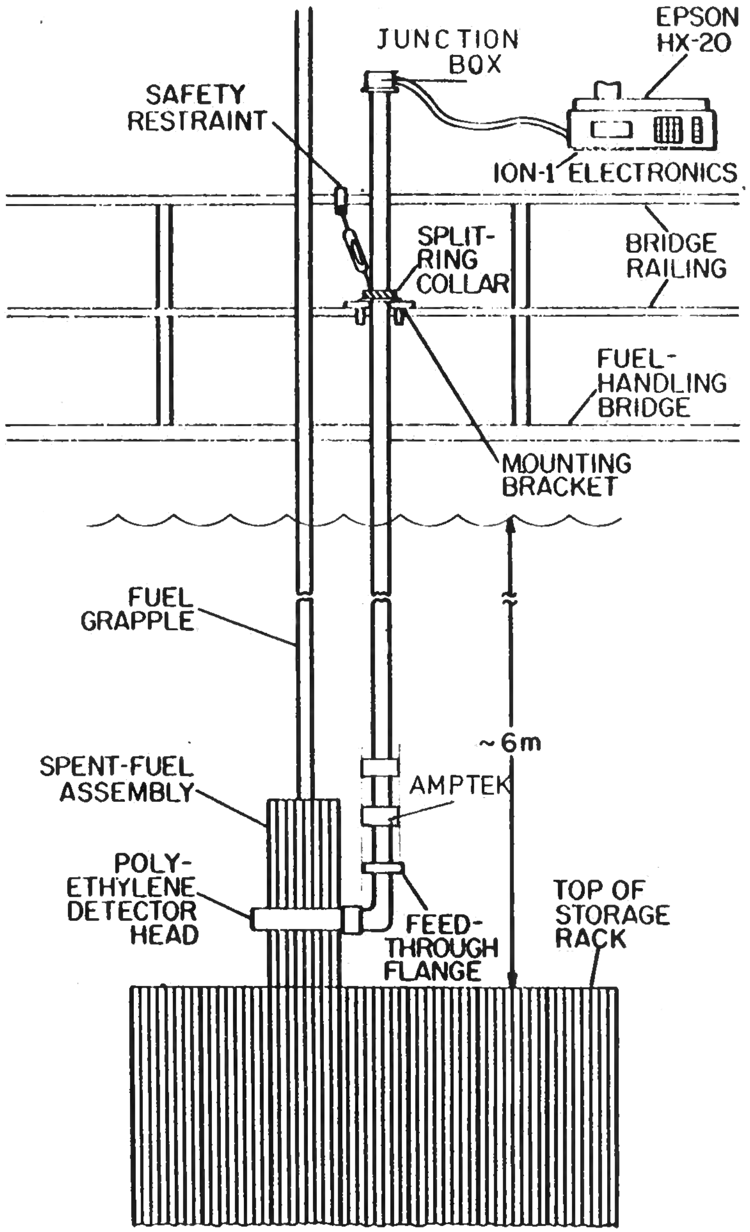
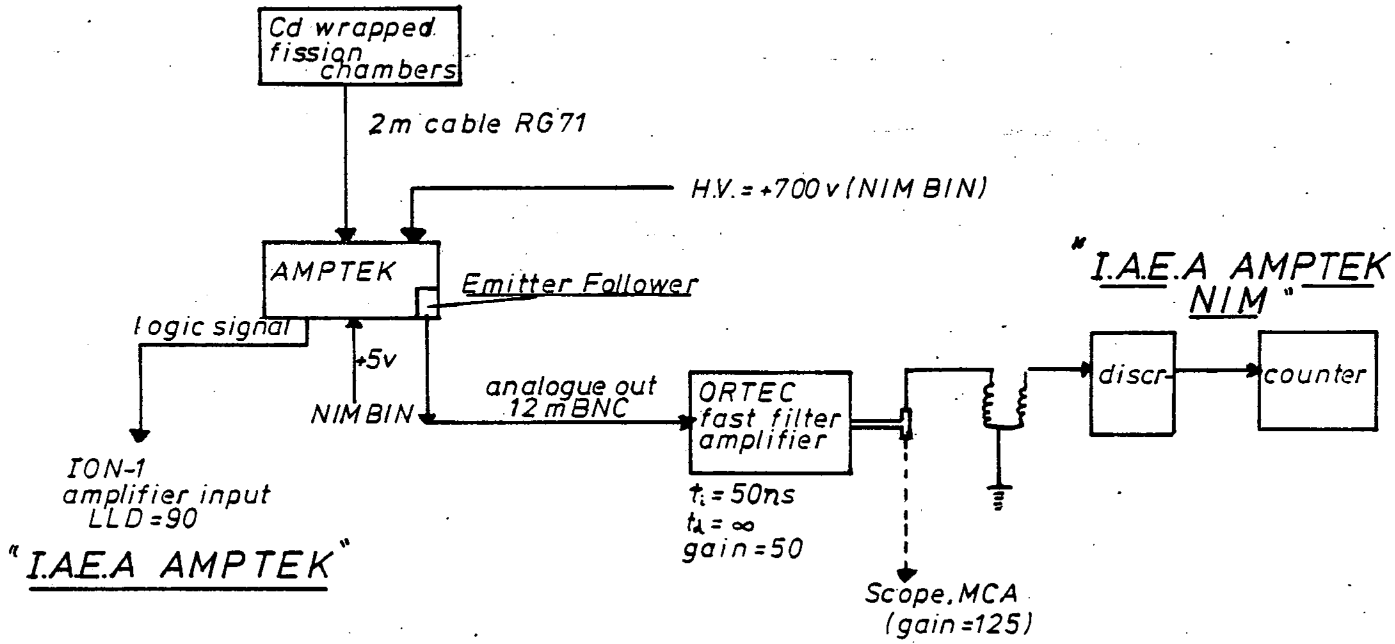


Fig.1.

Fig.3.

I.A.E.A SYSTEM



EURATOM ION-1 (NEW AMPTEK SYSTEM)

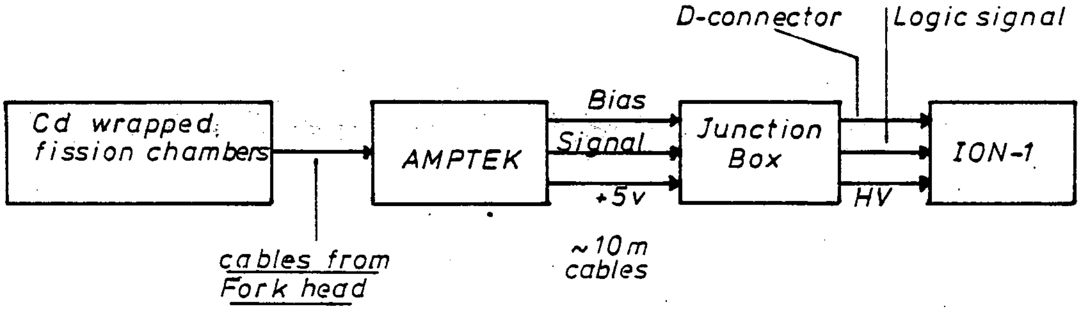


Fig. 4.

CYCLE	DATES
1	09.03.75 – 30.09.76
2	28.02.77 – 13.01.78
3	01.03.78 – 12.01.79
4	09.03.79 – 11.04.80
5	22.05.80 – 19.02.81
6	09.04.81 – 11.02.82
7	01.04.82 – 24.02.83
8	04.04.83 01.03.84
9	01.04.84 01.04.85

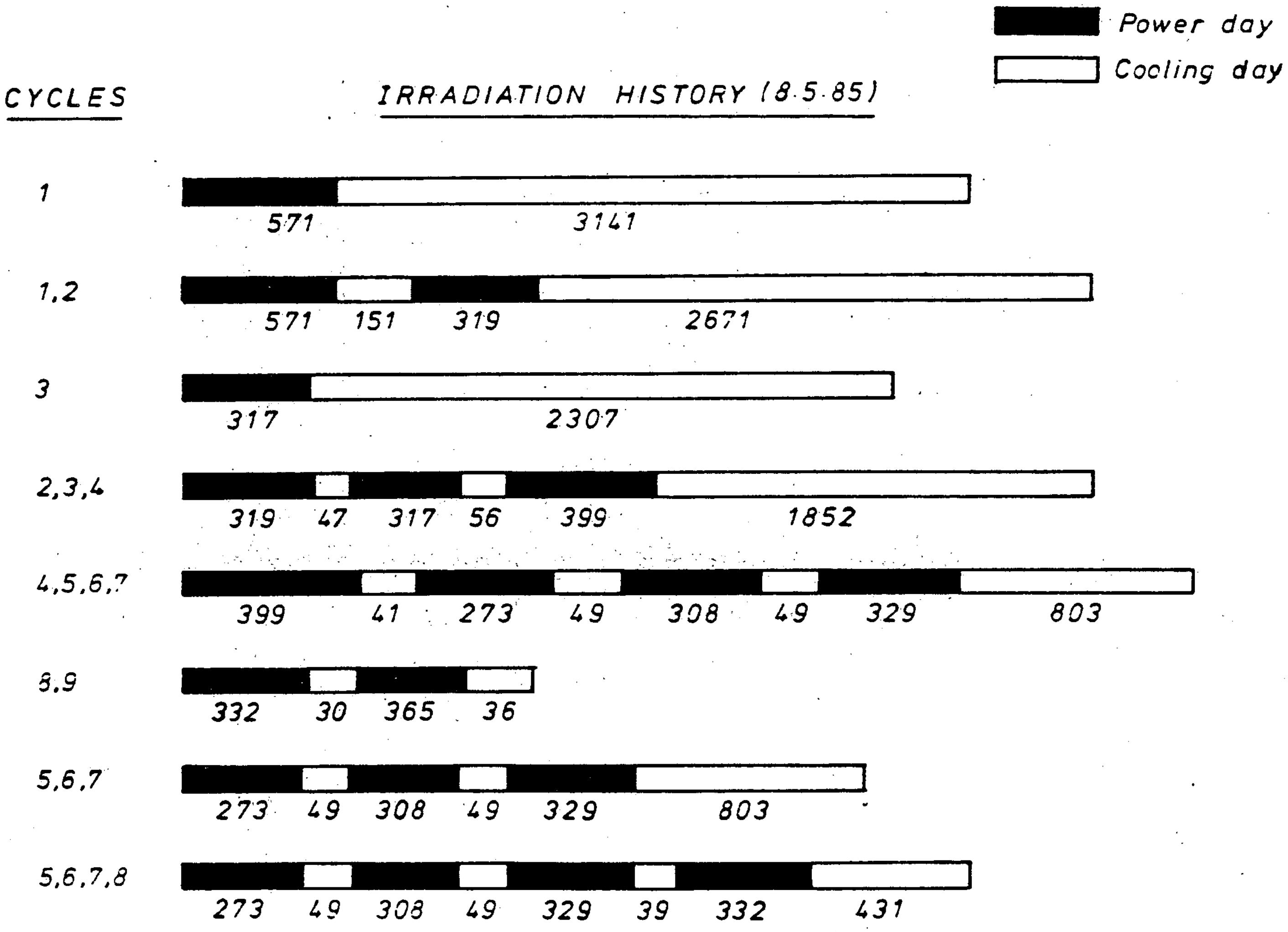
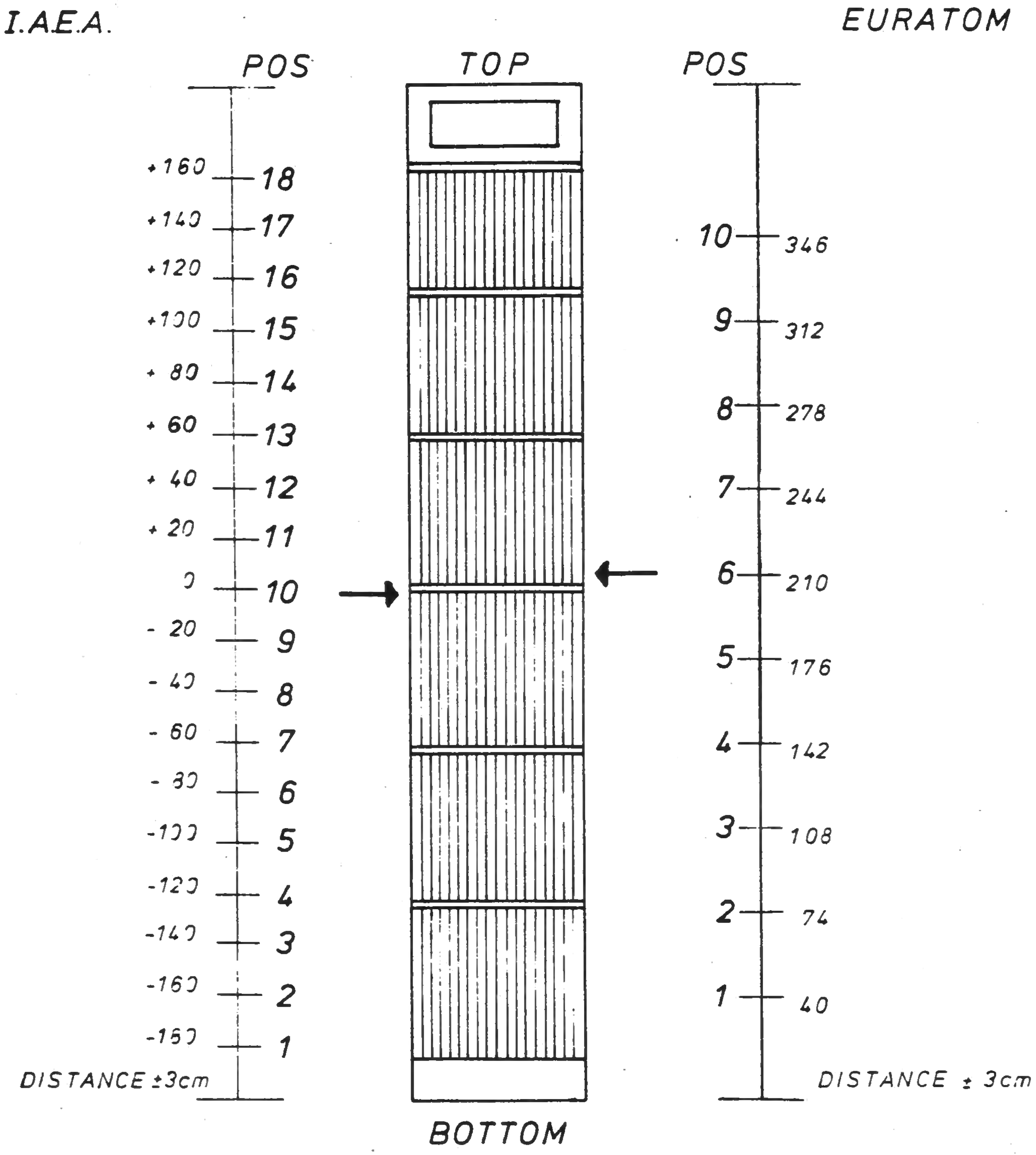


Fig. 5.


