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Calculation of Fast-Neutron Induced-Fission Multiplication in Large PuO_2 Samples

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CALCULATION OF FAST-NEUTRON INDUCED-FISSION MULTIPLICATION IN LARGE PuO_2 SAMPLES

by

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ABSTRACT

Fast-neutron multiplication in large PuO_2 samples has been studied using both Monte Carlo computer codes and the coincidence correlation equations developed by K. Böhnel and N. Ensslin. Samples covering the mass range from 0.1 to 7.2 kg of plutonium have been measured and the multiplication results were compared with the theoretical predictions. The results are in agreement within the uncertainties in the sample characteristics. A parametric study was performed to determine the effect of sample density and moisture variation on the neutron multiplication.

I. INTRODUCTION

Neutron coincidence measurements have been used for the assay of plutonium samples with generally good results. However, for high-mass samples, the neutron multiplication can give a contribution to the coincidence signal that is equal to or larger than the primary signal from spontaneous fission.

When neutron multiplication is significant, corrections can be made using the formulas developed by K. Böhnel¹ and N. Ensslin.² These corrections are accurate when the (α, n) neutron yield from the sample can be calculated from the isotopic composition and chemical content. However, when moisture is present in the PuO_2 , the calculated results are in error.

Monte Carlo neutronic calculations³ can be used to predict the perturbations in the neutron coincidence results caused by different amounts of impurities and moisture. We calculated the neutron leakage multiplication (M) from bulk PuO_2 samples with Monte Carlo codes and compared this result with the value of M derived from the equations given in Ref. 2.

A wide range of PuO_2 samples (0.1-7.2 kg) were measured using an HLNC-II detector⁴ to obtain a totals rate (T) and a coincidence rate (R). These rates were used to solve for M, and the results were then directly compared with the value of M determined from the Monte Carlo calculations. This comparison checks the validity of the theoretical equations describing the multiplication.^{1,2}

Parametric studies on the effects of varying the PuO_2 density and moisture content also were performed.

II. MULTIPLICATION CALCULATIONS

A. Multiplication Equations

Ensslin² gives the following equations describing the multiplication corrections to be used in neutron coincidence counting:

$$R_{\text{mc}} = R/CF \quad ,$$

$$CF \equiv M \cdot r \quad ,$$

$$r \equiv \frac{(R/T)}{\rho_o} (1 + \alpha) \quad ,$$

$$\rho_o = (R/T)_o (1 + \alpha_o) \approx 0.103 \quad (\text{for the HLNC-II}) \quad ,$$

$$M = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \quad ,$$

$$A = 2.074(1 + \alpha) \quad ,$$

$$B = -(2.074\alpha + 1.074) \quad ,$$

$$C = -r \quad ,$$

$$\alpha = \frac{134 f_{238} + 0.381 f_{239} + 1.41 f_{240} + 0.013 f_{241} + 0.02 f_{242} + 26.9 f_{241Am}}{10.22(243 f_{238} + f_{240} + 1.69 f_{242})} ,$$

where the f_m 's are the weight fractions of the plutonium isotopes with mass number m .

The neutron leakage multiplication is calculated in the above equations as M if the correct values of ρ_o and α are used. M is a parameter related to the sample's mass and size, and it should have nothing to do with the particular detector (neglecting neutron reflection from the detector's walls). The detector wall reflection of neutrons increases M slightly.

B. Multiplication Constant

The parameter ρ_o is defined by

$$\rho_o = \left(\frac{R}{T} \right)_o (1 + \alpha_o)$$

for a nonmultiplying sample, measured to be ~ 0.103 for a small sample in the HLNC-II. This parameter is proportional to the singles efficiency and the fraction of time-correlated neutrons that fall within the coincidence gate.

We calculated the leakage multiplication from the above set of equations, using the measured values of R , T , and Pu for a wide range of PuO_2 samples. These values of M will be compared with the Monte Carlo values of M .

C. Calculating M with a Monte Carlo Method

The multiplication of a sample can be calculated with Monte Carlo methods. Either M or k -effective can be calculated by a computer code. It is usually quicker to have the computer find k -effective and then deduce M ; the disadvantage is that the average number of neutrons per fission ($\bar{\nu}$) must be known to convert k -effective into M :

$$M = \frac{1 - (k\text{-eff})/(\bar{\nu})}{1 - (k\text{-eff})} .$$

For the calculations here, k-effective was found from the Monte Carlo code and converted into M. The value of $\bar{v}$ was found from a small number of Monte Carlo calculations of M.

