Human Biokinetics of Plutonium: a Compilation of Experimental Data

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ABSTRACT

This report has been prepared to give a detailed compilation of all the available data from the UK plutonium human volunteer studies except where they are fully documented elsewhere. It is not intended to review the results but rather to bring available data together in one publication. References are given to published work in which results are analysed. As the studies are still in progress, the report will be updated as more data becomes available.

Data from two studies are included, one initiated by the National Radiological Protection Board (NRPB), now the Radiation Protection Division of the Health Protection Agency (HPA) and one initiated by AEA Technology, Harwell (AEAT) which was subsequently continued by Middlesex University (MU). A third study, initiated at NRPB, is described but data are not yet included.

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CONTENTS

1	**Introduction**	**1**
2	**The HPA-RPD (NRPB) study following ingestion and intravenous injection in men**	**1**
	2.1 Outline of methodology	**1**
	2.2 Uncertainties	**2**
	2.3 Results	**3**
3	**The AEAT/MU study following intravenous injection in women**	**5**
	3.1 Outline of methodology	**5**
	3.2 Uncertainties	**5**
	3.2.1 Stability of machine operation	5
	3.2.2 Isobaric interferences	5
	3.2.3 Contamination effects in AMS determinations	6
	3.2.4 Indications of possible systematic error	7
	3.3 Results	**7**
4	**The HPA-RPD (NRPB) study following inhalation in men**	**13**
	4.1 Outline of methodology	**13**
5	**Discussion**	**14**
6	**References**	**14**

1 INTRODUCTION

There have been three long-term human volunteer studies involving plutonium in the UK. The first was initiated by the National Radiological Protection Board (NRPB), now the Radiation Protection Division of the Health Protection Agency (HPA-RPD). This study was designed to measure the absorption of ingested plutonium as well as its long-term urinary excretion after intravenous administration. The second study was led by NRPB, with the administration of plutonium to the volunteers carried out under sub-contract by AEA Technology (AEAT). This study was performed to investigate the absorption from the respiratory tract of inhaled plutonium nitrate in humans, and to evaluate absorption parameters for comparison with values determined for the same aerosol inhaled by other mammalian species. In the third study, which was initiated at AEAT and subsequently continued by Middlesex University (MU), comprehensive measurements were made after intravenous injection of plutonium. Each of the studies is described separately below and all results obtained to date are given for two studies; data for the inhalation study will be included in a revised version of the report. All received ethics committee approval and involved very low radiation doses approved by the DH Administration of Radioactive Substances Advisory Committee. The tracers used were ^{237}Pu, which has a half-life of 45.3 d (ICRP, 1983; NEA, 2005)[1] and so is suitable for short-term studies, and ^{244}Pu, which has a half-life of 8.26×10^{7} y (ICRP, 1983) and so is suitable for long-term studies. Plutonium-237 decays by electron capture and is thus quantifiable in bioassay samples and *in vivo* by measurement of its K X-ray emissions, while the long half-life of ^{244}Pu means that it is quantifiable in bioassay samples by mass spectrometry.

2 THE HPA-RPD (NRPB) STUDY FOLLOWING INGESTION AND INTRAVENOUS INJECTION IN MEN

2.1 Outline of methodology

The gastrointestinal absorption and urinary excretion of ^{244}Pu were measured in five healthy adult males in a two-stage study. Firstly, the volunteers ingested about 10^{14} atoms (~ 4×10^{-8} g) of ^{244}Pu in citrate solution with a mid-day meal and urinary excretion was measured for the following 7 - 9 days. After a period of at least six months, the same volunteers were given an intravenous injection of 2 x 10^{12} atoms (~ 8×10^{-10} g) of ^{244}Pu in citrate solution. Urinary excretion was then measured for the following 7 - 9 days and subsequently at intervals over periods, currently up to 8 – 9 years after injection. Samples awaiting measurement will extend observations to 13 years after injection.

[1] ICRP Publication 38 and the NEA's Joint Evaluated Fission and Fusion Library (JEFF) both give the half-life for ^{237}Pu as 45.3 d. Talbot *et al*. (1994) give a value of 45.66 $\pm$ 0.04 d, and it was the latter value that was used in the interpretation of the AEAT study.

Each sample was analysed by adding ^{242}Pu tracer and using established radiochemical methods to isolate the plutonium. In the earlier years of the experiment, measurements were made by thermal ionisation mass spectrometry at the Atomic Weapons Establishment, Aldermaston, UK. Since 1996, measurements have been made by resonance ion mass spectrometry at the Johannes Gutenberg University at Mainz in Germany. The latter technique was used for samples collected after day no. 1600 for volunteer 1, after day no. 1200 for volunteers 2 and 3 and for all samples for volunteers 4 & 5; these are indicated by bold type in Table 2.

