Actinide Fission Rate Measurements in Zebra 14

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1 Introduction

Fission chambers have been used to measure the U238, Pu240, Pu241, Pu242, Am241, Am243 and Cm244 fission rates relative to fission in Pu239 at the centre of Zebra Core 14/1, which had a neutron spectrum closely resembling that of PFR. The experimental technique, the results, and their comparison with FGL5 data are reported below.

2 Fission Chambers

2.1 General

The fission chambers used were of the standard Zebra parallel-plate design (Ref 1). The plutonium and uranium chambers already existed (Refs 1 and 2). New chambers were obtained containing deposits of the americium and curium isotopes, prepared by Actinides Group, Harwell.

2.2 Plutonium and Uranium Chambers

The preparation of accurately calibrated Pu239 fission chamber deposits of nominal 50 μg mass for Zebra has been described in Ref 2. One of these deposits was used in a fission chamber (Zeb 45) for these measurements, while the second (Zeb 46) was used as an alpha-counting standard.

The Pu240, Pu241 and Pu242 chambers used were those described in Ref 1. In previous Zebra cores, ie up to MZB, these chambers were counted together with the Pu239 chambers described in Ref 1, which contained 2 mg of Pu239. The quoted masses of the Pu239 chambers have been shown to be (2.8 $\pm$ 1.0)% low by fission comparisons with Zeb 45. It has been found that this discrepancy comprised two components, viz (1.3 $\pm$ 0.6)% arising from the alpha calibration (see Ref 3) and (1.5 $\pm$ 0.8)% due to errors in the corrections (about 9%) for loss of fragments when fission counting the heavy deposits. The Pu240 chambers incur similar large corrections, and their masses have consequently been increased by (2.8 $\pm$ 1.0)%, so that the Pu240/Pu239 fission ratios measured here are directly comparable with previous values. The Pu241 and Pu242 chambers, however, contain comparatively thin deposits incuring corrections for fission fragment loss of between 2 and 3%; their masses have therefore been increased by only (1.3 $\pm$ 0.6)%, and it is necessary to increase previously measured Pu241/Pu239 and Pu242/Pu239 ratios by (1.5 $\pm$ 0.8)% to compare with the present results; ie previous C/E values for these two ratios have to be reduced by (1.5 $\pm$ 0.8)%.

The half-life data used for the plutonium deposits were taken from Ref 1, and are reproduced here in Table 1. The atomic content of each fission chamber is given in Table 2.

As a check on the Pu241 chamber alpha calibration, the Pu241/Pu239 fission cross-section in the NESTOR thermal column was measured. A value of 1.326 $\pm$ 2.5% was obtained; this compares with a ratio of 1.364 $\pm$ 1.8% obtained from the Pu241 thermal average cross-section recommended in Ref 4 and the corresponding Pu239 figure used in Ref 2. The 2.9% discrepancy is not surprising in view of the uncertainty (2%) on the original alpha calibration and the large correction (about 30%) for the Pu241 decay to Am241, since the deposits were prepared nine years ago.

The U238 fission rate was measured using a natural uranium fission chamber, Zeb 9. This chamber had been calibrated by thermal fission assay of the U235 content relative to a standard U235 chamber (see Ref 2). A U235 fission measurement was also made here to correct for U235 fission in the natural uranium. The atomic content of Zeb 9 is included in Table 2.

2.3 Americium and Curium Chambers

2.3.1 Deposit Specification

One deposit each of Am241, Am243 and two of Cm244 have been prepared. The general specification of the deposits was the same as that of the Pu239 standard deposits (Ref 2); ie they were 20 mm in diameter on polished steel trays 28 mm in diameter and prepared by vacuum sublimation. The nominal masses for each nuclide were 10 μg, 50 μg and 1 μg respectively. These were selected to provide adequate fast fission rates without incurring excessive alpha decay rates.

2.3.2 Isotope Stocks

The Am241 and Am243 deposits (labelled Zeb 51 and Zeb 52 respectively) were taken from stocks used for the recent capture cross-section measurements in Zebra. They had been treated repeatedly to remove plutonium. Isotopic analyses obtained at AWRE have confirmed the absence of significant contamination by other americium isotopes (less than 0.05% by atoms, with Am242 less than 0.01%) while further measurements, described below, have confirmed the absence of significant contamination by other elements.