The value of M is a sensitive function of k-effective but not very sensitive to $\bar{v}$. The rate of change of M with k is about 1.062, for values of k-effective and $\bar{v}$ typical of the present situation; the rate of change of M with $\bar{v}$ is only 0.026. Thus, the choice of $\bar{v}$ is not crucial.

III. MONTE CARLO MODEL

A. Description of the Code

The Monte Carlo code used was the Los Alamos MCNP, Version 3A. Only a draft copy of this version of the manual is available; however, Version 2B of the manual is given in Ref. 3.

MCNP is a general-purpose transport code featuring continuous neutron (and/or gamma-ray) energies and generalized geometries. The code can be run on a CDC-7600 (as was done here) or on a Cray.

B. The Monte Carlo Geometry

The code allows a variety of surfaces to be specified to form various volumes or cells of the detector. Each cell contains a single type of material with a uniform density (polyethylene at 0.95 g/cm³, for example). An HLNC-II model, shown in Fig. 1, was carefully constructed of such cells, ignoring only minor features of no importance to these calculations. The detector tube cells were simply left void. The thermal-neutron absorption in the ³He gas has no effect on the plutonium sample multiplication because the sample cavity is lined with cadmium to prevent thermal-neutron return to the sample.

A model sample can was placed in the sample cavity; the can could be filled to any depth with PuO₂ and H₂O of any density. The size, shape, and location of the can could be adjusted to match a facility's can by specifying a few surface locations.

Fig. 1. HLNC-II geometry, material cells, and sample used for the Monte Carlo code calculations. Detector tubes were included as voids, but none show in this cross section.

C. Precision and Run Time

The precision of a calculated k -effective value depends on the number of neutrons started within the sample and traced through the geometry. Higher precisions naturally require longer run times.

For the results presented here, we used 12 cycles of 1000 neutrons each. During each cycle, 1000 neutrons were started throughout the sample and traced to their escape or capture; fission neutrons were similarly traced. The first five cycles were used to establish a representative source term within the sample. The next seven cycles yielded values of k -effective that were averaged in several ways to produce the most precise results.

The precision achieved depends on the amount of material in the sample; with more material, a better estimate of k -effective is possible for the same number of neutrons started. Almost all the k -effective values (and their M values) were found with a precision of 1-3%.

The typical CDC-7600 computer time needed for one k -effective calculation was 5-6 minutes.

D. Average Number of Fission Neutrons

When a neutron creates a fission event in the sample, the number of neutrons released is sampled according to the known statistics for that fissioning

nucleus. The average number of all fission neutrons is needed to convert k -effective into M .

After doing some Monte Carlo calculations for M directly, we found that the value of $\bar{\nu}$ was 3.122, which was practically constant over the range of samples described in this report. This value was considered quite accurate, especially considering the very small effect a reasonable error in $\bar{\nu}$ would produce in M (Sec. II.C).

IV. EXPERIMENTAL DESCRIPTION

A. Detector

We used the HLNC-II detector (shown in Fig. 2) for the PuO_2 measurements. The measured and calculated values of M are primarily a function of the sample (size, density, and fissile content); however, a small perturbation (5%) on M from reflected epithermal neutrons that return to the sample from the detector walls. The key detector parameters of interest are the size of the sample cavity (see Fig. 2) and the liner (0.4-mm cadmium) on the inside of the cavity.

B. Facility Setups

To collect the neutron data, the same HLNC-II detector (Los Alamos SN-002) was used at three different nuclear facilities to cover a wide range of PuO_2 sample loadings and isotopic ratios. Table I gives the facilities, dates, and sample ranges.

A Hewlett-Packard HP-85 minicomputer was interfaced to the shift-register coincidence electronics (IRT Model HEC-100) for data collection, analysis, and multiplication corrections.

C. Experimental Precision

The high counting rates for the PuO_2 samples resulted in good statistical precision ($1\sigma < 0.5\%$) for R and T . The resulting statistical uncertainty in the calculated value of M was $< 1\%$.