I.A.E.A.
POS
TOP
POS
EURATOM
+160
18
+140
17
+120
16
+100
15
+ 80
14
+ 60
13
+ 40
12
+ 20
11
0
10
- 20
9
- 40
8
- 60
7
- 80
6
-100
5
-120
4
-140
3
-160
2
-150
1
DISTANCE ±3cm
10
346
9
312
8
278
7
244
6
210
5
176
4
142
3
108
2
74
1
40
DISTANCE ± 3cm
BOTTOM

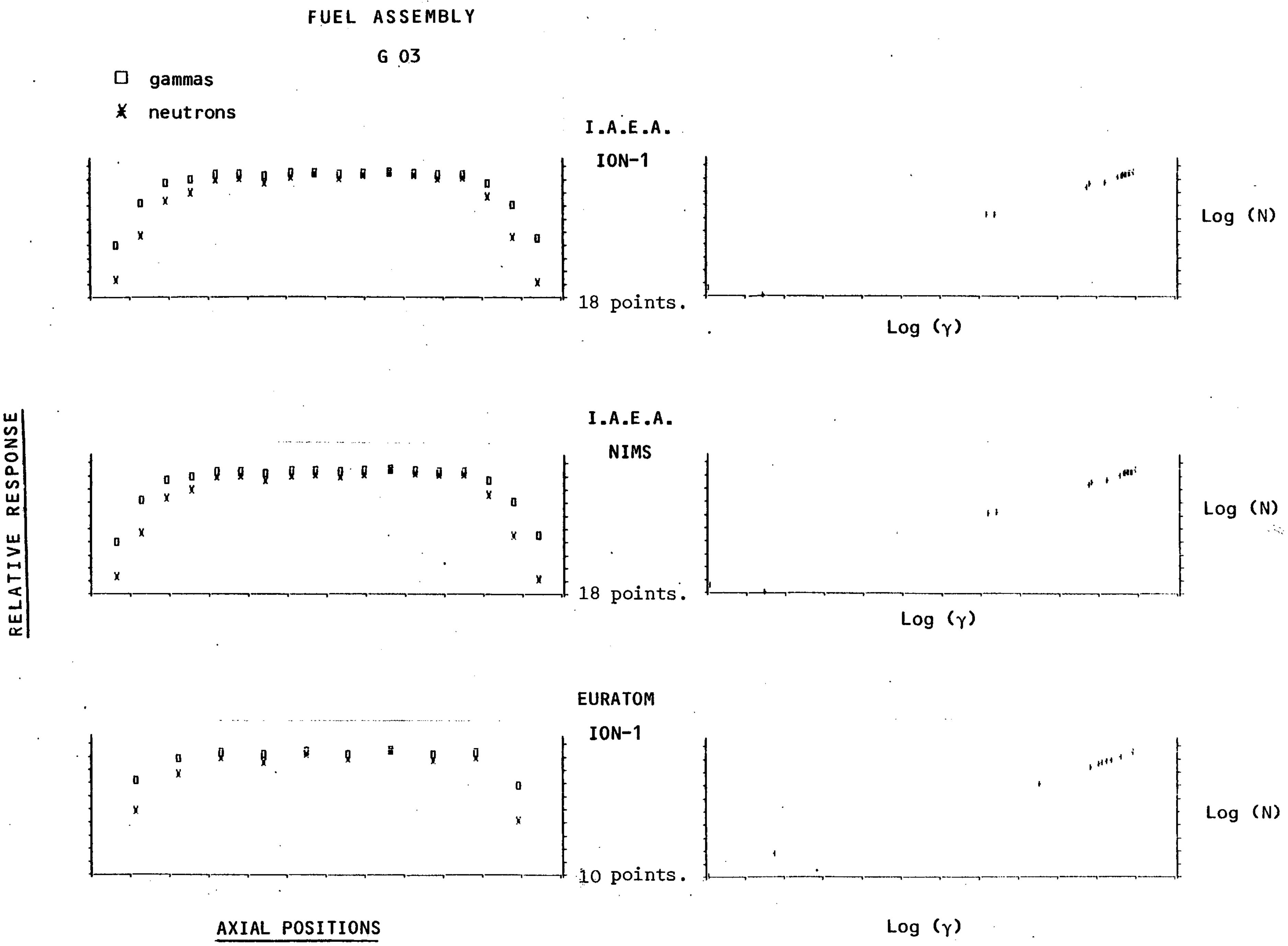

FUEL ASSEMBLY
G 03
□ gammas
X neutrons
RELATIVE RESPONSE
I.A.E.A.
ION-1
18 points.
Log (N)
Log (γ)
I.A.E.A.
NIMS
18 points.
Log (N)
Log (γ)
EURATOM
ION-1
10 points.
Log (N)
Log (γ)
AXIAL POSITIONS

Fig. 6.

FUEL ASSEMBLY
A 13

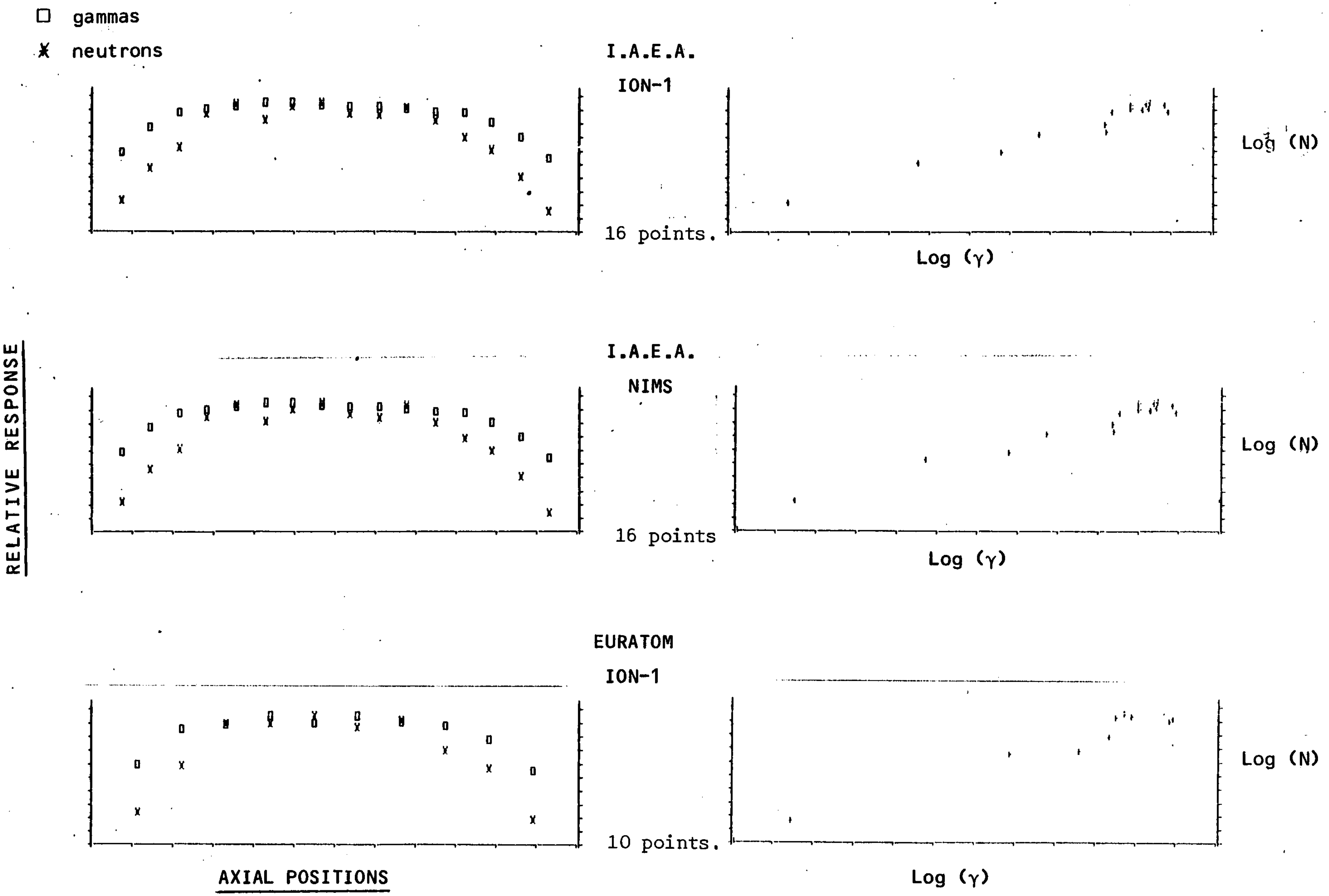


Fig. 7.

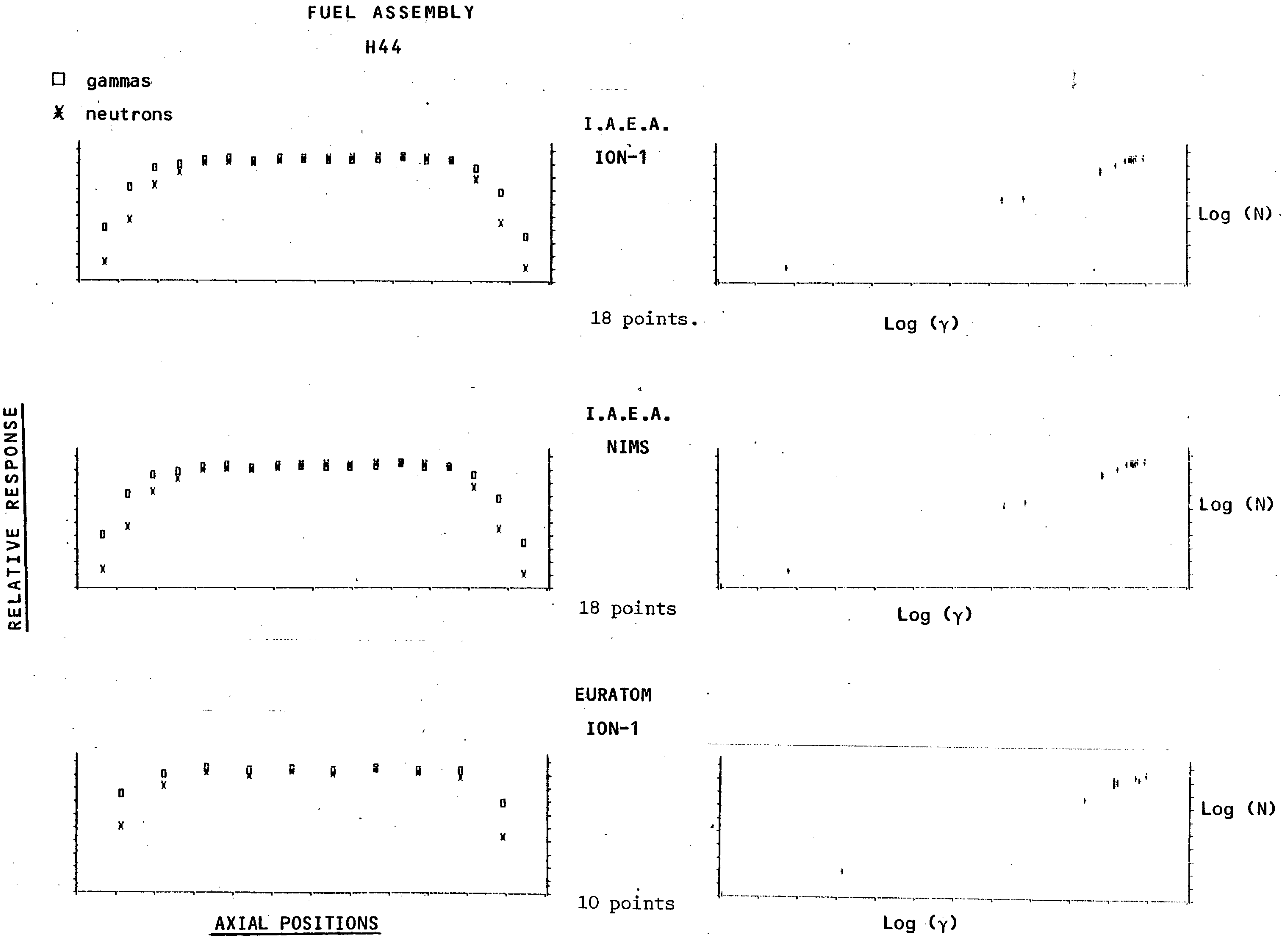

FUEL ASSEMBLY
H44
□ gammas
X neutrons
RELATIVE RESPONSE
I.A.E.A.
ION-1
18 points.
Log (N)
Log (γ)
I.A.E.A.
NIMS
18 points
Log (N)
Log (γ)
EURATOM
ION-1
10 points
Log (N)
Log (γ)
AXIAL POSITIONS

Fig. 8.

Fig. 9.

