British Pugwash Group

Report of Working Group on

The Management of Separated Plutonium in the UK

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About British Pugwash

Pugwash is an international network of scientists and others concerned about the social impact of science. It shared the Nobel Peace Prize in 1995 with the founder of British Pugwash, Joseph Rotblat, for its work during the Cold War era. Its success has depended on its reputation for impeccable scientific integrity and lack of bias. It has representatives in over 50 countries, and the British Pugwash Group plays a major role in many of its international activities.

The organisation was born when Bertrand Russell released, on 9 July 1955, the Russell-Einstein Manifesto, which called on world leaders to "learn to think in a new way". The launch was chaired by Joseph Rotblat. This led to the first conference in 1957 in Pugwash, Nova Scotia, which set up a "British Advisory Committee for Pugwash". This evolved in 1963 into the British Pugwash Group, initially under the chairmanship of Sir Neville Mott. Other scientists, including Cecil Powell, Rudolf Peierls, and Dorothy Hodgkin, have guided British Pugwash over the years.

The British Pugwash Group, linking with experts from Pugwash's international network, uses the best scientific expertise to inform the government and the public about issues relating to weapons of mass destruction – especially nuclear weapons and nuclear power – matters of war and peace, the environment, and the social responsibility of scientists. Membership is open to anyone in the UK qualified by profession or experience to contribute to the work of Pugwash. Many of our leading scientists, engineers, and technologists are members of the British Pugwash Group. BPG currently has more than 200 members, about a third of whom are Fellows of the Royal Society. British Pugwash activities range from private meetings with officials to regular public discussion meetings, and from in-depth publications and books to letters to newspaper editors.

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The Management of Separated Plutonium in the UK

Acronyms

AGR	Advanced Gas-cooled Reactor
ATW	Accelerator Transmutation of Waste
BE	British Energy
BERR	Business, Enterprise, and Regulatory Reform
BPG	British Pugwash Group
BNFL	British Nuclear Fuels Limited
CCTV	Closed-Circuit Television
CNC	Civil Nuclear Constabulary
CPNI	Centre for the Protection of National Infrastructure
CoRWM	Committee on Radioactive Waste Management
DBT	Design Basis Threat
DOE	Department of Energy (US)
EdF	Electricite de France
EOD	Explosives Ordnance Disposal
EPR	European Pressurised Reactor
ERM	Environmental Resources Management Ltd
Euratom	European Atomic Energy Community
GNEP	Global Nuclear Energy Partnership
HIP	Hot Isostatic Pressing
HLW	High Level Waste
HMG	Her Majesty’s Government
HSE	Health & Safety Executive
IAEA	International Atomic Energy Agency
IDM	Integrated Decision Management (IDM Associates)
ILW	Intermediate Level Waste
IT	Information Technology
MOD	Ministry of Defence (UK)
MOX	Mixed Oxide
MDF	MOX Demonstration Facility
NDA	Nuclear Decommissioning Authority
NII	Nuclear Installations Inspectorate
NIMBY	“Not in My Backyard”
NPT	Non-Proliferation Treaty
OCNS	Office for Civil Nuclear Security
Pu	Plutonium
PWR	Pressurised Water Reactor
QA	Quality Assurance
R&D	Research and Development
RS	Royal Society
SAIS	Scientific Aspects of International Security
SGHWR	Steam-Generating Heavy Water Reactor
SLC	Site License Company
SMP	Sellafield MOX Plant
SPRS	Sellafield Product and Residue Store
SNS	Spallation Neutron Source (US)
THORP	Thermal Oxide Reprocessing Plant, Sellafield
TRD	Technical Requirements Document
UKAEAC	United Kingdom Atomic Energy Authority Constabulary

Report Outline and Summary

The UK is currently at a technical and strategic cross-roads. Over the past 50 years it has built up a stockpile of about 100 tons of separated plutonium. The initial motivation for doing so was the belief that this would be the fuel for a first generation of fast breeder reactors, and that these would enable the UK in due course to make full use of the energy contained in natural uranium to generate electricity. For various reasons, described more fully in this report, this strategic vision has not been realised, and there are many who doubt whether it ever will be. However the required technical infrastructure (facilities to reprocess the spent fuel from non-breeder reactors, and to separate off its contained plutonium) was established in the 1960s, and the separated plutonium has continued to accumulate ever since. Following the discovery of North Sea oil and gas, the pace of reactor development in the UK slowed down, and in 1988 the government decided to stop the fast reactor programme altogether. Shortly after this, it was decided that the UK should move towards a policy of burning the separated plutonium in non-breeder reactors, by fuelling these with Mixed Oxide (MOX) fuel containing up to 7% of plutonium. Work on the fabrication of MOX fuel elements had been proceeding on a modest scale since 1960, and in 1993 the MOX Demonstration Facility (MDF) was built at Sellafield to undertake small-scale production of MOX fuel. During the 1980s Sellafield also started to develop an improved manufacturing process, which was eventually incorporated into the design of a new fully-automated production facility, the Sellafield MOX Plant (SMP), which started commissioning in 2001.

The designed throughput of SMP was 120 tons of heavy metal/year, and this figure would be sufficient to enable the UK to convert the whole of its present 100 ton plutonium stockpile into MOX (and thereby create about 1500 tons of MOX) in a reasonable period of time (about 15 years). However, for various reasons, mostly unpublished, SMP has never achieved its design throughput, and in the most recent year for which figures are available (2006/7) it only produced 2.6 tons of finished fuel assemblies. A further difficulty has been that no UK power reactor is currently licensed to burn MOX fuel, so SMP has always been dependent on overseas sales to dispose of its product. So the strategy developed in the 1990s for managing the UK stockpile of separated plutonium is currently in disarray. Meanwhile in France, the equivalent Melox plant at Marcoule has been successfully producing MOX since 1995, at a rate of about 140 tons/year and is planning to increase its throughput to 195 tons/year shortly. France has some 20 reactors licensed to burn MOX.

Throughout the period 1990-2004, UK policy in this area was complicated by a combination of technical problems and governmental delays. The technical problems included a disastrous failure of the quality assurance system at Sellafield in 1999 for MOX produced for overseas customers, and problems over the commissioning of the SMP plant. Governmental problems included delays over the decision to dismantle British Nuclear Fuels Limited (BNFL), and to pass responsibility for both reprocessing and MOX production to the newly formed Nuclear Decommissioning Authority (NDA), which finally took over in 2004. Since then, the NDA has been engaged in work to define a rational policy in this area, and during the period 2006-8 it undertook a series of optioneering studies on the way forward for managing the plutonium stockpile.

In parallel with these developments within the UK government (and the various agencies responsible to it), there has been a series of attempts by independent experts to initiate a public debate. These have included two important studies undertaken by the Royal Society. In 1996, it set up a working group on plutonium under the chairmanship of Sir Ronald Mason, which published a largely-ignored report in 1998, urging the UK government to undertake an urgent review of its policy in this area. In 2006 it set up a second working group, chaired by Prof Geoffrey Boulton, whose report was published in September 2007. This reviewed the options which were available to the British government, and made a large number of recommendations.

During the period September 2007 – April 2008, the British Pugwash Group (BPG) Executive Committee reviewed these two reports, and other information which was published around the same time, and concluded that the subject merited further attention. The areas which BPG felt should be explored further included:

- Opinion within the UK nuclear industry;
- Plutonium-management practices in other nuclear-capable countries;
- The reasons why the Sellafield MOX plant (SMP) was currently operating so far below its design throughput - and the feasibility, timescale and cost of remedying this situation;
- The current level of physical protection of the stockpile;
- The risks involved in leaving the material in its present form indefinitely; and
- The relative costs of various possible management options.

This last point was particularly significant in view of the substantial, if erratic, increase in the price of uranium on the world market in the past decade, from an all-time low of $7/lb in 1991 to a temporary peak of $136/lb in June 2007. Prices near the top of this range clearly strengthened the economic case for making MOX fuel. The BPG also noted that the UK government had recently published its Energy White Paper 2008, in which it committed itself (with some qualifications) to a substantial programme of new nuclear power plant construction in the UK. This again substantially altered the relative credibility of the options for managing the stockpile. In view of all this, the BPG Executive Committee decided, at its meeting on 27 September 2007, to set up a Working Group to prepare the report presented here, which would address these issues as far as its resources permitted.

The present report recognises that the need for a carefully-planned strategy for the management of the UK's stockpile of separated plutonium is part of a wider need to have a policy which addresses two objectives which are not always readily reconciled:

1. The UK needs to have a secure and stable energy supply policy, which sufficiently protects it from large fluctuations in supply and demand (and hence prices) and enables it to meet its international obligations in relation to global warming;

2. The international community needs to create and sustain a nuclear security regime, in which threats from rogue states and terrorist groups can be contained, if not eliminated.

The Working Group concluded that the available plutonium management options could be broadly classified as:

1. **Do nothing** (other than ensuring that the risks involved in storing it are kept at an acceptably low level, by an appropriate combination of physical protection and security measures);

2. **Bury it** (ie put it into a form that would allow it to be safely disposed of as a waste material in some suitably designed repository—either immediately or at some future date. The form of the waste would also make it difficult for a malefactor to recover the plutonium for malign purposes);

3. **Burn it** (ie convert it into nuclear fuel that would be suitable for use in existing or reasonably foreseeable future reactors, either in this country or elsewhere. Having been burned in such reactors, the resulting spent nuclear fuel would then meet the 'spent fuel standard' for disposal as a 'self-protecting' waste).

The present report reviews each of these three options (including several variants of each). It concludes that it is not yet possible to reach a firm conclusion on the relative merits of each, because of the serious absence of scientific, technical and commercial information in the public domain. Some of this information is quite properly classified, because of legitimate security concerns. But much of the information has been withheld for less creditable reasons, and there is an urgent need to open up the debate by making it publicly available. Only then can a decision be taken which commands widespread public support.

1. Introduction

It is a fairly well-known fact that during the past 50 years, the UK has progressively accumulated a stockpile of about 100 tons of separated plutonium. Most of this material was created in nuclear reactors operating in this country, some of which were explicitly intended to produce plutonium for military purposes, and some of which were intended to generate electricity for civilian use, and only incidentally (but unavoidably) produced plutonium. In both cases, the plutonium was initially contained within spent nuclear fuel discharged from the reactor, which also incorporated unburnt uranium and fission products. This highly radioactive material was then reprocessed chemically, mostly in one of the plants at Sellafield, to produce three separate output streams – uranium which could be re-utilised in reactors, ‘separated plutonium’, and high level radioactive waste, which contained the fission products. The separated plutonium was in some cases used (or stockpiled to be used in due course) as a raw material for the production of nuclear weapons (either in this country or, to a small extent, in the USA): the remainder was stockpiled at Sellafield in the expectation that it would at some stage be used within the civilian nuclear power programme.

At various stages in the history of the UK nuclear industry, there have been different ideas about the ultimate fate of this stockpiled material. Initially, the expectation was that it would eventually be used to generate energy in a new generation of fast breeder reactors. The reasoning behind this view was that first generation ‘thermal’ reactors only utilised a very small fraction of the nuclear energy contained within their fuel – essentially they only released the energy content of the U-235 in the fresh fuel, which amounted to less than 1% of the total nuclear energy in the mined uranium (which contains 99.3% of U-238). It was felt that this was very wasteful of the world’s uranium resources, which were then believed to be very limited, and that in due course the nuclear industry would be obliged (and would also be economically motivated) to move on to second generation ‘fast breeder’ reactors, which would be capable of burning the entire content of the mined uranium, and indeed any plutonium produced en route. The stockpiled plutonium could be used as a fuel within such reactors, and in consequence was of high economic value.

Various issues prevented this scenario from being played out as planned. The early prototype fast breeder reactors encountered a number of technical difficulties (mostly problems relating to heat exchangers which were in principle soluble but which led to embarrassing delays in the programme). The capital cost of fast breeder reactors also seemed to be rather high in comparison with thermal reactors with the same power output. Then came the discovery of North Sea oil and gas, which made the UK temporarily energy-self-sufficient, and removed the immediate economic pressure on the UK to develop its nuclear industry. This was followed by the accidents at Three Mile Island and Chernobyl, which led to a major downturn in the nuclear industry worldwide, and for a while made it politically impossible for any UK government to embark on the construction of new nuclear power plants of any design. In parallel with these civilian developments came the breakup of the Soviet Union, the negotiation of a series of nuclear disarmament treaties, and the signature of the Comprehensive Test Ban Treaty which greatly reduced the demand for plutonium for military purposes, and indeed led the UK to declare part of its stockpile of weapons-grade plutonium to be surplus to requirements.

Faced with this history, the nuclear industry worldwide (including the UK industry) began to explore possible alternative ways of making use of the plutonium produced in reactors, which would be less expensive than developing and installing fast breeder reactors. The route taken was to develop the concept of using MOX fuel in slightly-adapted thermal reactors. MOX (an acronym for Mixed Oxide fuel) is a fuel in which the uranium-235 is largely replaced by plutonium. A typical MOX fuel element contains 5-7% of plutonium, and the uranium is either natural uranium or almost pure U-238 (ie the tailings from a plant used to extract the U-235 from natural uranium). The performance of MOX fuel in a thermal reactor is not identical to that of a conventional fuel element (containing 3-5% U-235), but it is very similar, and the cost of modifying a conventional thermal reactor to burn MOX is not great, and is even lower if the capability to burn MOX is designed in at the outset. Overall, a country which has a suitable combination of normal thermal reactors and reactors burning MOX fuel can use its mined uranium more efficiently (typically by ~30%), and does not need to have a steadily-increasing stockpile of separated plutonium. Nevertheless, the use of MOX is by no means a complete solution to the problem of making full use of the energy in the mined uranium: to do that would eventually require the adoption of fast breeder technology.

Among the countries which have an advanced nuclear industry, there is a spread of different historical approaches to this problem, and this is reflected in large variations in the national inventories of separated plutonium which they hold. As at the end of 2007, the UK stockpile of separated plutonium consisted of 108 tons of material, as compared with France: 82.2, USA: 53.9, Russia: 44.9, and Japan: 8.7 tons (as reported to the IAEA[1] : the size of the UK figure is partly due to its commercial activity in reprocessing fuel from other countries such as Japan and Germany). Faced with the anomalously large UK stockpile, there has been on ongoing debate, both within the UK nuclear industry and outside it, about how the UK ought to proceed.

A relatively early input to this debate was a working group on the subject set up by the Royal Society in 1996 under the chairmanship of Sir Ronald Mason, which published its report in 1998[2]. That report urged the UK government to undertake a prompt review of its policy in this area, a recommendation which does not appear to have been taken up by the government of the day. Since then there have been a number of relevant developments within the UK and elsewhere, and this led the Royal Society to set up a second working group, chaired by Prof Geoffrey Boulton, to consider the matter further, and its report on this subject was published in September 2007[3]. That report identified the problem facing the UK government as follows:

- There are no current plans for further reprocessing in the UK after 2012, so at that date the UK inventory of separated plutonium will become static unless further steps are taken;
- Maintaining the stockpile at this level involves a certain level of risk:
    - An explosion or fire at the store could release plutonium oxide powder into the environment around Sellafield as an aerosol;
    - Theft of the stockpiled plutonium by national or sub-national groups could lead to nuclear weapon proliferation or to manufacture of ‘home-made’ weapons;
- It noted that certain security measures have recently been put in place:
    - Physical/personnel security at Sellafield have been upgraded since 9/11;
    - A new ‘Special products and residues’ store is being built in Sellafield;

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[1] Addenda to Infcirc549. See http://www.iaea.org/Publications/Documents/Infcircs/2008/infcircnr12008.shtml

2 Royal Society, “Management of Separated Plutonium,” 1 February 1998. http://royalsociety.org/document.asp?id=1915

[3] Royal Society, “Strategy options for the UK’s separated plutonium”, Policy document 24/07, 21 Sep 2007. http://royalsociety.org/document.asp?latest=1&id=7080

- Nevertheless it is arguable that the security status quo is not acceptable.

On this basis, the report reviewed the options which were available to the British government, and listed a large number of recommendations.

During the period September 2007 – April 2008, the British Pugwash Group Executive Committee reviewed these two reports, and other information which was published around the same time, and concluded that there was a lot more work that could usefully be done in this area. In particular, BPG noted that:

1. The RS standing committee on Scientific Aspects of International Security (SAIS) which sponsored these reports, did not extensively review the current thinking in the UK nuclear industry on this problem;
2. The RS did not take evidence on, or incorporate in their report, information on plutonium management practices in other nuclear-capable countries, particularly France, Russia, Japan and the USA – or on ideas for the internationalisation of the plutonium management problem;
3. The RS report did not provide information on the reasons why the Sellafield MOX plant (SMP) is currently operating well below its design throughput, or indicate the feasibility, timescale and cost of remedying this situation;
4. The RS report did not analyse the current level of physical protection of the stockpile, and did not quantify the risk of leaving the material in its present form indefinitely;
5. The RS report was very helpful in providing a list of options that the UK government might consider, but the arguments which it provided for or against each of those options were not always compelling, and it did not reach very clear conclusions about the best way forward;
6. The RS report was published before the UK government published its Energy White Paper 2008[4], in which it committed itself (with some qualifications) to a substantial programme of new nuclear power plant construction in the UK. It was felt that this substantially altered the relative credibility of the options for managing the stockpile;
7. The RS report was published before the prestigious International Panel on Fissile Materials published their report for 2007[5], which has highlighted the risk of large plutonium stockpiles for international security, and encouraged states to consider direct disposal;
8. The BPG noted that there had been a substantial, if erratic, increase in the price of uranium on the world market, from an all-time low of $7/lb in 1991 to a temporary peak of $136/lb in June 2007, and that the current price (Sep 07) was $85/lb. It felt that prices in this upper range made the economic case for MOX fuel much stronger.

