Production and destination of British civil plutonium

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The amount of plutonium produced by the Magnox reactors belonging to the CEGB and SSEB is estimated using three different methods which give similar results for total plutonium production. The difference between this total and the UK civil plutonium inventory is 6.3 ± 0.8 tonne. This balance was apparently sent to the United States in exchange for fissile material for UK military requirements. The US destinations published by the UK government appear to accommodate significantly less plutonium.

We believe that if the international non-proliferation regime is to be strengthened, all links between civil and military nuclear programmes should be broken. If such links existed in the past the details should be clarified, effective safeguards introduced to prevent re-occurrence and information made available to allow compliance with the safeguards to be monitored. Within the framework of the Non-Proliferation Treaty (NPT) these injunctions clearly apply to the three nuclear powers which are signatories of the treaty, Britain, the Soviet Union and the United States.

Accordingly, we have set out to determine, for the case of the United Kingdom, how much plutonium has been produced in its civil reactors. Because much of the information required for such an investigation is not available, we have used three methods to estimate the total plutonium production. We believe our calculations are an interesting demonstration of the precision with which the production of fissile material such as plutonium-239 may be inferred from published data about reactor operations.

The British situation is complicated by the arrangement sanctioned by the mutual defence agreements with the United States under the terms of which[1] plutonium from the British civil programme has been transferred to the United States in exchange for highly enriched uranium and tritium required for the British military programme. British government spokesmen have stated[2] that no plutonium from the British civil reactors operated by the Central Electricity Generating Board (CEGB) and the South of Scotland Electricity Board (SSEB) has been used for military purposes in Britain and that none of the plutonium transferred to the United States has been so used. Our calculations, however, lead us to conclude that the civil uses for British plutonium in the United States do not fully account for the missing material. We have also encountered what we believe are serious shortcomings in the procedures for plutonium accountancy in Britain.

An earlier version of this paper was first submitted for publication in June 1984 and presented at the Sizewell Inquiry in October 1984[3]. The CEGB responded[4] with a number of criticisms, which they did not quantify on advice from the Department of Energy. We have investigated all these criticisms and incorporated some changes. These make only small differences to our numerical results.

Yield and burn-up

The British Magnox reactors with which we are concerned are graphite-moderated reactors using natural uranium fuel. A series of these reactors were built in Britain primarily for production of military plutonium. The first of these, at Calder Hall in Cumbria, was commissioned in 1956; others followed at Chapelcross in Scotland. We are not here concerned with the production of plutonium at these reactors, but at the civil reactors designed on similar principles but operated by the electricity utilities.

Our first objective is to calculate the total quantity of all plutonium isotopes produced per tonne of original fuel as a function of the total thermal energy generated by a tonne of fuel, called the burn-up, B, in units of MW-days per tonne (MWd/te). We represent plutonium isotope production by the function $G(B)$, in units of kilograms per tonne (kg/te). This can be obtained by the numerical solution of the equations[5] giving as a function of irradiation time the concentrations of the principal isotopes of uranium (235 and 238) and of plutonium (239 to 242 inclusive). The burn-up, the energy released by fission of uranium 235 and 238 and of plutonium 239 and 241, is a by-product of these equations. We correct the energy release for radiative capture effects as in ref.6. The cross-sections we use[7] depend on the mean neutron temperature which we take to be the mean moderator temperature T_m, and on the proportion of epithermal neutrons in the total neutron spectrum governed by the parameter r. Resonance absorption and fast fission are allowed for by the adjustment of the uranium-238 cross-section using parameters for each reactor given by IAEA[8]. A detailed description of our calculations will be published elsewhere.

There are no direct tests we can make of our $G(B)$ on data for the CEGB and SSEB reactors. The only clear information published on plutonium production in Magnox reactors concerns the military reactors at Calder Hall. Figures by Tyror[9] and Griggs and Harper[10] illustrate plutonium production and isotopic composition as a function of burn-up for a typical point in the Calder Hall reactor core. At a moderator temperature appropriate to Calder Hall and with $r = 0.055$, we find our $G(B)$ reproduces these curves very closely. Our best fit to the Tyror curves for isotopic composition is obtained with a fast fission factor of 1.02, corrected for fast radiative captures, as used by Griggs and Harper[10], rather than using 1.03, as quoted by the IAEA[8].