FUEL ASSEMBLY
G03

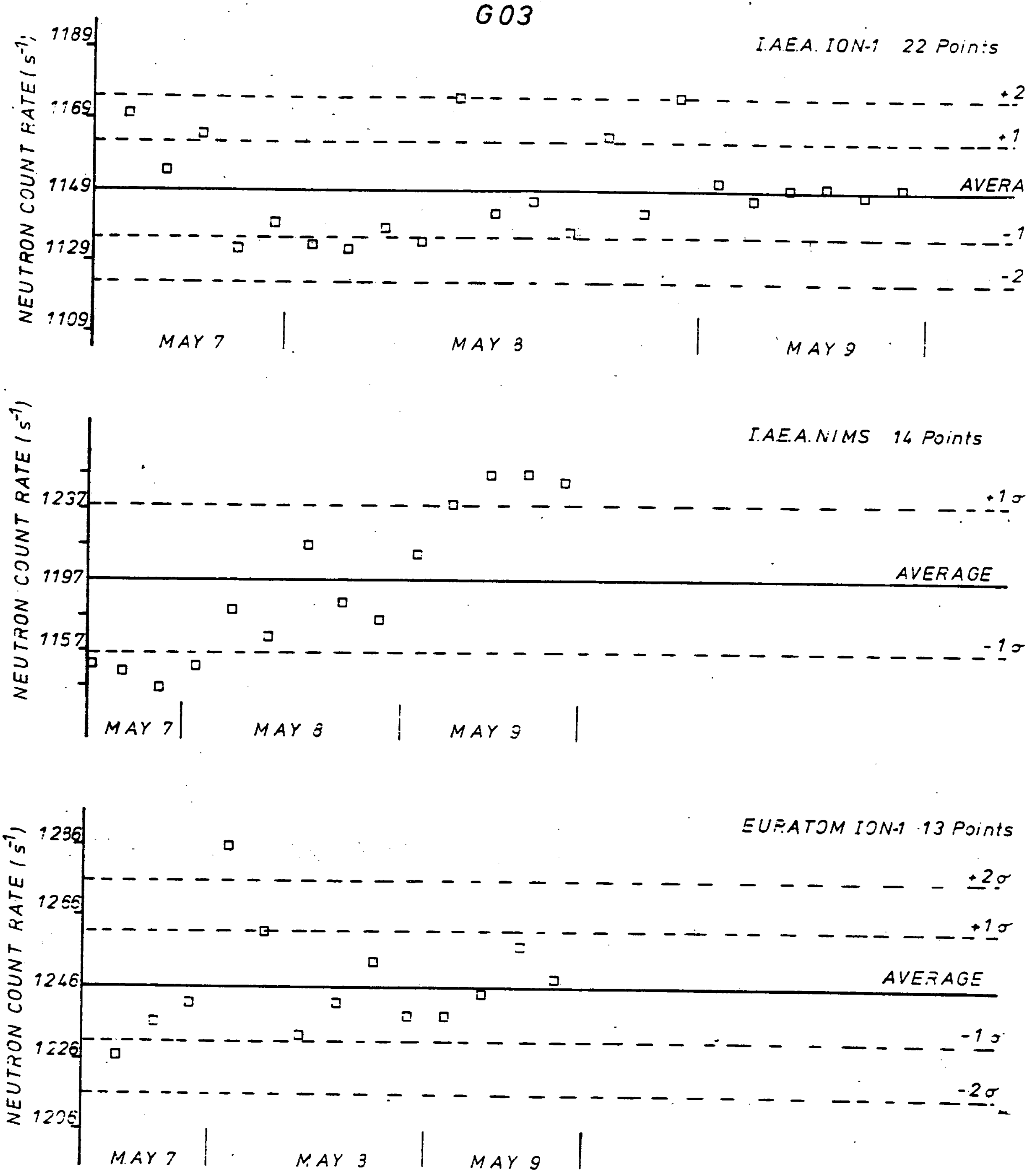
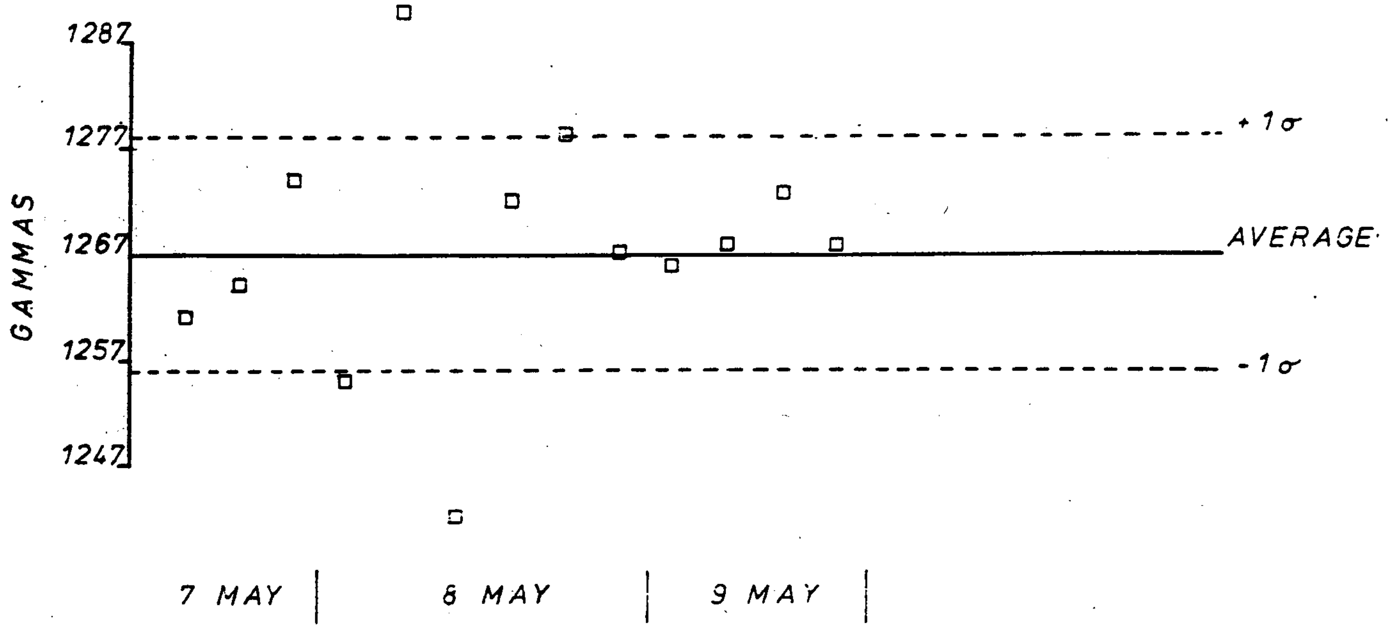


Fig. 10.

FUEL ASSEMBLY
G03

EURATOM ION-1 13 Points



I.A.E.A. ION-1 20 Points

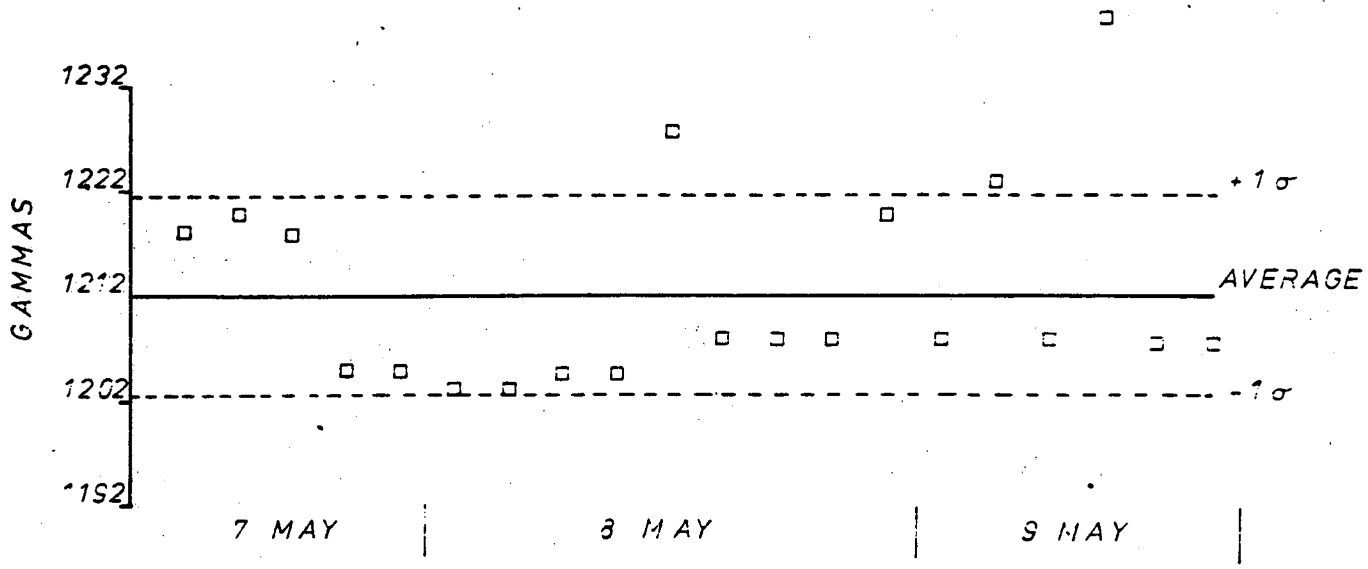


Fig. 11 a.

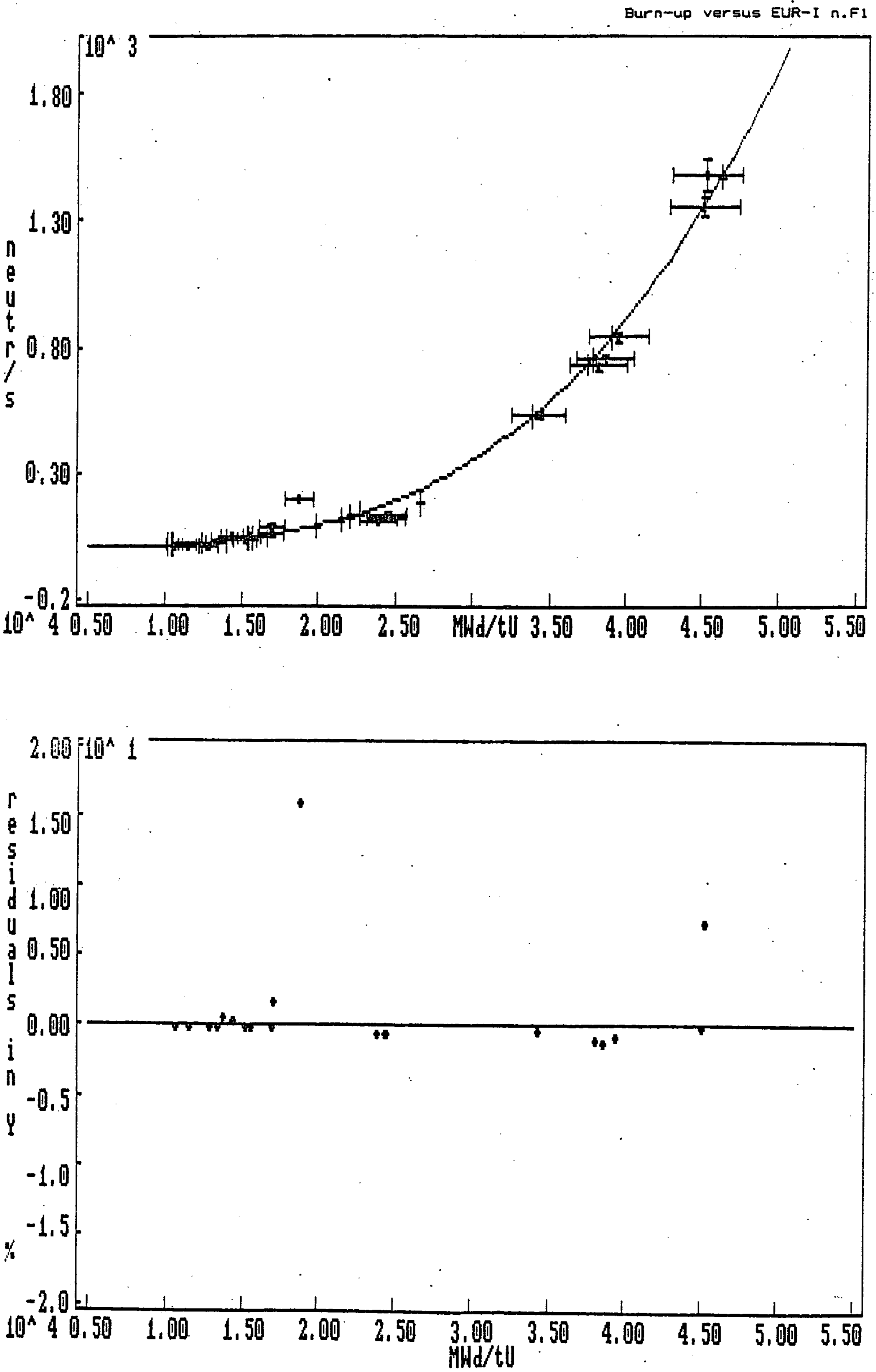
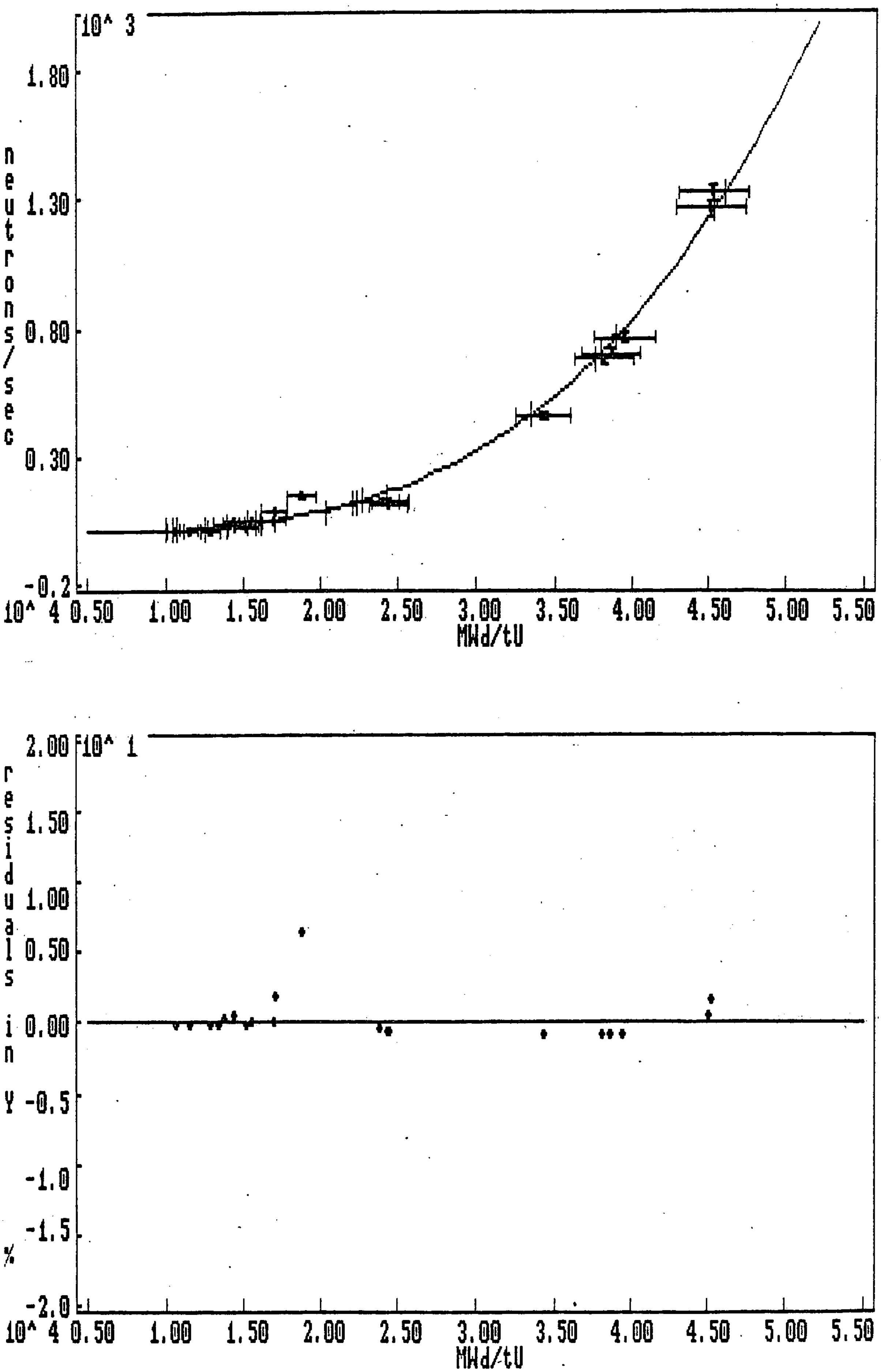