Alpha spectrometry showed that the first Cm244 deposit (Zeb 53) was prepared from stock containing a high level of Pu240 contamination (see Section 2.3.3). A second deposit (Zeb 54) was prepared from the same stock after chemical treatment to remove plutonium. Isotopic analyses of the curium obtained at Harwell revealed significant concentrations of Cm245 (1.5%) Cm246 (5.6%) Cm247 (0.12%) and Cm248 (0.07%) where the concentrations are % by atoms of total Cm content. No uncertainties were provided with the analyses, but it is thought that these should be small compared with those of the cross-sections assumed when applying corrections for fast fission. The analyses also provided the isotopic content of the Pu contamination in the first stock, the Pu239/Pu240 and Pu238/Pu240 ratios being 0.019 and 0.005 respectively. There was no evidence on the concentration of plutonium in the separated stock.

2.3.3 Alpha Counting

Alpha spectrometric analyses of the deposits were made at Harwell. Detectable contamination of both the americium isotopes was insignificant, ie would contribute less than 0.1% of the total fission in Zebra. The curium alpha spectrum was found to contain (0.116 ± 0.005)% Pu240 activity, implying a Pu240 atom content of (29 ± 1)%, which had presumably 'grown in' from Cm244 alpha decay (half-life 17.85 years). Alpha analysis of the second deposit, of purified curium, showed no plutonium

activity, though the limit of detection was only 0.05% by alpha activity. The Pu^{240} content has been taken as zero, but an error corresponding to the limit on the alpha spectrometry has been included in the results ($\pm$ 11%). An uncertainty has also been included to allow for Am^{243} contamination up to the level of detection on the first alpha spectrometry measurement - viz 0.01% by alpha - since no evidence is available as to the level of separation achieved when the Cm^{244} stock was originally purified. (Am^{243} is the previous long-lived nuclide in the capture chain leading to Cm^{244}). Both Cm^{244} deposits were retained and used in fission chambers.

Absolute calibration of the deposits was achieved by low-geometry alpha assay at Zebra, using the same geometries as for the Pu^{239} deposits (Ref 2). Each deposit was counted in at least two geometries, the efficiency of which varied by not less than a factor of two. No significant variation in the disintegration rates obtained from the different geometries was observed within the experimental accuracy of $\pm$ 0.3%.

A standard Pu^{239} deposit (Zeb 46) was counted repeatedly throughout the measurements and no significant variation was observed from previous measurements within a statistical accuracy of about $\pm$ 0.2%. Absolute disintegration rates were also obtained at Harwell, and the results are compared in Table 3.

The deposit masses were calculated using the Zebra alpha-assay results and the alpha spectrometric analyses from Harwell. The half-lives used were obtained from Ref 5 and are given in Table 1. The atomic content of the deposits is given in Table 2.

2.3.4 Preliminary Fission Measurements

Following the alpha assay, the deposits were sealed in Zebra fission chambers. Examination of the pulse height distributions obtained from the chambers confirmed that the quality of the deposits was satisfactory; the corrections required for the loss of fission fragments below the discriminator bias level were 0.4%, 0.3% and 0.7% for the Am^{241}, Am^{243} and Cm^{244} chambers respectively. The somewhat lower resolution exhibited by the Cm^{244} chambers was caused by alpha build-up (the alpha activity from a 1 μg Cm^{244} deposit is equivalent to that from about 1 mg of Pu^{239}).

The spontaneous fission rate in the two curium chambers was recorded; the results of this measurement are shown in Table 4 where the spontaneous fission rate is compared with the alpha decay rate and the ratio of the two decay modes compared with published data (Ref 6). The agreement is excellent after a correction of (5.1 $\pm$ 0.4)% for spontaneous fission in other Cm isotopes. There is no significant difference between the two chambers.