The major difference in $G(B)$ between Calder Hall and the civil Magnox reactors arises from different moderator temperatures[4,8]. For each civil reactor we use the $G(B)$ described above evaluated at the temperature appropriate to that reactor[8,11]. The effect of changing other parameters is considered later.

Table 1 Comparison of isotopic ratios in spent fuel dispatched 1978–84 with predictions for discharges 1977–83

	Plutonium-239 / Sum all plutonium isotopes	
	$G(B)$ predictions 1977–83	CEGB dispatch data 1978–84
Bradwell	0.730	0.744
Berkeley	0.740	0.721
Hinkley Point A	0.740	0.725
Trawsfynydd	0.719	0.717
Dungeness A	0.703	0.719
Sizewell	0.718	0.716
Oldbury	0.704	0.708
Wylfa	0.705	0.710
Mean	**0.720**	**0.720**

Table 2 Uranium fuel (tonnes) discharged from CEGB and SSEB power stations 1963–72

Fiscal year	Bradwell			Berkeley			Hinkley Pt			Trawsfynydd		Dungeness			Sizewell		Oldbury		Wylfa		Hunterston*	
	IME	SUB	BEST	IME	SUB	BEST	IME	SUB	BEST	SUB	BEST	IME	SUB	BEST	SUB	BEST	SUB	BEST	SUB	BEST	IME	BEST
63–64	44	40	44	45	49	45																
64–65	83	93	83	60	43	60																
65–66	133	120	133	188	147	188	10	63	10	33	33	6	63	6								
66–67	117	120	117	128	147	128	47	63	47	33	33	67	63	67	48	48					29	29
67–68	97	120	97	118	147	118	208	63	208	33	33	146	63	146	48	48					99	99
68–69		74	74		110	110	440†	408	408	73	73		178	178	212	212	44	44			178‡	178
69–70		94	94		118	118		174	174	170	170		173	173	149	149	91	91			122‡	122
70–71		93	106		116	118		100	105	155	142		169	182	142	167	110	118			73‡	73
71–72		81	68‖		106	104‖		18	13‖	52	65‖		158	145‖	160	135‖	136	128‖	16	14‖		42§

* Calendar year basis, given by first year in first column.
† Based on rate for April–August 1968.
‡ Assuming proposed curve followed.
§ Ref. 18.
‖ Ref. 15

This $G(B)$ refers to a point within the reactor core. The spatial variation of neutron flux in the core gives rise to a spread in the irradiation of the fuel elements in any particular channel. We have investigated typical axial variations of burn-up for a Magnox reactor[12] and used such a variation to obtain a channel-averaged $G(B)$. As G(B) is approximately linear over the appropriate range of burn-ups, averaging reduces $G(B)$ by only 1–2 per cent. Possible radial variations in burn-up have also been investigated. Though the neutron flux falls at large radius, we find that for sensible refuelling procedures in the steady state, radial averaging compensates in part for the effect of axial averaging. A comprehensive reactor-average of $G(B)$ is not feasible in the absence of detailed information on refuelling schemes. Henceforth we use a $G(B)$ that is channel-averaged only, noting that this will underestimate the real situation.

We have been unable to find detailed information against which to test our $G(B)$ for civil Magnox reactors apart from Fig. 5 of the sixth report of the Royal Commission on Environmental Protection (the "Flowers Report")[13], which gives the rate of plutonium production for a "power" reactor. Our original interpretation of this unreferenced figure as typical of civil Magnox reactors has been criticized by the CEGB[4], but our $G(B)$ does reproduce this curve well at a temperature within the range appropriate to civil Magnox reactors.

As an additional test, we have compared the isotopic ratios resulting from our calculations with the data provided by the CEGB on the isotopic composition of fuel dispatched from their Magnox stations for the six fiscal years 1978–84[14]. We believe that the isotopic composition of the fuel dispatched should approximate to that of the fuel discharged one year earlier. Table 1 shows the good agreement between our predicted isotopic ratios, calculated at the average of the discharge burn-ups for the appropriate years (as in Method A below) and the CEGB dispatch data, giving confidence in our extrapolation of the Calder Hall fit.