Burn-up versus EUR-I n.F1
10^ 3
1.80
1.30
0.80
0.30
-0.2
neutr/s
10^ 4 0.50
1.00
1.50
2.00
2.50
MWd/tU 3.50
4.00
4.50
5.00
5.50
2.00 10^ 1
1.50
1.00
0.50
0.00
-0.5
-1.0
-1.5
-2.0
residuals in y
%
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU

Fig. 11 b.



Burn-up versus IAEA-I n.F1

Fig. 11 c.

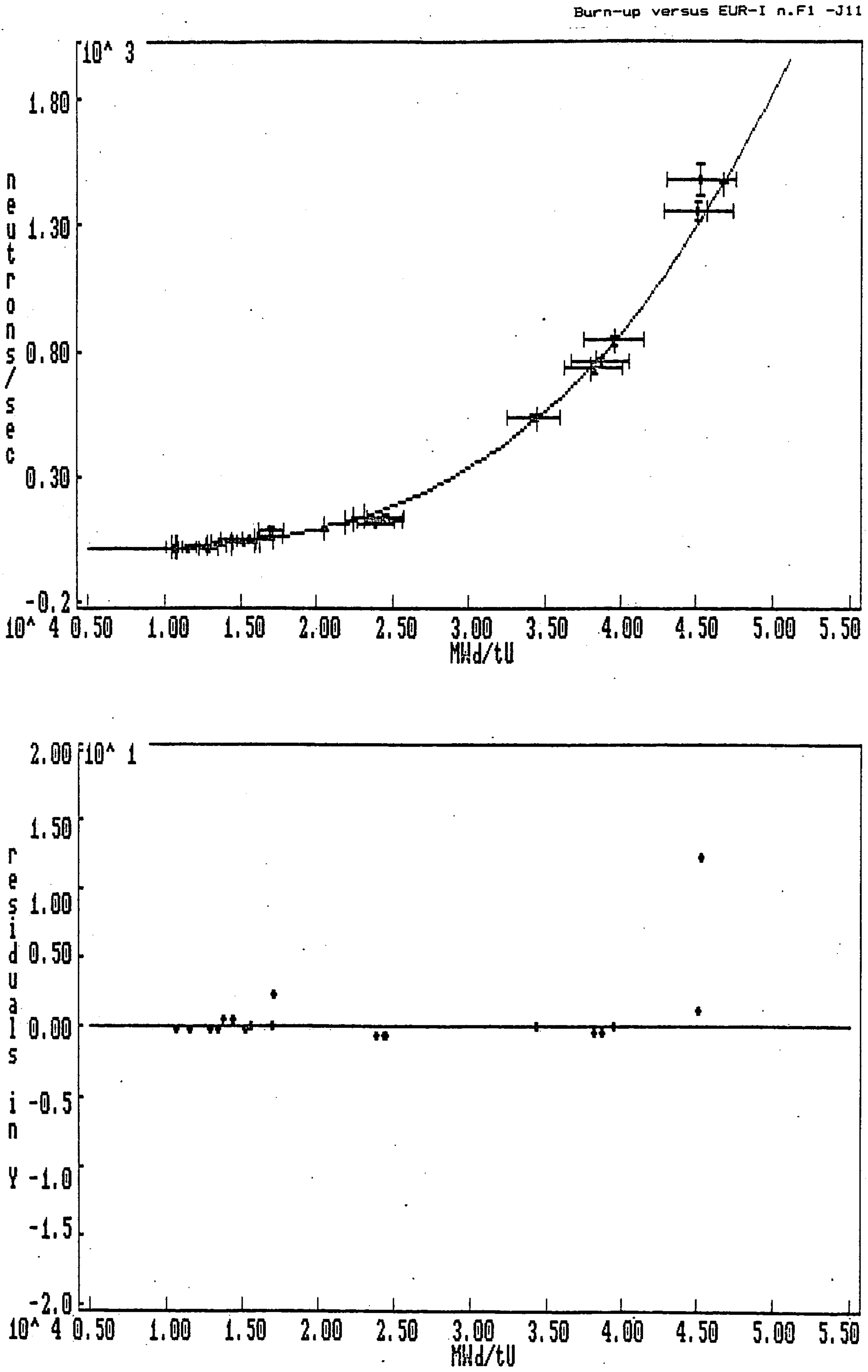

Burn-up versus EUR-I n.F1 -J11
10^ 3
1.80
1.30
0.80
0.30
-0.2
neutrons/sec
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU
2.00
10^ 1
1.50
1.00
0.50
0.00
-0.5
-1.0
-1.5
-2.0
residuals in Y
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU

Fig. 11 d.

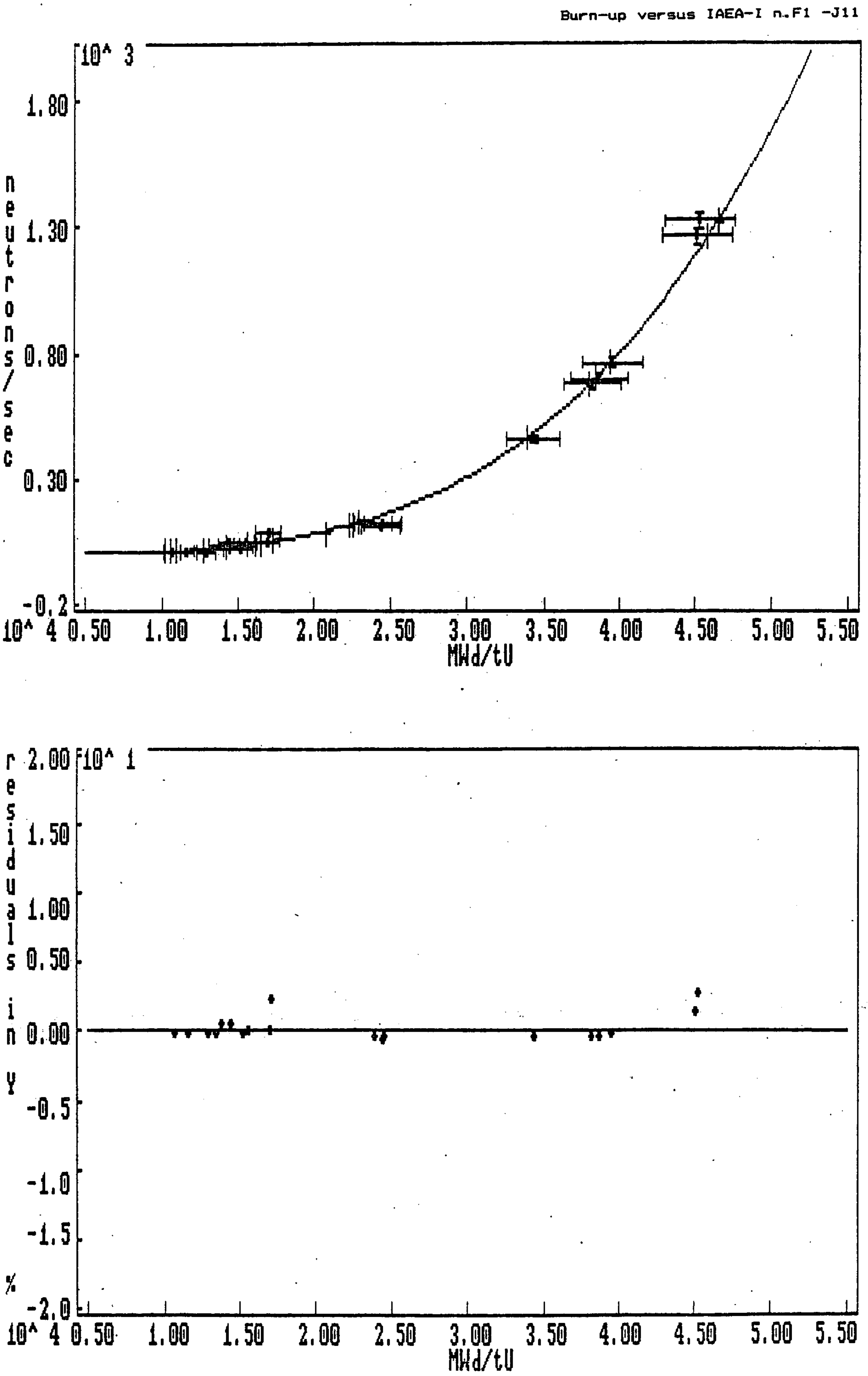
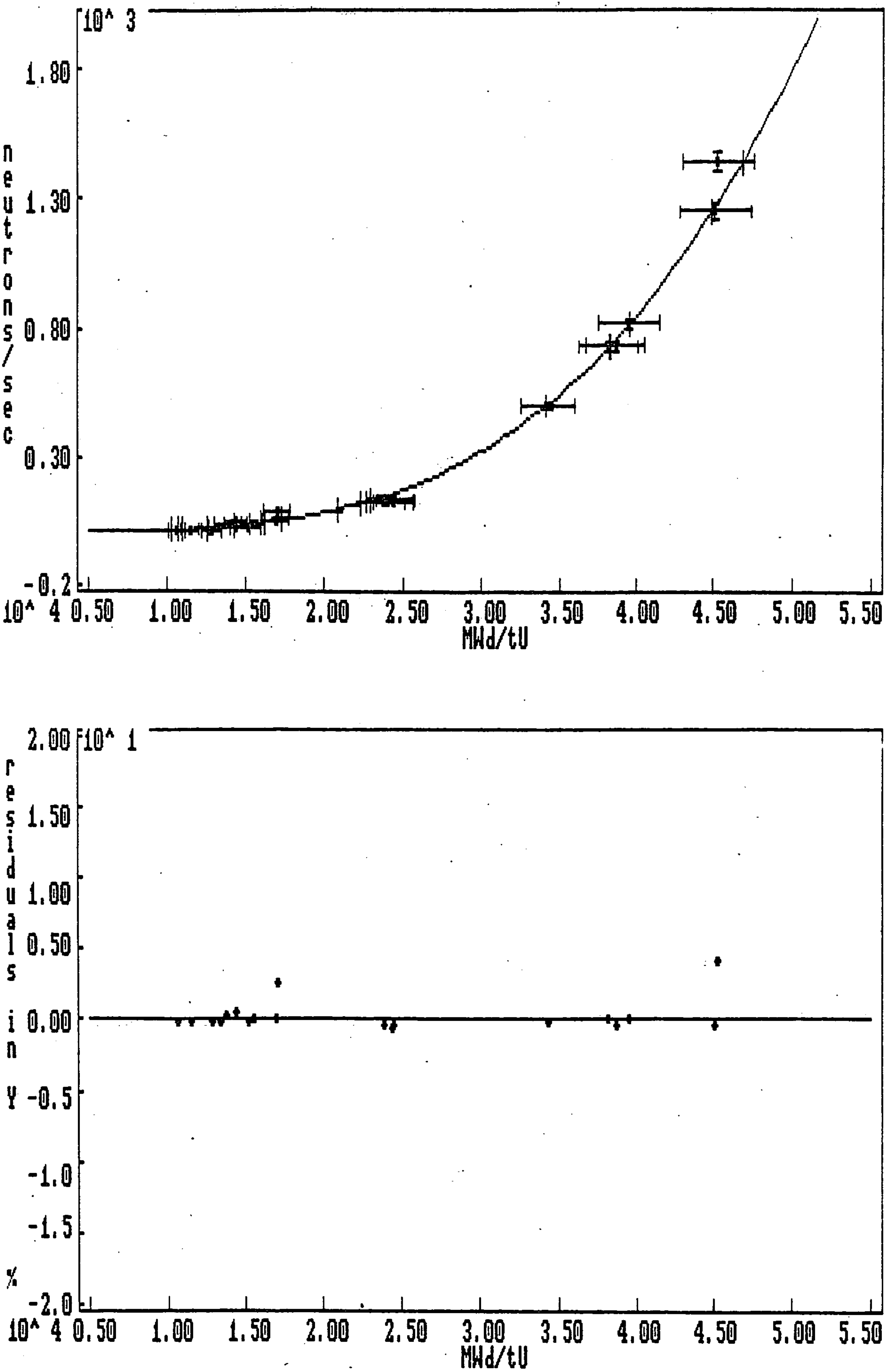

Burn-up versus IAEA-I n.F1 -J11
10^ 3
1.80
1.30
0.80
0.30
-0.2
neutrons/sec
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU
10^ 1
2.00
1.50
1.00
0.50
0.00
-0.5
-1.0
-1.5
-2.0
residuals in y %
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU

Fig. 11 e.