The chambers were irradiated in the Nestor thermal column together with Pu^{239} fission chamber, Zeb 45, to assay any thermally-fissile contamination which might have escaped detection by alpha or mass analysis. Contamination of the americium chambers was found to be sufficient to produce less than 0.1% of the total fission in Zebra. The curium chambers however recorded fission events equivalent to (4.9 $\pm$ 0.1)% and (4.0 $\pm$ 0.1)% Pu^{239} by atoms respectively relative to Cm^{244} content. It was assumed that the 0.9% difference in these levels was made up of Pu^{239}, since plutonium was separated from the stock before producing

the second chamber. The alpha spectrometry results for the first stock, taken together with the mass spectrometry result, indicate a concentration of 0.8% of Pu239 in good agreement; the balance of the contamination is equivalent to (1.5 ± 0.1)% by atoms of Cm245, which is also in excellent agreement with the concentration obtained by isotopic analysis. The Cm245 would not have been detected by alpha assay (contributing 3.1×10^{-3}% of the activity on the low energy side of the Cm244 peak). The Cm245/Pu239 thermal fission cross-section ratio of 2.7 was obtained from Ref 7.

The Cm245 and Pu239 atom concentrations deduced for the Cm chambers are included in Table 2.

To summarise, the americium chambers contain adequately pure deposits but the Cm244 chambers are significantly contaminated as follows:-

1 Pu240 contributes (25 ± 1.1)% of fast fissions in Zeb 53. The corresponding figure for Zeb 54 is (0.0 ± 11)%.

2 Cm245 and Cm247 together contribute (6.9 ± 2.4)% and (9.6 ± 3.2)% of fast fissions in Zeb 53 and Zeb 54 respectively. Cm246 contributes (2.6 ± 1.3)% and (3.6 ± 1.8)%.

3 Am243 contamination may contribute up to about 3% of fast fissions in the chambers.

3 Measurement in Zebra

3.1 Experimental Procedure

Fission chambers were located in turn in a half-element at position 50-50, the centre of Core 14/1. The half-element was terminated at the centre line and contained 5 core cells with a sodium plate at the top. Fission chambers were inserted on a rigid extension via a brass guide tube and were located (1.0 ± 0.5) mm above the sodium plate. The arrangement is illustrated in Figure 1.

During the measurements the reactor power was monitored by the four reactor pulse channels. Variations in power were small (less than 0.2%); the nominal central flux was 12×10^9 neutrons cm^{-2} s^{-1}. Two chambers were used to measure the Pu240, Pu241, Pu242 and Cm244 fission rates. The Pu239, Am241 and Am243 fission rates were measured with a single chamber, but the measurements were repeated. One measurement of the U238 fission rate was made. The data for the Pu239 chamber was checked by counting relative to a second Pu239 standard chamber, Zeb 32; no significant change in the ratio of the response of the two chambers compared with previous measurements was observed within the experimental accuracy of ± 0.3%.

3.2 Experimental Results

The results are summarised in Table 5. Associated uncertainties are listed in Table 6.

The result of each chamber measurement has been corrected for fission in other isotopes, so that the results quoted are the fission rates for the principal isotope alone. The estimated contributions of impurity isotopes to fission in each chamber are given in Table 7.

The Pu241 chamber masses used here were corrected for decay of the isotope since assay assuming a half life of 14.0 ± 0.6 years. Current reassessments, however (Ref 5), indicate a value of 14.9 years. If this figure were used, the measured Pu241 fission rate would be reduced by 2.5%.

It has been noted above (Section 2.3) that although curium stock treated to remove plutonium was used to produce the deposit for Zeb 54, no evidence is yet available to prove that the plutonium concentration is insignificant; the modest discrepancy of 1.7% between the two results is, however, encouraging.

4 Comparison with FGL5 Data

Data for all the isotopes under discussion is available in the FGL5 library. For U238, Pu239, Pu240 and Pu241 the data is in fine (2000) group form; for Pu242, Am241, Am243 and Cm244 it is in 37 groups.