Fuel discharges

Fuel discharges from 1971–72 onwards have been provided by the British government in response to parliamentary questions[15–20], but the government has refused to give information on fuel discharges for the 1960s[15]. The figures in Table 2 in the column headed "SUB" are derived by subtraction of the numbers of fuel elements discharged by certain dates given in various sources[21–25]. For five stations, refuelling curves to mid-1968 are given in an Institute of Mechanical Engineers symposium (IME)[26] on the refuelling of gas-cooled reactors. Bearing in mind that the SUB data for 1965–68 are averaged over three years, the two sources are in reasonable agreement.

The refuelling policy adopted at Magnox stations in their early years was to follow an "ideal refuelling line"[26] with the total spent fuel discharged, ΣD_i, increasing linearly with "core-average" irradiation

$$B = (\Sigma E_i)/M \qquad \text{MWd/te} \quad (1)$$

up to a predetermined maximum burn-up B_{max}. Here ΣE_i is the total thermal energy generated (in MWd) and M is the total mass of uranium in the core. If this "ideal refuelling line" is followed, then all of the initial charge will have been discharged by the time the "core-average" burn-up reaches B_{max}. In addition, if each D_i discharged is replaced by an equal amount of fresh fuel, then when B_{max} is reached the core will contain fuel with all burn-ups equally represented. This is the ideal steady-state situation.

The refuelling curves available[26] show that the Magnox stations fell behind the ideal refuelling line in the early years, but that in the late 1960s, strenuous efforts were made to increase refuelling rates until the ideal, or a line parallel to it, was achieved. As operating experience was acquired, B_{max} was increased, so that the steady-state description only approximately represents the situation in the 1970s. The effects of such factors will be considered later.

Two of our models require E_i, the thermal energy generated. For CEGB stations we have obtained these by fiscal year from the CEGB[27] and parliamentary answers[16,17] and for Hunterston A by calendar year up to 1982 from the SSEB[18] and fiscal year subsequently[19,20].

The models

Given the fuel discharges of Table 2 and $G(B)$, only the burn-up at which the fuel was discharged is needed to calculate the plutonium production. The CEGB, however, have refused to provide average discharge burn-ups[28]. In method A, we have taken discharge burn-ups from a number of sources[29]. For other years we linearly interpolate between these published figures or between the earliest published figure and zero burn-up on starting up. We then calculate plutonium discharge using these discharge burn-ups, the fuel discharges of Table 2 and our channel-averaged $G(B)$. The totals to 31 March 1985 for each reactor are presented in Table 3.

Method B also uses the fuel discharge figures of Table 2, but attempts a more detailed calculation of burn-ups using figures on the thermal energy generated per year. We increment the core-average burn-up by E_i/M each year and determine the burn-up each batch would receive by mid-year. Discharged fuel is replaced by equal amounts of fresh fuel, the burn-up of which we increase by the core average in subsequent years. When all the initial charge is discharged, we then discharge the fuel loaded in the first year assuming a policy of "first in, first out". Using a computer program for the book keeping, we find that the burn-ups of the spent fuel discharged in the steady state are similar to but in general slightly lower than the discharge irridiations assumed in Method A. This result is expected as we calculate an average burn-up and in practice chan-

nels with higher than average burn-up will be preferentially discharged. As a result Method B probably underestimates plutonium discharged and overestimates plutonium in core. In fact the total plutonium in core at 31 March 1985 according to Method B is 9.6 te to be compared with the value of 9.5 te quoted to the nearest half-tonne in a parliamentary answer[13], suggesting that this can only be a small effect. We determine plutonium discharge at each burn-up from $G(B)$ and the size of the batches. The results obtained from Method B are presented in Table 3.