More complete descriptions of the study have been published (Popplewell *et al*. 1994; Ham and Harrison, 2000).

2.2 Uncertainties

The uncertainty on individual measurements resulting from counting statistics, expressed as a calculated standard deviation, was between 2 and 5% of the measured values. Other sources of uncertainty are much harder to quantify. However the change from thermal ionisation to resonance ion mass spectrometry did not produce a discontinuity in the excretion curve of the existing volunteers or a significant difference between results at similar post-injection times measured by different techniques. This strongly suggests that there is no bias between the methods and that uncertainties from the particular measurement technique are not significant.

The systematic uncertainty from the ^{242}Pu tracer used was about 2% (at one sigma) as it was prepared by gravimetric dilution of an NPL certified tracer solution. The tracer purity was confirmed on both spectrometers by analysis of pure tracer samples. Because the same tracer solution was used for the calibration of the injection solution and the measurement of the urine samples, its accuracy does not affect the measure of percentage excreted. Reagent blanks were analysed alongside all samples. For most analyses the ^{244}Pu content was below the limit of detection, for the few cases where ^{244}Pu was measurable the blank values have been subtracted from the analytical result.

It can be concluded that analytical uncertainties are small and of little importance in comparison to biological variability. Differences between volunteers are attributable to differences in metabolism.

2.3 Results

Table 1 Gut transfer of ^{244}Pu in male volunteers

Volunteer	1	2	3	4	5
Age at ingestion, years	58	40	54	64	36
Atoms ingested	1.44×10^{14}	1.33×10^{14}	1.18×10^{14}	1.20×10^{14}	1.15×10^{14}
Urine collection, days	8	9	9	7	8
Urine collection, atoms ^{244}Pu	2.32×10^{9}	8.02×10^{8}	2.12×10^{9}	2.97×10^{9}	4.48×10^{8}
% excreted of total absorbed[a]	1.82	2.50	2.30	2.14	3.02
Total absorbed, atoms ^{244}Pu	1.27×10^{11}	3.21×10^{10}	9.21×10^{10}	1.39×10^{11}	1.48×10^{10}
Fractional absorption, f_1	8.9×10^{-4}	2.4×10^{-4}	7.8×10^{-4}	1.2×10^{-3}	1.3×10^{-4}

[a]Taken as % excreted in same time period after intravenous injection (from Table 2).

Table 2 Plutonium excretion after intravenous injection

Day	Measured Atoms					Percent per day				
	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Vol. 5	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Vol. 5
	Atoms Injected									
	2.35E+12	1.97E+12	1.92E+12	**2.17E+12**	**2.12E+12**					
1	2.08E+10	2.70E+10	2.25E+10	**3.13E+10**	**4.11E+10**	0.8835%	1.3706%	1.1712%	**1.4411%**	**1.9405%**
2	7.42E+09	5.44E+09	5.18E+09	**5.50E+09**	**7.27E+09**	0.3157%	0.2760%	0.2695%	**0.2532%**	**0.3432%**
3	3.26E+09	4.51E+09	4.62E+09	**3.03E+09**	**3.52E+09**	0.1389%	0.2287%	0.2404%	**0.1395%**	**0.1662%**
4	3.18E+09	3.41E+09	3.10E+09	**2.07E+09**	**3.92E+09**	0.1351%	0.1731%	0.1610%	**0.0953%**	**0.1851%**
5	2.23E+09	2.51E+09	2.18E+09	**1.78E+09**	**1.76E+09**	0.0948%	0.1275%	0.1134%	**0.0820%**	**0.0831%**
6	1.94E+09	1.74E+09	1.88E+09	**1.56E+09**	**2.70E+09**	0.0825%	0.0881%	0.0978%	**0.0718%**	**0.1275%**
7	2.51E+09	2.00E+09	1.78E+09	**1.15E+09**	**1.90E+09**	0.1069%	0.1013%	0.0924%	**0.0529%**	**0.0897%**
8	1.39E+09	1.33E+09	1.56E+09		**1.84E+09**	0.0591%	0.0676%	0.0809%		**0.0869%**
9		1.29E+09	1.37E+09		**1.56E+09**		0.0653%	0.0713%		**0.0737%**
9.5	1.08E+09					0.0460%				
11		5.78E+08					0.0293%			
13.5		7.57E+08					0.0384%			
14					**7.37E+08**					**0.0348%**
15.5	6.07E+08					0.0258%				
18.5		6.34E+08					0.0322%			
19.5	4.39E+08					0.0187%				
20					**4.06E+08**					**0.0192%**
23					**3.46E+08**					**0.0163%**
26.5		5.23E+08					0.0265%			
27.5	4.13E+08					0.0176%				
30					**3.97E+08**					**0.0187%**
40		3.63E+08					0.0184%			
45	2.47E+08					0.0105%				
68		3.20E+08					0.0163%			
71					**2.49E+08**					**0.0117%**
75			1.69E+08					0.0088%		
78	1.62E+08					0.0069%				
84				**1.21E+08**					**0.0055%**	
105			2.72E+08					0.0142%		