Burn-up versus IAEA-N n.F1

Fig. 12 a.

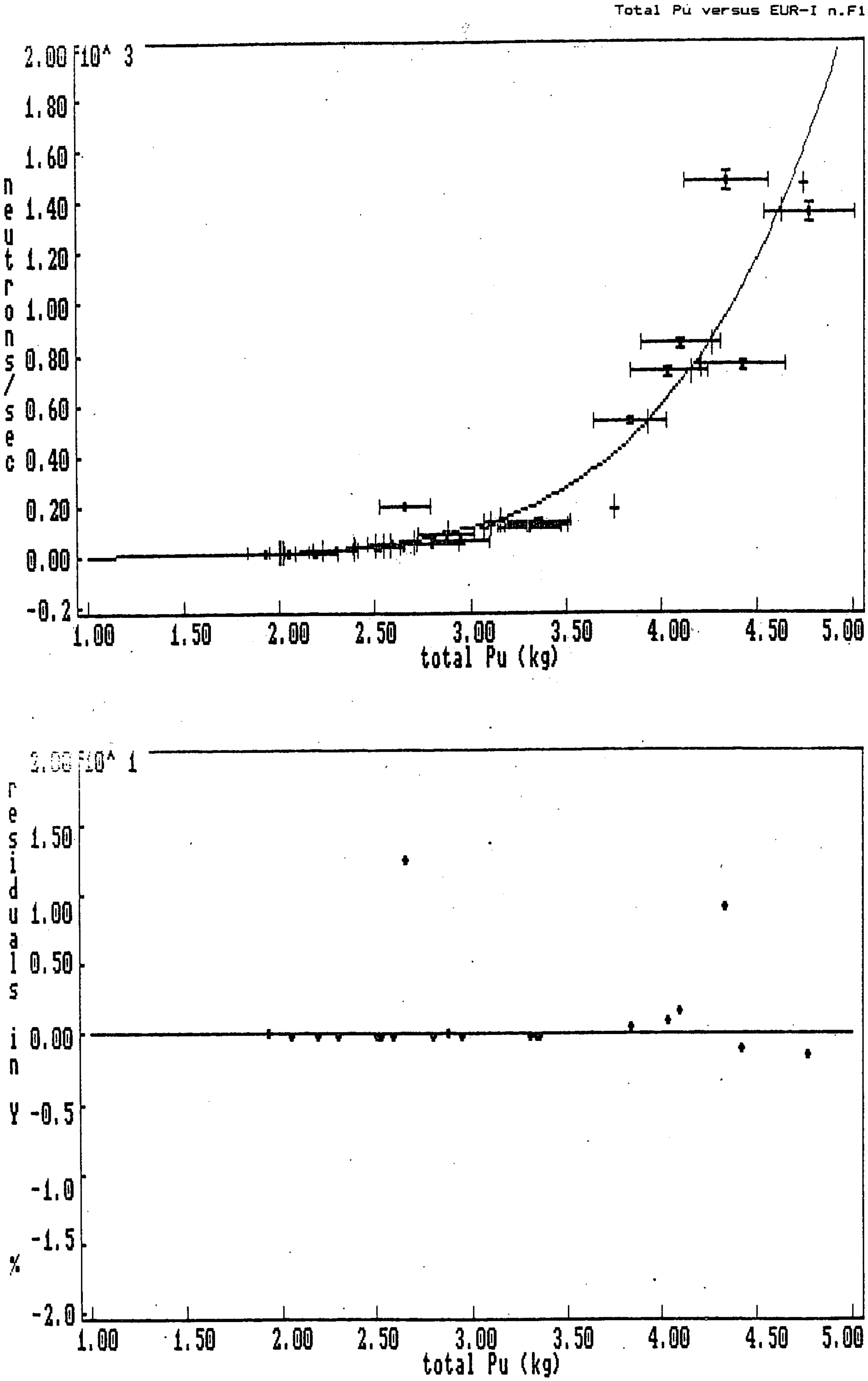
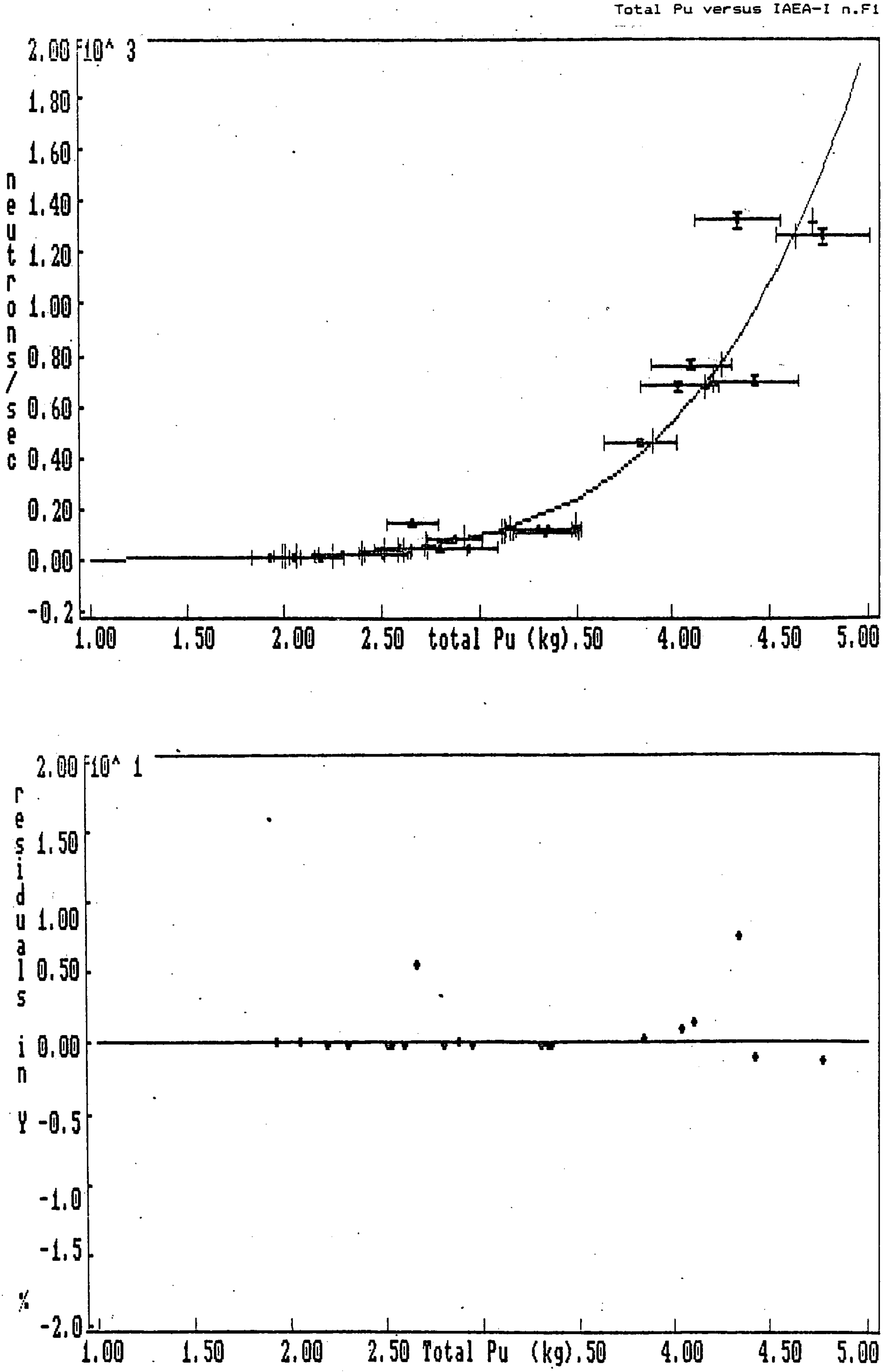

Total Pu versus EUR-I n.F1
2.00 10^ 3
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.2
neutrons/sec
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
total Pu (kg)
2.00 10^ 1
1.50
1.00
0.50
0.00
-0.5
-1.0
-1.5
-2.0
residuals in Y %
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
total Pu (kg)

Fig. 12 b.



Total Pu versus IAEA-I n.F1
2.00 10^ 3
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.2
neutrons/sec
1.00
1.50
2.00
2.50
total Pu (kg).50
4.00
4.50
5.00
2.00 10^ 1
1.50
1.00
0.50
0.00
-0.5
-1.0
-1.5
-2.0
residuals in Y %
1.00
1.50
2.00
2.50 Total Pu (kg).50
4.00
4.50
5.00

Fig. 12 c.

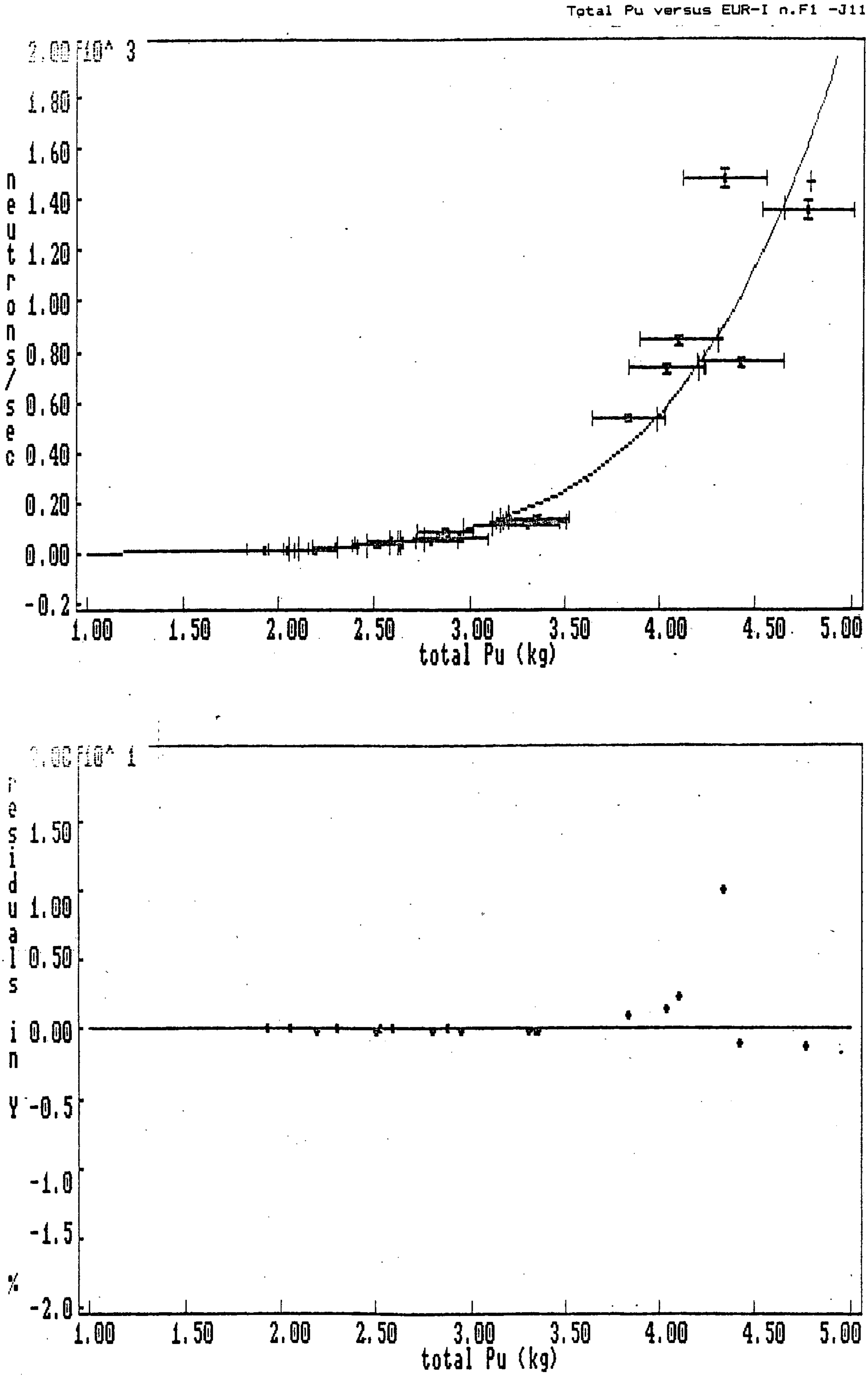
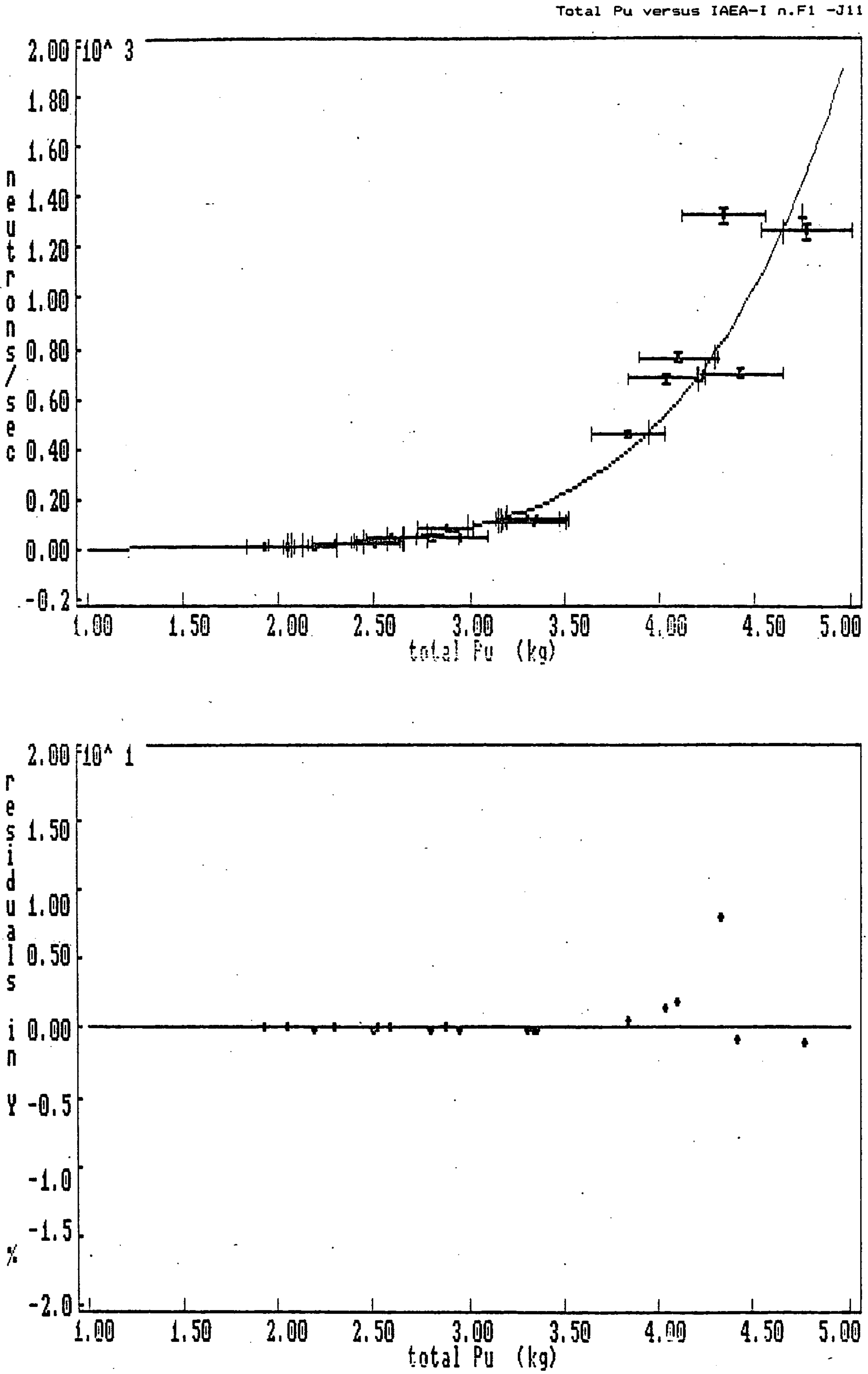
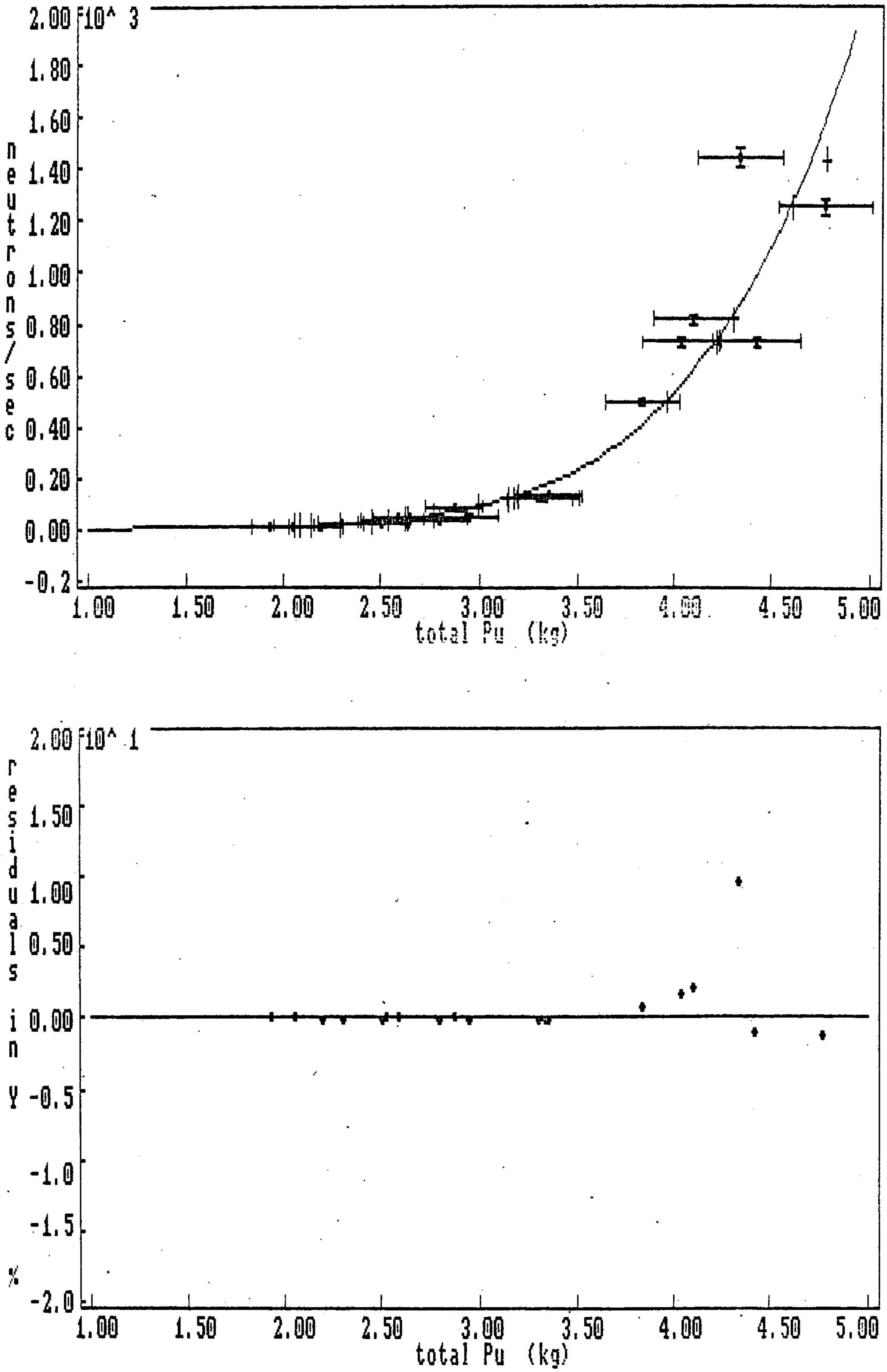