A further test of Method B is provided by the plutonium content of the fuel dispatched from CEGB stations in the years 1978-84[14]. Seven CEGB stations keep discharged fuel in cooling ponds where the fuel cannot remain indefinitely because the cladding would corrode. The average time between discharge and dispatch for the fuel in ref. 14 was 1.2 years. However this average probably includes Wylfa which has a dry store. We believe that, for the stations with cooling ponds, the total plutonium dispatched over a six year period should be similar to the total of the plutonium produced in a similar period starting one year earlier. We compare CEGB dispatch data with appropriate Method B production figures in Table 4. Note that the reactor-to-reactor variation given by Method B is similar to that in the CEGB data and overall our predictions are a 3.6% underestimate. The CEGB have refused to publish[4] totals of plutonium in the ponds at the start and the end of the six-year period which could discredit or confirm our calculations.

Method C uses the total thermal energy generated and does not use any figures for spent fuel discharged. The principle of the method is to assume that the "ideal refuelling line" was followed. If a linear rise to a certain maximum value of burn-up (B_{max}) is assumed then the energy extracted from fuel in core on rise to steady state,

$$E_c = \int_0^{B_{max}} B\,dD = MB_{max}/2$$

and E_c is equal to E_d, the energy extracted from the fuel discharged in this period.

If in the steady state the amount of fuel D_s is discharged at the burn-up, B_{max} over a period of time in which thermal energy E_s is generated, then it is straightforward to show that to keep the steady state situation constant

$$D_s = E_s/B_{max} \qquad (2)$$

Therefore total thermal energy generated

$$E_T = E_c + E_d + E_s = MB_{max} + D_sB_{max} \qquad (3)$$

Plutonium production can similarly be divided into three parts. Plutonium in core at start (and end) of steady state

Table 3 Plutonium discharge (te) by year (Method B) and totals (Methods A, B, C)

	BRADWELL	BERKELEY	HINCKLEY POINT A	TRAWSFY-NYDD	DUNGENESS A	SIZEWELL	OLDBURY	WYLFA	HUNTERSTON A (CALENDAR YEARS)	
63–64	0.02	0.03								
64–65	0.09	0.06								
65–66	0.19	0.28		0.01						
66–67	0.22	0.25	0.05	0.02	0.04	0.01			0.03	
67–68	0.21	0.24	0.32	0.04	0.16	0.03			0.15	
68–69	0.16	0.21	0.81	0.11	0.28	0.26	0.01		0.34	
69–70	0.20	0.26	0.29	0.33	0.34	0.25	0.07		0.28	
70–71	0.23	0.26	0.17	0.33	0.37	0.34	0.14		0.19	
71–72	0.15	0.24	0.02	0.17	0.28	0.29	0.20		0.09	
72–73	0.20	0.25	0.15	0.03	0.19	0.30	0.18	0.02	0.21	
73–74	0.16	0.26	0.30	0.61	0.22	0.29	0.32	0.07	0.27	
74–75	0.18	0.20	0.36	0.32	0.34	0.30	0.23	0.18	0.26	
75–76	0.19	0.23	0.28	0.25	0.31	0.32	0.24	0.11	0.12	
76–77	0.17	0.24	0.32	0.19	0.30	0.30	0.23	0.29	0.12	
77–78	0.20	0.10	0.38	0.31	0.15	0.29	0.30	0.18	0.20	
78–79	0.15	0.15	0.27	0.25	0.17	0.26	0.18	0.25	0.28	
79–80	0.11	0.21	0.29	0.30	0.08	0.21	0.30	0.48	0.29	
80–81	0.01	0.09	0.36	0.13	0.00	0.35	0.28	0.70	0.21	
81–82	0.01	0.00	0.25	0.27	0.05	0.18	0.25	0.57	0.15	Total discharge all reactors 31–3–85
82–83	0.13	0.06	0.29	0.35	0.22	0.22	0.25	0.63	0.22*	
83–84	0.15	0.02	0.28	0.28	0.25	0.25	0.28	0.35	0.18†	
84–85	0.17	0.07	0.29	0.26	0.23	0.21	0.23	0.63	0.22†	
Total discharge method B	3.30	3.71	5.51	4.58	3.99	4.66	3.69	4.46	3.82*	37.72
Total discharge method A	3.45	3.75	5.47	4.39	3.95	4.57	4.13	5.03	3.96*	38.69
Total discharge method C	3.09	3.69	5.55	4.66	3.80	4.50	3.70	4.82	3.67*	37.49