Table 2 Plutonium excretion after intravenous injection

Day	Measured Atoms					Percent per day				
	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Vol. 5	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Vol. 5
109		2.62E+08					0.0133%			
122	1.55E+08					0.0066%				
146	1.44E+08					0.0061%				
157			1.81E+08					0.0094%		
160		2.10E+08					0.0106%			
174	1.36E+08					0.0058%				
193			1.51E+08					0.0079%		
205	1.20E+08					0.0051%				
216		1.68E+08					0.0085%			
254	1.09E+08					0.0046%				
263		1.85E+08	1.30E+08				0.0094%	0.0067%		
290				**3.10E+08**					**0.0143%**	
294					**7.00E+07**					**0.0033%**
325	1.11E+08					0.0047%				
378		1.31E+08					0.0066%			
382			1.23E+08					0.0064%		
470					**1.30E+08**					**0.0061%**
471				**2.63E+08**					**0.0121%**	
483		1.61E+08					0.0081%			
484			1.02E+08					0.0053%		
521	9.69E+07					0.0041%				
648		1.43E+08					0.0073%			
651			1.01E+08					0.0053%		
664	7.88E+07					0.0034%				
743					**4.27E+07**					**0.0020%**
853	5.60E+07					0.0024%				
1111			8.40E+07					0.0044%		
1119			9.62E+07					0.0050%		
1139		9.90E+07					0.0050%			
1155	6.03E+07					0.0026%				
1236				**4.86E+07**					**0.0022%**	
1256					**6.40E+07**					**0.0030%**
1583			**7.33E+07**					**0.0038%**		
1584		**8.50E+07**					**0.0043%**			
1798		**7.50E+07**					**0.0038%**			
1801			**8.45E+07**					**0.0044%**		
1943	**1.16E+08**					**0.0050%**				
1970		**1.22E+08**					**0.0062%**			
2197	**6.12E+07**					**0.0026%**				
2224			**1.97E+07**					**0.0010%**		
2459		**6.25E+07**					**0.0032%**			
2667	**4.55E+07**					**0.0019%**				
2730			**4.98E+07**					**0.0026%**		
2927		**7.20E+07**					**0.0037%**			
3190	**6.75E+07**					**0.0029%**				

Bold type indicates Mass spectrometry performed at Mainz.

3 THE AEAT/MU STUDY FOLLOWING INTRAVENOUS INJECTION IN WOMEN

3.1 Outline of methodology

This work was initiated by AEA Technology, Harwell (AEAT) but was subsequently continued by Middlesex University (MU). It followed earlier work by AEAT in which six healthy men had received injections of ^{237}Pu (Talbot *et al*., 1993, 1997; Talbot and Newton, 1994; Warner *et al*., 1994; Newton *et al*., 1998).

Six healthy women (Table 3) received intravenous injections of ^{237}Pu and ^{244}Pu as Pu(IV) citrate; other details of the volunteers, including haematology, are given elsewhere (Talbot *et al*. 1997). Early patterns of excretion, retention in blood and uptake by liver were based on the radioactivity of ^{237}Pu (Talbot *et al*. 1997; Newton *et al*. 1998). Later samples of excreta up to 8-9 years were analysed for ^{244}Pu by inductively-coupled plasma mass spectrometry (ICPMS), using the Micromass PlasmaTrace 2 double-focussing instrument operated by AEAT, or by accelerator mass spectrometry (AMS) performed by the Australian National University, Canberra (Priest *et al*. 2001). Further samples awaiting measurement will extend observations to 11 years. It was clear that ICPMS would be too insensitive for determining ^{244}Pu in blood in the long term, and only AMS was used.

3.2 Uncertainties

The uncertainties quoted in Tables 4-6 are simply those arising from the statistics of recorded events. Other sources of potential error are as follows.

3.2.1 Stability of machine operation

With both ICPMS and AMS, the mass of ^{244}Pu present was determined relative to that of the ^{242}Pu, added to each sample in known quantity prior to processing. With either method, collection of the relevant ions of ^{244}Pu and ^{242}Pu did not occur simultaneously; typically there would be a series of cycles with alternating collections of each isotope. The validity of this procedure depends on how stable are the ion currents during measurement of a sample. Unstable operation could produce errors in estimates of ^{244}Pu in individual samples but these would be random in size and direction and so should not affect averaged results or trends (Newton *et al*. 2005) from sampling over a long period.