The BPG Executive Committee decided, at its meeting on 27 September 2007, to set up a Working Party to prepare a report which would address these issues as far as its resources permitted. The Working Party made a progress report to the BPG Executive Committee at its meeting on 8 April 2008. The discussion at that meeting made it clear that there was a wide spectrum of opinion within BPG about the relative merits of the various options that existed, and that it was unlikely that the Working Group would achieve unanimity in recommending any one option. It was therefore agreed that the report should be, in effect, an optioneering study, in which each of the credible options was developed as far resources permitted, and the

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[4] "Meeting the Energy Challenge A White Paper on Nuclear Power," January 2008, Department for Business, Enterprise & Regulatory Reform, http://www.berr.gov.uk/energy/sources/nuclear/whitepaper/page42765.html

[5] IPFM, "Global Fissile Material Report 2007" http://www.fissilematerials.org/ipfm/pages_us_en/documents/documents/documents.php

arguments for and against each would then be presented as objectively as possible, leaving the reader (including, it was hoped, the UK government) to decide where wisdom lay. The present report seeks to carry out that mandate.

A draft of this report was produced in October 2008, and was submitted to the NDA in time for the series of consultation meetings which it held with interested parties in November 2008. Following that submission, BPG held a meeting with NDA representatives on 27 November, at which NDA explained the process by which they intended to interact with the British government on the development of policy in this area. This included the development of a document defining options, and clarifying the issues which would have to be resolved before a rational decision could be taken. They have now published on their website a set of four documents which are:

- NDA Plutonium Topic Strategy - Current Position January 2009;
- NDA Plutonium Topic Strategy - Credible Options Summary January 2009;
- NDA Plutonium Topic Strategy - Credible Options Technical Summary January 2009;
- NDA Plutonium Topic Strategy - Credible Options Technical Analysis January 2009. [6]

These documents represent a very valuable step in the direction of openness in the development of public policy, particularly in the identification of credible options for HMG to consider, but they have a number of very significant gaps. They contain no quantitative information about costs (all the points where the argument requires such information, the figures are replaced by xxxx), they provide almost no new scientific data, and no information about the security situation. They give indicative timescales for various options, but these are in most cases not explained, and tend to be extremely long. So it seems that there is still a place for the present report to assist in the public debate on this issue.

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[6] These documents can be accessed via http://www.nda.gov.uk/documents/ via nuclear materials p4-5
NDA Plutonium Topic Strategy, January 2009.
http://www.nda.gov.uk/documents/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=27434
Stage A: Credible Options Summary – Plutonium, 30 January 2009.
http://www.nda.gov.uk/documents/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=27429
NDA Plutonium Topic Strategy: Credible Options Technical Summary, 30 January 2009.
http://www.nda.gov.uk/documents/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=27424
Stage A: Credible Options Technical Analysis, 30 January 2009.
http://www.nda.gov.uk/documents/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=27419

2. The overall strategic context for this study

The need for a carefully-planned strategy for the management of the UK's stockpile of separated plutonium is part of a wider need to have a policy which addresses two objectives which are not always readily reconciled:

1. The need for the UK to have a secure and stable energy supply policy, which is sufficiently diverse to give some degree of insulation from large fluctuations in supply and demand (and hence prices) on the world energy market, and which will enable it to meet its international obligations in relation to global warming;
2. The need to create and sustain an international nuclear security regime, in which threats from rogue states and terrorist groups can be contained, if not eliminated.

Historically, the UK has relied upon nuclear energy to provide part of its energy mix, and it currently accounts for about 18% of our electric power production. The government White Paper[7] proposes that this fraction should at least be conserved, in spite of the fact that the present generation of nuclear reactors are coming to the end of their design lives, and (eg on 14 July 2008) statements[8] by the Prime Minister have indicated that he would wish this figure to increase. To meet this objective, in the short term, the UK has no alternative to building advanced thermal reactors of non-UK design, since it has allowed its domestic nuclear power supply industry to wither during the years of North Sea oil and gas plenty, and it does not now have domestic designs of either thermal or fast breeder reactors to offer. However it is currently in a good position to influence decisions on the nuclear fuel which the next generation of reactors should be able to burn, and within a period of one or two decades it should be able to ensure (if it so wishes) that at least some of them can burn MOX fuel. Until recently, the UK was one of the world's leaders in reprocessing spent nuclear fuel, and was poised to become a major producer of MOX fuel, which would have enabled it to manage its plutonium inventory. However in recent years it has allowed its THORP reprocessing plant at Sellafield to become partially disabled by technical difficulties, and its MOX production plant at Sellafield (SMP) has been subject to teething troubles such that it has not yet even approached its design throughput (120 tons/year), and there are now doubts at whether it ever will, unless it undergoes major reconstruction.

On the nuclear security front, the international situation is far from being satisfactory. The number of countries owning (or thought to own) nuclear weapons has risen to nine, and a number of other countries are believed to be approaching the nuclear threshold. At least two of the countries concerned (India and Pakistan) have been close to military confrontation during the past few years, and it seems conceivable that tensions could flare up there again. Although the Non-Proliferation Treaty has been signed by 187 countries, this is no longer seen as a guarantee of good behaviour (as the cases of North Korea and Iraq have shown), and the last quinquennial review of that treaty in 2005 ended badly. At the forthcoming quinquennial review (in 2010), the five leading nuclear nations (including Britain) are likely to come under considerable pressure from other signatories to go much further in honouring the letter and spirit of the treaty, by moving towards eventual complete nuclear disarmament. If they are seen to be reluctant to do so, other signatories may consider withdrawing, thereby further undermining the authority of the treaty. The number of incidents involving the theft of

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[7] See ref 4.
http://www.berr.gov.uk/whatwedo/energy/sources/nuclear/whitepaper/page42765.html

[8] Andrew Grice, "Brown sets 'no limit' on number of nuclear reactors to be built", *The Independent*, 14 July 2008.
http://www.independent.co.uk/news/uk/politics/brown-sets-no-limit-on-number-of-reactors-to-be-built-866896.html

nuclear materials reported to the IAEA has grown sharply during the past few years[9], and although none of the reported thefts has yet involved a sufficient quantity to permit the construction of a terrorist bomb, some of them have been getting close to that. The general level of terrorism has risen sharply in the past decade.

Given this background, there is a significant body of opinion in the UK that believes that the national policy on the management of nuclear materials ought to be driven by security considerations rather than by the need to maintain a balanced portfolio of energy sources, and that very active steps ought to be taken to prevent the emergence of what has been termed the ‘plutonium economy’. There is an alternative view however, that the world-wide ‘nuclear renaissance’ is now unstoppable, and that the goal should be to bring the nuclear fuel cycle fully under international control, so that all the relevant facilities are subject to IAEA scrutiny, all nuclear materials subject to IAEA accountancy, and all signatories to the NPT should be guaranteed supply of their nuclear fuel requirements by a few international suppliers. The existing international regime still falls considerably short of this objective.

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[9] IAEA Illicit trafficking database (ITDB), Fact Sheet.
http://www.iaea.org/NewsCenter/Features/RadSources/PDF/fact_figures2007.pdf

3. Options for the management of the UK separated plutonium

Although the Royal Society 2007 report lists a considerable number of different options for managing the UK stockpile of separated plutonium, it is convenient to group these as follows:

1. Do nothing

This is shorthand for the option of leaving the plutonium in essentially the physical form in which it is now held, and doing no more than is necessary to ensure that the risks involved in storing it are kept at an acceptably low level, by an appropriate combination of physical protection and security measures. By implication, this arrangement is assumed to persist for at least some decades, though the option is left open for some alternative management strategy to be adopted at some future date.

2. Bury it

This is shorthand for putting the plutonium into a form that could be safely disposed of as a waste material in a suitably designed repository (either immediately or at some future date). The form of the waste should also make it difficult for a malefactor to recover the plutonium for malign purposes (by implication, the malefactor is assumed not to possess the kind of shielded processing facilities which would enable it to reprocess highly radioactive material safely – ie it would be sufficient to put it in a form which meets the ‘spent fuel standard’ for disposal as ‘radiologically self-protecting’ waste).

3. Burn it

This is shorthand for converting the plutonium into nuclear fuel which is suitable for use in existing or reasonably foreseeable future reactors, either in this country or elsewhere. Burning the plutonium in this way would produce spent nuclear fuel which, by definition, would then meet the ‘spent fuel standard’ for disposal as a ‘self-protecting’ waste.

Each of these options has several variants, with different timescales, costs, risks and potential benefits attached. These are explored in the following sections of the report. In each case, our approach has been to ask members of the Working Party to act as ‘champions’ for that option, giving an account of the variants where relevant, and making the case for adopting it as strongly as the scientific evidence permits. Other members of the Working Party were then asked to play ‘devil’s advocate’ and identify weaknesses in the cases made. In the final section, we seek to sum up, and identify the key issues where further information or analysis is required before a judgement can reasonably be made.

3.1 Option 1: Do nothing

Champion: General Sir Hugh Beach

This section of the report explores the option of leaving the plutonium at Sellafield in essentially the physical form in which it is now held, and doing no more than necessary to ensure that the risks involved in storing it are kept at an acceptably low level, by an appropriate combination of physical protection and procedural security measures. This is in a sense the default option, which will have been taken if no alternative decision is taken – either to dispose of the material in a deep geological repository or to convert it into nuclear fuel for use in reactors. The ‘do nothing’ option is assumed to persist for many decades, while leaving open the possibility that other solutions may be adopted at some future date. Even if a decision were taken today to pursue one of the other options for managing the inventory, there could still be a requirement to maintain the present arrangements for a considerable number of years.

The main difficulty in presenting a clear analysis of this option is that so much of the relevant information is, quite properly, classified. However in this report we have taken the view that this need not preclude a rational discussion of the option. Our approach has been to gather information which is in the public domain and then setting bounds to the relevant parameters. In most cases, those bounds have proved to be sufficiently narrow to permit reasonable conclusions to be drawn. On some aspects of this option however, it is clear that HMG would wish to use classified information in reaching its conclusions, and in these areas we have sought to identify the questions which they should consider.

3.1.1 What does the material stored at Sellafield consist of?

The separated plutonium at Sellafield is stored in the chemical form of powdered plutonium oxide PuO_2. The plutonium is a mixture of the seven different long-lived isotopes of plutonium, with atomic numbers 236 to 244, with half-lives ranging from 2.87 years to 82 million years, but it seems from published information that it is almost all ‘reactor grade’ rather than ‘weapons grade’ – ie the content of Pu-239 is less than about 90%, either because it came from reactors in which the fuel had a relatively high level of ‘burn-up’ or because it was obtained by ‘blending down’ ‘weapons grade’ material by mixing in ‘reactor grade’ plutonium[10]. This reactor grade material contains a significant fraction of the isotope Pu-241, the relatively short-lived isotope (with a half-life of 14 years) which decays to form americium, Am-241. This ‘in-growth’ of americium makes the material which is currently stored more difficult to handle than pure plutonium: americium 241 has a half-life of 432 years, and is a strong gamma-emitter. Both the americium 241 and the plutonium 238 are relatively short lived isotopes, and their decay is a source of heat.

3.1.2 What are the hazards created by the stored plutonium?

Plutonium itself is not a particularly hazardous material. Most of its isotopes decay by alpha emission, so their radiation can be shielded by a sheet of paper or a person’s surface layer of dead skin. So in the absence of in-grown americium, it can safely be carried around, particularly if it is in a sealed container. Plutonium itself is however hazardous to humans if it is swallowed or breathed in. Swallowing is unlikely, unless the powder were used to poison

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[10] The isotopic content of material transferred to Sellafield from other nuclear establishments is not published, and it cannot be excluded that this still includes some weapons-grade material.

someone, or it were ingested by eating meat from contaminated livestock (eg if the material were spread on the land). However for a given intake, plutonium is much more hazardous when inhaled, because it is more easily absorbed into the blood stream through the lungs than through the gut. The health effects may be acute or chronic – acute pulmonary oedema or an increased risk of cancer. The inhalation of as little as 0.05 mg of plutonium is virtually certain to cause the disease.[11] Nevertheless, because plutonium is a heavy metal, it is not easy to put it into airborne form. It is unlikely that the particle size in the Sellafield store is sufficiently small (say < 3 microns) for it to be immediately suspendable in an air-flow. So to cause widespread harm, it would be necessary either to grind it down to small particle size (a difficult and hazardous undertaking) or to vaporise it by means of a very high-temperature fire or explosion. This latter possibility is one of the real hazards created by the store: even a comparatively small explosion - say a few kilograms of Semtex - might create a temperature high enough to disperse a lot of PuO_2 in respirable form. And the same would be true *a fortiori* if an aeroplane crashed into the store, whether by accident or design. In the resulting intense heat a significant fraction of the plutonium might be converted into respirable PuO_2. Anyone lingering in the area would be likely to breathe in enough to cause a fatal cancer. And many square kilometers of land might be contaminated with relatively insoluble radioactive fine particles to a density requiring decontamination.[12]

The second major hazard is the possibility that a terrorist group might steal plutonium oxide from the store at Sellafield, and then seek to use it to make a crude atomic bomb. There has been much discussion in the open literature about the feasibility of making a significant nuclear weapon from ‘reactor grade’ plutonium[13]. The general consensus is that it would be feasible, though such a weapon would be less reliable than a weapon made with ‘weapons grade’ material, and would have a greater chance of producing a ‘fizzle’ rather than a full-scale explosion – eg a yield of order one kiloton equivalent of TNT or less, rather than tens of kilotons[14]. Nevertheless there is a real possibility of producing a kiloton yield, using perhaps 10-20 kilograms of plutonium. The construction of such a device, starting with PuO_2 powder, is not very technologically demanding, and much of the information required is freely available in the open literature (there is some debate as to whether any really significant information remains classified). The process would require some sophistication, but it does not require materials from specialist suppliers. Terrorist organizations are certainly capable of sophisticated application of scientific principles[15]. The significance of the un-predictability of the yield of the weapon is debatable. Even if it were only a ‘fizzle’ (ie of order 1 kt or less), it would still be of the same order as the largest bombs used in conventional warfare, and it would have a catastrophic effect in an urban area[16]. In addition, it would create a very significant level of radioactive fallout. A terrorist organization might well regard these effects as sufficient to make its point. If the device turned out to have the full-scale explosive power of say 20 kilotons of TNT, it would have an even more catastrophic effect. Another

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[11] ‘Nuclear Free Local Authorities: Greater London Authority Liability Paper’. Annex 1. http://www.nuclearpolicy.info/information/GLA_transport_liability.php

[12] See ref 11.

[13] For a range of views see Jim Green, “Reactor Grade Plutonium and Nuclear Weapons”, May 2005. http://www.geocities.com/jimgreen3/rgpu.html The US Department of Energy has released a statement to the effect that an underground nuclear weapon test was carried out in Nevada in 1962 using reactor grade plutonium supplied by the UK, but details of its composition and the yield have not been released.

[14] The probabilistic aspect of the matter is well explained by J Carson Mark in “Reactor-Grade Plutonium's Explosive Properties”, Nuclear Control Institute, August 1990. http://www.nci.org/NEW/NT/rgpu-mark-90.pdf

[15] The construction of the conventional explosive device that destroyed the PanAm jumbo jet over Lockerbie on 21 December 1988, required considerable planning and scientific skills, as did the construction of the nerve gas weapon used in the Tokyo underground by the Aum group on 20 March 1995.

[16] See ref 11.

possibility is that the stolen material might be sold on to a country with nuclear weapon aspirations and a more highly developed nuclear science and engineering base than any terrorist group, with correspondingly greater probable effect.

3.1.3 How is the material stored?

There are three general classes of UK-owned plutonium at Sellafield:

- Magnox-derived (≈83 tons);
- THORP-derived (≈15 tons);
- Residues transferred from Aldermaston etc (≈3 tons).

The weight figures are as at December 2005[17]. The first class derives from the cohort of Magnox reactors which have operated in the UK since 1956. Spent fuel from these reactors was reprocessed in the B204 plant, and later in the B205 plant at Sellafield, which started operation in 1964. The second class derives from the THORP reprocessing plant at Sellafield, which started operation in 1997, and reprocesses fuel from UK Advanced Gas-cooled Reactors (AGR) and from foreign light-water reactors. The third class derives from material which was initially produced for military purposes, but has now been classified as 'surplus to military requirements' and transferred to Sellafield.