D. Sample Description

To calculate the multiplication using the Monte Carlo code, it is necessary to input the sample size, mass, and isotopic composition. Tables II, III,

Fig. 2. Diagram of HLNC-II detector used for the PuO_2 measurements.

TABLE I
FACILITIES USED FOR PuO_2 COINCIDENCE DATA COLLECTION

Date	Facility	Plutonium Sample Mass Range (kg)
June 1984	Los Alamos National Laboratory	0.06-0.9
September 1984	Belgonucleaire, Belgium	1.5-2.8
February 1985	BNFL Sellafield, United Kingdom	2.5-7.2

TABLE II
LOS ALAMOS PLUTONIUM STANDARDS DATA
(June 1, 1984)

Sample No.	Pu (g)	Isotopic Wt%						240Pu-eff	α
		²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu	²⁴¹ Am		
1	59.97	0.058	82.18	16.19	1.24	0.334	0.145	10.11	0.381
2	171.92	0.065	81.96	16.36	1.28	0.344	0.158	19.33	0.384
3	321.89	0.057	82.13	16.22	1.25	0.344	0.150	54.42	0.377
4	384.84	0.060	82.10	16.26	1.24	0.339	0.132	65.19	0.379
5	543.84	0.070	82.07	16.26	1.25	0.340	0.149	92.31	0.388
6	616.69	0.057	81.97	16.38	1.24	0.356	0.176	105.33	0.381
7	848.60	0.060	81.98	16.35	1.28	0.340	0.126	144.53	0.376
8	876.58	0.060	81.98	16.35	1.28	0.340	0.126	149.29	0.376

TABLE III
BELGONUCLEAIRE PuO₂ DATA
(Updated to September 25, 1984)

Sample	Pu (g)	Isotopic Composition Wt%					²⁴¹ Am (ppm)	α	H ₂ O -(ppm)	240Pu-eff. (g)	239+241Pu (g)
		²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu					
S00720	1 589	0.125	75.20	21.54	2.43	0.710	14 057	0.483	5 500	364.9	1 233
S00849	1 836	0.135	75.67	21.11	2.41	0.673	13 019	0.484	6 500	413.2	1 434
S00850	1 873	0.135	75.67	21.11	2.41	0.673	13 019	0.484	6 500	421.4	1 462
XN 1055	2 106	1.541	58.31	25.56	8.84	5.74	32 180	0.882	--	809.1	1 414
XN 1025	2 498	1.027	63.00	24.39	7.40	4.19	28 084	0.783	--	837.4	1 758
XN 1066	1 456	1.541	58.44	25.56	8.74	5.72	32 887	0.887	--	558.9	975
XN 1064	2 540	1.541	58.44	25.56	8.74	5.72	32 887	0.887	--	974.8	1 706
XN 1059	2 672	1.541	58.44	25.56	8.74	5.72	32 887	0.887	--	1 025.6	1 795
XN 1062	2 727	1.541	58.44	25.56	8.74	5.72	32 887	0.887	--	1 046.8	1 832
XN 1123	2 654	1.158	60.87	24.98	8.26	4.74	30 169	0.806	--	936.9	1 835
XN 1076	2 594	1.443	59.39	25.02	8.86	5.28	32 900	0.888	--	957.5	1 770
XN 1097	2 782	1.445	59.22	25.00	9.05	5.29	33 814	0.895	--	1 026.8	1 899

and IV give sample specification data for the Los Alamos samples,⁴ the Belgonucleaire samples,⁵ and the Sellafield samples,⁶ respectively.

Figure 3 shows the geometry of the cylindrical sample cans used at the three facilities. The cans' diameter-to-height ratios significantly affect both the measured and calculated values of M.

V. RESULTS

A. Neutron Measurements

The results of the measurements from the three facilities are given in Table V (Los Alamos), Table VI (Belgonucleaire), and Table VII (Sellafield). We corrected the measured R and T values for deadtime⁴ and used the R/T ratio to calculate the multiplication-corrected reals rate (R_{mc}) and M.