3.2.2 Isobaric interferences

AMS for ^{244}Pu is not prone to isobaric interferences, but with ICPMS complications can arise from lead/chlorine or thorium/carbon species formed in the plasma, with masses summing to 244; the requirements for chemical processing of the samples are consequently more stringent. It was therefore

important to confirm, through ICPMS analysis of analytical blanks, that the separation had been effective; these samples were ^{244}Pu-free solutions with ^{242}Pu as the recovery tracer, which had been subjected to the same procedures as applied to the excretion samples, and with the same contemporary stock of reagents used. The 85 excretion samples analysed by ICPMS (Tables 4 and 5) had been processed in five batches at various times over a 9-months period. The blank test solutions processed with each batch all gave a positive "^{244}Pu" estimate. For two of the 41 urine samples this "background" amounted to >20% of the indicated sample content; this was true for 14 of the 44 faecal samples, which generally contained less ^{244}Pu than was present in contemporary urine.

The indicated contents of the relevant blank solutions were subtracted from the measured ^{244}Pu contents from ICPMS before the excretion rates in Tables 4 and 5 were calculated, and in most cases the result is assumed to be valid. Supporting evidence may be seen in Table 7, where averaged results by ICPMS for two subjects during 1½ - 3 years are compared with those obtained by AMS (where investigations showed no evidence for "background" effects attributable to the chemical content of excretion samples). However, the ICPMS blanks prepared for one particular batch of samples showed greater, and more variable, "^{244}Pu" contents than had their predecessors. The reason for this could not be established, but conceivably contamination with adventitious lead occurred between the ion-exchange removal of lead and preparation of the final solution for ICPMS. In this case the affected data, identified in Tables 4 and 5, could contain errors of unknown size and direction. However, in Table 4 none of the potentially affected urine samples shows a result grossly different from those found in others from the subject taken at about the same time; any such differences as may be discerned in Table 5 should be viewed in the context of the day-to-day variability of faecal excretion evident from unaffected results, both those based on ICPMS and AMS. Because of this, and because the potentially affected samples are relatively few in number and are confined to the first year after injection, their retention in analyses of the long-term trends in plutonium excretion by these subjects (Newton et al. 2005) would not change the outcome.

3.2.3 Contamination effects in AMS determinations

Positive estimates of ^{244}Pu in blank samples were obtained but, compared with those recorded with ICPMS, they were at levels much lower relative to the content of excretion samples, and were not due to other constituents of the sample. They arose instead from residual ^{244}Pu in the vicinity of the ion source, left after periodic checks of the efficiency of ion production in which a test sample, of much greater ^{244}Pu content than those under investigation, was used.

Under the operating conditions employed, analysis of four samples containing ^{242}Pu, but with no ^{244}Pu, gave estimated "^{244}Pu" contents of 0.3±0.1 (SEM) fg, and this value was subtracted from the indicated ^{244}Pu contents from AMS before the excretion rates or concentrations in blood were calculated. Contributions from the contamination were unimportant in relation to amounts present in excretion samples. The measured content of ^{244}Pu in faecal samples

was never < 6 fg, and in only five of the 45 samples in Table 5 was it <10 fg; with urine (Table 4) the smallest value determined was 14 fg.

The situation is less satisfactory for some of the later blood samples, with ^{244}Pu contents much smaller than in contemporary excretion collections. The inferred interference level (0.3 fg) is not strictly applicable to all samples examined during the intervals of several hours between performance checks, because the ^{244}Pu contamination around the ion source would reduce during that time. Consequently, the uncertainties displayed in Table 6, based solely on the statistics of recorded events, will in some cases underestimate the true values; samples for which the assumed interference (0.3 fg) amounts to >20% of the estimated ^{244}Pu content have been identified in the table.

3.2.4 Indications of possible systematic error

Table 7 includes estimates of the fractional ^{244}Pu excretion by Subject J on six occasions between 20 and 84 d. These may be compared with the corresponding results for ^{237}Pu excretion (Talbot *et al*. 1997) determined by x-ray counting of the same samples. The mean ratio (^{244}Pu/^{237}Pu) was 1.02±0.06 (SEM), i.e. as was to be expected, the isotopic ratio in urine was consistent with that in the injected mixture. By contrast, Table 8 compares concentrations in blood, sampled at 14-15 days, as determined by the two methods; here a mean ratio of 0.86 ± 0.03 is found.

An explanation may lie in the fact that the ^{242}Pu solutions used to spike the excretion collections and the blood samples were of different origins. The excretion collections had been spiked at Harwell with ^{242}Pu calibrated by traceable reference to a solution provided by the UK National Physical Laboratory, while the blood samples were spiked by MU with a solution which, although derived from one with National Bureau of Standards certification, had undergone dilution elsewhere. The assumed calibration of the two solutions, if inconsistent, could account for the low ratios seen in Table 8, and the possibility should be borne in mind that all of the concentrations given in Table 6 underestimate the true values by ~16%.