The total weight in 2005 amounted to some 101 tons: it has since increased to 108 tons. By the completion of the currently planned reprocessing campaign (nominally set at 2011, but possibly delayed due to the accident in 2005), a further ~30 tons of foreign-owned plutonium will have been separated at Sellafield on behalf of foreign customers. Most of this is derived from reprocessing Light Water Reactor fuel. This combined stockpile is the largest single accumulation of plutonium in the world (France comes second with 82 tons).

Magnox-derived plutonium has comparatively good isotopic quality. However some of this grade of plutonium has been stored for up to 65 years, so that much of its Pu-241 (14.4 year half life) will by now have decayed to Am-241. It can be exported, since there are transport containers licenced for suitably packaged Magnox plutonium cans. THORP-derived plutonium was mostly produced by reprocessing spent British Energy (BE) fuel, and is hence owned by BE. It currently has a reasonable isotopic quality, as the bulk of the material has not been stored for more than 15 years. It cannot at present be exported as there is no transport container licensed for THORP plutonium cans, though NDA estimate that the lead time for the manufacture and licensing of a transport container could be less than 5 years[18]

The plutonium is stored in amounts small enough to prevent criticality, using well-engineered heavy duty steel cans. PuO_2 derived from THORP is stored in steel triple packs each containing approximately 7.5 kg of plutonium (by metal weight). Material derived from the Magnox reactors is stored in aluminium inner cans, each containing about 5.5 kg of PuO_2. The size of such cans is around 400 ml (about the size of a coke can) so there must be over 17,000 of them in the stores. The stored containers are air cooled, to remove the heat generated by radioactive decay (about 125 W/can), and the radiation hazard within the store is increasing with time as Pu-241 is replaced by the gamma-emitting Am-241.

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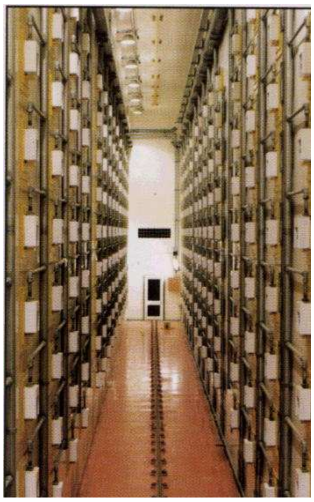
[17] "NDA Plutonium options for comment, August 2008 – October 2008". www.nda.gov.uk/documents/upload/Plutonium-Options-for-Comment-August-2008.pdf

[18] "NDA Plutonium Topic Strategy - Credible Options Technical Analysis", January 2009, p112. http://www.nda.gov.uk/documents/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=27419

There are currently two operational plutonium stores at Sellafield. According to a report in 2000 the Magnox store had recently been extended to have a capacity of 80 tons, and the THORP store has a capacity of approximately 45 tons[19]. The locations of these stores (designated B302 and B302.1 respectively) are shown on several unofficial maps:[20]

Aerial view of Sellafield plant

The appearance of these mini-vaults at Sellafield was first shown publicly in Charles Stuarts ‘Inside Sellafield’ screened on Channel Four in November 1989. *(See picture below)* [21] .



In January 2002, the *Observer* newspaper reported[22] having sight of a highly confidential report which described the plutonium stores as inadequate buildings that needed to be rebuilt. This report, which followed a security review board attended by MI5, the Nuclear

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[19] Radioactive Waste Management Advisory Committee. ”Advice to Ministers on the Radioactive Waste Implications of Reprocessing”, Annex 6, November 2000. http://collections.europarchive.org/tna/20080727101330/http://defra.gov.uk/rwmac/reports/reprocess/index.htm

[20] Wise-Paris, “Airliner Crash on Nuclear Facilities: The Sellafield case”, October 2001. http://www.wise-paris.org/english/ourbriefings_pdf/011029AircraftCrashSellafield3.pdf

[21] ‘Plutonium.’ http://www.lakestay.co.uk/pluto.htm

[22] Nick Paton Walsh, “UK's plutonium 'kept in a shed'”, *The Guardian,* 20 January 2002. http://www.guardian.co.uk/environment/2002/jan/20/energy.politics

Installations Inspectorate (NII) and the Atomic Energy Authority, described the stores as being ‘not much more than a shed’ and unable to resist attack or even a fire. In 2000 British Nuclear Fuels Limited (BNFL) had made a provision of £50m to expand the capacity of these stores, which were likely to become full as a result of ongoing reprocessing operations.

The protection of these stores has been described in a local newspaper article[23] saying that the West Cumbrian local authority Copeland Borough Council had recently (in 2004) approved BNFL plans to build a blast-proof concrete protective barrier around the two Sellafield plutonium stores. The construction of this barrier was seen as a direct response by BNFL to post 9/11 fears of terrorist acts against the stores, which were never constructed to withstand the deliberate crashing of civilian aircraft. No details of the thickness or other dimensions of these particular walls are available, but the concrete walls around some of Sellafield’s facilities are quoted as being 30 feet thick, to protect nuclear fuel plants from side-impacts by planes, including the next generation of passenger aircraft. The whole Sellafield site is surrounded by a high razor-wire fence within which the plutonium stores are surrounded by a secondary razor-wire fence enclosing an inner area, which has a single entry point with a barrier system to prevent unauthorised access. The THORP vault was described in a report dated 1995[24] as being a ‘state of the art’ facility in an inner area with stringent personnel vetting, guarded and restricted access, plutonium storage compartments with ‘bank vault’ type doors, and an automated system such that human access to the store is on an infrequent basis. By 2004 BNFL were said to have spent some £30m on physical security enhancements[25].

In the same year BNFL sought NII approval to proceed with the construction of a new store, designated B556. NII gave approval in May 2005, and according to a report published in April 2006 the first £200m phase of the new store was under construction. In April 2008 this construction was reported to be substantially complete, with work starting on fitting out the internal systems and equipment. It is designated the Sellafield Product and Residue Store (SPRS) and according to the planning application to Copeland Borough Council it is being designed as a high integrity facility which will enable the THORP, Magnox and SMP plants to meet their operational requirements. It is planned that plutonium from the older stores will be transferred to the new store in a phased manner over the next decade or more. But the new store has been designed with a nominal capacity of only 9600 cans, not enough to hold the full plutonium inventory, and it is likely that new store modules will need to be added in 30-40 years, at a similar cost, to allow for the continued safe and secure storage of the plutonium contained in current stores as they reach their end of life. The new store has a design life of between 50 and 100 years, but clearly would eventually need to be replaced if the policy of ongoing plutonium storage continues.[26]

3.1.4 Organisation for the protection of the stores

Plutonium management is governed by international safeguards administered world-wide by the International Atomic Energy Agency (IAEA) and regionally by the European Atomic

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[23] CORE, “Blast Proof Wall for Sellafield’s Plutonium Stores”, 22 March 2004. http://www.corecumbria.co.uk/newsapp/briefings/briefsmain.asp?StrNewsID=189

[24] R Howsley, “Security & Safeguards Aspects of Plutonium Facilities in BNFL”, in E R Merz, C E Walter, Gennady M Pasquín (eds), *Mixed Oxide Fuel (MOX) Exploitation & Destruction in Power Reactors*, NATO ASI Series 1995, pp51-57.

[25] R. Howsley, Conf on Nuclear Power: Risks and Future Governance, London, 21 April 2005

[26] HM Nuclear Installations Inspectorate, BNFL Sellafield and DRIGG and UKAEA Windscale Local Liaison Committee Report, Quarterly Report for 1 October to 31 December 2004. http://www.hse.gov.uk/nuclear/llc/2004/sella4.pdf
HM Nuclear Installations Inspectorate, BNGSL Sellafield and DRIGG, and UKAEA Windscale West Cumbria Sites Stakeholder Group, Quarterly report for 1 April to 30 June 2005. www.hse.gov.uk/nuclear/llc/2005/sella2.htm
NDA Strategy, 2006. http://www.nda.gov.uk/documents/upload/NDA_Final_Strategy_published_7_April_2006.pdf

Energy Community (Euratom). Both IAEA and Euratom inspectors and facilities are installed at Sellafield. The IAEA regime is implemented in the UK by the Office for Civil Nuclear Security (OCNS). This has recently been merged with the Nuclear Safety Directorate and the UK Safeguards Office to form a Nuclear Directorate under the Health and Safety Executive. Security regulation for the civil nuclear industry was reviewed following the terrorist attacks in the USA in September 2001 and the Nuclear Industries Security Regulations 2003 (NISR 03) came into force on 22 March 2003 following consultation with the civil nuclear industry. These require that operators of civil licensed nuclear sites must have site security plans approved by OCNS. A Technical Requirements Document (TRD) is issued to help operators meet the requirements of the NISR 03. This is a classified document, subject to regular review and was last reissued in May 2007. The resulting plans detail the security arrangements for the protection of each site. These arrangements cover, for example, physical security protection features such as fencing, CCTV, access controls, intruder alarms and the roles of security guards and the Civil Nuclear Constabulary. Also covered are the arrangements for the protection of sensitive nuclear information, IT systems and Personnel Security. A Nuclear Security Inspector is currently attached to Sellafield on a permanent basis.

Recently OCNS invited the Centre for the Protection of National Infrastructure (CPNI) to examine its Vital Area Review methodology, view the solutions on the ground, and to report on their findings. This included a high level CPNI visit to the Sellafield site in 2008. OCNS has also recently carried out a review of the planning assumptions against which security profiles at civil licensed nuclear sites are set. This was a classified project drawing on material provided by the national intelligence agencies which allow a judgement to be made on the malicious capabilities that could be deployed against a nuclear site and which security measures should protect against. This project is now complete and the operators have begun testing their existing security measures against this revised set of adversary malicious capabilities. A consequence has been new security measures that include precautions against car and truck bombs and individual suicide bombers, as well as attacks by aircraft. [27]

Rather than rely on Home Office Police Forces, a specialist police force, the Civil Nuclear Constabulary (CNC), was formed in April 2005 from the United Kingdom Atomic Energy Authority Constabulary (UKAEAC). This provides a dedicated, on-site armed response force at designated civil licensed nuclear sites, including Sellafield. The CNC operates under the direction of the Civil Nuclear Police Authority, a non-departmental public body responsible to the Secretary of State for Business, Enterprise, and Regulatory Reform (BERR), for maintaining an ‘efficient and effective constabulary’. Officers of the CNC patrol the site, conduct searches, monitor alarm systems and provide an immediate on-site armed response in the form of a Tactical Response Group. About 70% of the force consists of authorized firearms officers. Guard dogs and explosive-detecting sniffer dogs are also used. The force has policing primacy until the County Police Force arrives, but has no responsibility for fire fighting or rescue. The CNC has over 800 police officers and staff country wide. It has a budget for 2008/9 of £51.8m. which it is expected to recover in full, mainly from the nuclear operating companies. Fire engines and crews are also kept on site as is done at airports.[28]

Every civil licensed nuclear site is required to hold counter terrorist exercises at regular intervals, including both live-play and tabletop exercises, to test counter-terrorist procedures and responses to serious breaches of security. These exercises are based on scenarios approved by OCNS to test tactical and strategic outcomes in order to certify that requirements meet the security regulations. They are planned to be both credible and testing, ensuring that

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[27] Health and Safety Executive: Nuclear ‘Live issues’ 2008. www.hse.gov.uk/nuclear/issues.htm

[28] Civil Nuclear Police Authority, Annual Report and Accounts 2007/8. www.cnc.police.uk/files/civil_nuclear_police_authority_annual_report_and_accounts_200712.pdf

the greatest possible proportion of the workforce on each site can benefit from them. They exercise command and control arrangements, probe the interfaces between security agencies, and encourage interaction between safety and security. The lessons learned during the exercises are documented and subsequently reflected in revised counter-terrorist contingency planning. OCNS has also encouraged greater participation from other likely key responders - in particular Army Explosives Ordnance Disposal (EOD) teams. At Sellafield it is intended that eight exercises should be completed each year, involving all the officers of the force in at least one exercise.

The work of OCNS Information Security Inspectors includes advising operators over the security of sensitive nuclear information held on civil licensed nuclear sites. Information Security Inspectors examine IT systems, paper filing and recording arrangements, handling procedures, and the security furniture in which sensitive nuclear information is kept. They also keep in close touch with OCNS Personnel Security Inspectors to ensure that those with access to sensitive nuclear information are security cleared, to a level commensurate with the protective marking carried by such material.

The IAEA has developed standards of protection of nuclear facilities against what is known as a Design Basis Threat (DBT) and countries are required to submit their national DBT to the Authority. This document is classified SECRET and little on the subject has been published. A lecture was given in April 2005 by Dr Roger Howsley, then the Director of Security, Safeguards and International Affairs at BNFL and Chairman of the UKAEAC Police Authority.[29] He said that the DBT is based on intelligence about the motives, intentions and capabilities of potential adversaries and includes a definitive statement of possible scale and methods of attack. These include 38 different malicious capabilities, including mortar attacks, vehicle borne bombs, suicide bombers and the insider threat. The DBT is being, in his words, ‘mapped across to existing operational security arrangements and policies’. He says that this approach is ‘very powerful’ creating a ‘dynamic performance driven culture’ and will be kept permanently under review. He added that BNFL has been working on a range of projects representing an investment of about £30m since 2001, over and above normal security expenditure. These include:

- Physical security enhancements and virtual reality modelling;
- Emergency response arrangements;
- Identity management – integrated vetting and aftercare;
- Access control – pass reissue and integrated access systems including biometrics;
- Advanced search and screening technologies;
- Asset tracking utilizing GPS.

An Executive Sub-Committee meets quarterly to review security policy, goals and performance at Sellafield. Over the past year it has reviewed policy areas and security performance in accordance with an assurance programme. This programme is the mechanism that ensures that security performance is routinely checked and re-affirmed as being satisfactory. On the basis of this programme, it has been assessed that the overall security performance at Sellafield has been effective throughout 2007/08.[30]

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[29] http://www.westminsterenergy.org/events_archive/downloads/aprnuclear/Howsley.pdf

[30] Director of Civil Nuclear Security, “The State of Security in the Civil Nuclear Industry and the Effectiveness of Security Regulation April 2007 to March 2008”. www.hse.gov.uk/nuclear/ocns/ocns0708.pdf

3.1.5 Higher Management

Responsibility for managing nuclear sites and facilities previously operated by the UKAEA and BNFL is now vested in the Nuclear Decommissioning Authority (NDA). Its purpose is to deliver savings in the decommissioning and clean-up of the UK's civil nuclear legacy in a safe and cost-effective manner, and where possible to accelerate programmes of work that reduce hazard. It carries out its function by licensing companies to manage individual plants. The Site License Company (SLC) for Sellafield is Sellafield Limited, comprising Sellafield's nuclear chemical facilities (previously in BNFL's British Nuclear Group subsidiary) as well as Calder Hall, Windscale and Capenhurst.

During 2007/08, the NDA reviewed its senior management structure. As part of that review Alan Rae was appointed as the new Director of Nuclear Safety, Security, Safeguards, Environment and Health within a new Assurance Division. Dr Janet E. Wilson was appointed as Head of Nuclear Security, Safeguards and Non-Proliferation reporting to Alan Rae. She also sits on the board of the Civil Nuclear Police Authority.[31] An assurance team was created to provide independent assurance that the SLCs are meeting the required security, safeguards and non-proliferation performance at the sites. A recruitment campaign in early 2008 culminated with the appointment of two nuclear security and safeguards assurance managers, to take up their appointments later in 2008.

In November 2008 the NDA signed a contract with Nuclear Management Partners Limited, the preferred bidders for the Sellafield management contract.[32] This firm consists of URS Washington Division, AMEC and AREVA. It will become the Parent Body Organisation owning the shares in Sellafield Limited, the SLC. The contract will be for an initial five years, extendable for up to 17 years, and will offer business initially of around £1.3bn a year. Sellafield will remain a Category I licensed nuclear site and the current Site Security Plan will be assumed by the new Operator.

3.1.6 Assessment of the risks involved in option 1

(i) Deterioration of the storage facility

The short-term behaviour of plutonium in storage under the current arrangements is well known. Because of the presence in the cans of small amounts of water and salts (including chloride), there continue to occur radiolytic and chemical reactions. These can lead to the build up of pressure in the cans, and occasionally damage to the packaging materials. However the safety case which has been developed for the store has large safety margins, and the issues involved in managing the store to ensure continued short-term safety are well understood. Very long-term storage is less well understood, as the longest that any plutonium has been stored is around 65 years, so this is the subject of an ongoing R&D programme. There are indications that it may eventually be necessary to treat or repackage some of the material, a process which might be expensive and dose-intensive for the operators unless very expensive remote handling equipment were back-fitted into the facilities.[33]

(ii) Natural hazards

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[31] "Janet cops Police Authority role", NDA Stakeholders Newsletter, 21 May 2008. http://www.nda.gov.uk/stakeholders/newsletter/police-authority-member.cfm

[32] NDA announces preferred bidder for the Sellafield competition, 11 July 2008. www.nda.gov.uk/news/sellafield-preferred-bidder.cfm http://www.whitehaven-news.co.uk/news/who_nuclear_management_partners_are

[33] NDA Plutonium Options for comment: August 2008 - October 2008 www.nda.gov.uk/documents/upload/Plutonium-Options-for-Comment-August-2008.pdf

The normal environmental hazards of earthquake, fire and flood are well understood, and no doubt the new store is being built to the highest standards of safety in these respects, although the older stores may not be so well-designed in this respect. Presumably the same applies to the hazard resulting from a major nuclear emergency elsewhere on the site. In those circumstances the state of the separated plutonium store might constitute the least of the resulting problems.

