Report to: Natural Resources Wales

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Misleading information from the Environment Agency concerning evidence for Plutonium Microparticles in the Hinkley Point sediment

The National Resources Wales (NRW) report *Response to report NRPB-M173* has been brought to my attention. It is undated and has no identifier, but hopefully can be located from the title.

The NRW report contains a number of misleading statements that I assume originated with the nuclear regulator the Environment Agency (EA). I would appreciate this report being forwarded to the EA with a request that they give immediate attention to the questions and requests raised. I would be grateful to be copied into the email correspondence as it will be clear from Refs. 1 and 2 (attached) that I have relevant expertise. NRW's contacts may wish to question me directly.

1) **It is a matter of public record (Hansard, 19582) that the Hinkley Point A reactors 'could' be used to produce Plutonium for the weapons programme but the regulator (EA) has no evidence that they were ever used to produce Plutonium for the weapons programme. Moreover, were Plutonium produced in the Hinkley Point A reactors, this could not have been extracted from the fuel as this could only take place during the fuel repossessing at NRPs such as Sellafield.**

As Ref.1 describes, in 2000 the Ministry of Defence reported that it had found 0.37 tonnes of weapons grade plutonium, the origins of which they could not identify. The calculations which we published in 1985 [2] show that the UK Magnox reactors produced 0.36 tonnes of weapon's grade plutonium in their early years, the bulk of this from Hinkley Point A (HPA). This is relevant to the discussion of Plutonium Microparticles (PMPs). The requirement to extract the fuel while the plutonium was still weapons grade and to get it to Sellafield before the start of the NPT (which would forbid the practice), resulted in more than half the HPA core being extracted in 1968 with equipment designed to change 20% of the core a year. This resulted in the accidents which compromised the Magnox cladding of the spent fuel elements. Then in 1969, according to a MAFF report [3], an accidental release of sulphuric acid into the pond resulted in

"irreparable damage…..to the particularly large amount of spent fuel that was there at the time…..not merely corrosion of the magnox which has in some cases disintegrated completely, but extends……to extensive surface corrosion of the uranium itself."

Whoever at the EA wrote theat plutonium could only be extracted at Sellafield in appears unaware that these accidents were the origin of the plutonium in the waste discharge recorded in NRPB-M173. This prompts the first question for the EA:

Q.1 When the original decision was taken in 2018 to dredge and dump the sediment without alpha testing, were those who took the decision aware of the extent of the accidents recorded in Ref. 3 and the plutonium record in liquid waste in NRPB-M173?

2) Over many years of annual monitoring, and to the best of our technical advisors' knowledge, hot particles have never been identified around the Hinkley area. The high levels emitted by these particles will mean that they would have been detected by gamma spectrometry in the first instance. Furthermore, no hot particles have been identified in the previous subsurface or surface sediment samples taken for the previous dredging application for Hinkley Point.

Plutonium Microparticles were identified in the liquid waste discharged from HPA by their alpha emissions recorded in NRPB-M173 (red line in Fig.1). All the plutonium signal recorded in NRPB must have come from particles of less than 5 micron diameter as this is the size of the filters at the exit of the cooling ponds. Note the MNP peak in 1982 is larger than the original peak due to the accidents in 1969. Clearly a lot more PMPs got through the filters in 1982 but there is no sign of a peak in the dotted blue line, which is the gamma signal. The PMPs in the Hinkley sediment do not emit gammas and cannot be identified by gamma spectroscopy.