A MURAL calculation was made for the C13-1A cell using FGL5 data in which the sodium plate adjacent to the fission chamber during the measurements, and the cores of the plutonium metal and uranium oxide plates were isolated. The remaining regions were homogenised. Since approximately half the neutrons incident on the chamber deposit come from the adjacent sodium plate and the remainder originate above the chamber in the various regions of the neighbouring elements, it is thought that the mean of a volume average reaction rate and the value of the reaction rate in the sodium plate provides the best estimate of the value in the chamber (Ref 10). A value for the fission rate of each isotope of interest in the fission chamber relative to Pu239 fission was obtained in this way. The difference between the two ratios making up the mean was in no case greater than 5% (see Table 5). The 37-group spectrum in the sodium plate is given in Table 8; the standard spectrum used to obtain the one-group FOGD5(A) data set (Ref 8) for CFR and PFR is also given and the one-group cross-sections obtained here for the sodium plate are compared with the FOGD5(A) values in Table 9. The origin of the FGL5 data is indicated in this Table.

In Table 5, the calculated and experimental fission ratios are compared, and C/E values obtained. Estimated corrections of $(0.0 \pm 0.1)\%$ for Pu241/Pu239 fission, $+ (1.5 \pm 1.0)\%$ for U238/Pu239 fission and $+(0.6 \pm 0.4)\%$ for each of the other ratios have been applied to the chamber measurements to account for inelastic scattering in the fission chamber walls and the empty sheath. These corrections are based on calculations reported in Refs 1 and 11.

Additional uncertainties arise when the calculations are compared with experiment because of the chamber geometry in Zebra. These are estimated to be $\pm$ 1% for F1/F9 and $\pm$ 4% for the remaining ratios (Ref 10). It is thought that further work could reduce the $\pm$ 4% error, perhaps by a factor of two.

It should be noted that further work to establish more accurately the magnitude of Am243 and plutonium contamination in the curium stock could reduce the uncertainty on the result reported here from over 6% to about 4%.

5 Summary

Measurements of fission in seven actinide isotopes relative to Pu239 fission have been made and the results compared with FGL5 data. C/E values obtained were as follows:-

U238	$1.043 \pm 4.4\%$	(cf $1.032 \pm 4.4\%$ in MZB)
Pu240	$1.003 \pm 4.6\%$	(cf 1.000 ± 4.4* in MZB)
Pu241	$1.048 \pm 3.2\%$	(cf $1.049 \pm 3.3\%$* in MZB)
Pu242	$1.231 \pm 5.0\%$	
Am241	$1.260 \pm 4.1\%$	
Am243	$0.882 \pm 4.1\%$	
Cm244	$1.348 \pm 7.5\%$	

* corrected value (see Section 2.2)

In all cases except Pu241 and Cm244 the major error arises from the uncertainty in treating the chamber geometry ($\pm$ 4%). Further work would probably allow a reduction of this error to about $\pm$ 2%.

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It is hoped to improve the accuracy of the Cm result by about 2% by determining the levels of Pu^{240} and Am^{243} contamination more precisely.

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Table 1 - Alpha Half-Lives Used to Calculate Deposit Masses

Isotope	Half-life (years)	Reference
U234	0.2442×10^6	15
U235	0.704×10^9	16
Pu239	$2.435 \times 10^4 \pm 0.2\%$	1
Pu240	$6.600 \times 10^3 \pm 0.6\%$	1
Pu241	$5.72 \times 10^5 \pm 0.2\%$	1
Pu242	$3.76 \times 10^5 \pm 1.1\%$	1
Am241	$433 \pm 0.5\%$	5
Am243	$7400 \pm 0.5\%$	5
Cm244	$17.85 \pm 0.3\%$	5

Note: U234 and U235 half lives quoted were used to calibrate the U235 chamber against which the natural uranium chamber was calibrated by thermal fission assay.

Table 2 - Number of Atoms x 10^{18} of Fissile Isotopes Present in Significant Quantities in Chamber Deposits