(iii) Terrorist attack – theft or sabotage

There has been no experience so far of a terrorist attack on a nuclear site. Such an attack might take one of two forms: either an attempt to obtain radioactive material for use elsewhere as a radiological or nuclear weapon (theft) or alternatively a destructive attack on Sellafield itself in the hope of causing a radiological catastrophe (sabotage).

As regards the theft alternative: the aim of the would-be thieves might be to obtain, say, half a dozen cans (ie sufficient for one or two nuclear devices). They could attempt entry through one of the gates, by some form of bluff or false identity, but large barriers have been erected at entry points and even with insider assistance this would be very difficult to pull off. Entry by tunneling seems equally implausible. A raiding party could be delivered by boat or lorry. To blow a hole through the perimeter wall with explosive would then be possible, most probably using a suicide bomber, but this would alert the whole site. The separated plutonium storage area now has additional fencing and a dedicated police patrol. The raiders would have difficulty in reaching the plutonium store, burgling it and getting out again safely. An alternative would be entry by parachute, glider or helicopter. Parachutists or a glider crew might conceivably get in unobserved, but would have to force or bluff their way out. A helicopter or micro-light aircraft could solve the exit problem but would be far less likely to land unobserved because of the noise. In all these cases there would be the difficulty of forcing entry to the plutonium stores - no doubt by blowing the locks – and then getting access to the locked vaults where the cans are secured. In this case explosive attack might be very ill-advised and a crow bar ineffective. Some form of insider assistance might be indispensable. It is fair to conclude that, given normal vigilance on the part of the security guards and patrols, and provided the vetting system is reasonably watertight, the Sellafield plutonium stores are not an attractive target for burglary. Even with insider help and given complete surprise, a thieving raid would need some degree of luck to succeed.

As regards the sabotage alternative: the problems of breaking into the stores and extraction would not arise, and a variety of other approaches would be feasible. A mortar attack could be mounted from several kilometers outside the perimeter, but a mortar round would be unlikely to pack enough punch to do serious damage inside the plutonium store. Terrorists could acquire a light aircraft and use it to attack the store by means of a rocket propelled grenade or an improvised bomb with a shaped-charge warhead (as in many off-road bombs in Iraq and Afghanistan). These weapons do their damage by means of a very high velocity slug of molten metal which then distributes itself around the interior of the target. This effectively attacks crew members and stored ammunition in an armoured vehicle, but such an attack on canned plutonium powder in protected vaults would probably only cause local contamination.

The deliberate crashing of a large aircraft would be a very different matter. More than 700 airliners pass within 50 nautical miles of Sellafield every week on their way from Europe to North America. Since they are near the start of their journey they contain large amounts of fuel which would burst into flames on impact. Such an attack could involve a Boeing 747, laden with 150 tons of fuel, descending at 250 meters a second. If such an attack was mounted without warning it could be very hard to identify it as such in time to launch effective counter-measures.[34]

3.1.7 Defensive measures against these threats

(i) Deterioration of the storage facility

Maintenance of the integrity of the plutonium stores is the responsibility of the NDA. In June 2007 the NDA received a report from consultants entitled ‘Uranium and Plutonium: Macro-economic study’.[35] This examined the financial implications of keeping the plutonium in long-term storage for a period of around 250 years. It assumed that the plutonium would continue to be stored as PuO_2 powder in the currently defined secure facilities, and that these would need to be refurbished at 10% of initial costs after 50 and 100 years, and to be replaced after 150 years. The undiscounted cost of this scenario is given as in the range £3.5 – 7 billion. This is more expensive than the ‘bury it’ scenario – it includes the same waste processing and disposal activities but adds additional storage and, importantly, needs an extra new Repository (whose undiscounted cost is estimated to range from £1.25 – 3.75 billion). More recent work by the NDA has focused on the option of storing it until 2120, with an initial conditioning activity in 2016, to make the material acceptable for placement in the SPRS store, and a further reconditioning activity in 2060.

(ii) Natural hazards

It is a reasonable assumption that the new Sellafield Product and Residue Store (SPRS) has been designed to resist these hazards: however it is less clear that the old plutonium stores are adequately designed, which raises the question as to how quickly those will be made redundant.

(iii) Terrorist attack – theft

As noted above, on any reasonable assumption about the effectiveness of the security regime, including the vetting of staff with access to the plutonium store, this is a low-probability threat.

(iv) Terrorist attack – sabotage

As noted above, Sellafield is less than 10 minutes flying time away from the normal flight path of many civil aircraft, so there would be very little warning of a significant departure from the normal flight path. To assist in the recognition of such an event, on 25 October 2001, the French government greatly increased the no-fly zone around the La Hague reprocessing plant from 100 m to 10 km radius and to 5000 feet height, and installed an unspecified number of CROTALE anti-aircraft missiles on the site. The no-flying zone around Sellafield extends only to a 2-mile radius and 2,200 feet height[36] and there is no published information on any anti-aircraft defences. Britain in principle possesses the equipment, if not necessarily the political will, to deploy a defensive shield around Sellafield, to protect it against this kind of attack. One possible option would be the defensive missile system, Rapier, which is designed to engage supersonic low-level attack aircraft of high manoeuvrability.

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[34] Rob Edwards, “The nightmare scenario”, reprinted from *The New Scientist,* 13 October 2001. http://www.robedwards.info/2001/10/the_nightmare_s.html)

[35] NDA, “Uranium and Plutonium: Macro-Economic Study, Final Report”, June 2007. www.nda.gov.uk/documents/upload/Uranium-and-Plutonium-Macro-Economic-Study-June-2007.pdf

[36] http://www.wise-paris.org/english/ourbriefings_pdf/011029AircraftCrashSellafield3.pdf

The maximum detection range of the radars is more than 15 kilometers. The missile is guided towards the target at speed in excess of Mach 2.5 and is equipped with a high explosive warhead and a laser proximity fuse. The automatic reaction time is less than 5 seconds and a second target engagement takes less than 3 seconds. A full reload is carried out manually in 2 minutes.[37] Rapier would be able to destroy an incoming airliner, though it would be impossible to know where the resulting debris and burning fuel would come to earth. There are however various operational and political problems with this approach. The British army will in future deploy only 24 Rapier fire units world-wide, the RAF Regiment having relinquished this role. At least one of these fire units would have to be stationed on site, and on notice to be alert for this type of attack. The difficulty of getting sufficiently precise intelligence to justify such a deployment is self-evident.

A second possible option would be to alert a fighter aircraft from an adjacent airfield. The government claims that the Royal Air Force maintains a high state of readiness in the air defence of the UK, including the defence of particularly sensitive targets, and its state of readiness is kept under constant review. But for any aircraft hijacked and forced to divert to Sellafield from the nearest point, the flight time to the plant is estimated to be between 4 and 6 minutes. Even at times of high alert, RAF fighters at Leuchars and Leeming are on five-minute standby. Any RAF Tornadoes that happened to be airborne in the nearby Lake District low-flying training area might be able to reach a hijacked airliner sooner. But even if they managed to intercept it, they would be unable to shoot it down because they do not carry live weapons on training missions. The feasibility of interception therefore appears low if hijacked aircraft are able to take the shortest distances to the target from their planned routes.

Either of these options would depend on a high-speed political decision to order the deliberate killing of hundreds of innocent civilians by shooting the aircraft down as a means of preventing it from being flown into a nuclear facility.

The issue of protecting the Sellafield plutonium stores against this form of sabotage is, of course, part of a much larger problem – the protection of all Sellafield's high-activity nuclear material against such an attack. The radiological content of the plutonium stores is trivial in comparison with the total radioactive inventory on Sellafield site. For example, within a few hundred yards of the plutonium stores is building B215 which contains 21 stainless steel tanks containing more than 1000 m^3 of high-level radioactive liquid waste, with a total

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[37] The British Army. Artillery. Rapier (FS 'C'). www.armedforces.co.uk/army/listings/l0120.html

radioactive inventory (in the form of Cs-137 alone) of at least 300 MCi – ie about 100 times the amount released in the Chernobyl disaster. An airliner crash into B215 would have a huge impact on the local environment. After the Chernobyl disaster in Ukraine in 1986, an exclusion zone of 4800 square kilometres had to be set up around the plant, more than a quarter of a million people were resettled. In the case of B215, the resulting radioactive plume would contaminate large parts of Britain and, depending on which way the wind was blowing, Ireland, continental Europe and beyond. Some places could become uninhabitable.[38] It is arguable that B215 is a far more vulnerable and dangerous target than the plutonium stores, but a suicide pilot might well be unable to distinguish between them, and in any case the crashing of an airliner anywhere within the Sellafield perimeter would be liable to have catastrophic consequences.

The above discussion of the operational issues in defending Sellafield against the various threats identified naturally raises the question whether the management structure is actually capable of initiating the relevant responses in due time. In the absence of security clearance and a license to inspect there is no way to make an independent judgment on the adequacy of precautions against natural hazards, accidents or malevolent attack other than by study of the published documents. All the relevant bodies have well designed web sites. The issues of security are directly addressed in two annual reports: from the Director of Civil Nuclear Security[39] and the Civil Nuclear Police Authority[40] respectively. These are bureaucratic documents, rich in management jargon, but competently produced. At the conclusion of his current report the Director of Civil Nuclear Security formally assures the Minister of State for Energy at the Department for BERR that during the 12 months to March 2008 security in the industry was effective. He could scarcely do otherwise. Great efforts are certainly being made to address shortcomings, as witness the construction of the new Plutonium Store at Sellafield costing several hundred million pounds, the continual analysis of future threats and options, the high level of security inspections and the emphasis on training at all levels. And efforts are made to maintain public confidence, notably through a variety of stakeholder and local liaison groups and the publication by the HSE of regular e-bulletins and newsletters.[41] These contain surprisingly frank discussion of various mishaps and shortcomings. All this is commendable as far as it goes.

But the Director was wise to add that there is no room for complacency. Readers of the national press, not to mention the various official histories of Sellafield and the wide range of unofficial publications on the internet, will be well aware that over its half-century of nuclear work, the Sellafield complex has been more than usually prone to accident. Major incidents have included the fire at the Calder Hall reactors in 1956, the discharge of water contaminated with radioactive waste substances into the Irish Sea in the 1970s, the rejection of MOX fuel assemblies sent to Japan in 1999 when a whistle-blower revealed that the Quality Assurance data accompanying the fuel had been falsified by bored night workers, and the leak from the THORP reprocessing plant in 2005. Although none of the foregoing relates directly to the plutonium stores, it does undermine confidence in statements such as that in the NDA Annual Health, Safety, Security and Environment Report that ‘a high standard of performance has been maintained in all these areas during 2007/08 with continuing improvements in each of the key indicators.’

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[38] Rob Edwards, ibid. footnote 34

[39] As in footnote 23

[40] As in footnote 24

[41] HSE Nuclear Newsletter Issue 42, April 2008. www.hse.gov.uk/nuclear/nsn4208.pdf and
BNGSL Sellafield and Drigg, and UKAEA Windscale West Cumbria Sites Stakeholder Group, “Quarterly Report for 1 January 2007 to 31 March 2007”, Para 2.5. www.hse.gov.uk/nuclear/llc/2007/sellafield1.htm

3.1.8 Overall assessment of option 1

The Royal Society Working Party, under the chairmanship of Professor Geoffrey Boulton, in their report of September 2007 [42] gave their opinion that although the plutonium stockpile could in principle be maintained in an unmodified powdered state until a deep geological repository for High Level Waste is ready to receive it, in their view *indefinite* storage in its present form was unacceptable from a safety and security perspective. The report stated the well known features of the threat, and reviewed the countermeasures now being put in place. However, the report did not give the full reasoning behind their conclusion. Among the arguments which they might have given, three stand out:

- Sellafield's very uneven safety record does not inspire confidence.
- Money is certain to be tight, and this will prevent ideal solutions to problems from being taken as they arise.
- Al Qaeda and their ilk make a habit of outflanking expectations.

On the other hand, a large investment is being made in protecting and managing the existing plutonium stock, and the measures show every sign of being well designed and adequately resourced. In the opinion of this writer, the issue of security, while very important, should not be the driver compelling premature decisions on management of the stockpile by burning or burying. These should be taken on their merits and in their own good time.

Option 1 is in one sense inevitable, because all the other options under discussion in this report rely to a greater or lesser extent on the use of interim storage while new plants are designed and constructed and the plutonium processed. If a decision were taken today on another solution for the inventory, there could still be a requirement to provide storage for as much as 40 years. It is therefore imperative to provide means of safeguarding PuO_2 in powder form at least till mid-century. As far as can be judged from published sources, an adequate start has been made. Obviously the issue of security at Sellafield, both in relation to the plutonium stockpile and other radioactive materials, needs to be reassessed continuously, and sufficient money and energy devoted to it – unless or until the level of threat dies away.

Commentary on option 1 by devil's advocate:

The case presented by the champion of option 1 leaves a lot of questions un-answered, many of which cannot be answered using information which is in the public domain.

Unanswered questions relating to the current situation

These can be summarised under the headings of the three key threats:

1. Theft of plutonium to make 'home-made' nuclear weapons
What scenarios are the most credible for the theft or forcible removal of material from the store? The champion has identified two possible scenarios:

(i) A commando raid such as the SAS operation in Norway during WW2, beginning by either cutting through the perimeter fences (mechanically or by explosive) or using a helicopter or micro-light aircraft or parachute landing to gain access. The key question here is the level of force that might plausibly be deployed, and whether effective measures are in place to counter that level of threat? Either explosive cutting or a helicopter landing would be liable to trigger

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[42] Royal Society, "Strategy options for the UK's separated plutonium", Policy document 24/07, 21 Sep 2007. http://royalsociety.org/document.asp?latest=1&id=7080 see ref 3 above

a security reaction, but would that be fast enough or effective enough? Having gained access to the vault door, the commandos would have to break in, raising questions about the locking arrangements, and the level of explosive attack that the vault walls and roof are designed to withstand.

(ii) An insider-assisted operation using defector or blackmailed staff to assist them.

This raises a large number of security questions. What are the security arrangements at the entrance to the stores? What guard system is there in operation? What level of military force are they prepared to encounter? What security clearance do those staff possess? What are the supervision arrangements for these staff? Who has the right to enter the store? Is there a multiple key system? How widely known are the supervision arrangements? How close can Sellafield contractors get to the store?

What system of secondary monitoring is there? (eg TV camera surveillance, automatic alarm systems, etc). What equipment is in operation which could detect cans of plutonium and trigger an alarm before they left the site? What testing of the security system has been carried out, and with what results?

2. Dispersal of plutonium by a terrorist military attack
How vulnerable are the existing stores to an attack using high explosives?

What is the thickness of the wall and roofs of the stores, and what secondary protection is there around the store (secondary walls, earth mounds, etc), and what level of explosive attack could all these withstand? The argument given by the champion, questioning the likelihood of a successful attack using a mortar or bazooka, which could be mounted from several kilometers outside the perimeter, is less than wholly convincing.

3. Diversion of a civil airliner by terrorists to crash on the store
In the case presented by the champion, the use of fighter aircraft deployed from local airfields to counter this threat is (rightly) dismissed as unrealistic. However the alternative which he suggests (albeit with serious reservations) – to use a Rapier missile system to shoot down any aircraft flying within some ‘forbidden zone’ – seems comparably incredible. Even if the authorities had 5 minutes notice (ie the zone diameter were set at ~50 miles), this gives very little time for them to assemble the evidence that would justify a decision to shoot down a civilian airliner, because its behaviour is judged to threaten an even larger disaster. Is it credible that a British government could delegate such a decision, and would the command structure within government, within MOD and within Sellafield management, responsible for taking it, actually be capable of taking the decision on the required timescale?

Questions relating to planned or desirable improvements in the situation

It seems that the physical protection of the plutonium will experience a major leap forward as soon as it is transferred into the ‘Special products and residues’ store. How firm is the timetable for the start-up of that store? And what is going to be done with all the existing material which cannot immediately be accommodated in the SPRS store, and how soon can a fully-aircraft-resistant store be created of a size required to hold the entire stockpile?

Questions relating to the sustainability of the current level of protection

It seems that there is as yet no clear view within the NDA on how long the existing arrangements should be sustained. However estimates have been made of the extent to which it might be necessary to rebuild or replace the existing stores, if they have to continue operation for more than 50 years.

Managerial and economic questions

What is the content of the IAEA-approved security plan for the existing stores? What exactly is the design-based threat that it is based on? Have IAEA officials inspected the facilities and reported on their conclusions?

What command structure exists within government, within MOD and within Sellafield management, to take security-related decisions on the required (perhaps very short) timescale?

Have the management at Sellafield taken sufficient steps to convince the UK public that the risk of a successful attempt to sabotage its store, or divert plutonium from it, is sufficiently low to make option 1 defensible?