Q.2 What do the EA records indicate was the origin of the large number of PMPs emitted in 1982?
Q.3 Were any alpha measurements made on liquid discharges from HPA in later years than 1984. If so, please provide them. If not, why not?
Q.4 Have those dealing with the clean up of the HPA cooling ponds measured the plutonium content of the sludge at the bottom of the ponds?
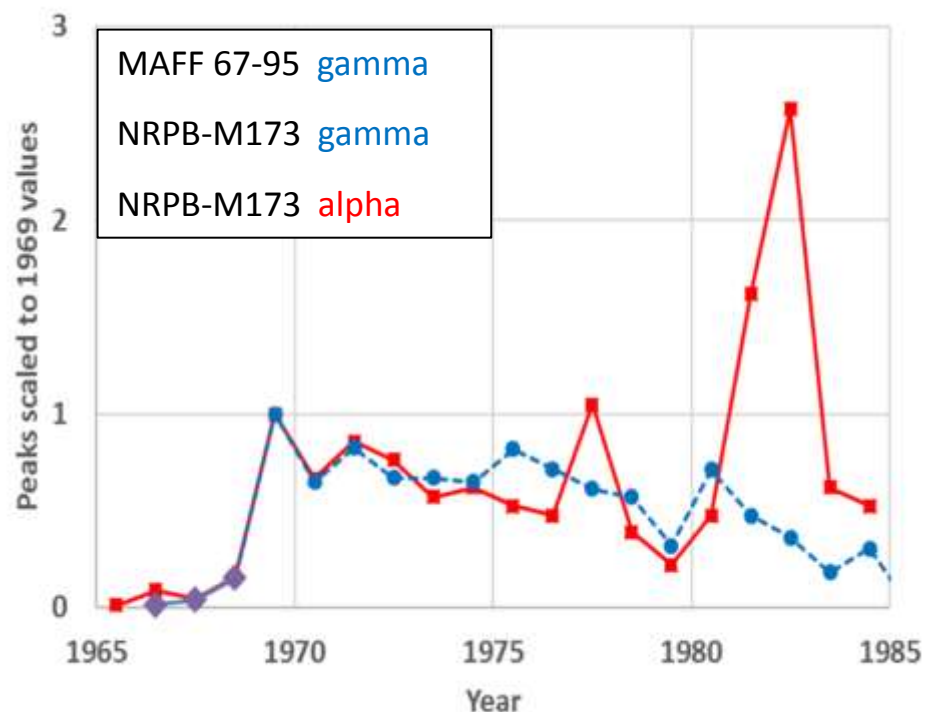
3) **…..levels of Americium-241 measured by gamma spectrometry can be used to infer the presence of …….some radioisotopes of Plutonium – as they would be expected to behave similarly in the environment. Plutonium concentrations are estimated using a model that assumes their activities are proportional to the ratio in Sellafield discharges………… Alpha spectrometry has not been necessary for the samples from the Hinkley dredge area as the doses from all contributing radionuclides, including measured concentrations of Americium-241 and those estimated for Plutonium concentrations, were not exceeded.**

The bulk of the plutonium in sediments in the Hinkley area probably originated in the discharges from the HPA cooling ponds. Your model can therefore be refined:

1) The correction for Americium-241 decays can start from 1968, the most likely date for generation.
2) Our calculations estimate that the isotopic ratio of Plutonium-241 in these discharges was

$$Pu\text{-}241/\text{all isotopes} = (3.05 + 0.39/\text{-}0.25)\%\ \text{by weight.}$$

Finally two requests:

 Request 1. Please use your model to recalculate the plutonium concentrations from the measured Americium-241 in the dredge area referred to above, using these two corrections and compare the results with safety limits.

 Request 2. Given that Fig. 1 clearly shows that the HPA PMPs are not detectable by gamma emission, we request that all samples be tested for PMPs by techniques such as those used in Ref. 4, whether or not they show a gamma signal.