TABLE IV
SELLAFIELD PuO₂ SAMPLE SPECIFICATIONS
(Updated to January 1, 1985)

Sample No.	Pu (g)	²³⁸ Pu (%)	²³⁹ Pu (%)	²⁴⁰ Pu (%)	²⁴¹ Pu (%)	²⁴² Pu (%)	²⁴¹ Am (ppm)	²⁴⁰ Pu-Eff. (g)	α	²³⁹⁺²⁴¹ Pu (g)
1	7 156.5	0.188	72.09	22.87	3.91	0.943	2 978	1 776	0.365	5 439
2	6 807.4	0.188	71.22	23.59	4.00	1.004	4 162	1 745	0.368	5 120
3	6 704.5	0.200	70.35	23.83	4.59	1.041	670	1 740	0.334	5 024
4	6 531.7	0.118	73.02	22.45	3.53	0.874	5 057	1 575	0.359	5 000
5	6 254.6	0.114	75.80	20.97	2.49	0.638	12 210	1 391.7	0.467	4 897
6	5 951.9	0.135	74.78	21.52	2.84	0.737	9 973	1 369	0.440	4 620
7	5 753.9	0.124	75.54	21.05	2.61	0.678	11 680	1 289.9	0.463	4 497
8	5 647.4	0.133	75.03	21.47	2.64	0.729	12 496	1 295.8	0.469	4 386
9	5 432.9	0.105	75.01	21.46	2.69	0.738	10 748	1 243	0.434	4 221
10	5 332.6	0.113	76.47	20.62	2.17	0.628	12 817	1 167	0.481	4 194
11	4 968.4	0.469	76.65	17.66	3.71	1.512	28 143	1 053	0.883	3 993
12	4 768.0	0.113	75.88	20.96	2.39	0.658	12 813	1 062	0.474	3 732
13	4 597.6	0.114	75.57	21.11	2.56	0.649	13 173	1 030	0.476	3 592
14	4 488.4	0.122	76.72	20.34	2.21	0.608	12 845	969.5	0.492	3 543
15	3 811.6	0.113	75.47	21.31	2.40	0.710	14 069	865.4	0.480	2 968
16	3 821.8	0.178	73.12	22.35	3.51	0.842	2 904	921.5	0.368	2 929
17	2 671.8	0.915	67.55	23.32	4.59	3.63	35 452	836.0	0.855	1 927
18	2 541.3	0.946	66.31	22.90	6.28	3.57	47 630	784.2	0.979	1 845
19	2 476.0	0.915	67.55	23.32	4.59	3.63	35 452	774.8	0.855	1 786

Fig. 3. Diagram of cylindrical sample cans containing PuO_2 that were used for the measurements and calculations of M .

B. Calculation of M Using the R/T Ratio

The equations in Sec. II.A can be used to calculate M , where we input the values of R , T , α , and ρ_0 . Tables V-VII give the results of these calculations corresponding to a ρ_0 value of 0.103.

This ρ_0 was determined by the extrapolation of the curve of $(R/T)(1 + \alpha_0)$ vs plutonium mass to zero mass, where the multiplication is zero; however, the true value of ρ_0 is sample dependent because the larger PuO_2 samples actually increase the counting efficiency of the HLNC-II. The scattering of neutrons in the sample matrix causes this efficiency increase, thus lowering the average energy of the emitted neutrons. The HLNC-II is undermoderated, so the lower-energy neutrons have a higher probability of being counted.

For samples above a few hundred grams in mass, a more accurate value of ρ_0 would be .0.108. This 5% increase in ρ_0 will decrease the calculated value

TABLE V

MEASUREMENT RESULTS FOR LOS ALAMOS PuO₂ IN HLNC-II

Sample No.	²⁴⁰ Pu-eff (g)	Totals Rate (s ⁻¹)	Reals Rate (s ⁻¹)	σ_R (%)	Corrected Rate R_{mc}^a (s ⁻¹)	R_{mc}/g	M
1	10.11	2 520	208.3	0.53	182.9	18.09	1.022
2	29.33	7 469	663.3	0.48	529.8	18.06	1.048
3	54.42	14 063	1 322	0.44	988.9	18.17	1.064
4	65.19	16 868	1 636	0.43	1 173	18.00	1.073
5	92.31	24 236	2 441	0.47	1 654	17.92	1.087
6	105.33	27 841	2 832	0.46	1 907	18.11	1.088
7	144.53	38 467	4 137	0.44	2 604	18.02	1.108
8	149.29	39 833	4 320	0.44	2 689	18.01	1.108
Av =						18.05	
						±0.07	
CR-6 CF-252 31 050 5 890 0.20 (Measured on 6/6/84)							

^aMultiplication correction made with Method 2.

of M by 1.4%. This small reduction results in excellent agreement between the measured and Monte Carlo values of M.