The undiscounted cost of this scenario is quoted (from ref 86) as being in the range £3.5 – 7 billion. However it seems that this figure does not relate exclusively to the plutonium store, but the report cited does not give sufficient detail to permit the plutonium-related cost to be isolated.

3.2 Option 2: Bury it

Champions: Dr Ian Crossland and Dr Jack Harris

This section makes the case for burying the whole of the UK stockpile of separated plutonium as soon as possible in a suitably designed deep geological repository. It recognises that no such repository exists at present, but that it is government policy that a repository for long-lived intermediate-level waste, high-level waste, and spent fuel, should be established as soon as the relevant technical and planning issues have been resolved. The term 'bury it' is therefore understood to be shorthand for the interim storage of plutonium followed by deep geological disposal as soon as a suitable repository becomes available. This section examines the feasibility of this option.

It may be worth pointing out that, even if all the separated plutonium were to be recycled, using reprocessing and MOX-burning reactors, this recycling could not be continued indefinitely so that eventually the spent fuel must be dispatched for deep geological disposal. In principle then, the question is not so much about 'if' as 'when'.

3.2.1 Deep geological disposal in the UK

In response to the 'Managing Radioactive Waste Safely' consultation, the UK government has rejected all other options and formally committed to a policy of deep geological disposal for the UK's high- and intermediate-level radioactive waste[43]. While, for the most part, this material will consist of long-lived intermediate-level waste and vitrified fission products, it is likely that it will also include some non-reprocessed spent nuclear fuel, although the precise quantity is uncertain. It is not known, for instance, whether spent fuel from the Sizewell B reactor will be sent for reprocessing. The government has said that, while reprocessing of spent nuclear fuel remains the national strategy, British Energy is free to make its own decision on reprocessing based on commercial considerations[44].

As a result of the historical policy of reprocessing, there is now about 100 tons of separated plutonium in store. According to a report prepared for the Committee on Radioactive Waste Management (CoRWM)[45], before THORP's current reprocessing contracts end, this figure may increase to around 140 tons, of which 37 tons will be foreign owned. Within this stockpile, some 5% of the plutonium may be so contaminated that it is uneconomic to use it to manufacture new fuel, and at least that material will presumably be dispatched for deep disposal[44].

In this section, we maintain the conventional distinction between 'storage' and 'disposal'. Storage implies an intention to retrieve; disposal implies <u>no</u> intention to retrieve, so that disposal is only applied to materials that are waste. Retrieval from a disposal facility might be possible, but it is likely to be so difficult and expensive that, if there is a real possibility that this material might have some future use, disposal would not be appropriate. The UK has no

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[43] UK Government and Devolved Administrations, "Response to the report and recommendations of the Committee on Radioactive Waste Management (CoRWM)", Defra, 2006. http://www.defra.gov.uk/environment/radioactivity/waste/pdf/corwm-govresponse.pdf

[44] UK Government, "The United Kingdom's second national report on compliance with the obligations of the Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management", Feb 2006. http://www.defra.gov.uk/environment/radioactivity/government/international/pdf/jointconreport06.pdf

[45] NNC Limited, "The Immobilisation of Plutonium and Uranium as Wastes, Committee on Radioactive Waste Management", CoRWM Document No: 776, November 2004.

stated intention to regard its repository as anything other than a ‘disposal’ facility, though in the recommendations of CoRWM, retrievability was not ruled out, but retained as a possibility meriting further research.[46]

The following three main sections cover:

- The current status of deep geological disposal of radioactive waste;
- The feasibility, safety and security of deep geological disposal of plutonium;
- Conclusions.

3.2.2 Current status of deep geological disposal worldwide

General

Emplacement in a deep geological repository is the only generally recognised disposal method for high-level and long-lived intermediate-level radioactive waste. This is because, after more than thirty years’ work, this is the only established way of providing the necessary level of containment and isolation for these wastes. Exceptionally, The Netherlands has adopted a policy of long-term storage for radioactive waste (where ‘long-term’ has been defined as 100 years, possibly extending to 300 years) though it has, at the same time, recognised the need for eventual deep disposal. Their long-term storage strategy is simply a means of buying time to allow deep disposal techniques to come to maturity[47].

Progress internationally

Internationally, there are three national programmes that are making good progress towards providing a deep disposal facility – those in Sweden, Finland and France. Sweden and Finland may be considered together because they have similar wastes and geology and use the same method of disposal – the Swedish KBS3 system. This consists of placing spent fuel assemblies inside high integrity containers made from a combination of steel (for strength) and copper (for corrosion resistance). These are buried 500 m underground, surrounded by a so-called ‘buffer’ of swelling clay. According to their current programmes, Finland will start construction of its repository around 2012[48], Sweden in 2018. The UK reference design for disposal of vitrified high-level waste and spent fuel follows the KBS3 system.

France, like the UK, has a policy of reprocessing of nuclear fuel, so the range of radioactive wastes held by France is very similar to that held by the UK, though with a larger volume. The French radioactive waste agency, Andra, is currently constructing an underground rock characterisation facility at a site in eastern France. This facility is similar to the one proposed by Nirex at Sellafield, which however was refused planning permission following a public inquiry in 1997. Assuming that the underground characterisation facility finds that that the rocks are suitable (and this is not thought to be in doubt[49]) a repository will follow, and will use thick walled steel canisters to house heat-generating wastes (spent fuel and vitrified high-level waste, which is a by-product of spent fuel reprocessing). The canisters will then be placed in horizontal boreholes drilled from the underground galleries.

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[46] Committee on Radioactive Waste Management, “Managing our Radioactive Waste Safely: CoRWM’s Recommendations to Government”, CoRWM Doc 700, July 2006. http://www.corwm.org.uk/Pages/Current%20Publications/700%20-%20CoRWM%20July%202006%20Recommendations%20to%20Government.pdf

[47] See, for example, Witherspoon, P.A. and Bodvarsson, G.S., “Geological Challenges in Radioactive Waste Isolation. Third Worldwide Review.” Lawrence Berkeley National Laboratory, LBNL-49767, December 2001. http://www-library.lbl.gov/docs/LBNL/497/67/PDF/LBNL-49767.pdf

[48] http://www.posiva.fi/files/514/Posiva_YLPS_en.pdf

[49] Andra, 2006, “Synthesis: Evaluation of the feasibility of a geological repository in an argillaceous formation. Meuse/Haute-Marne site”, Dossier 2005 $^{\text{Argille}}$.

A different system is used for the non-heat generating, long-lived, intermediate-level wastes (most of which result from reprocessing). These are immobilised using cement grout within cube-shaped concrete containers, and stacked inside an underground gallery. Many of these wastes contain uranium and, at smaller concentrations, plutonium also. Similarly, the inventory which has been made of waste materials for deep disposal in the UK indicates that, even if separated plutonium is not considered for disposal, the UK deep repository for intermediate level wastes will already contain 7 tons of plutonium, 5 tons of which will be plutonium-239[50].

The immobilisation system for intermediate-level wastes entails the use of large quantities of concrete. This dominates the chemistry of the repository, imposing high pH conditions that reduce the mobility of the actinides in the waste.

3.2.3 Safety of deep disposal

The outcome of a post-closure safety assessment for a radioactive waste repository is usually expressed as a radiation dose vs time or risk vs time curve.

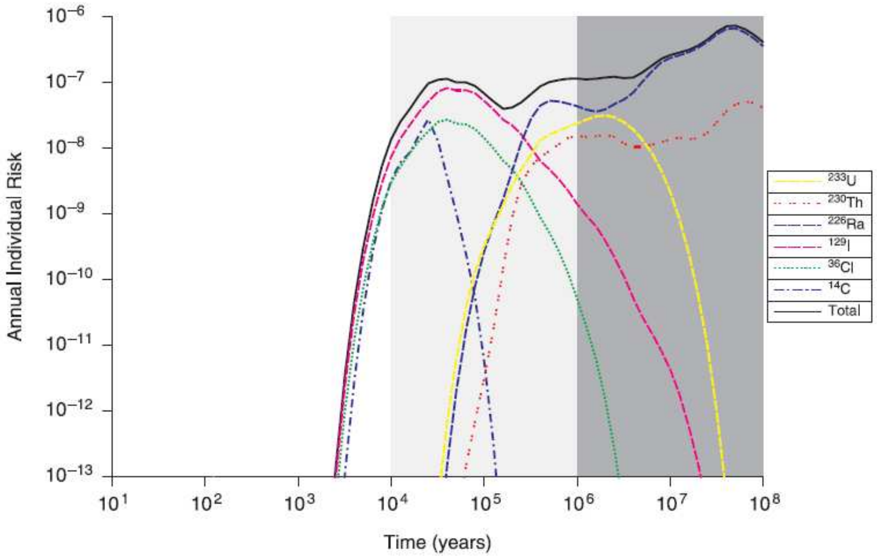

Fig.1: Risk time curve from Nirex-97 showing the contributions from the most significant radionuclides (see ref 50)

The risk estimate is based on the calculated radiation exposure of the most exposed group of people present when radionuclides from the repository reach the surface (risk is linearly proportional to radiation dose). Normally, this peaks at tens or hundreds of thousands of years in the future. As shown in Fig.1, the total risk is made up from individual radionuclide contributions. The transit time for a given radionuclide is a function of its transport properties so that different radionuclides appear at the surface (and contribute to the total risk) at different times. The process is analogous to the behaviour of migrating species in a chromatographic column.

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[50] Nirex , "An Assessment of the Post-closure Performance of a Deep Waste Repository at Sellafield Volume 3: The Groundwater Pathway", Science Report S(97)12-3, 1997 This document indicates that the total inventory of Pu-239 considered in the assessment is 11,700 TBq, which is equivalent to 5.1 tons.

Such post-closure safety assessments invariably show that the earliest contributors to the calculated risk are radionuclides that are freely soluble and whose migration is subject to little retardation. Typically, these are anionic species of long-lived radionuclides such as iodine-129 in the form of iodide, chlorine-36 as chloride and technetium-99 as pertechnetate. Almost always, there is a second peak to the curve, typically at about one million years. This usually results from uranium-238[51] which migrates extremely slowly. We do not know of a single case where plutonium makes a significant contribution to the total risk. This is entirely due to the property of compounds of plutonium to have extremely low solubility (typically less than 10^{-10} M at high pH) and high retardation coefficients[52].

As noted above, plutonium already occurs in the UK's inventory of low- and intermediate-level waste and plans for the deep disposal of these wastes have existed for many years. The only way in which this radionuclide is treated differently from the other radionuclides in the inventory is that there is a separate need to demonstrate that the presence of fissile material will not give rise to a criticality. Work done to date gives confidence that the probability of a criticality is extremely low and that, were one to occur, it would not lead to unacceptable outcomes. Nonetheless, research continues in this area.

It should also be added that plutonium in bulk generates significant quantities of heat. For this reason it would not be possible to dispose separated plutonium by packing waste containers into a tunnel (as for the long-lived intermediate-level waste just described). As with spent fuel and vitrified high-level waste, it will be necessary to distribute the plutonium over a large volume of rock to avoid the generation of excessive temperatures.

3.2.4 The feasibility, safety and acceptability of deep geological disposal of separated plutonium

As noted above, the disposal of relatively small quantities of plutonium, mixed in with other nuclides in the high and intermediate level wastes for which disposal planning has already been undertaken, has indicated that this is feasible and raises no special unresolved safety issues.

In this section we consider what further issues arise if larger quantities of separated plutonium are to be disposed of in a deep repository. A crucial issue in deep disposal is the determination of a suitable wasteform, because if a waste cannot be disposed safely, it will not be disposed at all. For this reason, the issue of disposability, which amounts to the ability to make a strong post-closure safety case, is addressed first.

Disposability

From the previous section it is clear that the existing policy of deep disposal of long-lived intermediate-level wastes already commits the UK to disposal of tons of plutonium. Admittedly, this is present throughout the wastes adventitiously so that heat generation is not an issue but, nevertheless, 7 tons is a significant quantity and it seems reasonable to argue that, if this amount of plutonium has no significant impact on the post-closure performance of the repository, then an increase by a factor of twenty (ie by including all the separated plutonium) should be manageable. In any case, the fact that some of the UK's separated plutonium cannot be used for fuel manufacture inevitably implies that, whatever decision is taken on the stockpile as a whole, some of it at least will be sent for deep disposal. Without

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[51] Actually, the risk arises from the more radiotoxic daughter of uranium-238, radium-226.

[52] When contaminated water moves through a porous medium, the retardation coefficient is the ratio of the speed of the water to the speed of the dissolved contaminant.

doubt, further research will be needed to investigate the safety implications of this development and, in particular, to decide on the most appropriate wasteform.

From the point of view of post-closure safety (which mostly determines disposability), the main issue is the leachability of the wasteform – whether groundwater would be able to wash plutonium out of the waste and carry it away from the repository. An influencing factor is instability of the wasteform brought about by radiation damage. As explained above, plutonium compounds have a very low mobility, so for intermediate-level wastes (albeit with plutonium concentrations at relatively low levels), immobilisation in a cement grout produces acceptably low leach rates. Furthermore, cement grouts have good long-term stability. This may not be the case, of course, for the higher concentrations that would inevitably result from a decision to dispose of all the UK's separated plutonium. Alternative wasteforms might be borosilicate glass (as currently used for fission products extracted during reprocessing)[53] or a ceramic matrix exemplified by Synroc or similar ceramic forms.

There is a high probability that one of these wasteforms could safely be used for plutonium, though there may still be some questions regarding their long-term stability and, perhaps, the achievable loading of plutonium. At high plutonium loadings it may be necessary for the wasteform to include a neutron absorber so as to reduce the likelihood of a criticality. An alternative approach would be to opt for a cheaper, more leachable wasteform (eg low grade MOX pellets fabricated in a similar way to nuclear fuel) but couple this with a high integrity container, as is done in spent fuel disposal. All these are essentially technical questions that are susceptible to research and, indeed, there exist such a lot of research data that some of the answers may be already available.

Pre-processing measures prior to deep disposal

It will be 30 years at least before a UK repository could become available – the NDA website says "around two to three decades from the beginning of the [imminent] site selection process". Some of this time could be used to decide on a suitable wasteform. In the meantime, the plutonium must be stored. It will be important, however, to be sure that nothing is done to the plutonium that might make it more difficult to dispose – or even make it non-disposable. To keep costs within reasonable bounds and worker doses as low as reasonably achievable, double handling should be avoided - ie the conversion of the plutonium into a new form should be done only once. So, if it is decided (for reasons of proliferation resistance, say) that conversion is necessary for storage, then the conversion must meet the needs of disposal as well as storage.

The champion of option 1 has argued that the existing storage arrangements at Sellafield represent an acceptable interim measure, and if so, then no further measures may be required, other than those eventually required to convert the plutonium into an acceptable wasteform for disposal. However the arguments against the adequacy of option 1 are also quite strong, so we consider here some alternative measures that have been suggested in the past:

Measure 1. Convert the stockpile to 'low-specification' MOX – ie mix the plutonium with depleted uranium oxide and convert it to pellet form[54] (eg by using the SMP facility at Sellafield), but do not seek to meet the rigorous specification which would be required if it were to be used in a reactor. As with genuine fuel, the pellets could then be loaded into a fuel

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[53] Barker and Sadnicki (op.cit.) suggest that cost savings could be made by converting the existing vitrification plant at Sellafield to this purpose.

[54] C Küppers, 1999, ÖKO Institute, various references quoted by Barker and Sadnicki, 2001, "The disposition of civil plutonium in the UK".

rod and the required number of rods loaded into a fuel assembly. In this form, it would have a significantly reduced risk of release in a fire or explosion, though it would remain somewhat vulnerable to diversion by a malefactor with suitable chemical skills. The proliferation resistance could be increased by storing the dummy fuel assembly alongside spent fuel assemblies or, with significantly greater difficulty and higher worker doses, by removing individual fuel rods from a spent fuel assembly and replacing these with the dummy rods.

There are non-trivial costs associated with these options, and there is also a question as to whether SMP is capable of providing this service on a reasonable timescale – its track record to date has been lamentable – but it may be that the lower standards required for low-spec MOX would allow a greater throughput. The secrecy that surrounds SMP prevents us from coming to a judgement on this. Because of the need to avoid double handling, conversion to low grade MOX would, in effect, dictate the disposal wasteform. Disposal would need to be based on designs for spent fuel that use high integrity containers. Blending with depleted uranium, which is another stockpiled material that could be declared as waste and thus require disposal, would help to make this route more competitive on cost; furthermore, fabrication of a dummy fuel assembly would allow the plutonium to be handled in an identical way to spent fuel – another saving.

Measure 2. Mix (dissolve) the plutonium in vitrified high-level waste. This would bring it up to the 'spent fuel standard'[55], in which form it could be stored until a repository became available. This would result in a vitrified disposal wasteform that, almost certainly, would be technically suitable for deep disposal – probably using the same high integrity containers used for spent fuel. Cost would be determined by the ease or difficulty of the immobilisation process, the achievable loading of plutonium in the glass, the amount of decay heat generation and the need for remote handling at all stages. This option would require significant research and development and modification of the Sellafield waste vitrification plant (or construction of a new one), all of which have cost implications.