	U235	U238	Pu238	Pu239	Pu240	Pu241	Pu242	Am241	Am243	Cm243	Cm244	Cm245	Cm246	Cm247	Cm248
9	0.1147	4.633	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	0.039	3.974	-	-	-	-	-	-	-	-	-	-
7	-	-	-	0.039	3.912	-	-	-	-	-	-	-	-	-	-
22	-	-	-	0.032	0.033	0.283	-	0.157	-	-	-	-	-	-	-
23	-	-	-	0.032	0.034	0.286	-	0.158	-	-	-	-	-	-	-
24	-	-	-	0.048	0.038	0.031	1.553	0.024	-	-	-	-	-	-	-
25	-	-	-	0.047	0.038	0.030	1.498	0.023	-	-	-	-	-	-	-
5	-	-	-	0.1147	0.0011	-	-	-	-	-	-	-	-	-	-
1	-	-	-	-	-	-	-	0.02300	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	0.00004	0.1147	-	-	-	-	-	-
3	-	-	0.000005	0.000017	0.000960	-	-	-	-	0.000003	0.002234	0.000037	0.000134	0.000027	0.000001
4	-	-	-	-	<0.00005	-	-	-	-	0.000003	0.002859	0.000047	0.000172	0.000035	0.00000

Notes: 1 The errors associated with the atom numbers are given in Table 6. See also text, Section 2.3.

2 The atom numbers have been reduced to allow for self-absorption of fission fragments in the deposits. The corrections were not significant (ie less than 0.2%) except for chambers 4 and 7 (4.9%), 22 and 23 (0.7%) and 24 and 25 (1.0%). No correction was necessary for the natural uranium chamber since it was calibrated by thermal fission assay.

3 The contents of the Pu241 and Pu242 fission chambers have been corrected to allow for the Pu241 decay. A half-life of (14.0 ± 0.6) years has been used.

Table 3 - Comparison of Alpha Assay Results Obtained at Harwell and Zebra

Chamber No	Alpha disintegration rate (total) x 10^6 s^{-1}		Zebra result / Harwell result
	Obtained at Zebra	Obtained at Harwell	
51 (Am241)	1.167 ± .2%	1.162 ± 0.2%	1.004 ± 0.3%
52 (Am243)	0.3426 ± .2%	0.3432 ± 0.2%	0.998 ± 0.3%
53 (Cm244)	2.755 ± 0.2%	2.742 ± 0.2%	1.005 ± 0.3%
54 (Cm244)	3.517 ± 0.2%	3.482 ± 0.2%	1.010 ± 0.3%

Table 4 - Cm244 Alpha and Spontaneous Fission Decay

Chamber No	Alpha disintegration rate x $10^6 S^{-1}$	Fission disintegration rate S^{-1}	Experimental Alpha / Fission x 10^6	Mean experimental Ratio	Expected Ratio	Expected ratio / Experimental ratio
Zeb 53	2.749 ± 0.2%	3.709 ± 0.4%r 0.5%s	0.7412 ± 0.5%r 0.5%s	0.7426 ± 0.6%	0.743 ± 1.3%	1.001 ± 1.4%
Zeb 54	3.517 ± 0.2%	4.728 ± 0.4%r 0.4%s	0.7439 ± 0.5%r 0.4%s			

Note to Table 4: The random errors on the experimental numbers arise from counting statistics and from corrections for biased off low energy events. The systematic error on the spontaneous fission measurements arises from the uncertainties in the Cm246 and Cm248 spontaneous fission half lives (± 6% and ± 11%) and in the isotopic analyses of the stocks (± 5%), corrections for spontaneous fission in these isotopes being (4.8 ± 0.4)% and (0.2 ± 0.02)% respectively.