Total Pu versus EUR-I n.F1 -J11
2.00 *10^ 3
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.2
neutrons/sec
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
total Pu (kg)
2.00 *10^ 1
1.50
1.00
0.50
0.00
-0.5
-1.0
-1.5
-2.0
Residuals in Y
%
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
total Pu (kg)

Fig. 12 d.



Total Pu versus IAEA-I n.F1 -J11
10^ 3
neutrons/sec
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.2
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
total Pu (kg)
10^ 1
residuals in Y %
2.00
1.50
1.00
0.50
0.00
-0.5
-1.0
-1.5
-2.0
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
total Pu (kg)

Fig. 12 e.



Total Pu versus IAEA-N n.F1

Fig. 13 a.

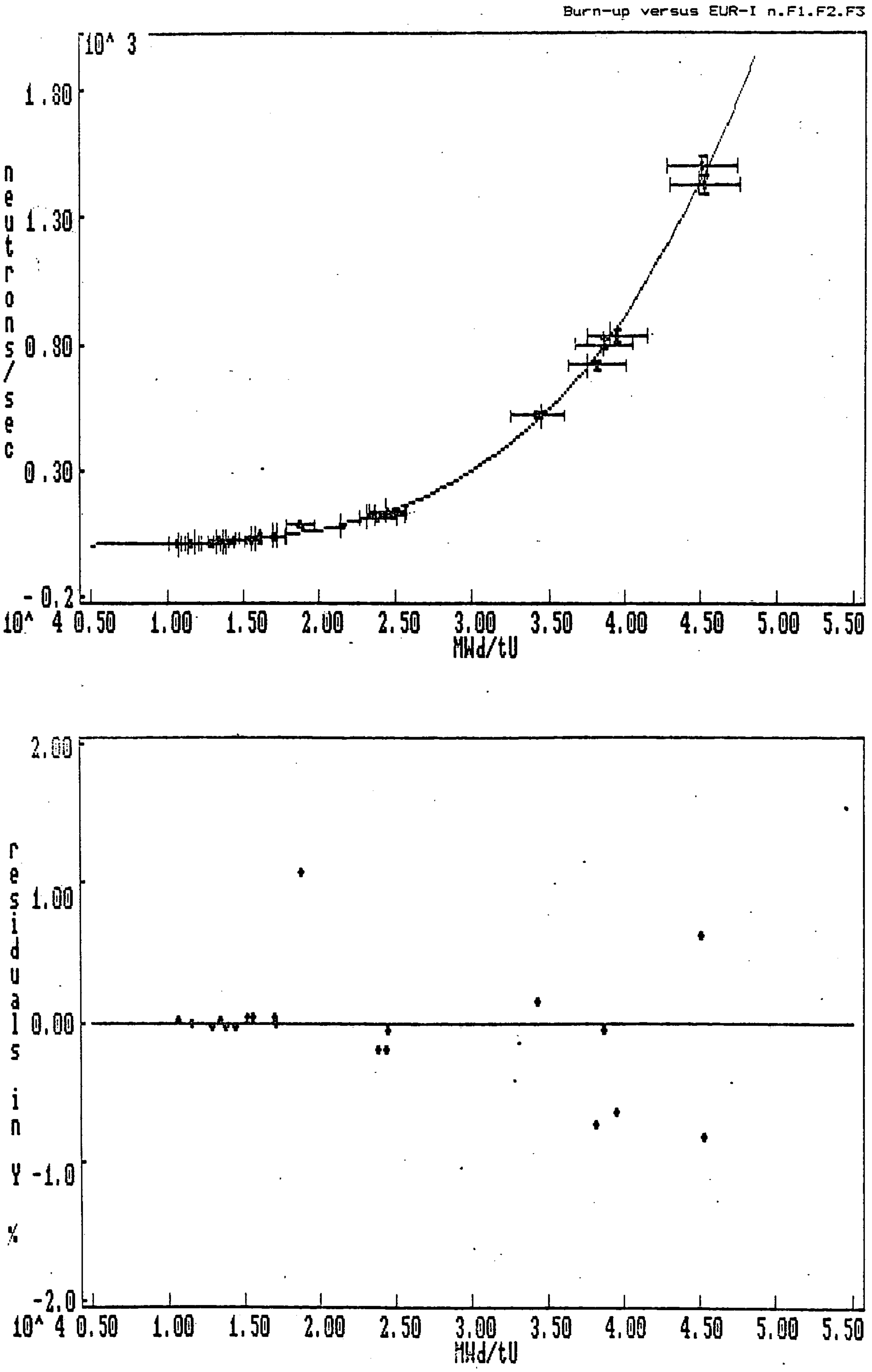

Burn-up versus EUR-I n.F1.F2.F3
10^ 3
neutrons/sec
1.80
1.30
0.80
0.30
- 0.2
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU
residuals in Y %
2.00
1.00
0.00
-1.0
-2.0
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU

Fig. 13 b.

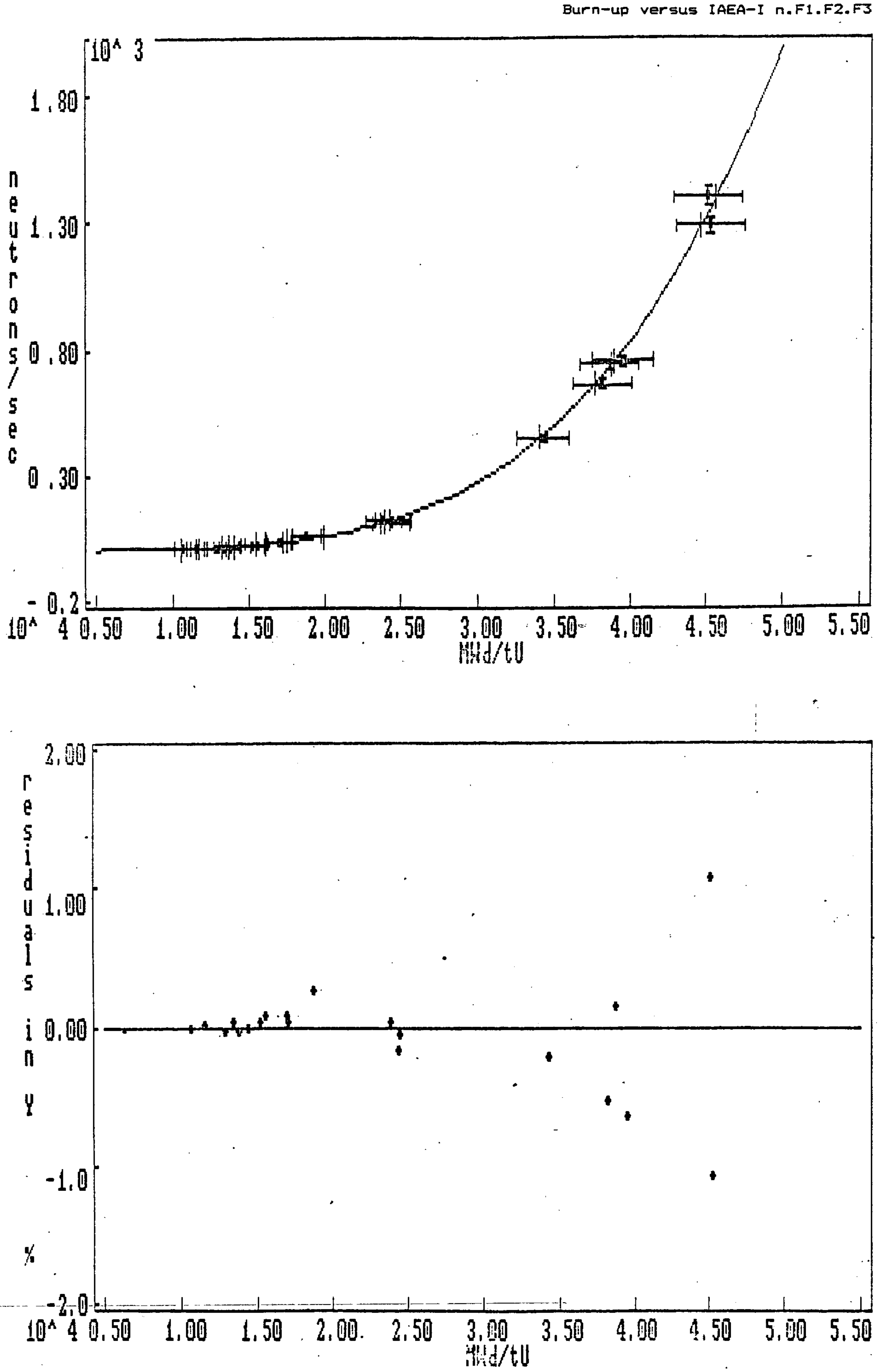

Burn-up versus IAEA-I n.F1.F2.F3
10^ 3
neutrons/sec
1.80
1.30
0.80
0.30
- 0.2
10^ 4 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50
MWd/tU
residuals in y %
2.00
1.00
0.00
-1.0
-2.0
10^ 4 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50
MWd/tU

Fig. 13 c.