Measure 3. Jacket the plutonium with vitrified high-level waste, so as to bring it up to the 'spent fuel standard' and then store. Proponents of this option imagine a plutonium wasteform in the form of simulated fuel pellets contained within tubes (similar to fuel rods) that are then placed in a larger container. The gap between the rods and the surrounding container is then filled with vitrified high-level waste. Clearly, this option requires the prior identification of a suitable wasteform. A draft US DOE document provisionally recommended a ceramic wasteform based on a titanate ceramic[56] but R&D on immobilization options for plutonium was subsequently discontinued by DOE due to budgetary constraints[57]. However a scheme based on vitrification has recently been revived at Savannah River[58]. If the ceramic option were to be pursued, low specification MOX pellets may be a viable alternative to titanate. Again, disposal of low specification MOX pellets and heat generation from the vitrified high level waste would probably require a disposal design similar to that for spent fuel.

Measure 4. Use the Hot Isostatic Pressing (HIP) technique to create a solid block of ceramic (eg titanate-based or zirconate-based ceramic) into which the plutonium dioxide is incorporated by mixing it with ceramic powders and subjecting them to temperature and pressure. The technique is already being developed at Sellafield[59] for the immobilisation of

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[55] US National Academy of Sciences, "Management and Disposition of Excess Weapons Plutonium, National Academy Press, 1994. http://www.nap.edu/catalog.php?record_id=2345

[56] US DOE, "Surplus Plutonium Disposition Draft Environmental Impact Statement", DOE/EIS-0283-D, 1998.

[57] US Federal Register, Federal Register / Vol. 67, No. 76 p19432, Friday, April 19, 2002.

[58] Jean M Ridley, Plutonium disposition through Defense Waste Processing Facility, Sep 2008 (cited by F v Hippel)

[59] See p11 of Nuclear Decommissioning Authority, "NDA Plutonium Options: For Comment August 2008 – October 2008", http://www.nda.gov.uk/documents/upload/Plutonium-Options-for-Comment-August-2008.pdf

plutonium containing residues, where it has been established that operating temperatures are limited to around 1350°C. The HIP process would typically make 20kg ceramic blocks, which are suitable for storage in the new store at Sellafield and exhibit good packing characteristics. However, this technology is at a comparatively low stage of technology maturity, as HIP processing of plutonium containing waste forms has yet to be carried out above the ten gram plutonium scale.

3.2.5 Proliferation resistance when disposed to a deep geological formation

As already mentioned in the context of storage, the US National Academy of Sciences has devised and promoted its ‘spent fuel standard’ as a means of preventing diversion or theft of plutonium for malicious use. A plutonium package which achieves this standard would have a similar degree of proliferation resistance to spent nuclear fuel – ie the package would emit sufficient radiation to kill anyone in close proximity within a matter of minutes. Separation of the plutonium from such a package could only be performed in a large shielded facility that would be detectable by safeguards inspectors, satellite surveillance or other means.

Of course, if plutonium in storage has already been conditioned to the spent fuel (or similar) standard, to avoid double handling it will be necessary to dispose of it in this condition. If, on the other hand, the ‘do nothing’ option is pursued, the plutonium will eventually need to be processed into an acceptable wasteform for disposal, but the provision of a radiation barrier (which would bring the wasteform up to the spent fuel standard) may be unnecessary. This is because burial at 500 m depth in a radioactive waste repository, coupled with institutional control of the site (eg international monitoring by satellite surveillance), should itself provide sufficient resistance to proliferation. The argument is that, in order to close a repository, the access ways have to be completely backfilled, and since disposal will be below the water table, any attempt to retrieve the plutonium would require the deployment of significant resources and ought to be readily detectable. Furthermore, in designing a wasteform for disposal, an important aim is to produce a material that is resistant to leaching and chemical attack generally – a key design aim in the development of wasteforms such as Synroc. Chemical removal of the plutonium from this wasteform will be made difficult by this process, further increasing the proliferation resistance.

3.2.6 Cost of disposal

Costs are controversial, and different experts have during the past decade come up with diametrically opposed conclusions. For example, work performed in 2001[60] indicated that immobilization of plutonium for disposal would be around 25% cheaper than burning it as MOX in a reactor. However it can be argued that these authors produced an implausibly precise result, given that comparisons of radioactive waste disposal costs in different countries typically show a range (for a given volume of waste) of up to a factor of five. Nevertheless these authors also found that the cost of modifying Sizewell B to allow it to burn MOX fuel would give a negative economic return. They also found that construction of a new fleet of reactors which could burn MOX could not be justified on a commercial basis. However their calculations were based on a return on electricity generation of 2.2 p/kWh, as compared with 3.8 p/kWh earned by British Energy in 2007[61]. Perhaps because of this

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[60] Barker, F and Sadnicki, M. 2001, op.cit. .
[61] BERR Quarterly Energy Prices March 2008. http://www.berr.gov.uk/files/file45393.pdf

increase in the price of electricity, a recent press article reported the value of separated plutonium in the UK stockpile as nuclear fuel as £160 bn[62]. It is clear that the absolute value of separated plutonium will be sensitive to the price of electricity. This is a different matter from the relative benefits of using the separated plutonium to make MOX fuel as opposed to disposing of it directly where, as explained in Section 3, the financial balance largely depends on the price of uranium.

A further issue affecting costs is the tendency to argue (in our view erroneously) that plutonium disposal requires extraordinary measures such as very deep boreholes. If such measures were required, one would lose the benefits of scale that would arise from the use of a repository that has been constructed primarily for other radioactive wastes, as argued above.

3.2.7 Public acceptability

World-leading radioactive waste management programmes (eg Sweden, Finland, France) recognise the importance of public acceptability by, in effect, adopting a volunteer approach to choosing and developing a disposal site. In this model, a local community that offers to host a deep disposal will probably have a right of veto over the development and, through this, a powerful position in negotiating with government for associated benefits. In addition, the developer aims to keep the local community 'on-side' by maintaining good communication and being responsive to the community's fears and wishes.

Following the collapse of the Nirex waste disposal programme and, with it, government radioactive waste management policy in 1997, the UK government has also moved towards a volunteer approach through its 'Managing Radioactive Waste Safely' consultation and the recommendations of its advisory body, CoRWM. So far, only Copeland Borough Council (where Sellafield is located) has expressed an interest. At the present time, the proposed inventory for deep disposal includes no separated plutonium, not even the small amount that will almost inevitably need to be disposed. The reaction of the local community to the inclusion of this material has yet to be seen. Local people, most of whom have some economic connection to the Sellafield works, have been long aware of the BNFL 'new fuel from old' mantra and may be resistant to the classification of plutonium as waste and its consequent disposal in a deep repository.

3.2.8 Overall assessment of option 2

Retrieval of material from a deep geological disposal facility may not be impossible but it will be sufficiently difficult and expensive that, if there is a serious possibility that disposed material may be wanted at some future date, interim storage at surface level, not deep disposal, is likely to be the more appropriate option.

From a technical point of view, to achieve an adequate level of safety in the deep geological disposal of separated plutonium is hardly more difficult that doing so for long-lived intermediate-level wastes or spent fuel, for which disposal plans are progressing in the UK. Achieving public acceptance may be more problematic however. The key technical issue to be decided is the most appropriate wasteform.

There appears to be no reason why, following development of a suitable wasteform, separated plutonium should not be disposed of alongside other heat generating wastes. This would be

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[62] Angela Jameson, "Britain holds £160bn stockpile of nuclear fuel", *The Times*, Business section, 18 Aug 2008. http://business.timesonline.co.uk/tol/business/industry_sectors/utilities/article4553489.ece - A more realistic assessment is £27bn – see p40 below

much more cost-effective than special measures such as very deep boreholes or a ‘plutonium-only’ repository.

Studies of plutonium disposition usually emphasise the need to make the plutonium proliferation resistant. This need is, however, more relevant to storage than disposal. If it is decided that, whilst awaiting disposal, plutonium must be processed into a proliferation resistant. ‘spent fuel standard’ form, this form must be itself be disposable; indeed, the chosen form will have a profound impact on the disposal design and its cost. It will be important for the plutonium-containing waste package to conform to existing spent fuel or vitrified high-level waste geometries so as to reduce costs. If, on the other hand, an option of ‘do nothing pending disposal’ is adopted, the plutonium wasteform can be designed over a longer period of time and, we argue here, need not incorporate a radiation barrier. This would probably reduce costs significantly compared to a wasteform that complies with the ’spent fuel standard’.

Commentary on option 2 by devil’s advocates:

The case presented by the champions of option 2 has a number of gaps and weaknesses. These may be summarised as follows:

Technical feasibility of deep disposal of separated plutonium

The champions recognise that there is no waste form for separated plutonium which has already been demonstrated to meet the requirements for disposal in the kind of repository which is envisaged for the other UK radioactive wastes (ILW, HLW, spent fuel), but they are confident that such a waste form could be found. The options include vitrification and Hot Isostatic Pressing (to form a ceramic block). Their case is not very explicit on the timescale or cost of either the R&D required to establish the acceptability of such a wasteform, or of building the plant which would in due course be required to convert the existing PuO_2 powder into this wasteform. They note that work on the vitrification option, which was at one time being studied seriously at Savannah River in the US, was discontinued by the DOE in 2002 ‘due to budgetary constraints’. It is worth asking whether there were technical difficulties as well.

Proliferation resistance of plutonium during interim storage or after disposal

The champions claim that after conversion to the wasteform in which it will eventually be disposed, and *a fortiori* after disposal, it will be highly proliferation-resistant. However the case which they make is less than compelling. Any wasteform which does not meet the ‘spent fuel standard’ – ie is self-protecting because of the high level of radiation emitted by it – is ultimately usable by a technically competent terrorist organisation to make metallic plutonium. Incorporation in MOX pellets or in a ceramic merely increases the difficulty of the chemistry somewhat. Either form can be dissolved by sufficiently aggressive chemical agents, as is demonstrated by the existence of reprocessing facilities which can handle irradiated MOX fuel. Disposal is, of course, a further barrier which the terrorist would face, but the champions dismiss rather too lightly the possibility of recovering the material after disposal. After all, the repository has to have means of access to the disposal level during its operational phase, and even post-closure, those access channels will not be unusable by a determined engineer. The ease with which such an operation could be detected will depend on the level of surveillance which is maintained, and some decades after closure, that will presumably be fairly minimal. This concern has recently been popularised with the slogan that a disposal facility containing separated plutonium which had not first been made strongly radioactive would in the long term become a ‘plutonium mine’. The above arguments would, of course, be further strengthened if the UK were to decide to allow some provision for subsequent retrieval into its repository.

The timetable for achieving disposal of the whole plutonium stockpile

This is not discussed in detail by the champions, but some studies have suggested that this could be very long – perhaps as much as 100 years (see for example the ERM report commissioned by the NDA, “Uranium and Plutonium: Macro-Economic Study,Final Report”, NDA KP000040, June 2007, http://www.nda.gov.uk/documents/upload/Uranium-and-Plutonium-Macro-Economic-Study-June-2007.pdf). This timetable is set by the lengthy process of obtaining planning permission for a UK repository, and is subject to all the ‘Not in my back yard’ delays with which the nuclear community is so familiar. In addition, there is the need to design and get regulatory approval for the plant to condition the plutonium into the approved wasteform. So the timetable for option 3 might end up being shorter.

The comparative cost of options 2 and 3

The champions cite a 2001 report commissioned by the Friends of the Earth, written by Barker and Sadnicki, which claims that option 2 would be cheaper. However their view is contradicted by a more recent study, commissioned by the NDA (see section 3.3 below).

Possible public acceptance problems with option 2

The champions correctly draw attention to the possibility that local inhabitants in the Sellafield region, who are aware of the economic issues, might oppose option 2, because they would see it as a misuse of potentially economically valuable material to classify it as waste. Such attitudes might influence the public acceptance of the Sellafield area as a possible site for the UK radwaste repository, and might lead the government to have second thoughts about this option. It is perhaps worth making the point that this view might become more widespread than just in the Sellafield area, as UK energy policy becomes more widely debated.

3.3 Option 3: Burn it

Champion: Prof Roger Cowley

This section makes the case for converting most (if not all) of the UK stockpile of separated plutonium into a nuclear fuel – either MOX fuel or fast reactor fuel or target material for an accelerator-driven sub-critical assembly – and 'burning' this fuel to produce electrical energy. It is recognised that the UK cannot implement any of these variants immediately, since it does not have a properly operational MOX plant, nor a reactor licensed to burn MOX, nor a current fast reactor programme, nor a suitable accelerator facility. It could, of course, seek to sell its plutonium to other countries which do have such facilities. However the UK has a semi-operational MOX plant (SMP at Sellafield) and the UK government White Paper on energy policy[63] is generally sympathetic to the idea that the next generation of nuclear power plants to be built in the UK should be capable of burning MOX, and it has a long history of fast reactor development and it has a significant accelerator research programme. So in this section, the case is made that the UK should have the courage of its convictions, and gear up to 'burn' its plutonium – ie that it should implement a two-stage process – (i) establishing and operating a fuel production facility with the required throughput to convert all (or almost all – see below) of the plutonium stockpile, on a reasonable timescale, into a form (MOX fuel) which can be used as fuel in a suitable reactor, and (ii) constructing or modifying sufficient reactors (conventional or accelerator-driven) to burn this fuel at a suitable rate.

The fundamental reason for advocating this approach to the management of our plutonium stockpile is that it represents a continuation of a strategy which has developed within the UK nuclear industry over decades. The underlying argument for doing so has not changed – namely, that existing thermal reactors only extract about 1% of the energy contained in uranium mined from the ground (ie essentially that possessed by the U-235), and that in the long run, mankind is going to have to find a way of extracting the remaining 99% (ie that possessed by the U-238), since the world's reserves of uranium are finite. Adopting the MOX fuel cycle is a defensible first step in this direction, and moving on to the fast breeder reactor is a natural subsequent step. So if mankind is going to depend on nuclear fission to meet a significant fraction of its energy needs into the future, it will in due course have to implement these technologies. The MOX step is regarded as making economic sense, and is being implemented, in a number of countries today, and several countries are also taking the fast reactor step seriously.

The UK decision to construct a full-scale MOX plant at Sellafield, known as SMP, was taken shortly after the government decided, on a mixture of technical and economic grounds, to close its fast reactor programme in 1988. Construction of SMP was completed in 1996, but since then it has been beset by difficulties, and even today it is only operating at a small fraction of its planned output. It will require a major act of public policy, and a considerable further investment, to get it back on course. If the UK does so, it can become a major supplier of MOX to its own internal and/or the international market, and it will be able to make much better use of the uranium that it owns or purchases. It will also be able to make full use of its plutonium stockpile, which will immediately acquire a commercial value, since it could

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[63] UK Energy White Paper, 2008, paras 2.188 and 2.221, http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/nuclear/white_paper_08/white_paper_08.aspx

generate some 550 TW-h of electricity with a current wholesale value of £27b[64]. It will also save the burning of some 1 B tons of fossil fuels[65], making a corresponding contribution to the reduction in global warming. If it does not do so, the UK will have to fall back on options 1 or 2 above, either of which will involve a major, and un-rewarding, expenditure of public money.

The down side of taking this option is that it will contribute to the establishment of a ‘plutonium economy’, which will arguably have implications for international security and non-proliferation, so the ‘costs’ should not solely be evaluated in monetary terms. This issue is addressed in section 3.3.6 below.

The following sections consider:

- The conversion of the existing stockpile into MOX fuel;
- The establishment of a sufficient cohort of reactors capable of burning MOX;
- The eventual disposal of spent fuel from MOX-burning reactors;
- The economics of the MOX fuel cycle in relation to direct disposal;
- Other variants of the ‘burn it’ option;
- The ‘plutonium economy’ issue;
- Conclusions.

3.3.1 The conversion of the existing stockpile into MOX fuel

As noted in section 3.1 above, the current UK stockpile at Sellafield consists of three blocks of material[66]:

- Magnox reactor-derived (≈83 tons);
- THORP-derived (AGR and light water reactors) (≈15 tons); and
- Residues transferred from Aldermaston (≈3 tons).

There is some uncertainty about the extent to which further amounts of plutonium of military origin may in due course be transferred to the Sellafield stockpile from various other nuclear sites in the UK. Details of the complex pattern of transfers of plutonium between Aldermaston, Dounreay, Harwell, Winfrith and Sellafield from 1940 up to 2000 are given in an official history[67] In 2006 it was announced[68] that about 40 nuclear weapons were being decommissioned, but no information has been published on what has happened to the plutonium from those weapons. The 1996 Strategic Defence Review[69] audited the sites at which plutonium is stored. According to these documents, 0.3 tons of weapons grade plutonium was moved from Aldermaston to Sellafield and 4.1 tons of non-weapons grade

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[64] NDA Macro-economic study quotes 550 TW-h, http://www.publications.parliament.uk/pa/cm200708/cmselect/cmberr/293/29306.htm gives wholesale price of £50/MW-h

[65] Taking a typical 1 GW coal-fired station as burning 500 tons/hour

[66] See ref 17.