For the normal application of Ensslin's equations to determine R_{mc} , the absolute value of ρ_0 is not important because it cancels out in the calibration curve; however, for the direct comparison of M from the equations and from the Monte Carlo code, the accurate value of ρ_0 must be used to get agreement.

C. Multiplications Calculated with the Monte Carlo Method

The density of the PuO₂ in a sample can be an important parameter affecting k-effective. Unfortunately, the densities of the measured samples were not known precisely. Thus, we chose a range of densities that includes the probable densities.

TABLE VI

MEASUREMENT RESULTS FOR BELGONUCLEAIRE PuO₂
 IN HLNC-II COUNTER EURATOM/LOS ALAMOS
 (Serial No. 002)

Sample	²⁴⁰ Pu-eff. (q)	Totals (s ⁻¹)	Reals (s ⁻¹)	s _R (%)	R _{C2} (s ⁻¹)	R _{C/q-240}	M
S00720	364.9	108 717	11 249	0.56	6 798	18.63	1.109
S00849	413.2	121 160	13 398	0.53	7 423	17.96	1.131
S00850	421.4	124 036	13 734	0.43	7 596	18.03	1.131
XN 1066	558.9	213 516	18 288	0.55	10 524	18.83	1.110
XN 1064	974.8	377 874	35 204	0.53	18 237	18.71	1.132
XN 1059	1 025.6	401 348	38 174	0.52	19 267	18.79	1.137
XN 1062	1 046.8	409 971	39 881	0.51	19 567	18.69	1.144
XN 1055	809.1	318 017	29 132	0.57	15 468	19.11	1.129
XN 1025	837.4	315 461	32 468	0.46	15 858	18.93	1.151
XN 1123	936.9	341 329	32 718	0.51	17 220	18.38	1.132
XN 1076	957.5	371 049	34 897	0.45	17 855	18.65	1.134
XN 1097	1 026.8	396 554	37 984	0.51	18 913	18.42	1.140
						Av =	18.59
							±0.34
D-372	²⁵² Cf	1 744	329.6	0.04	(on 9/24/84)		

TABLE VII

NEUTRON DATA SUMMARY FOR HLNC-II COUNTER EURATOM/LOS ALAMOS

Sample	Deadtime Correction ^a	T_c (s ⁻¹)	R_c (s ⁻¹)	Multiple Correction R_{mc}	$\frac{R_{mc}}{q}$	M
1	1.470	538 267	93 726	31 670	17.83	1.282
2	1.462	530 964	92 168	31 190	17.87	1.282
3	1.450	519 551	90 763	31 373	18.03	1.278
4	1.415	486 152	82 667	28 971	18.39	1.271
5	1.379	451 564	72 054	25 101	18.03	1.263
6	1.359	430 887	64 535	24 989	18.25	1.234
7	1.352	424 253	61 172	24 424	18.93	1.223
8	1.336	407 951	59 916	23 247	17.94	1.230
9	1.314	385 079	54 754	22 807	18.35	1.213
10	1.298	368 076	51 459	20 914	17.92	1.215
11	1.353	425 209	52 723	19 067	18.11	1.220
12	1.285	354 233	44 850	21 048	19.82	1.177
13	1.250	316 010	40 808	18 630	18.09	1.184
14	1.244	309 202	41 610	17 775	18.35	1.201
15	1.202	262 131	32 142	15 637	18.07	1.166
16	1.203	263 410	37 669	16 473	17.88	1.204
17	1.265	332 751	32 257	16 229	19.41	1.139
18	1.259	326 596	32 524	14 667	18.70	1.159
19	1.251	317 652	31 214	15 438	19.93	1.143
Average					18.41	
Scatter (1 σ)					± 0.65	
1 σ (%)					$\pm 3.5\%$	
D-372	1.001	1 581	297.7			

^aThe coincidence deadtime coefficient was $\delta = (0.68 + 0.22 T \cdot 10^{-6}) \mu s$.