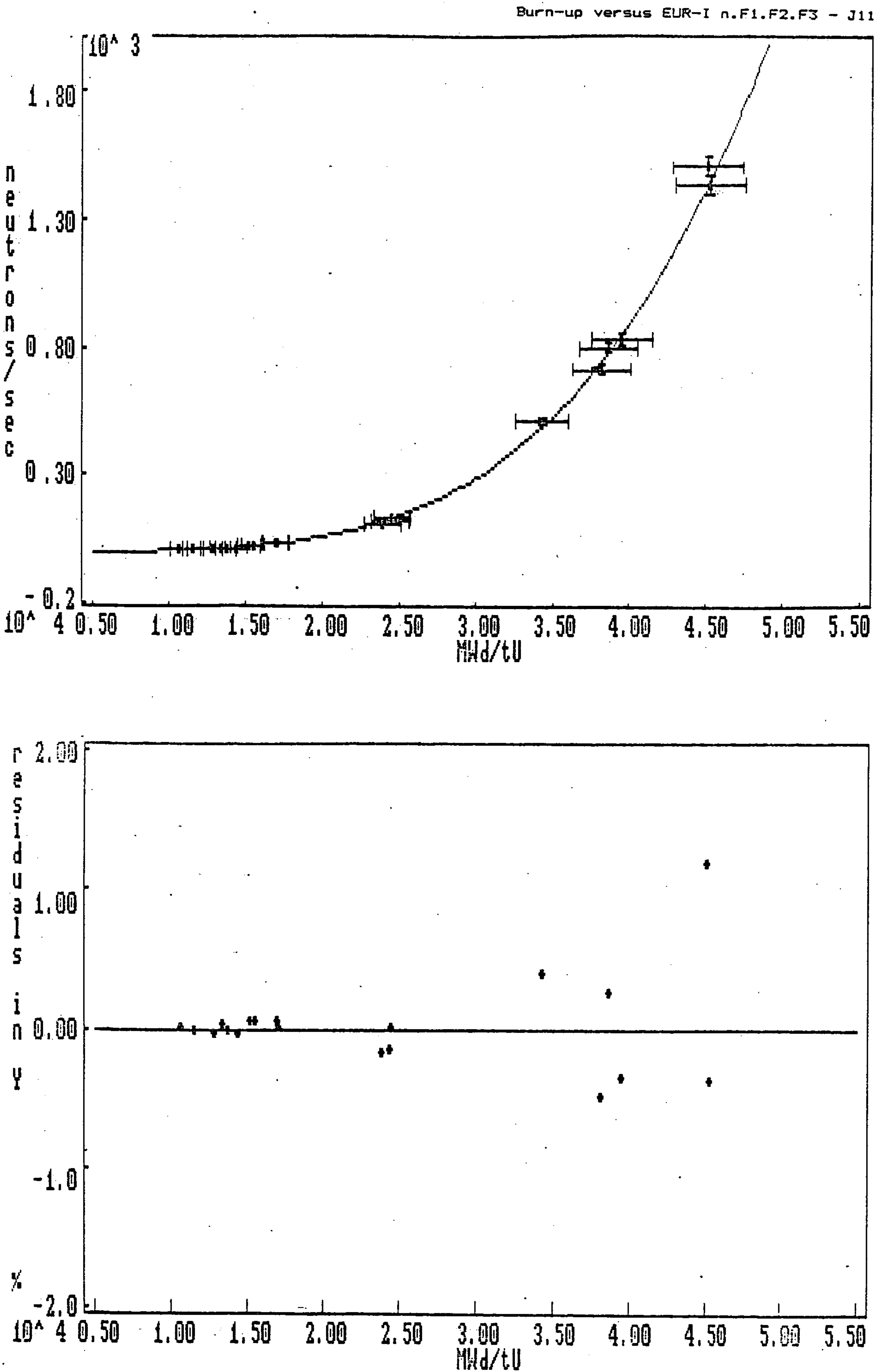

Burn-up versus EUR-I n.F1.F2.F3 - J11
10^ 3
1.80
1.30
0.80
0.30
- 0.2
neutrons/sec
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU
2.00
1.00
0.00
-1.0
-2.0
residuals in y %
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU

Fig. 13 d.

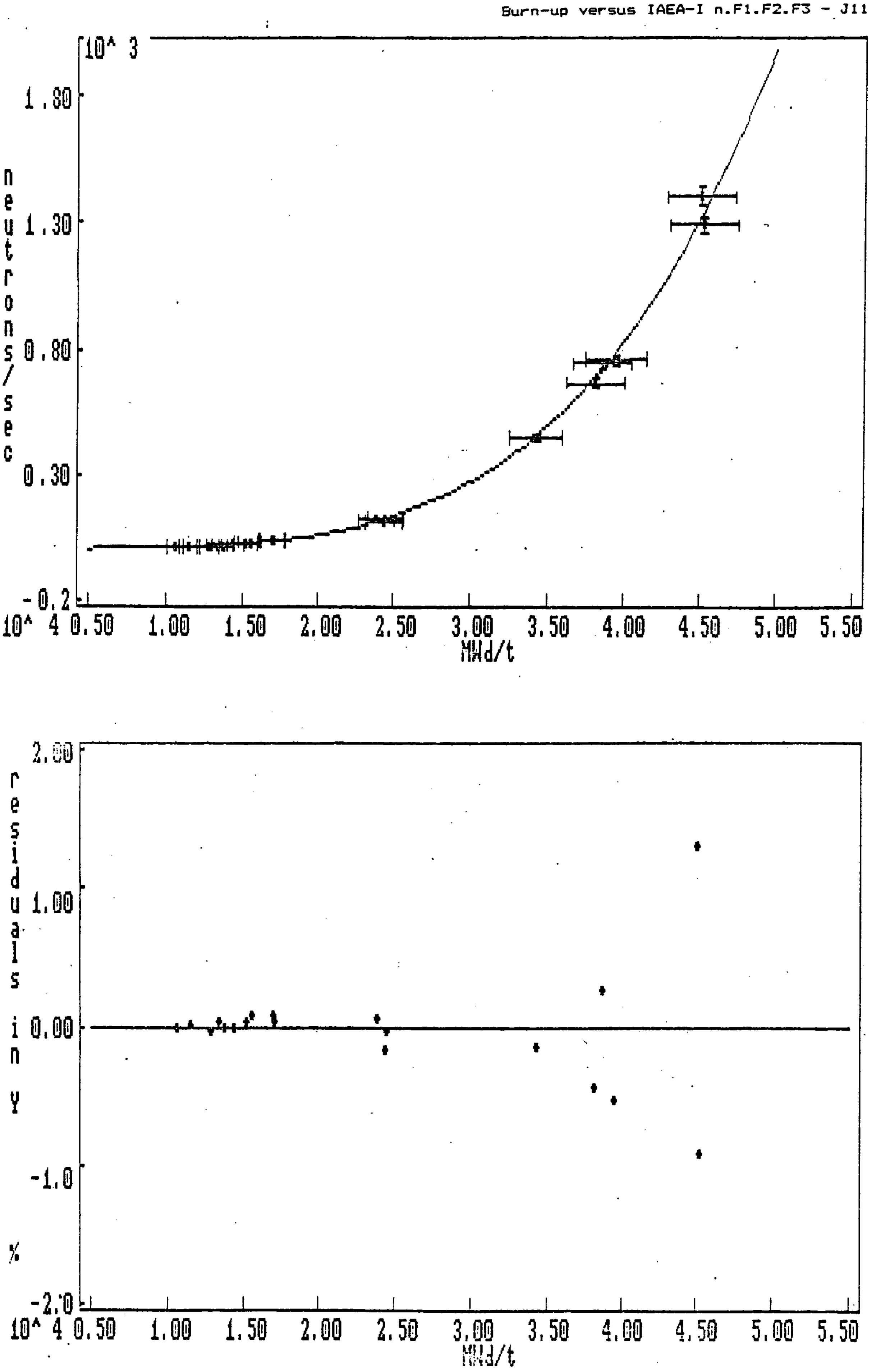
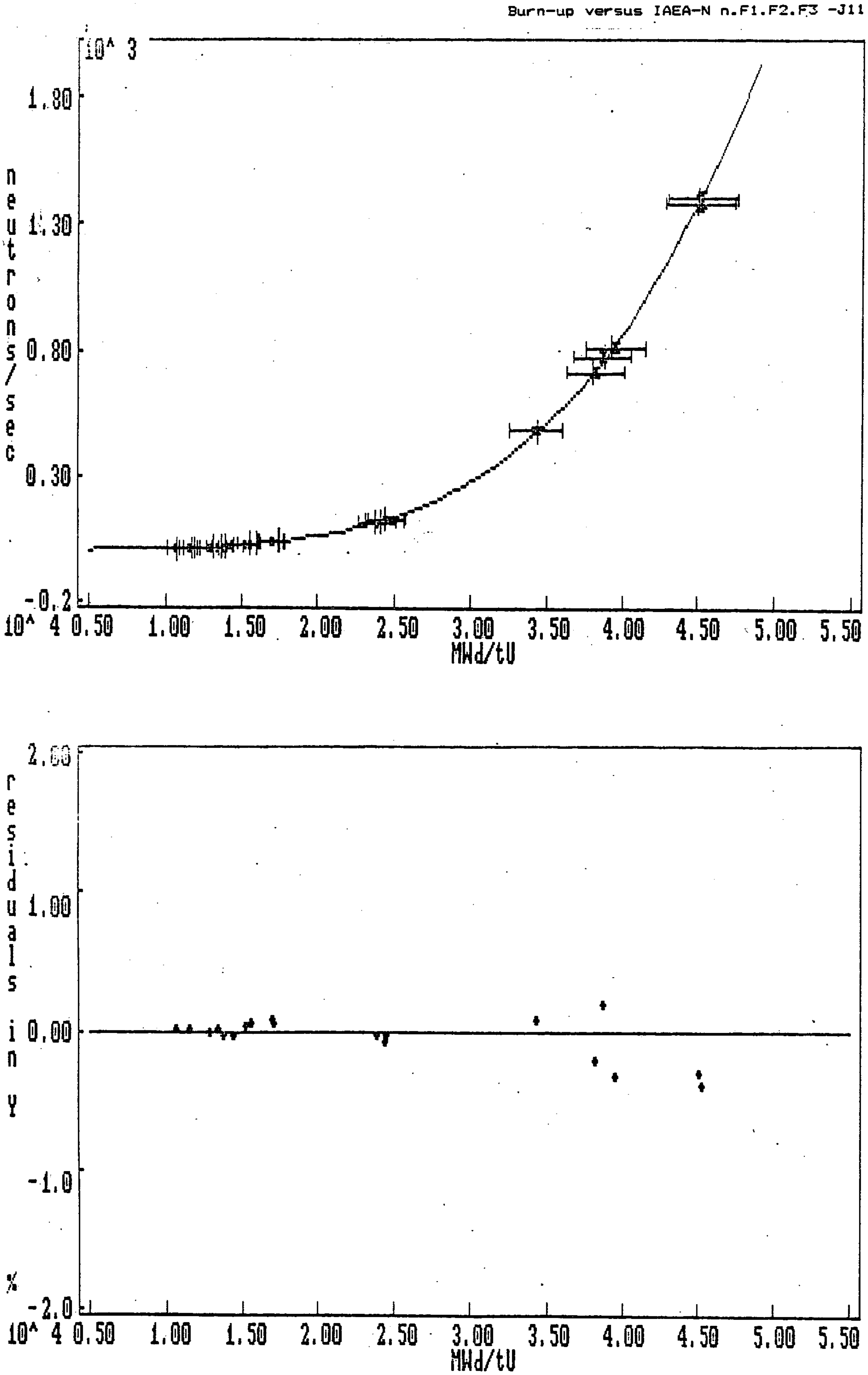

Burn-up versus IAEA-I n.F1.F2.F3 - J11
10^ 3
1.80
1.30
0.80
0.30
-0.2
neutrons/sec
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/t
2.00
1.00
0.00
-1.0
-2.0
residuals in y %
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/t

Fig. 13 e.



Burn-up versus IAEA-N n.F1.F2.F3 -J11
10^ 3
1.80
1.30
0.80
0.30
-0.2
neutrons/sec
10^ 4
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU
2.00
1.00
0.00
-1.0
-2.0
residuals in y
%
10^ 4
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU

Fig. 14 a.