[67] “The United Kingdom's Defence Nuclear Weapons Programme”, http://www.mod.uk/NR/rdonlyres/B31B4EF0-A584-4CC6-9B14-B5E89E6848F8/0/plutoniumandaldermaston.pdf and “Plutonium and Aldermaston - an historical account”, http://www.fas.org/news/uk/000414-uk2.htm

[68] Ambassador John Duncan, Ambassador for Multilateral Arms Control and Disarmament, “UK Statement

to the 2008 Non-Proliferation Treaty Preparatory Committee, Cluster 1 – Nuclear Disarmament”, Geneva, 30 April 2008. http://ukunarmscontrol.fco.gov.uk/resources/en/pdf/pdf1/postgv_npt2008cluster1

[69] “The United Kingdom's Defence Nuclear Weapons Programme”, http://www.mod.uk/NR/rdonlyres/B31B4EF0-A584-4CC6-9B14-B5E89E6848F8/0/plutoniumandaldermaston.pdf

plutonium that had been used by the military are now held at Sellafield. The 1998 Strategic Defence Review reported that the total UK stock of military plutonium was 7.6 tons, of which 4.4 tons had been put under international safeguards.[70]

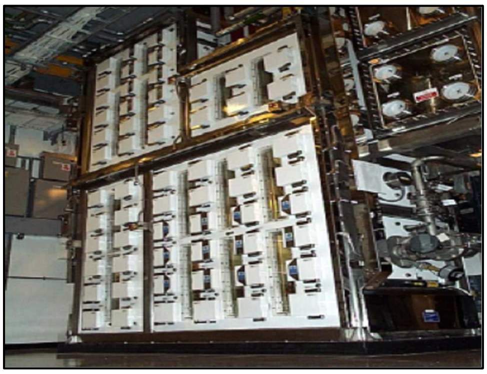
It is foreseen that when the current foreign reprocessing contracts have been completed (say by 2015), these will have generated a further 34 tons of separated plutonium at Sellafield[71], and the destiny of this material remains somewhat uncertain.

The isotopic composition of these various blocks differ considerably: the fuel elements of the Magnox reactors generate plutonium with 68.5% of Pu-239, whereas fuel elements from the AGR and light water reactors produce plutonium with only about 52% of Pu-239. The plutonium used in nuclear weapons is at least 92% Pu-239, but it seems that most, if not all, of the material which has been transferred from Aldermaston to the Sellafield stockpile is below the 92% threshold[72]. The remaining isotopes in all these blocks include Pu-241 and, as noted in the option 1 section above, this isotope decays to yield Am-241 , and the 'in-growth' of this contaminant progressively makes the plutonium less suitable for the manufacture of MOX, because of its γ activity. Material containing more than about 3% of Am-241 needs to be pre-processed to reduce the Am content before the plutonium can be converted to MOX for the commercial market[73]. This is technically feasible, but adds to the cost.

The history of MOX manufacture at Sellafield[74]

The conversion of plutonium oxide into MOX fuel has been an ongoing activity at Sellafield since 1960, when work started on the manufacture of MOX fuel elements with a Pu content of up to 7% for AGRs, SGHWR and continental PWRs. The activity was expanded in 1963 to produce fuel elements for the UK Fast Breeder programme, with a Pu content of up to 32%. Initially, production was carried out in an experimental facility in B33. In 1993, it was transferred to the MOX Demonstration Facility (MDF), a small-scale plant based on glove boxes, using (at best) semi-automated procedures. In the early 1980s Sellafield started to develop an improved manufacturing process, which was eventually incorporated into the design of a new fully-automated production facility, the Sellafield MOX Plant (SMP).

View of SMP at Sellafield



The Powder Processing Tower

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[70] The Strategic Defense Review White Paper, 1998
[71] See ref 21.
[72] It is difficult to find an authoritative source for this
[73] http://en.wikipedia.org/wiki/MOX; World Information Service on Energy, http://www10.antenna.nl/wise/index.html
[74] Dr John Edwards, "MOX Development in the UK and the Current Status of SMP", Presentation, February 2002. http://www.jaea.go.jp/jnc/news/topics/PT021203/pdf/engilsih_original/09_j_edwards.pdf

Rod fabrication glovebox

Fuel assembly area

Pictures of the Sellafield MOX plant[75],[74]

The history of this plant is a long and sad story[76]

The decision to build SMP was taken in 1991, and BNFL received planning permission to build it in 1994. Construction was completed in 1996 at an initial cost of £300m, though maintenance and upgrading brought the total cost up to £473m. On 20 August 1999, BNFL became aware of a problem over the quality assurance data produced in its smaller MOX Demonstration Facility (MDF) which was at that time making fuel pellets for a Japanese customer. On 10 September 1999, the news broke that their staff had been fabricating Quality Assurance (QA) data, and this led to a confrontation with the customer, and involvement of the NII and the UK government, and it developed into a major international incident. The Japanese demanded suspension of shipments, and the NII closed the MDF, pending changes in its operating practices. BNFL took the decision to close down MDF permanently, and to rely exclusively on SMP for further MOX production. In view of these political problems, it took the UK government until 3 October 2001 to decide to give the go-ahead for SMP operation, which it only did after commissioning an independent review of the SMP Business Case by Arthur D Little, a review which reported in June 2001 that there was a significant economic benefit. Commissioning of SMP started on 20 December 2001, but a series of technical problems were then encountered, and the management's forecast of its annual production progressively dropped from 120 tons to 72 tons to 40 tons[77]. Details of these technical problems have never been published in full (though a 'redacted' version of a further review by Arthur D Little dated 21 July 2006 is given in[78]). However it is reported that the underlying problem was that SMP sought to introduce radically new technology on a large scale without having previously tested it at the pilot plant scale. Equipment repeatedly failed to perform to specification.

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[75] http://www.fissilematerials.org/ipfm/site_down/rr05.pdf

[76] http://www.fissilematerials.org/ipfm/site_down/rr05.pdf and http://www.greenpeace.se/files/900-999/file_931.pdf

[77] Rob Edwards, "Fuel for scandal", Comment is Free, The Guardian, 14 May 2008, http://www.guardian.co.uk/commentisfree/2008/may/14/fuelforscandal

[78] Arthur D. Little Ltd., "Review of the Sellafield MOX Plant and the MOX Fuel Business: Report to Nuclear Decommissioning Authority", 21 July 2006. http://www.nda.gov.uk/documents/upload/review_of_the_sellafield_mox_plant_smp_report_2006_redacted.pdf

The magnitude of these problems can be inferred from the figures given to Parliament on 22 February 2008 by the Minister for BERR for SMP production during the past five years (tons of heavy metal as finished fuel assemblies)[79]:

Year	2002/3	2003/4	2004/5	2005/6	2006/7
Production	0.0	0.0	0.3	2.3	2.6

Because of this very inadequate performance, the NDA (which has now taken over responsibility for the management of SMP from BNFL) has been obliged to ship UK plutonium to the French MOX plant at Cap la Hague for fabrication into MOX fuel, in order to fulfil one of SMP's contracts. Throughout this period, SMP has been the subject of repeated legal proceedings, all ultimately unsuccessful, by Greenpeace, the Friends of the Earth and the Irish government. It has recently been the subject of criticism for managerial incompetence from a number of quarters.

In its recent optioneering report[80], the NDA has indicated that it discounts the possibility of taking technical measures to recover from this situation, but does not give reasons for this. On the face of it, there is no obvious reason why Sellafield should not be able to do so – Melox, the equivalent French plant at Marcoule, has been successfully producing MOX since 1995, at a rate of about 140 tons/year and is planning to increase its throughput to 195 tons/year shortly. But it is clear that if the UK wishes to convert the whole of its present 100 ton plutonium stockpile into MOX (and thereby create about 1500 tons of MOX), it will need a plant with a throughput of at least 100 tons/year in order to clear the stockpile in a reasonable period of time (say 15 years). So if SMP cannot be brought up to something approaching its original design throughput, a new plant will need to be built, presumably again at Sellafield, which does produce MOX fuel efficiently and reliably. A complete replacement for the SMP plant at Sellafield might cost somewhere between £600m (the estimated cost of the new plant at Rokkashomura in Japan) and £1.5b (the cost of the new MOX plant at Savannah River in the US). Hopefully, the cost of refurbishing SMP would be considerably less than either of these 'new build' figures.

It is arguable that because of its high proliferation hazard potential, some special measures should be taken, as a matter of urgency, to blend down any weapons-grade plutonium that may remain in the UK stockpile, by intimately mixing it with other plutonium in the stockpile which derives from spent fuel which has experienced higher burn-up, and hence has a higher proportion of the higher isotopes of plutonium.

3.3.2 The establishment of a sufficient cohort of reactors capable of burning MOX

At present, there is no power reactor in the UK fleet which is licensed to burn MOX fuel. However the changes which are required to enable a modern PWR reactor such as Sizewell B to use MOX fuel are not very great – at most, some minor adaptations of the plant, such as additional control rods and adjustments to boron concentrations, and some changes in operating procedures, such as core management, and revision of the reactor safety case. In France no less than 20 PWRs have been modified to permit the use of MOX fuel[81], and there

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[79] Malcolm Wicks, Written Answer, *Hansard*, 22 Feb 2008, Column 1034W. http://www.publications.parliament.uk/pa/cm200708/cmhansrd/cm080222/text/80222w0002.htm

[80] see NDA Plutonium Topic Strategy - Credible Options Technical Analysis, p101, accessible as in ref 6 above

[81] Bernard Tinturier and Michel Debes, "Nuclear Energy in France", presentation, January 2005. http://www.aec.go.jp/jicst/NC/tyoki/chokei2004/chokei19/siryo1.pdf

is no reason to suppose that Sizewell B could not be modified similarly. Furthermore the majority of next-generation reactors, such as the reactors under consideration for the new build which is foreseen in the latest government White Paper, are capable of being specified to include MOX-burning capability. Of the four systems which have already been endorsed by the UK nuclear regulators:

- The Atomic Energy of Canada Ltd – ACR 1000;
- EdF/Areva – EPR;
- GE-Hitachi – GE ESBWR;
- Toshiba – Westinghouse – AP 1000

at least the last three[82] have been designed to be able to burn MOX fuel – in the case of AP1000, up to 100% MOX fuel. Now that EdF has purchased British Energy[83], and has announced its intention to build four new reactors, it seems likely that these will be of the EPR type, and that they will be able to burn MOX.

A typical light water reactor with a full-core load of MOX (taking the figures in ref 84) will burn about 25 tons of MOX fuel each year, containing about 1.6 tons of plutonium, so Sizewell B alone would not be able to burn the whole of the UK stockpile before its currently-planned decommissioning date of 2035. However the government could, if it wishes, lean on EdF to ensure that the four (or more) new build reactors are able to operate with MOX fuel, and will actually use at least a proportion of MOX fuel. There is no reason why this should be unacceptable to EdF, provided that the cost of using MOX fuel is no higher than that of using uranium fuel.

After the MOX fuel has received the permitted burn-up in the reactor, it still has plutonium in it, though typically 30% less than its initial content. Thereafter it can either be put into interim storage and ultimately disposed of like other spent fuel from reactors, or it can be reprocessed, and the separated plutonium can again be used to make reactor fuel.

3.3.3 The eventual disposal of spent fuel from MOX-burning reactors

In comparison with spent fuel from reactors burning conventional uranium fuel, spent MOX fuel has a higher plutonium and minor actinide content, and this results in higher heat load after discharge from the reactor. In consequence, spent MOX fuel requires longer interim storage before transport and final disposal, and the costs of both are somewhat higher[84]. It is very adequately protected against proliferation, since it is fully up to the ‘spent fuel standard’.

3.3.4 The economics of the MOX fuel cycle in relation to direct disposal

This subject is bedevilled by arguments about the correct treatment of historically-incurred costs and uncertainties about the future cost of uranium. This section takes the view that in the

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[82] World Nuclear Association, “Mixed Oxide (MOX) Fuel”, updated March 2009, http://www.world-nuclear.org/info/inf29.html

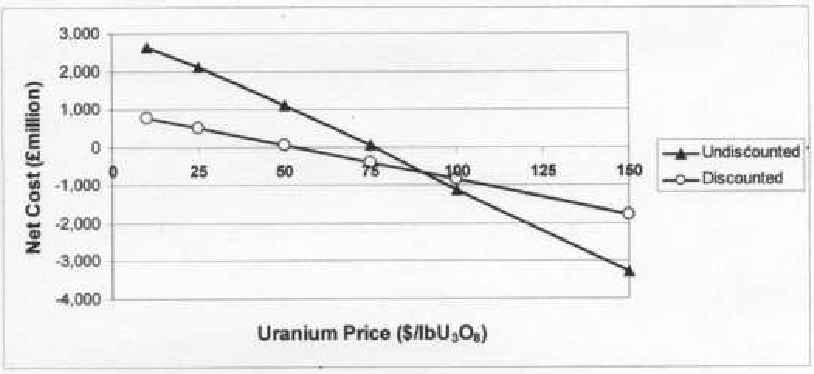
[83] E-Politix.com, “MP urges scrutiny of British Energy sale”, 25 September 2008, www.epolitix.com/latestnews/article-detail/newsarticle/mps-urges-scrutiny-of-british-energy-sale/

[84] Bunn, Holdren, Fetter, van der Zwaan, “The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel”, *Nuclear Technology*, Vol 150, June 2005, 209-230. http://www.publicpolicy.umd.edu/Fetter/2005-NT-repro.pdf

UK, any historically-incurred costs of the SMP plant should be treated as ‘sunk costs’, and that it should be recognised that the spot price of uranium on the international market during the past five years has ranged from $15 to $136/lb, and is currently (June 09) $65/lb[85] (Plant operators do not, of course buy at the spot price, but at some negotiated mean price).

The only ‘official’ estimate of the economics of these two options is the study commissioned by NDA, and undertaken by ERM and IDM in 2007.[86] On their assumptions, the disposal option (the ‘waste’ bounding scenario) would cost £2-3b over the ~100 years timescale (dictated by the non-availability of a UK repository during the next 67 years), or ~£1b if discounted to 2007 prices at the current Treasury discount rate, whereas the MOX option (the so-called ‘use’ bounding scenario) would have a cost or net benefit depending on the price of uranium as shown:

Figure 5 *Net Costs from Use Bounding Scenario as a function of Uranium Price*



It will be seen that the net cost of the MOX burning scenario is less than the cost of the disposal option for almost any uranium price, and becomes negative (ie the activity becomes profitable) if the price of uranium exceeds $50/lb (on a discounted basis) or $75/lb (on an un-discounted basis).

This conclusion is apparently in contradiction with that contained in a well-known, and widely cited, publication by Bunn, Holdren, Fetter and Zwaan[87] which assesses that recycling plutonium as MOX is un-economic as compared with direct disposal of spent fuel from a light water reactor until the price of uranium exceeds $168/lb. It should however be pointed out that these two studies are not making even approximately the same comparison.

The NDA study examines precisely the comparison which is of concern in this report – the cost of disposing of a pre-existing stockpile of separated plutonium in two different ways: (i) by conditioning it for direct disposal, storing it until a repository becomes available, and then disposing of it in that repository and (ii) converting it to MOX fuel, burning it in a light water reactor, storing the spent fuel until a repository becomes available, and then disposing of the spent fuel as a high activity (and hence self-protecting) waste.

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[85] Cameco, “Uranium Prices”, http://www.cameco.com/marketing/uranium_prices_and_spot_price/longterm_5yr_history/

[86] NDA, “Uranium and Plutonium: Macro-Economic Study, Final Report”, June 2007. www.nda.gov.uk/documents/upload/Uranium-and-Plutonium-Macro-Economic-Study-June-2007.pdf

[87] Bunn, Holdren, Fetter, van der Zwaan, “The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel”, *Nuclear Technology*, Vol 150, June 2005, 209-230. http://www.publicpolicy.umd.edu/Fetter/2005-NT-repro.pdf

The report by Bunn et al compares the cost of two different commercial operations, both aimed at generating power from uranium, and both starting by creating fuel elements containing low-enriched uranium and burning them in a light water reactor. The two operations differ in that thereafter: (i) the spent fuel is stored until a repository becomes available, and is then conditioned for, and disposed in, the repository and (ii) the spent fuel is reprocessed, the separated plutonium is converted to MOX, burned in a reactor adapted for that purpose, and the spent MOX fuel is stored until a repository becomes available, and is then conditioned for, and disposed in, the repository.

Because these are both regarded as strictly commercial operations, their study calculates the capital cost of both the reprocessing facility and the MOX fabrication facility, and estimates the charge which the operator will have to make to cover those capital costs. Unsurprisingly, the calculation is dominated by the capital cost of the reprocessing facility, and the conclusion is that reprocessing is uneconomic unless the cost of uranium is rather high (though they were writing before the recent peak in the spot price of uranium, and clearly do not regard as credible the price level which was actually reached in June 2007). In the NDA-commissioned report, the capital cost of both the THORP reprocessing plant and the SMP are regarded as sunk costs, and do not feature in the calculation at all.