References

1) K.W.J.Barnham et al., *Nature*, **407**, 833, (2000). (attached)
2) K.W.J.Barnham et al., *Nature*, **317**, 213, (1885). (attached)
3) MAFF "Liquid Waste Disposal Authorisation, CEGB Hinkley Point", PDRW (69) 74
4) S.R.Aston. D.J.Assinder and M.Kelly, *Estuarine, Coastal and Shelf Science* (1985),20,761-771

COMMENTARY

Production and destination of British civil plutonium

K.W.J. Barnham, D. Hart, J. Nelson and R.A. Stevens

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 IME	Bradwell SUB	Bradwell BEST	Berkeley IME	Berkeley SUB	Berkeley BEST	Hinkley Pt IME	Hinkley Pt SUB	Hinkley Pt BEST	Trawsfynydd SUB	Trawsfynydd BEST	Dungeness IME	Dungeness SUB	Dungeness BEST	Sizewell SUB	Sizewell BEST	Oldbury SUB	Oldbury BEST	Wylfa SUB	Wylfa BEST	Hunterston* IME	Hunterston* 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 was 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[33]. 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 re-fuelling 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

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

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 $P_s = D_s G(B_{max})$.

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

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

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

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

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.

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* Sub-total of civil stockpile (te)	Method A Total including core as in COL 2 (te)	Method A Difference from COL 2 (te)	Method B Total discharge +core (te)	Method B Difference From COL 2 (te)	Method C Total discharge +core (te)	Method C 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

——————————COMMENTARY——————————

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 Mag-

nox 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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Careers in science offer women an unusual bonus: immortality

Sir — I was alarmed to learn in your Opinion article[1] that President Clinton's National Science and Technology Council was "toothless" in its failure to address the shortage of women and minorities in science, technology and engineering, and that this situation could have "devastating" consequences by 2050 for the US economy and scientific leadership[2].

An analysis of death notices and obituaries in *Nature* every 10 years from 1949 to 1999, and in *Science* every 10 years from 1949 to 1969 (after which it stopped regularly publishing these) suggests a way of increasing the number of women scientists dramatically. As I show here, women scientists rarely die. Once word of this acquired immortality gets out, women should flock to scientific careers.

Of 1,184 obituaries in a three-year period coded for year of publication, sex, age at death, cause of death (if known) and field[3], women accounted for 49 of 917 (5.3%) in *Science* and 13 of 267 (4.9%) in *Nature*; of the 44 commemorated in both journals, two were women. *Science* carried 3.43 times more obituaries than *Nature*; but the proportion of women remained constant at about 5% in each journal.

The dramatic increase in the number of women entering science, technology and engineering during the past 40 years (in which the number of female doctorates has grown at more than twice the rate of that for men, averaging 7.5% per year[3]) coincided with acquisition of immortality in increasing numbers of these women.

Although women in the physical sciences were represented by 4.8% of the death notices in *Science* and 8.3% of the obituaries in *Nature* in 1969, by 1979 there were none — they had become immortal (see Fig. 1). Since women received only 2.2% of US doctorates in engineering by 1978, more time is needed to assess the degree, if any, to which women in this field have acquired immortality. Women in the life sciences started to become immortal in 1979, but immortality is not yet fixed in this group, since one obituary appeared in 1999 — a year after women received 45.4% of the doctorates in that field (see Fig. 1). This trend is also found in other scientific and science-related fields of endeavour.

The fact that women were featured in some obituaries between 1949 and 1969 for all fields except engineering demonstrates that noteworthy women were contributing to scientific and scholarly endeavours half a century ago. As more females received doctorates over
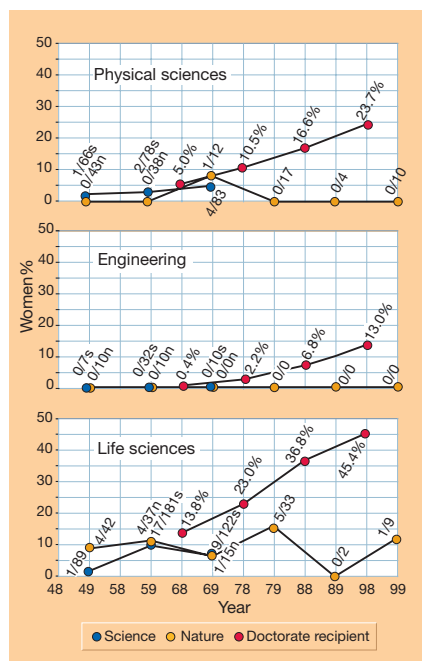