Because the amount of water in a sample also affects k-effective, we performed additional calculations with this measurement as another parameter.

PuO₂ Density Effect. Figures 4-6 display the effects of PuO₂ density for the Los Alamos, the Belgonucleaire, and the Sellafield facilities, respectively. For these calculations, the samples were assumed to be free of water. The multiplications deduced from the R/T ratios are also indicated on the figures.

To generate the curves in the figures, we calculated several k-effective and M values and then fitted a parabolic curve to the calculations; the fits were quite good so the calculated points on the curves are not shown.

The Los Alamos data in Fig. 4 are consistently above all the calculated curves. The density of the PuO₂ in this case is very near 2.5 g/cm³, as calculated from a radiograph of a can that revealed the can's fill height. The data points are probably high because of an incorrect ρ_o value, described in Sec. V.B. A reasonable change in the ρ_o value from 0.103 to 0.108 would give good agreement to the curve corresponding to a density of 2.5 g/cm³.

Fig. 4. Comparison between measured values of M and Monte Carlo calculations for the Los Alamos data set.

Fig. 5. Comparison between measured values of M and Monte Carlo calculations for the Belgonucleaire data set.

Fig. 6. Comparison between measured values of M and Monte Carlo calculations for the Sellafield data set. The different styles of data points correspond to different batches of plutonium that have different ages and possibly different densities and water contents.

The data from Belgonucleaire in Fig. 5 show less bias and indicate a density near 2.5 g/cm^3 .

Three types of data points are shown in Fig. 6 for the Sellafield multiplications. Each type represents a different batch and age of plutonium and probably a different density and/or water content. The actual densities of these samples are not well known. The plutonium masses are large, and thus small fractional changes in the density and moisture content are magnified in coincidence R.

All the data from Figs. 4-6 are combined in Fig. 7. The three arcs are the Monte Carlo calculated multiplications for densities of 2.5 g/cm^3 . The arcs do not form a single smooth curve because of the different shapes of the cans in the three facilities (see Fig. 3).

To study the effect of water in the sample, we made additional calculations of k-effective with parts per million by weight of water as a parameter. The results for two shapes of cans are shown in Figs. 8 and 9; Fig. 9 is an enlarged portion of Fig. 8 to show the realistic region of water content more clearly.

Fig. 7. Combined multiplication results for all three data sets. The Monte Carlo results are for a PuO_2 density of 2.5 g/cm^3 .

Fig. 8. Calculated multiplication vs water content in samples.

Fig. 9. Enlarged scale of calculated multiplication increase vs water fraction in PuO_2 samples.

The Los Alamos can's M value was practically unaffected by the water content until more than 50 000 ppm of water were added. This insensitivity of M to the moisture fraction is caused by the small sample mass. The Sellafield can was much more sensitive, but nevertheless the addition of 30 000 ppm of water raised M from 1.25 to only 1.30; however, this amount of water will have a much larger effect on the coincidence rate R for all of the sample sizes.

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VI. SUMMARY

The measurements of R/T to predict the multiplication M were compared with the direct Monte Carlo calculation of M. The results are in agreement within the uncertainties in the sample density and in the multiplication constant ρ_0 .

The most sensitive parameter affecting M is the sample density. The value of M, derived from the R/T ratio, is correct if α is known and the sample is dry, even when the sample density is not known.

On the other hand, the Monte Carlo calculation requires the density as an input parameter. Because the density is generally not known, it is the primary source of disagreement in the comparison.

The high values of M from the R/T ratio, shown as squares in Fig. 6, are most likely the true values with a higher density than some of the other batches of material. This conclusion is supported by the accurate assay of the same samples based on the R_{mc} vs ^{240}Pu -effective calibration curve,⁵ shown in Fig. 10.

For the quantitative use of Monte Carlo calculations in coincidence counting, it should be possible to determine the sample fill height (and thus the density) from a separate gamma-ray transmission measurement or autoradiography.

The primary use of the Monte Carlo calculations is to perform parametric studies of the corrections required in R and T as a result of changes in moisture content and/or (α, n) impurities. More detailed Monte Carlo calculations giving the actual R and T are in progress.⁷

Fig. 10. Multiplication-corrected R vs ^{240}Pu -effective mass for Sellafield sample set. The outliers are probably caused by high moisture content.

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