3.3 Results

Tables 4-6 show amounts of ^{244}Pu in individual samples, made by mass spectrometry; the data are expressed relative to the administered quantity, either as daily excretion rates or as concentrations in blood. Data based on x-ray counting of ^{237}Pu in samples taken during the first few months are tabulated elsewhere (Talbot *et al*. 1997).

TABLE 3 Subjects, amounts of ^{244}Pu administered and periods of study

Subject	Age (y)	Injection (ng)	Period of study (y)
G	53	0.98	8.8
H	47	0.98	8.8
I	36	1.21	7.9
J	57	1.18	5.1
K	35	1.12	7.7
L	51	1.13	4.5

TABLE 4 ^{244}Pu in urine collections of females G – L (percent of injection per 24h) measured by AMS (Method A) or by ICPMS (Method P). Quoted uncertainties (1σ) relate to statistics of recorded events.

	Time d	Duration h	Content % d^{-1} ± 1σ	Method
G				
*	172	24	0.0083 ± 0.0003	P
	173	24	0.0062 ± 0.0003	P
	292	24	0.0050 ± 0.0003	P
	293	24	0.0057 ± 0.0003	A
	514	24	0.0034 ± 0.0004	A
	516	24	0.0022 ± 0.0002	A
	517	24	0.0032 ± 0.0001	P
	518	24	0.0034 ± 0.0002	P
	727	24	0.0025 ± 0.0002	P
	728	24	0.0034 ± 0.0002	P
	729	24	0.0031 ± 0.0001	P
	942	24	0.0033 ± 0.0001	P
	943	24	0.0036 ± 0.0002	P
	944	24	0.0032 ± 0.0002	P
	945	24	0.0036 ± 0.0002	P
	1196	24	0.0034 ± 0.0004	A
	1197	24	0.0039 ± 0.0003	A
	1616	24	0.0030 ± 0.0002	A
	3221	72	0.0016 ± 0.0001	A
H				
*	157	21	0.0057 ± 0.0002	P
	158	17	0.0045 ± 0.0002	P
	159	28	0.0039 ± 0.0003	A
	286	24	0.0038 ± 0.0002	P
	288	24	0.0047 ± 0.0002	P
H				
	922	24	0.0036 ± 0.0004	A
	924	17	0.0038 ± 0.0003	P
	1153	24	0.0033 ± 0.0003	A
	1154	24	0.0041 ± 0.0003	A
	1657	72	0.0016 ± 0.0001	A
	3204	104	0.0017 ± 0.0001	A
I				
	155	24	0.0078 ± 0.0002	P
	156	24	0.0099 ± 0.0007	A
*	157	24	0.0085 ± 0.0002	P
	306	24	0.0037 ± 0.0002	P
	307	24	0.0043 ± 0.0002	P
	308	22	0.0045 ± 0.0004	A
	563	24	0.0040 ± 0.0004	A
	564	26	0.0051 ± 0.0001	P
	764	24	0.0050 ± 0.0003	A
	765	24	0.0041 ± 0.0003	A
	1033	24	0.0034 ± 0.0004	A
	1034	24	0.0043 ± 0.0005	A
	1278	73	0.0024 ± 0.0001	A
	1723	73	0.0014 ± 0.0001	A
	2897	71	0.0019 ± 0.0001	A
J				
	20.5	24	0.0439 ± 0.0022	A
	21.5	22	0.0370 ± 0.0012	A
J				
	552	24	0.0036 ± 0.0003	A
	553	25	0.0028 ± 0.0001	P
	799	25	0.0068 ± 0.0003	A
	800	24	0.0044 ± 0.0003	A
	801	24	0.0044 ± 0.0004	A
	1065	25	0.0044 ± 0.0004	A
	1066	24	0.0042 ± 0.0003	A
	1333	73	0.0024 ± 0.0001	A
	1863	72	0.0023 ± 0.0001	A
K				
	188	26	0.0038 ± 0.0004	A
*	189	22	0.0042 ± 0.0001	P
	190	24	0.0051 ± 0.0001	P
	353	25	0.0031 ± 0.0003	A
	355	25	0.0069 ± 0.0002	P
	588	24	0.0031 ± 0.0004	A
	589	24	0.0023 ± 0.0003	A
	797	24	0.0024 ± 0.0003	A
	798	24	0.0013 ± 0.0002	A
	1090	71	0.0015 ± 0.0001	A
	1651	77	0.0018 ± 0.0001	A
	2805	47	0.0018 ± 0.0001	A
L				
*	179	27	0.0071 ± 0.0003	P
*	180	23	0.0065 ± 0.0002	P

TABLE 4 ^{244}Pu in urine collections of females G – L (percent of injection per 24h) measured by AMS (Method A) or by ICPMS (Method P). Quoted uncertainties (1σ) relate to statistics of recorded events.