* Includes 1.25 × (discharge '82) to bring Hunterston to 31–3–83
† Fiscal years for Hunterston

$$P_c = \int_0^{B_{max}} G(B)\,dD = \frac{M}{B_{max}} \int_0^{B_{max}} G(B)\,dB = P_d$$

where P_d is the plutonium discharged in the rise to the steady state. Plutonium discharged in steady state $P_s = D_sG(B_{max})$.

Therefore total plutonium production (including plutonium in core) after substitution from (3) is given by

$$P_T = \frac{E_TG(B_{max})}{B_{max}} + M\left\{\frac{2}{B_{max}}\int_0^{B_{max}} G(B)\,dB - G(B_{max})\right\} \qquad (4)$$

Hence, if the ideal refuelling line was followed, the total plutonium production when total thermal energy E_T has been generated is determined in terms of one parameter, the steady-state burn-up B_{max}.

In Table 3 we present the total plutonium discharged for each station by 31 March 1985 using a B_{max} which is the average of the discharge burnups in Method A for each station for the 10 years prior to 31 March 1985. When B_{max} is calculated for shorter periods or from equation (2) the totals for individual reactors vary in the range ± (0–3) per cent. This suggests that the method chosen to determine B_{max} is not

Table 4 Comparison of Method B predictions for plutonium production 1977–83 with CEGB figures for dispatched fuel 1978–84

	Plutonium produced during 1977–83 Method B (te)	Plutonium dispatched during 1978–84 CEGB (te)
Bradwell	0.605	0.594
Berkeley	0.613	0.637
Hinkley Point A	1.846	1.908
Trawsfynydd	1.625	1.565
Dungeness A	0.672	0.834
Sizewell	1.510	1.600
Oldbury	1.563	1.607
Total	**8.434**	**8.745**

critical.

An interesting result of Method C is that from equation (4) P_T consists of two parts: a first (larger) term which is proportional to E_T and a second (smaller) term which is always positive. The method used by Hesketh[34] and by Simpson[1] to estimate P_T assumes a quoted value for plutonium production per unit of electrical energy generated which for constant thermal efficiency means they were assuming plutonium production proportional to E_T. Since the second term in (4) is always positive, such estimates must be underestimates of P_T as Hesketh claimed. Our calculations suggest that the second term is approximately 2.4 te, summed over all the Magnox reactors.

The possible end uses of plutonium depend critically on its isotopic composition. We have calculated using Method B the plutonium discharged in two plutonium 240 purity bands 0–7 per cent and 0–15 per cent and the results are shown in Table 5. The 15 per cent figure is important because we know there is currently no plutonium of Pu 240 content less than 15 per cent in the civil stockpile[35]. The plutonium of Pu 240 content less than 7 per cent would be particularly useful for military purposes, though plutonium of considerably worse purity could be blended with very high-purity plutonium to form acceptable weapons-grade plutonium. To put the numbers in Table 5 in perspective, Lovins states that the critical mass for weapons-grade plutonium with a reflector is less than 5kg[36].

Plutonium balance

Plutonium must be 'lost' because reprocessing is not 100 per cent efficient. It may either be contained in solid or liquid waste, or discharged into the Irish Sea. By 1974 solid waste accumulated at Sellafield contained a little under half a tonne of plutonium[13]. It was anticipated that the corresponding figure for plutonium losses would not be so great over subsequent years. The Department of Energy have refused to answer parliamentary questions requesting an update of this figure[37] though they have admitted[38] that only about half of the quantity arises from CEGB and SSEB spent fuel.

From radiological data[39,40] on discharges of plutonium isotopes into the sea we calculate that approximately 280 kg of plutonium has been lost in this way up to end 1983. According to a recent parliamentary answer approximately 70 per cent of this arises from CEGB and SSEB spent fuel[40]. In total we assume 0.5 ± 0.2 te of plutonium from the civil stockpile has been lost during reprocessing.