Table 5 - Fission Rates in Chambers Expressed Relative to Pu239 Fission

Chamber No	Principal Isotope	Experimental fission rate ratio (1)	Mean experimental fission rate ratio for isotope	Experimental fission rate ratio corrected for inelastic scattering	Calculated fission rate ratio (2)	Calculation / Experiment
9	U238	0.02706 ± .6%r ± 1.5%r	0.02706 ± .8%r ± 1.5%s	0.02747 ± 1.1%r ± 1.5%s	0.02864	1.043 ± 4.4%
4	Pu240	0.2266 ± 1.2% r ± 1.9% s	0.2249 ± 1.1% r ± 1.9% s	0.2262 ± 1.2% r ± 1.9% s	0.2268	1.003 ± 4.6%
7	Pu240	0.2232 ± 1.2% r ± 1.9% s				
22	Pu241	1.318 ± 0.7% r ± 3.0% s	1.320 ± 0.6% r ± 3.0% s	1.320 ± 0.6%r ± 3.0% s	1.383	1.048 ± 3.2%
23	Pu241	1.321 ± 0.7% r ± 3.0% s				
24	Pu242	0.1437 ± 1.0% r ± 2.9% s	0.1459 ± 0.9% r ± 2.9% s	0.1468 ± 1.0% r ± 2.9% s	0.1807	1.231 ± 5.0%
25	Pu242	0.1480 ± 1.0% r ± 2.9% s				
51	Am241	0.1756 ± 0.4% r ± 0.7% s	0.1752 ± 0.3% r ± 0.7% s	0.1763 ± 0.5% r ± 0.7% s	0.2222	1.260 ± 4.1%
51	Am241	0.1748 ± 0.4% r ± 0.7% s				
52	Am243	0.1310 ± 0.4% r ± 0.7% s	0.1308 ± 0.3% r ± 0.7% s	0.1316 ± 0.5% r ± 0.7% s	0.1161	0.882 ± 4.1%
52	Am243	0.1305 ± 0.4% r ± 0.7% s				
53	Cm244	0.2417 ± 0.9% r ± 6.1% s	0.2408 ± 0.7% r ± 6.1%s	0.2422 ± 0.9% r ± 6.1% s	0.3265	1.348 ± 7.5%
54	Cm244	0.2376 ± 0.7% r ± 12% s				

Notes to Table 5 - Fission Rates in Chambers Expressed Relative to Pu239 Fission

1 r and s signify random and systematic errors respectively.

2 The calculated ratios are means of values in the sodium plate adjacent to the chamber and the volume average (see Section 4). The difference between the 2 calculated values were as follows:-

$\frac{U238}{Pu239}$	3.3%	$\frac{Pu241}{Pu239}$	.3%
$\frac{Pu240}{Pu239}$	3.0%	$\frac{Am241}{Pu239}$	2.6%
$\frac{Pu242}{Pu239}$	3.8%	$\frac{Cm244}{Pu239}$	2.8%
$\frac{Am243}{Pu239}$	4.8%		

Table 6 - Uncertainties Associated with Experimental Fission Ratios in Fission Chambers

Origin of Uncertainty	Isotope and Magnitude of Uncertainty							
	U238	Pu240	Pu241	Pu242	Am241	Am243	Cm244 (Chamber 53)	Cm244 (Chamber 54
Pu239 fission measurement ..	0.4%s0.3%r	0.4%s 0.3%r	0.4%s 0.3%r	0.4%s 0.3%r	0.4%s 0.3%r	0.4%s 0.3%r	0.4%s 0.3%r	0.4%s 0.3%r
Assay of Deposit	0.9%s	1.2%s	2.1%s	1.7%s	0.3%s	0.3%s	0.3%s	0.3%s
Alpha half life	0.6%s	0.6%s	0.2%s	1.1%s	0.5%s	0.5%s	0.3%s	0.3%s
Fission counting statistics ..	0.2%r	0.2%r	0.2%r	0.2%r	0.2%r	0.2%r	0.4%r	0.4%r
Corr. for biased off fission events	0.4%r	1.0%r	0.4%r	0.6%r	0.2%r	0.1%r	0.3%r	0.3%r
Correction for fission counting dead time losses	0.0%	0.3%r	0.3%r	0.2%r	0.0%r	0.0%r	0.0%r	0.0%r
Correction for self-absorption of fission fragments	-	1.0%s	0.3%s	0.3%s	0.1%s	0.1%s	0.1%s	0.1%s
Correction for fission in impurity isotopes	0.3%s	0.4%s	0.2%s	0.6%s	0.0%	0.0%	3.8%s	12%s
Correction for decay of Pu241	-	-	1.5%s	0.3%s	-	-	-	-
Correction for Cm244 spon. fiss.	-	-	-	-	-	-	0.2%s	0.2%s
Total error on chamber count rate	0.6%r1.2%s	1.1%r 1.8%s	0.6%r 2.6%s	0.8%r 2.2%s	0.4%r 0.7%s	0.4%r 0.7%s	0.6%r 3.8%s	0.6%r 12.0%
Total error on principal isotope	0.8%r1.5%s	1.2%r 1.9%s	0.7%r 3.0%s	1.0%r 2.9%s	0.4%r 0.7%s	0.4%r 0.7%s	0.9%r 6.1%s	0.7%r 14%s

Note: 1 r and s signify random and systematic errors respectively.