Figure 1 **Percentages of women who received doctorates compared with those who received obituaries. Red circles, percentages of US doctoral degrees awarded to women during 1968, 1978, 1988 and 1998; blue circles, percentage of death notices for women in *Science* for 1949, 1959 and 1969; yellow circles, percentages of obituaries for women in *Nature* for 1949, 1959, 1969, 1979, 1989 and 1999. The numerator of fractions provides the number of obituaries for women; the denominator represents the total number of obituaries; s, *Science*; n, *Nature*.**

subsequent years, however, the numbers of obituaries for women decreased to zero in the physical sciences, social sciences, education, humanities and other categories. One may therefore conclude that women in these fields no longer die.

The big question, of course, is what are the factors that led to their immortality? Is there a gene that predisposes women scientists to live for ever? If so, I propose the name *foy* (fountain of youth), and suggest that the researchers at DREADCO look into this.

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Enigma thief stole a very special machine

Sir — Natasha Loder writes (*Nature* **407,** 278; 2000) that the particular kind of four-rotor Enigma machine used by the German Abwehr — and stolen from

Bletchley Park earlier this year — is very rare, and that the only other known example is owned by the US National Security Agency.

This is correct. But, rare though the Abwehr versions are, there are several other four-rotor Enigma machines in existence and available to collectors by legal means. I myself own one: No. 877, bought at Sotheby's in March 1994 (it was previously sold at Phillips in April 1993). At least three others were sold at Phillips and Sotheby's during the 1990s.

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Did civil reactors supply plutonium for weapons?

Sir — We welcome the recent publication by the UK Ministry of Defence (MOD) of the first official inventory of the country's military plutonium[1,2]. The report contains a remarkable admission[2]: "These figures show that the weapon cycle stockpile is in fact some 0.3 tonnes larger than the amount of plutonium the records indicate as available". Hence, the MOD was not aware of the existence of 60 bombs' worth of weapons-grade plutonium. The report does not attempt to identify the origin of this plutonium, simply quoting[1] "From unidentified sites, 0.37 tonnes", despite there being very few sources of weapons-grade plutonium.

We believe some calculations we published 15 years ago[3] can help the MOD identify the source. In their early years (1963–72) the UK's civil Magnox reactors produced significant amounts of weapons-grade plutonium. In 1984 it was admitted that it was reprocessed at Sellafield in the same line, and at the same time, as the weapons-grade plutonium from military reactors[4]. British Nuclear Fuels Ltd, the plant operators, admitted that they called the weapons-grade plutonium "military" irrespective of origin[4]. It would have been consistent with these practices if all weapons-grade plutonium was shipped to the MOD's Aldermaston site. The government stated in 1983 that there was no weapons-grade plutonium in the civil stockpile[5].

Today, the UK government refuses to quantify plutonium production from civil reactors for these early years. In 1985 we published an estimate of (0.36 ± 0.11) tonnes for the total weapons-grade plutonium produced by the UK civil reactors[6]. This agrees remarkably well with the MOD figure of 0.37 tonnes for plutonium of unknown origin. We conclude that about 11% of the

correspondence

plutonium in UK nuclear weapons originated in civil reactors.

The MOD reports do not separate the transfer data into weapons-grade and non-weapons-grade plutonium, and there are no data on production in the country's dedicated military reactors at Calder Hall and Chapel Cross.

We call on the MOD to provide this information. Similar data have been made public in the United States[3]. The UK government is now in an anomalous position, having published the military stockpile while refusing to publish similar figures for civil plutonium. We request that they do so, and clarify the contradictory statements that have been made to Parliament about the fate of civil plutonium.

The Magnox reactors have entered their shutdown phase and are again producing significant amounts of weapons-grade plutonium. The UK government has recently decided to restrict information on plutonium production in civil reactors[7]. One hopes that history will not repeat itself.