Time d	Duration h	Content % d^{-1} ± 1σ	Method	Time d	Duration h	Content % d^{-1} ± 1σ	Method	Time d	Duration h	Content % d^{-1} ± 1σ	Method
508	26	0.0021 ± 0.0001	P	22.4	23	0.0407 ± 0.0020	A	333	23	0.0041 ± 0.0003	A
509	23	0.0039 ± 0.0003	A	39	24	0.0183 ± 0.0008	A	334	27	0.0039 ± 0.0002	A
510	24	0.0034 ± 0.0001	P	83	25	0.0076 ± 0.0007	A	593	24	0.0069 ± 0.0047	A
511	24	0.0026 ± 0.0002	A	84	26	0.0097 ± 0.0002	P	594	23	0.0041 ± 0.0006	A
705	24	0.0029 ± 0.0001	P	157	23	0.0063 ± 0.0002	P	796	24	0.0027 ± 0.0003	A
706	24	0.0030 ± 0.0001	P	159	24	0.0050 ± 0.0002	P	797	22	0.0026 ± 0.0004	A
707	24	0.0035 ± 0.0001	P	160	23	0.0055 ± 0.0005	A	1139	72	0.0019 ± 0.0001	A
708	24	0.0028 ± 0.0001	P	303	24	0.0042 ± 0.0003	A	1651	71	0.0036 ± 0.0002	A
709	24	0.0039 ± 0.0002	P	305	23	0.0042 ± 0.0002	P				
921	24	0.0046 ± 0.0001	P	306	25	0.0038 ± 0.0002	P				

* Result possibly affected by contamination with lead (see text)

TABLE 5 ^{244}Pu in faeces collections of females G – L (percent of injection per 24h) measured by AMS (Method A) or by ICPMS (Method P). Quoted uncertainties (1σ) relate to statistics of recorded events.

	Time d	Duration h	Content % d^{-1} ± 1σ	Method		Time d	Duration h	Content % d^{-1} ± 1σ	Method		Time d	Duration h	Content % d^{-1} ± 1σ	Method
G	172	21	0.0089 ± 0.0005	P	**H**	706	24	0.00053 ± 0.00017	P	**J**	304	33	0.0018 ± 0.0002	P
	173	49	0.0044 ± 0.0006	A		707	35	0.00057 ± 0.00005	P		306	39	0.0018 ± 0.0003	A
	175	23	0.0089 ± 0.0004	P		708	16	0.0021 ± 0.0002	P		307	24	0.0048 ± 0.0003	P
	291	24	0.0025 ± 0.0004	A		709	29	0.0011 ± 0.0001	P		554	13	0.0018 ± 0.0002	P
	293	48	0.0025 ± 0.0002	P		710	27	0.00092 ± 0.00018	P		1066	69	0.00079 ± 0.00015	A
*	294	23	0.0045 ± 0.0002	P		920	24	0.00017 ± 0.00007	P		1332	58	0.0019 ± 0.0002	A
	296	47	0.0037 ± 0.0004	A		921	21	0.00081 ± 0.00012	P		1863	72	0.0047 ± 0.0007	A
	517	25	0.0018 ± 0.0002	P		922	33	0.0014 ± 0.0002	A					
	519	48	0.0015 ± 0.0003	A		923	13	0.0012 ± 0.0001	A	**K**	187	24	0.0028 ± 0.0002	P
	520	23	0.0017 ± 0.0002	A		924	33	0.0020 ± 0.0002	P		188	26	0.0035 ± 0.0002	P
	521	25	0.0025 ± 0.0002	P		1657	79	0.0004 ± 0.0004	A	*	190	45	0.0026 ± 0.0002	P
	727	24	0.0028 ± 0.0003	P		3204	96	0.00066 ± 0.00015	A		354	22	0.0011 ± 0.0001	P
	728	24	0.00092 ± 0.00008	P						*	355	23	0.0020 ± 0.0001	P
	729	24	0.0027 ± 0.0001	P	**I**	155	24	0.0069 ± 0.0002	P		356	28	0.0013 ± 0.0001	P
	730	24	0.0019 ± 0.0002	P		157	52	0.0030 ± 0.0002	P		530	101	0.00074 ± 0.00011	A
	944	24	0.0024 ± 0.0001	P		305	27	0.0035 ± 0.0002	P		797	22	0.0018 ± 0.0004	A
	945	24	0.0032 ± 0.0002	A		306	20	0.0061 ± 0.0002	A		1091	70	0.00032 ± 0.00011	A
	946	24	0.0020 ± 0.0001	P		307	24	0.0049 ± 0.0007	A		1651	95	0.00086 ± 0.00018	A
	1196	24	0.00056 ± 0.00018	A		562	24	0.0047 ± 0.0003	A		2805	96	0.00073 ± 0.00008	A
	1624	70	0.00084 ± 0.00015	A		563	26	0.0085 ± 0.0003	A					
	3221	98	0.00078 ± 0.00018	A		564	27	0.0033 ± 0.0002	P	**L**	180	23	0.0066 ± 0.0003	A
						765	92	0.00076 ± 0.00039	A	*	181	23	0.0035 ± 0.0002	P
H	157	24	0.0019 ± 0.0003	P		1033	76	0.0016 ± 0.0001	A		182	11	0.0075 ± 0.0002	P
*	158	24	0.0023 ± 0.0001	P		1279	71	0.0029 ± 0.0003	A	*	333	24	0.0035 ± 0.0001	P
	159	48	0.0015 ± 0.0002	A		1720	123	0.00037 ± 0.00009	A		334	24	0.0053 ± 0.0003	A
	285	24	0.0043 ± 0.0011	A		2897	69	0.0017 ± 0.0002	A		335	25	0.0023 ± 0.0003	A
	286	24	0.0030 ± 0.0003	A							552	74	0.00072 ± 0.00006	A