Table 7 - Contributions from Fission in Impurity Isotopes

Chamber No and Principal Isotopes	Impurity Isotopes and % Contributions to Total Fission Rate										
	U235	Pu238	Pu239	Pu240	Pu241	Am241	Am243	Cm243	Cm245	Cm246	Total contribut
Zeb 9, U238	27.4±0.3										27.4 ± 0.3
Zeb 45, Pu239				0.2 ± .1							0.2 ± 0.1
Zeb 4 and 7, Pu240			4.1 ± 0.4								4.1 ± 0.4
Zeb 22 and 23, Pu241			7.2 ± 0.1	1.7 ± <.1		6.2 ± 0.1					15.1 ± 0.2
Zeb 24 and 25, Pu242			14.5 ± 0.2	2.6 ± <.1	12.2 ± .5	1.3 ± <.1					30.6 ± 0.6
Zeb 51, Am241											0.0 ± 0.0
Zeb 52, Am243											0.0 ± 0.0
Zeb 53, Cm244		0.4 ±0.2	2.0 ± 0.4	25.1±1.1			0.0 ± 2.2	0.5 ± 0.2	6.9±2.4	2.6 ±1.3	37.5 ± 3.8%
Zeb 54, Cm244				0.0± 11			0.0 ± 2.8	0.7 ± 0.3	9.6±3.2	3.6 ±3.2	13.9 ± 12%

Notes: 1 Insignificant contributions, ie less than 0.1%, are ignored.

2 Where possible, the corrections were obtained from the fission ratios measured here. Otherwise calculated cross-sections were used. The Pu238 and Cm243 cross-sections were obtained from Ref 8, while the Cm245 cross-section was calculated from the neutron spectrum and data from Ref 9. The cross-section for Cm246, relative to Cm244, was obtained from Ref 14.

3 Cm247 has been included with Cm245 in the Cm deposits. The concentration of Cm247 is small (0.13% of the Cm atoms).

Table 8 - Spectrum in Sodium Plate Adjacent to Fission Chamber

Group	Lower energy	Spectrum in sodium plate adjacent to chamber	Standard spectrum from Ref 8
1	10.0 Mev	0.012	0.012
2	6.065	0.233	0.229
3	3.679	1.147	1.115
4	2.231	3.240	3.149
5	1.353	4.753	4.366
6	820.9 Kev	5.871	5.199
7	497.9	10.408	9.481
8	302.0	10.686	9.444
9	183.2	12.614	11.859
10	111.1	12.603	12.219
11	67.38	10.314	10.503
12	40.87	7.912	8.419
13	24.79	5.593	6.242
14	15.03	4.907	5.583
15	9.119	3.349	4.035
16	5.531	1.866	2.383
17	3.355	1.169	1.477
18	2.035	0.435	0.579
19	1.234	1.317	1.619
20	748.5 eV	0.827	1.085
21	454.0	0.440	0.587
22	275.4	0.169	0.277
23	167.0	0.086	0.097
24	101.3	0.034	0.033
25	61.44	0.010	0.007
26	37.27	0.003	0.001
27	22.60	0.001	
28	13.71	0.001	
29	8.315		
30	5.044		
31	3.059		
32	1.855		
33	1.125		
34	0.683		
35	0.414		
36	0.1		
37	0.0001		

Table 9 - One-Group Cross-Sections

Reaction (nf)	Cross-section in sodium plate from MURAL	FOGD5 (A) Cross-Section	FGL5 data details (2)	
			UKNDL DFN (34)	Ref and Notes
U238	0.050	0.047	272	Adjusted ('71)
Pu239	1.79	1.82	269	Adjusted ('71)
Pu240	0.400	0.376	402	Adjusted ('71)
Pu241	2.48	2.64	403	Ref 12
Pu242	0.317	0.295	955	ENDFB2
Am241	0.393	0.404	956	ENDFB2
Am243	0.203	0.188	957	ENDFB2
Cm244	0.576	0.548	958	ENDFB2

Notes: 1 The apparently anomolous variation of the Am241 cross-section arises because of the high proportion of fission events below the 'threshold' at about 0.3 MeV.