Table 5 Production of high purity plutonium (te) for all CEGB and SSEB stations

	Plutonium 240 / Sum all plutonium isotopes	
	0% – 15%	0% – 7%
Up to 31–3–69	2.3 ± 0.4	0.2 ± 0.1
From 31–3–69 to 31–3–71	0.8 ± 0.2	0.07 ± 0.02
After 31–3–71	1.1 ± 0.2	0.09 ± 0.05

In Table 6 we show the total of plutonium in core and discharged according to Methods A, B and C at the four dates for which official information on plutonium stocks is available[16,33,35,41]. We note that the three methods give differences of 2 per cent or less for the plutonium total at each date. This agreement suggests that uncertainties in exact refuelling policy including discharge figures for the 1960s are not very important when considering the total of plutonium produced. This is supported by the small changes in the total of −0.5 per cent when SUB figures rather than BEST (Table 2) are used in Method B, and +1.7 per cent when a uniform discharge throughout the year is assumed rather than mid-year discharge.

The three methods also calculate discharge burn-up differently. Hence the similarity of results suggests that systematic errors due to the lack of detailed knowledge of the burn-up variation within the reactor are probably smaller than the differences between the totals of the three methods.

All three methods assume the same $G(B)$ which for the civil reactors cannot be directly checked against published data. As a test of the sensitivity of our results to our choice of $G(B)$ we investigate the effect of using a worst-case $G(B)$ specified by parameters at the extent of the range which is reasonable: a fast fission factor of 1.033; $r = 0.07$; higher T_m where there is ambiguity in the literature. This $G(B)$ for a Calder Hall temperature lies well below the Tyror curve and the agreement with the isotopic ratios in Table 1 worsens, but the plutonium total according to Method B falls by only 1.5 per cent. Given that our channel-averaged $G(B)$ underestimates the reactor averaged situation by approximately 1 per cent, we feel that the error on the missing plutonium given below accommodates such systematic effects.

According to Method B the total plutonium increase between 31 December 1981 and 31 March 1985 is 7.7 te. This agrees with the difference calculated from the parliamentary answers of 7.5 ± 0.5 te. Since an interpolation is required to produce plutonium totals at 31-12-81 it is probably safer to compare the difference between totals in 31-3-85 and 31-3-83 which is 4.9 te predicted by Method B and 5.0 ± 0.5 te in the parliamentary answers.

Missing plutonium

We conclude from Table 6 that the amount of plutonium unaccounted for is 6.8 ± 0.8 te according to our preferred Method B. After subtraction of the 0.5 ± 0.2 te lost in reprocessing (which is not included in the subtotal of civil stocks[42]), the missing balance is 6.3 ± 0.8 te.

It is interesting to note that our estimate for the balance agrees with the figure of 6.667 te which was expected to be the maximum involved in the exchange[1] between the United Kingdom and the United States, based on costs in the US enabling act.

Previous studies of UK plutonium production have arrived at the following estimates for the balance of civil plutonium: Durie and Edwards[43], 14.5 te; Hesketh[34], 3.4 te; Simpson[1], 3.3 te. As discussed earlier we believe that approximately 2.4 te should be added to both the Hesketh and Simpson estimates. Their estimates would then be in agreement with ours.

Simpson favoured 3-4 te for the amount consigned to the US on the basis of the amount of plutonium produced by 1969. On 1-4-69 plutonium in their spent fuel arriving at Windscale became the property of the CEGB rather than the UK Atomic Energy Authority. The CEGB has stated[44,45] that fuel reprocessed prior to 1

Table 6 Total plutonium (discharged and in core) from Methods A, B, & C and comparison with Parliamentary Answers

DATE	COL 2*	Method A		Method B		Method C	
	Sub-total of civil stockpile (te)	Total including core as in COL 2 (te)	Difference from COL 2 (te)	Total discharge +core (te)	Difference From COL 2 (te)	Total discharge +core (te)	Difference from COL 2 (te)
31–12–81	33.0	40.00	7.00	39.60	6.60	39.09	6.09
31–3–83	35.5	43.32	7.82	42.44	6.94	41.76	6.26
31–3–84	38.0	45.40	7.40	44.87	6.87	44.03	6.03
31–3–85	40.5	48.19	7.69	47.32	6.82	46.33	5.83
Mean difference			**7.48**		**6.81**		**6.05**