TABLE 5 ^{244}Pu in faeces collections of females G – L (percent of injection per 24h) measured by AMS (Method A) or by ICPMS (Method P). Quoted uncertainties (1σ) relate to statistics of recorded events.

Time d	Duration h	Content % d^{-1} ± 1σ	Method		Time d	Duration h	Content % d^{-1} ± 1σ	Method	Time d	Duration h	Content % d^{-1} ± 1σ	Method
287	23	0.0016 ± 0.0003	P	**J**	82	36	0.0080 ± 0.0007	A	797	44	0.0020 ± 0.0006	A
507	23	0.00076 ± 0.00038	A	*	157	24	0.0036 ± 0.0002	P	1138	102	0.00081 ± 0.00017	A
508	25	0.0015 ± 0.0002	P		158	36	0.0062 ± 0.0005	P	1651	72	0.0012 ± 0.0003	A
510	48	0.00080 ± 0.00004	P		159	11	0.0149 ± 0.0009	P				
512	50	0.00069 ± 0.00007	A		302	45	0.00032 ± 0.00004	A				

* Result possibly affected by contamination with lead (see text)

TABLE 6 ^{244}Pu in blood from females G – L (percent of injection per kg whole blood) measured by AMS. Quoted uncertainties (1σ) relate to statistics of recorded events.

	Time	Mass	Concentration		Time	Mass	Concentration
	d	g	% kg^{-1} ± 1σ		d	g	% kg^{-1} ± 1σ
G	14	21.8	0.737 ± 0.033	**I**	556	21.4	0.019 ± 0.005
	21	21.1	0.583 ± 0.029		791	20.8	0.010 ± 0.006
	49	21.5	0.192 ± 0.019		1736	21.3	0.009 ± 0.002
	87	21.2	0.099 ± 0.010	*	2891	16.2	0.0072 ± 0.0026
	151	21.4	0.062 ± 0.018	*	2891	17.4	0.0063 ± 0.0028
	326	21.6	0.013 ± 0.006				
	543	21.0	0.022 ± 0.003	**J**	15	21.3	0.186 ± 0.016
	710	43.6	0.015 ± 0.002		44	21.4	0.077 ± 0.006
	1208	42.9	0.011 ± 0.002		78	21.5	0.027 ± 0.002
	1705	36.3	0.019 ± 0.003		305	21.2	0.018 ± 0.004
	3202	17.8	0.010 ± 0.003		569	21.0	0.039 ± 0.005
*	3202	14.9	0.006 ± 0.003		826	21.2	0.010 ± 0.003
					1501	41.1	0.013 ± 0.002
H	14	21.5	0.316 ± 0.019		1815	21.2	0.016 ± 0.006
	49	21.5	0.109 ± 0.015				
	86	21.0	0.019 ± 0.007	**K**	14	21.4	0.387 ± 0.035
	161	21.6	0.029 ± 0.007		44	21.8	0.095 ± 0.007
	289	21.7	0.017 ± 0.008		106	21.1	0.032 ± 0.004
	508	19.7	0.013 ± 0.002		604	21.4	0.0072 ± 0.029
	710	44.0	0.012 ± 0.002	*	1172	19.6	0.0046 ± 0.0029
	1157	41.6	0.009 ± 0.002		1662	42.6	0.012 ± 0.003
	1868	44.6	0.010 ± 0.001	*	2821	13.0	0.0056 ± 0.0027
*	3201	19.3	0.0043 ± 0.0026				
*	3201	20.3	0.0026 ± 0.0020	**L**	14	21.3	0.477 ± 0.025
					44	21.3	0.063 ± 0.004
I	15	22.3	0.329 ± 0.015		172	21.3	0.032 ± 0.007
	42	21.9	0.076 ± 0.006		336	21.9	0.015 ± 0.003
	84	21.8	0.036 ± 0.004		1142	42.1	0.009 ± 0.002
	154	21.9	0.027 ± 0.003		1654	43.5	0.010 ± 0.002
	304	21.1	0.016 ± 0.003				