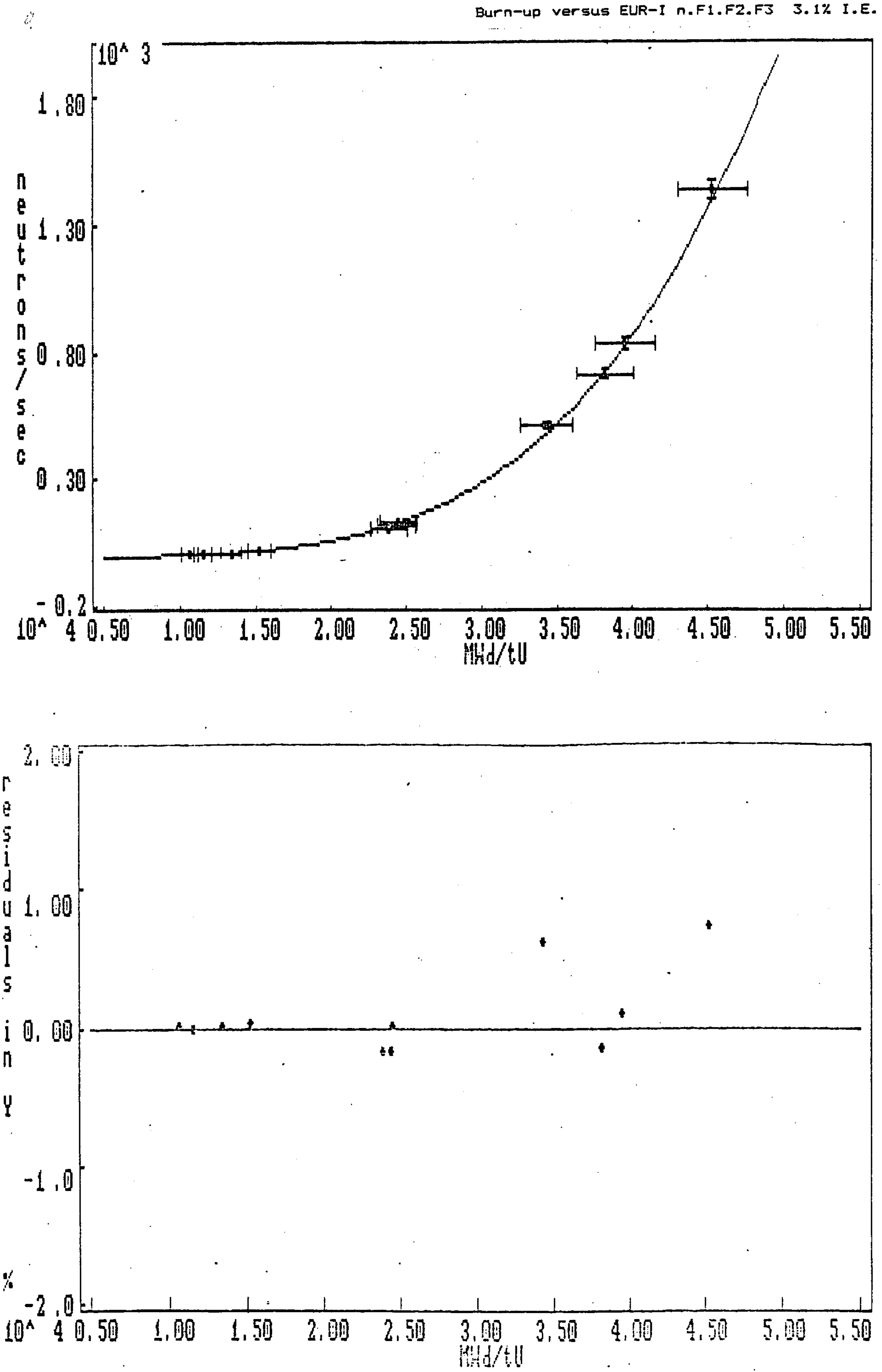

Burn-up versus EUR-I n.F1.F2.F3 3.1% I.E.
10^ 3
1.80
1.30
0.80
0.30
- 0.2
neutrons/sec
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU
2.00
1.00
0.00
-1.0
-2.0
residuals in Y
%
10^ 4 0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
MWd/tU

Fig. 14 b.

Burn-up versus IAEA-I n.F1.F2.F3 3.1% I.E.

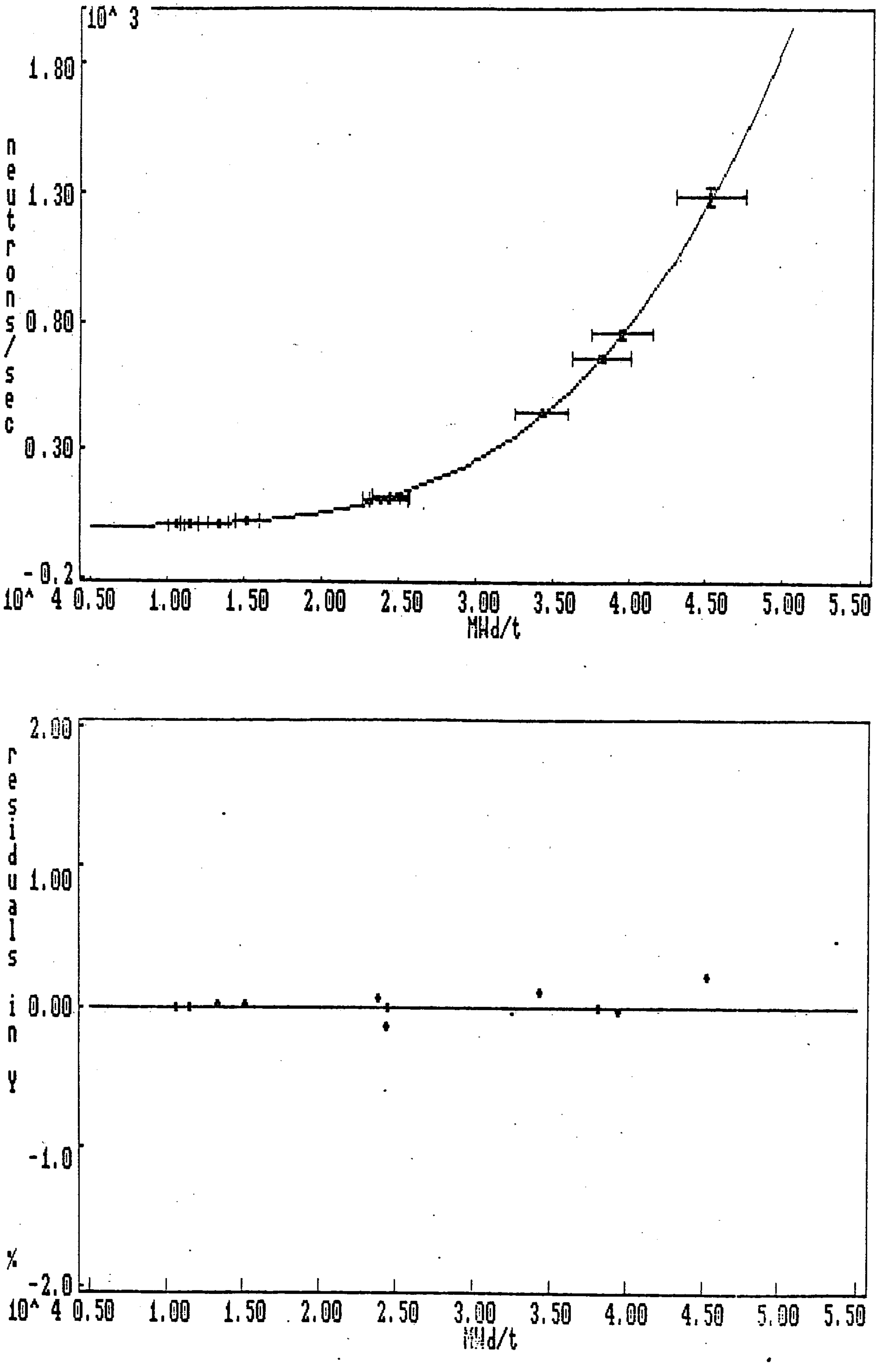
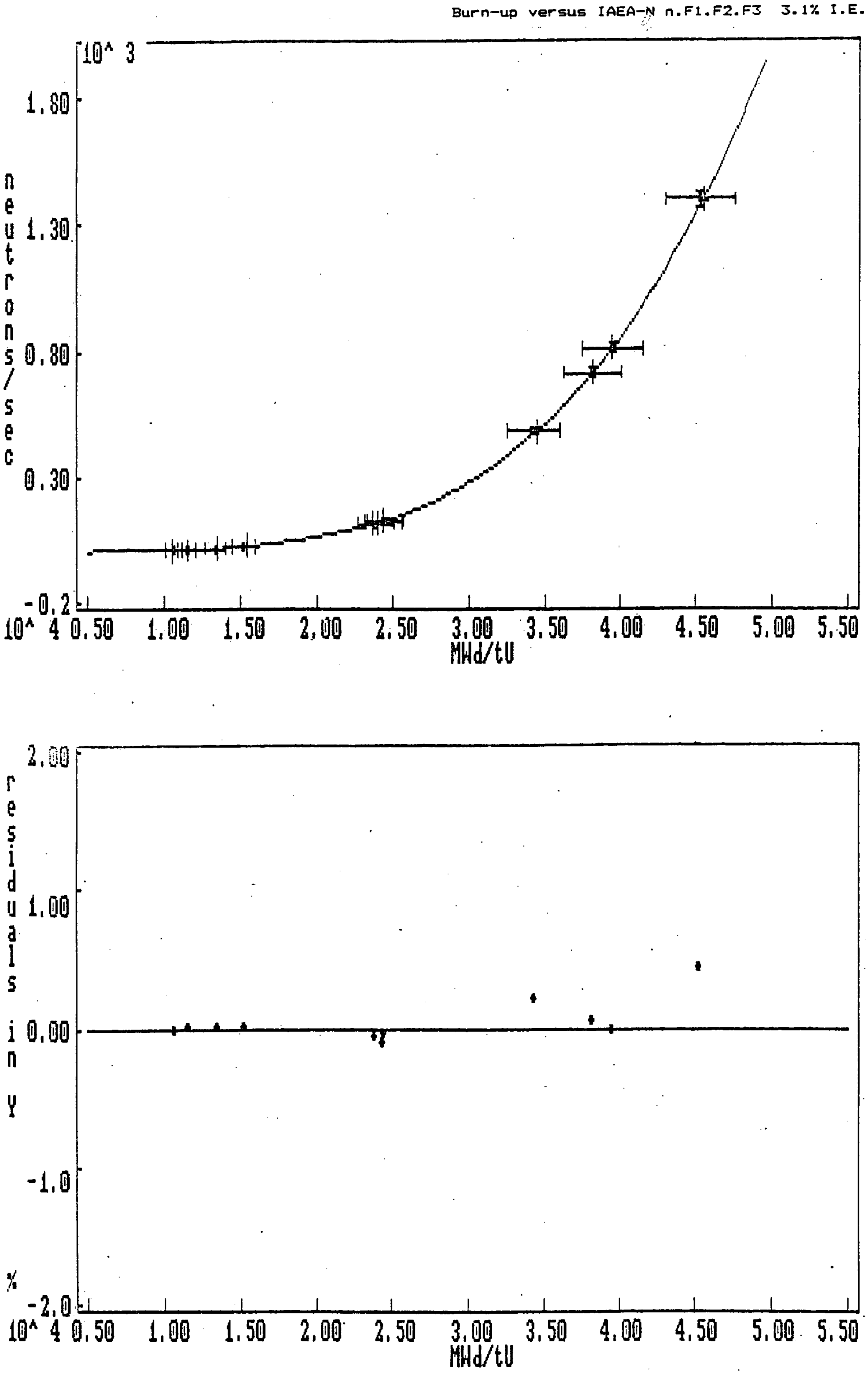
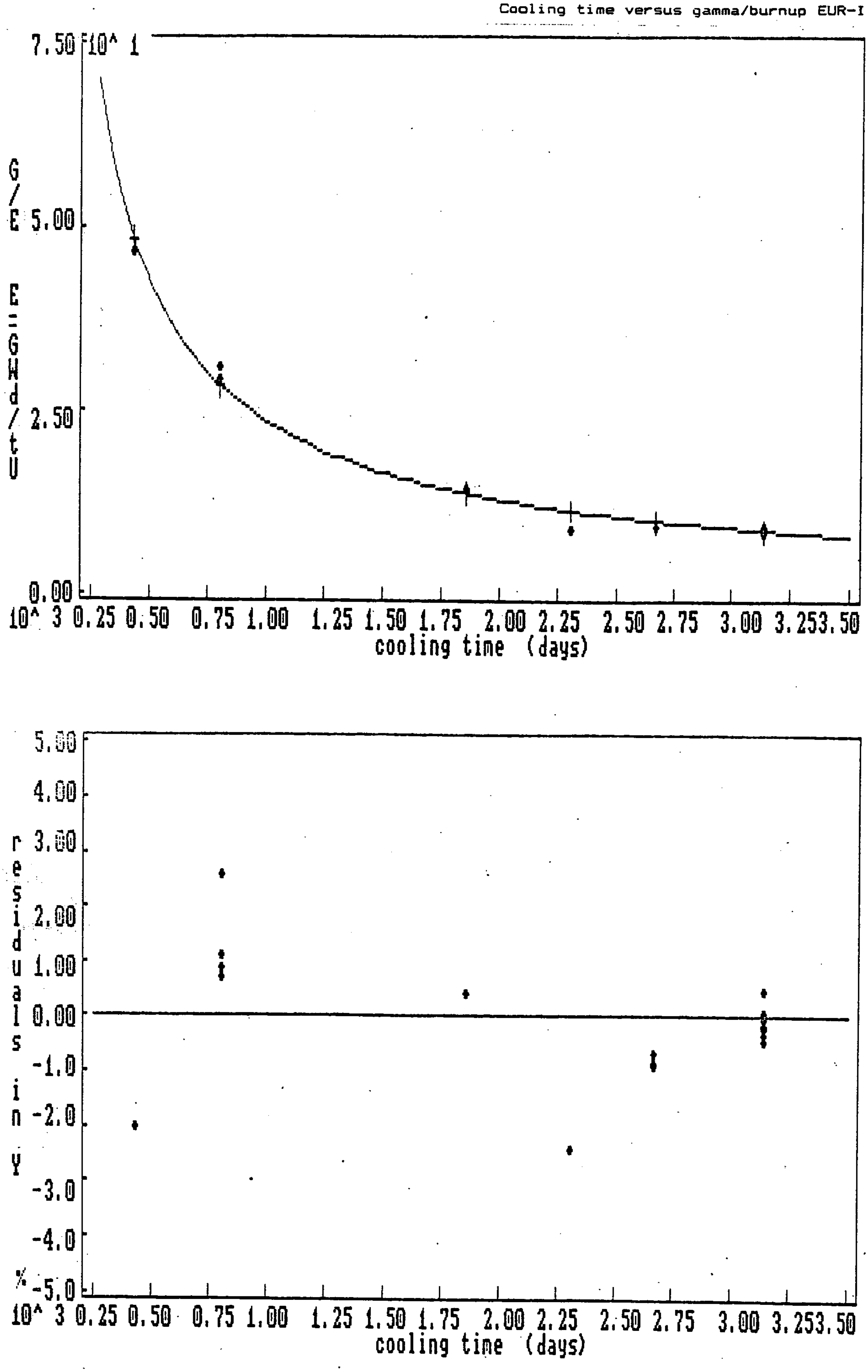


Fig. 14 c.



Burn-up versus IAEA-N n.F1.F2.F3 3.1% I.E.

Fig. 15 a.


Cooling time versus gamma/burnup EUR-I
7.50 10^ 1
5.00
2.50
0.00
G/E E:GWd/tU
10^ 3 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 3.25 3.50
cooling time (days)
5.00
4.00
3.00
2.00
1.00
0.00
-1.0
-2.0
-3.0
-4.0
-5.0
residuals in Y %
10^ 3 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 3.25 3.50
cooling time (days)