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Achievers should stay to aid Brazilian science …

Sir — The Opinion article "Genome sequencing for all" (*Nature* **406,** 109; 2000) exposed a patronising view of research in developing countries.

In my view, *Nature* could have used its valuable space to tackle more interesting, painful yet real issues surrounding scientists in developing countries (see the News feature "A springboard to success" in *Nature* **407,** 440–441; 2000). For example, why was the Brazilian paper celebrated in your Opinion article an exception rather than the rule?

Local antinationalism has allowed imperialism from industrialized countries to survive for centuries. So, although I understand the views of the Brazilian scientists abroad "who frequently decide not to return, citing a lack of scientific opportunity", they are also being used as cheap labour in rich countries. Hence they are perpetuating an unfair situation by their short-sightedness and selfishness (very often their studies have been funded by Brazilian public money).

By leaving Brazil they may well avoid having to carry out less 'important' or 'glamorous' science. But they also lose the chance to involve themselves in relevant issues such as the dismantling of Brazil's public university system, or to claim the right to better jobs and working conditions, or to build a better future for themselves and for future generations.

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…yet the path is strewn with needless obstacles

Sir — I am a young Brazilian scientist and I agree with Tomas Prolla's point in Correspondence[1] that the rigid bureaucracy in Brazil turns scientific research into a nightmare.

Four years ago, I asked the director of the institute where I did my PhD to release funds (about US$20) so I could send reprints to England, as one of my results was going to be cited in a textbook to be published there. The director punched his desk and said that he was not there to support my megalomania. I sent the reprints using my own money, and my result was cited in the book[2]. A professor from another university told me that to behave as I had done, at my level of seniority, would cause fear among my superiors.

I recently entered the selection process for a professor's position in one of Brazil's leading universities. One of the interviewers asked why I wanted to stay in academia instead of working in industry for better pay. I did not get the job.

The person who got the job has published about six papers in journals, and is corresponding author on none of these. My curriculum vitae lists 21 papers in good international journals. In 20 of these I am the corresponding author and in 11 I am the sole author. I have spent $23,000 of my own money doing serious research in this country and I receive about $200,000 as a government grant. In my laboratory I have the first atomic force microscope for biological research in the country.

This is the fourteenth selection process I have undergone in this country. Before I received the result of my latest attempt, I was advised by another professor to go to the United States as I do not fit in the Brazilian system.

It seems that Brazil can produce good scientists for export, but this material does not bring income into the country.

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If free speech costs lives that's a high price to pay

Sir — Stewart *et al.* are right to remind us that the 17 years following the discovery of HIV have been a long time (*Nature* **407,** 286; 2000).

Both of us lost grandparents and great-grandparents to tuberculosis. One might have thought that in the hundred or more years since Robert Koch discovered *Mycobacterium tuberculosis* (without fulfilling all his postulates), we would have done a little better than the state we are in today: some 1.7 billion infected, with an annual death rate of 1.8 million. Of course we could all agree on tuberculosis being caused by another, as yet undiscovered, microbe riding on the intimate coat-tails of *M. tuberculosis.* Then perhaps the lack of progress would make sense. Paradigm lost.

In an earlier life one of us was valet to the French philosopher Voltaire. I remember cleaning his room one day, coming across a letter to Jean-Jacques Rousseau. As a Huguenot, I rejoiced at the remark, "I disapprove of what you say, but I will defend to the death your right to say it". What is not widely known is the next sentence: "My only question, Sir, is whether the columns of *Nature* are appropriate?".

We are staunch believers in the right to free speech, but is *Nature* the appropriate place to militate in favour of the pre-Copernican model of the universe or the existence of phlogiston? After all, there is Speakers' Corner in Hyde Park, when it's not raining. To demand the right of reply or equal time on such matters is a trick the creationists have used.

HIV causes AIDS. Problems arise when the proposed alternative costs lives.

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