2 The FGL5 cross-section set is described in detail in Ref 13.

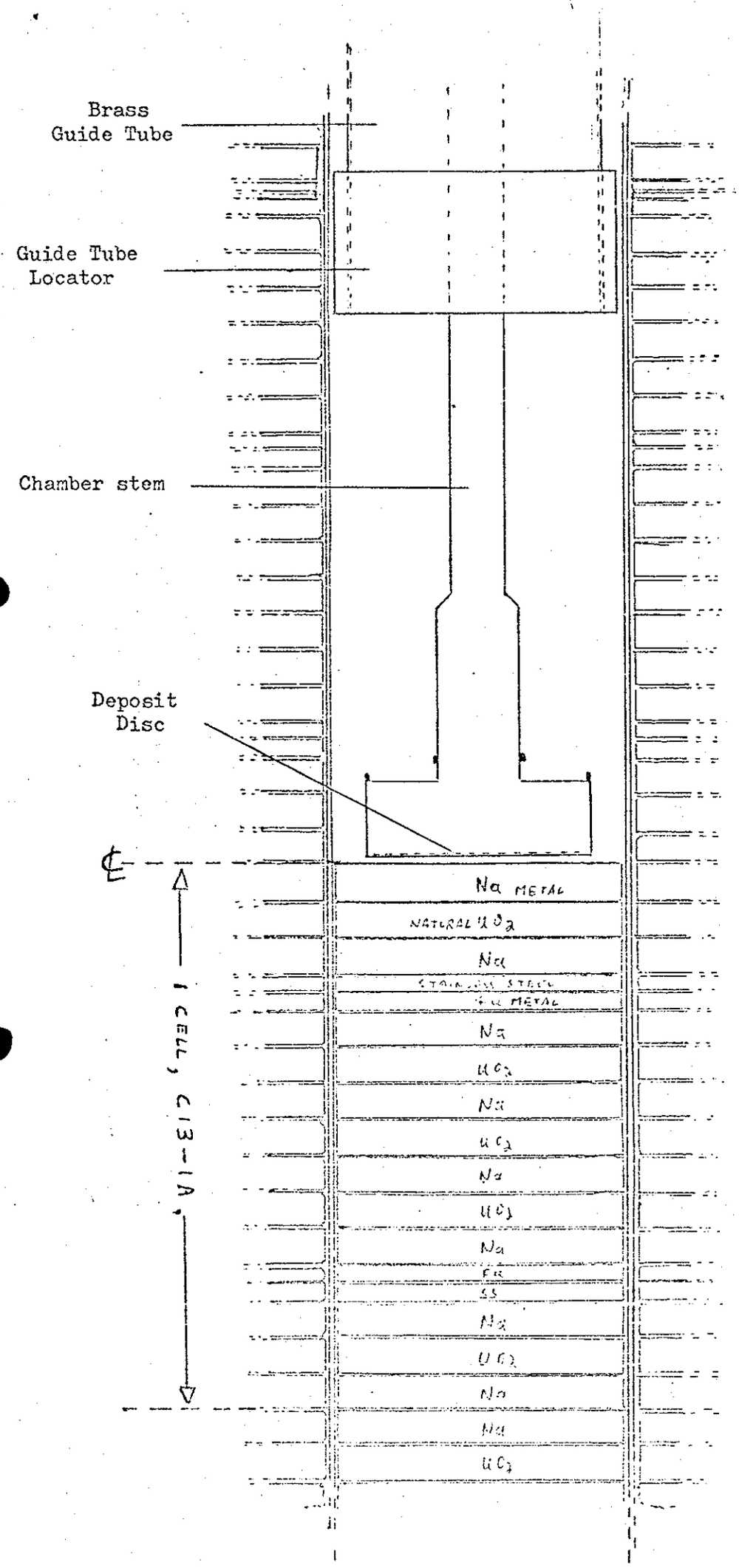

FIGURE 1

LOCATION OF FISSION CHAMBER IN HALF ELEMENT TYPE C13-6HE

(Drawn approximately to scale)

6511UU16