* Uncertainty possibly underestimated (see text)

TABLE 7 Mean 24-hour urinary excretion rates (percent of injection) in specified periods, showing consistency of analyses by ICPMS and AMS.

Subject	ICPMS				AMS			
	days*	n†	%	SEM	days*	n†	%	SEM
G	777	9	0.0032	0.0001	856	4	0.0032	0.0003
	(517-945)				(514-1197)			
H	711	9	0.0033	0.0002	850	5	0.0035	0.0003
	(508-924)				(509-1154)			

* mean and range † number of samples in period

TABLE 8 Concentrations in early blood samples determined both by AMS for ^{244}Pu and by x-ray counting of ^{237}Pu: evidence of bias. Quoted uncertainties (1σ) relate to statistics of recorded events.

Subject	Days	Concentration (% injection kg^{-1})		Ratio (AMS/x rays)
		AMS	x rays*	
G	14	0.737 ± 0.033	0.99 ± 0.02	0.74 ± 0.04
H	14	0.316 ± 0.019	0.33 ± 0.02	0.96 ± 0.08
I	15	0.329 ± 0.015	0.41 ± 0.02	0.80 ± 0.05
J	15	0.186 ± 0.016	0.22 ± 0.04	0.84 ± 0.17
K	14	0.387 ± 0.035	0.43 ± 0.01	0.90 ± 0.09
L	14	0.477 ± 0.025	0.53 ± 0.03	0.90 ± 0.07
mean ± SEM				0.86 ± 0.03

* from Talbot et al (1997)

4 THE HPA-RPD (NRPB) STUDY FOLLOWING INHALATION IN MEN

4.1 Outline of methodology

A mixed ^{237}Pu/^{244}Pu nitrate aerosol was generated from a 0.5% sodium nitrate/0.01M nitric acid solution containing these tracers. The nebulised droplets dried rapidly to produce an aerosol of 1.1 μm mass median aerodynamic diameter and geometric standard deviation (σ_g) ~ 1.2. Two healthy male volunteers inhaled the aerosol with a breathing pattern designed to maximise alveolar deposition. Initial lung deposits were approximately 8 kBq ^{237}Pu and 35 ng ^{244}Pu. Retention in each lung and uptake to the liver and skeleton were measured by external counting with 50 mm diameter semiconductor detectors mounted in pairs, up to 120 d after inhalation. Detectors were well-collimated, each having a field of view of about 16 cm diameter at a distance of 10 cm from the collimator face. Corrections were made to allow for the interference from liver (and lung) activity in the lung (and liver) measurements. The excretion of ^{237}Pu in urine and faecal samples was also measured over the same period. Individual urine samples were taken over the first 24-48 h, and continuous 24 h collections were then made until day 25. Collection of 3- or 5-day bulked samples has continued at increasing intervals. To date, ^{244}Pu in urine and blood has been measured by accelerator mass spectrometry (AMS) in samples taken up to 740 d after inhalation. Further details are given by Etherington *et al*. (2002) and Etherington *et al*. (2003).

Results will be included in a later issue of this report.

5 DISCUSSION

The purpose of this report is to provide a compilation of available data, updated as new results become available. Analysis of the data can be found in peer reviewed journal reports and conference proceedings: for the HPA ingestion study (Popplewell *et al*. 1994; Ham and Harrison, 2000) for the AEAT / MU study (Talbot *et al*., 1997; Newton *et al*. 1998, 2005), and for the HPA inhalation study (Etherington *et al*. 2002, Etherington *et al*. 2003).

The results of these studies have provided important input to the validation and improvement of models used by the International Commission on Radiological Protection (ICRP) for the calculation of doses from intakes of isotopes of plutonium and related elements (ICRP, 1989, 1993; Leggett, 2003; Leggett *et al*. 2005). Reliable models are important in routine protection but also in the interpretation of health outcomes in exposed workers, as illustrated by current efforts to estimate doses and provide risk estimates for lung cancer and other radiation related diseases in workers from the Russian Mayak plutonium plant (Kreisheimer *et al*. 2003; Shilnikova *et al*. 2003; Gilbert *et al*. 2004; Leggett *et al*. 2005).

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