* Figures as quoted in Paliamentary Answers

April 1969 provided the plutonium sent to the United States. Our Method B gives 3.5 ± 0.4 te as the total produced by mid fiscal-year 1968–69, which is consistent with Simpson's estimate. If the plutonium unaccounted for is to be reduced to the amount produced by mid-year 1968–69 our calculations would need to overestimate production by 9 per cent. However, comparison with the CEGB dispatch data suggests that our calculations are a 3.6 per cent underestimate. Furthermore our figure cannot be a 9 per cent overestimate since the adjusted Method B total of plutonium in core on 31 March 1985 would then be 8.8 te which is incompatible with the figure of 9.5 te quoted in the parliamentary answer to the nearest half-tonne.

US plutonium use

According to the government[46] the bulk of the civil plutonium sent to the US is in the inventory of one fast research reactor, the zero power plutonium reactor (ZPPR), "in the core" of another, the fast flux test facility (FFTF), and "a sizeable quantity was used to make californium for medical purposes. The remaining small quantity is in use for experimental purposes elsewhere in the civil programme, for example at Argonne and Batelle."

ZPPR has an inventory of 3.8 te, of which a "portion" of the 3.4 te of fuel-grade plutonium came from the United Kingdom[47]. FFTF only went into operation in 1981, has a core loading of 550 kg plutonium-239[8] and only a "small portion" of FFTF fuel was supplied by the United Kingdom[47]. It has been estimated that at most a few hundred kilograms of its inventory of 2.9 te came from the United Kingdom[48]. The amount of plutonium used for californium production has subsequently been revealed as 200 kg[2]. If 200 kg is a "sizeable quantity" then the "remaining small quantity" in use at Argonne and Batelle is insignificant.

We therefore estimate that the total UK plutonium in the destinations listed by the government is likely to be less than 4.0 te. The UK civil plutonium in these destinations could be considerably less if UK military plutonium was involved, as is possible[1,49].

Hence on the basis of our best Method B estimate we believe that at least 2.3 ± 0.8 te of UK civil plutonium is in destinations other than those given by the government.

Conclusions

The agreement between our three methods suggests that, despite the absence of public data on fuel discharges in the 1960s, it is possible to calculate the total plutonium produced by the civil Magnox reactors to a reasonable accuracy. We conclude that 6.3 ± 0.8 te of civil plutonium, approximately one-sixth of the total civil stockpile, are currently missing. We believe there is at least 2 te of UK civil plutonium in destinations other than those admitted in parliamentary answers. Until this is clarified the suspicion will exist that these destinations could be military.

Our calculations agree with the rather limited data available on plutonium production in civil Magnox reactors: parliamentary answers; isotopic ratios in CEGB dispatch data; and the "Flowers Report". Indeed they underestimate plutonium production when a comparison is made with CEGB dispatch figures.

In view of our findings we believe it is important that the UK government provides a much fuller explanation of the fate of civil plutonium produced during the 1960s, publishes more detailed information on civil plutonium production since 1971 and accepts effective safeguards on all civil nuclear facilities. This should include the currently unsafeguarded Magnox reprocessing line at Sellafield which handles both civil and military plutonium and which has been the subject of continuing conflict between the government and EURATOM (the appropriate safeguards agency) since the United Kingdom joined the EEC[50].

We also find it most unsatisfactory that the government refuses to publish information on plutonium production by individual civil reactors even in recent years[51], that this information is not supplied to EURATOM[52], and that the CEGB removes the necessary data from its computer records[53].

Only by clarifying the extent of past links between civil and military nuclear programmes in the United Kingdom and by implementing procedures to prevent any such future re-occurrence can the government and the nuclear industry hope to strengthen the international non-proliferation regime. Such clarification would now be timely with the Non-Proliferation Treaty review conference under way in Geneva.

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