The paper by Bunn et al is however relevant to this discussion in the following indirect way. As discussed in section 6 below, although it is in principle open to the UK to decide to renovate its MOX fabrication facility simply in order to solve its plutonium stockpile problem, it is much more credible that it would chose to do so as part of a broader strategy of burning uranium efficiently by operating a reprocessing-based fuel cycle. The comparison which Bunn et al make would then become more relevant. However even in that case it is by no means wholly relevant, since the UK would not be starting from scratch – it already has a very substantial investment in both reprocessing and MOX fabrication, and at most it would have to envisage some additional investment to bring the performance of these facilities up to the required standard. So a cost comparison which ignored sunk costs would be much more heavily weighted in favour of the MOX route than the calculation of Bunn et al would allow. We are not aware of any study which has attempted to make that comparison in detail.

3.3.5 Other variants of the ‘burn it’ option

As noted above, the MOX-burning route is not the only available variant of the ‘burn it’ option. Among the others are:

- Restart a UK fast breeder reactor programme, or a thorium-cycle breeder reactor programme, and use the plutonium for the initial fuel inventory.
- Start an accelerator transmutation programme, by building such a facility in the UK, perhaps modelled on the ATW facility which has been proposed by Los Alamos, USA, or the facility being considered by J-PARC in Japan.
- Ship the plutonium to a ‘reliable’ country that either has MOX fabrication facilities or a fast breeder reactor programme or an accelerator transmutation facility.

These three options are considered below.

(a) Fast reactors and thorium-cycle reactors

A fast reactor is one in which the chain reaction is sustained by fast neutrons, and a fraction of these are captured by U-238, thereby breeding plutonium, and unlocking its energy potential.

In a thorium cycle reactor, surplus fast neutrons are captured by Th-232, thereby breeding U-233, which is likewise a fissile material. As a result of breeding, a fast reactor can produce up to 100 times more energy than a thermal reactor from the same quantity of uranium, and a thorium cycle reactor can release the energy potential of the (otherwise un-reactive) natural thorium. Both fast reactors and thorium cycle reactors involve reprocessing, and both can make use of MOX or even pure plutonium fuel.

Despite the obvious advantages of these systems in the long term, until recently they have been held to be financially unviable, because it has been held cheaper to use uranium fuel in a single-pass reactor, with direct disposal of the spent fuel, rather than to reprocess the fuel and recycle the (somewhat radioactive) components. The single-pass arrangement was also held to have the advantage that it hindered the proliferation of nuclear weapons materials. As a result of this assessment, at a time when fossil energy was not seen as a problem, many of the countries that began to commercialise fast reactors, including the USA, France, Germany and Britain terminated their fast reactor programmes. In parallel with this, the USA and Germany stopped their reprocessing activities in the 1970s, though the UK and France continued. Currently only Russia, India and Japan have active commercial-scale fast reactor programmes. Several reactors have been built to test the thorium-cycle, including the Dragon reactor in the UK, and similar reactors in Germany, USA, and Japan. A number of technical problems have been found, although none of them seem insurmountable. Presently this scheme is only being pursued in India, which has large deposits of thorium. For details of the various ongoing programmes world-wide, the reader is referred to a recent IAEA review[88].

At various dates during the past decade, the UK has signalled a wish to reconsider either the fast reactor option or the thorium cycle. In January 2000, it joined the ‘Generation IV International Forum’, an R&D organisation set up by 11 nations, together with a number of leading international agencies, to look into the various possible reactor types (including several fast reactor designs) which had commercial potential, aiming at designs which:

- Advance Nuclear Safety;
- Address Nuclear Non-proliferation and Physical Protection Issues;
- Are Competitively Priced; and
- Minimize Waste and Optimize Natural Resource Utilization.

However in summer 2006, the UK decided to stand down as an active member of the Forum[89] since it “was not considered to be as relevant to the Department’s mission as other competing priorities”. At about the same time, the UK became involved in the US-led Global Nuclear Energy Partnership (GNEP), which has a broader nuclear-industry scope and a stronger non-proliferation focus. After a period of observer status, the UK formally became a member in February 2008.[90] However it appears to have done so because of its interest in nuclear waste management, not a wish to develop a new generation of reactors. So it seems rather doubtful whether the UK will choose to develop either a fast breeder or a thorium cycle reactor soon enough for either variant to play a part in the disposal of the UK plutonium stockpile.

(b) Accelerator based disposal of plutonium

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[88] IAEA, “Thorium fuel cycle — Potential benefits and challenges”, IAEA-TECDOC-1450, May 2005. http://www-pub.iaea.org/MTCD/publications/PDF/TE_1450_web.pdf

[89] Malcolm Wicks, Written Answer, *Hansard*, 18 Dec 2007 : Column 1471W. http://www.publications.parliament.uk/pa/cm200708/cmhansrd/cm071218/text/71218w0053.htm

[90] The Nuclear Communications Network, “UK Joins Global Nuclear Energy Partnership”, 26 Feb 2008. http://www.worldnuclear.org/_news_database/rss_detail_features.cfm?objID=532C6D60-7605-44E7-9F25EC6D10650951

An alternative way of disposing of the plutonium has been proposed by the Los Alamos National Laboratory in the USA. In its proposed ATW facility, in which protons would be accelerated by a linear accelerator to an energy of about 1Gev, and hit a spallation target, leading to the production of neutrons which are then used to sustain a reaction in a subcritical assembly[91]. The calculations suggest that if a blanket of plutonium surrounds the target, nuclear transmutations could reduce the amount of plutonium by about a factor of 500.

The proposed ATW accelerator can be seen as the next step after the ISIS accelerator at the Rutherford-Appleton Laboratory and the DOE's Spallation Neutron Source (SNS) at Oak Ridge that generate about 20 neutrons for each proton. These machines currently deliver pulsed beams of about 200µA and 800Mev, though SPS is designed to achieve an average of 1.4mA. The ATW concept requires much more current than either, 250mA and a somewhat larger energy, 1600Mev which means that the system needs to have a linear accelerator instead of a circular synchrotron and that there are considerable difficulties with the target that would need to be solved. The total power required is in excess of 400MW, which is comparable to a large power station although it is hoped to recover this from the heat generated in the target. The target would be surrounded by the plutonium or other radioactive waste and the whole system would be near to criticality even though kept below this level. The funding of ATW has not yet been assured. However a similar project J-PARC is being developed in Japan.

Although this is in many ways an attractive scheme, it requires considerably more development, both of accelerator technology and the target system, before it becomes certain that it will operate, and have an acceptable cost. There is substantial opposition to this approach in the USA, claiming that the facility would not be a cost effective way of eliminating radioactive isotopes, as compared with burial techniques.

(c) Ship the plutonium to another country

Another possibility is to ship the plutonium to another country which could use it in a reactor as a fuel. That country needs to have the capability to manufacture a suitable fuel (eg MOX) and then reactors capable of burning this. The country also needs to be trusted to destroy the plutonium and not to use it for military purposes. These requirements are arguably satisfied by France, which has the reprocessing ability and the ability to manufacture MOX fuel in larger quantities than can be produced at the SMP plant at Sellafield, and has a large cohort of reactors capable of burning MOX. There are indications[92] that France might be willing to purchase plutonium as fuel for their reactor programme. Although other candidates may emerge during the coming decades (for example Canada is considered as a possible candidate by the NDA), France is probably the only country that currently meets the criteria, and it is open to question what (if anything) it would be prepared to pay. This option faces a problem of transporting the plutonium to its destination, with the possibility of terrorist activity *en route*, and issues relating to compliance with the NPT. It also faces a political problem, in that it involves loss of control over the future of 'our' plutonium. If for some reason we decide not to adapt our own reactors to burn MOX, but we do establish a MOX manufacturing capability, we could, of course, sell our MOX to other countries which do have such reactors – eg France, Belgium, Germany, Japan or Russia. The export and transport of

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[91] Anatoly Blanovsky, "Nuclear Waste Transmutation in Subcritical Reactors Driven by Target-Distributed Accelerators," http://arxiv.org/ftp/physics/papers/0401/0401015.pdf
W. Gudowski, Why Accelerator-Driven Transmutation of Wastes Enables Future Nuclear Power?" http://www.neutron.kth.se/publications/conference_papers/W_Gudowski_FR202_1.PDF
"Sub critical reactors for energy production and transmutation of nuclear waste", http://www.kemi.kth.se/nuchem/eng/utbildning/rc/transmutation.pdf

[92] Royal Society Report 2007 para 55

MOX is not subject to many of the concerns attaching to the export of plutonium dioxide powder.

3.3.6 The 'plutonium economy' issue

It is implicit in much of the above discussion that the management of the UK plutonium stockpile should be part of a larger UK nuclear power programme in which reprocessing and the conversion of the resulting separated plutonium into MOX fuel are carried out. This is precisely the outcome which opponents of this option fear, on the grounds that it makes the UK part of the world-wide 'plutonium economy', instead of being one of the nations leading the movement to eliminate plutonium altogether. It is therefore worth making the point that there is in principle an intermediate position – that the UK should establish a MOX manufacturing capability which is just sufficient to convert its plutonium stockpile into MOX, but should then dispose of this material without burning it, and should not seek to operate the plant further. This option was previously discussed in the Royal Society report (see ref 2), which considered the possibility that this MOX should be of 'low specification' – ie not manufactured up to the QA standard required for burning in a reactor, but nevertheless possessing the limited degree of protection against terrorist dispersal or conversion to nuclear weapon material which MOX possesses by virtue of its chemical form. For a more recent study of this option, see [93] and option 2 above. The most obvious objection to this variant is that the UK would have to incur most of the (not inconsiderable) cost of creating a viable commercial MOX plant without gaining any of the corresponding economic benefit. In what follows, we assume that the intention is to create a commercially viable MOX programme.

It is recognised that there are hazards associated with a nuclear power programme which involves the creation and use of plutonium on the multi-ton scale. These have been discussed in previous sections of this report, and will not be repeated here. However there are several arguments which can be deployed to put these hazards into perspective.

The limited value of reactor grade plutonium as a nuclear explosive

It is no accident that all the nations which have sought to go down the plutonium route to produce a nuclear weapon have chosen to use 'weapons grade' plutonium – ie material with at least 92% of Pu-239. Even so, they have not always been successful, as the first test carried out in North Korea on 9 October 2006 seems to show[94] , though it is sometimes claimed that this test only used 2 kg of plutonium, so was never intended to have a significant yield.

The plutonium route to a nuclear weapon is more technically demanding than the uranium-235 route, because of the need to achieve a very high core density by a carefully-designed spherically-symmetric implosion, using the simultaneous ignition of shaped explosive charges. The problem with using material of less than weapons grade specification is that there is a greatly increased probability of initiation of the chain reaction before the implosion achieves the required density: under these circumstances only a 'fizzle' results, with an energy yield of perhaps one kiloton. Such an explosion, although of strong local and broader psychological significance, is a long way short of a full nuclear explosion in the 10 kiloton range. So it is relatively unlikely (not to put it more strongly) that a terrorist seeking to create a real nuclear explosion, would seek to go down the plutonium route (rather than the uranium route) and use plutonium of less than weapons grade. If he furthermore has to create an

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[93] This is implementation strategy 6 in the NDA Plutonium Topic Strategy – see ref 6.

[94] http://en.wikipedia.org/wiki/2006_North_Korean_nuclear_test

industrial facility to separate the plutonium from MOX fuel, it is even less likely that he will choose to go this way.

The relatively inert chemical form of MOX

MOX fuel is a mixed oxide material in the form of ceramic pellets produced by sintering at high temperature. It is completely incombustible, and very difficult to disperse into the form of fine particles which would permit it to be breathed in by a population. It is therefore very unsuitable for use by terrorists in a ‘dirty bomb’. The arguments which have been used to show that the military use of depleted uranium is unlikely to have been a significant cause of civilian casualties apply here with even greater force.

The measures which have been taken to protect MOX in transit worldwide have hitherto worked well, notwithstanding a number of attempts by protest groups to disrupt it. There are no recorded instances of theft of this material in transit. According to BNFL[95], the measures that it takes to protect MOX in transit by ship include:

- Two vessels sailing together for mutual support and protection;
- A wide range of protection systems, including naval guns, to deal with potential threats;
- Specially trained and armed officers of the United Kingdom Atomic Energy Authority Constabulary to escort the cargo and to protect both vessels;
- Contingency plans for identifying possible emergency situations and responses are established;
- Measures to impede removal of the MOX fuel at sea, including rendering inoperable the hatch removal mechanisms and locking and sealing of the transport casks to prevent access by unauthorized persons;
- Constant monitoring of the location of the vessels and the status of the MOX fuel elements by an operations centre in the United Kingdom.

It should be noted that even the transport of plutonium dioxide powder from Sellafield to France has proceeded without mishap, notwithstanding attempts to disrupt it.

There are international discussions in progress about the possible ‘internationalisation’ of the secure management of nuclear materials.

Both within GNEP and within the IAEA there are groups examining the possibility of creating an international framework for the safe management of the nuclear fuel cycle. There are considerable economic and security issues to be resolved, but there is widespread interest in such an approach.

It is however recognised that with a reprocessing plant, there is a stage at which the plutonium is potentially vulnerable to theft and misuse by terrorists, so the security arrangements discussed in section 1 above remain of crucial importance.

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[95] Environmental News Service, “Greenpeace Finds British MOX Fuel Ships Off Africa”, 20 August 2002. http://www.ens-newswire.com/ens/aug2002/2002-08-20-01.asp

3.3.7 Overall assessment of option 3

This section has outlined a number of routes by which the plutonium stockpile in the UK could be managed. On balance the safest and most cost-effective course would be to convert most (if not all) of the plutonium to MOX fuel and then to burn it in a reactor. This would require a programme to increase MOX production at Sellafield, either by a substantial upgrade of the SMP facility or by the construction of a new plant to make the MOX fuel. If this MOX fuel is to be burned on a reasonable timescale, it will be necessary to adapt a number of reactors to enable them to burn it. Sizewell B could be adapted in this way, but it alone will not be able to burn all the MOX fuel that is produced from the stockpile. It is recommended that the four 'new build' reactors to be built in the UK should be designed from the outset to use MOX fuel.

On a somewhat longer timescale, the UK should move in the direction of either fast reactors or a thorium cycle reactors, as a means of making the fullest possible use of natural resources. It is noted that the Generation 4 International Forum provided an excellent R&D framework within which the UK could participate in such a reactor development programme, and I regret that the UK government has withdrawn from this study, and by implication is not giving serious consideration to using either fast reactors or thorium-cycle reactors in the longer term, which could burn the plutonium being produced in a sustainable way.

I commend the steps that are being taken in the US and elsewhere to develop the option of disposing of plutonium and other long-lived isotopes by using a large current accelerator to burn them, though we recognise that this is a long-term R&D programme, with an uncertain outcome. But this should not prevent the possibility being pursued.

Finally I do not exclude the possibility of arranging for another country to solve the plutonium problem for us. France has a working MOX plant as well as a reprocessing facility. If it is not possible for the UK to solve its domestic MOX production problems, but solutions could be found to the problems of transporting our plutonium abroad and satisfying the requirements of the Non-Proliferation Treaty, the UK could perhaps dispose of the UK stockpile of plutonium by selling it to France. The option of exporting it to Canada should also be considered.

Commentary on option 3 by devil's advocates:

The case presented by the champion of option 3 has a number of gaps and weaknesses. These may be summarised as follows:

The americium in-growth problem

The champion recognises that there may be a problem in this area, but does not quantify it. The issue is essentially an economic one. The more americium there is in the plutonium feedstock, the more heavily shielded does the plant used to convert it into MOX have to be, and the more radiological protection has to be provided for the operators of both the MOX plant and the reactor used to burn it. The current rule of thumb is that plutonium feedstock containing more than about 3% of Am-241 needs to be pre-processed to reduce the Am content before the plutonium can be converted to MOX for the commercial market[96]. Such a 'plutonium polishing' facility is expensive, and BNFL has hitherto preferred to use the part of the stockpile with low americium content (largely that derived from Magnox reactors),

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[96] See ref 73.

thereby deferring the problem. An alternative approach would be to blend Magnox and THORP-derived material so as to stay within the limit. Bunn et al (ref 84) have quoted ‘commercial’ costs in the range of $10m-$27m/ton for americium removal, so this is a real issue.

Uncertainties and costs of SMP reconstruction

Because of the wall of silence surrounding the technical difficulties which are still being experienced with the SMP plant, it is difficult for an outsider to have an informed view on the likely cost of bringing this plant up to something approaching its design throughput (120 tons/year). It would be very helpful if the Arthur D Little review dated 2006 could be published in its full, and not ‘redacted’ form, since almost all the relevant technical information has been ‘redacted’ out. Equally, it would be helpful to know what other studies the NDA may have commissioned on this option. Until this information is in the public domain, it will be very difficult to have an informed public debate about the merits of option 3.

Uncertainties over availability/ economic performance of MOX-burning reactors

The champion seems confident that Sizewell B could be converted to burn MOX, and that this would be cost-effective. Not all experts agree. See for example [97]. He also assumes that EdF would rapidly implement the UK government strategy of making the ‘new build’ reactors in the UK capable of burning MOX. Although public statements made by EdF have been encouraging in this regard, they have not yet made any commitment to do so. Although France has a large number of power reactors which are capable of burning MOX (and are doing so), their reasons for doing so are not very clear (France is much less open than the UK in publishing costs relating to its nuclear programme, so the economic case for their technical/commercial decisions is not clear).

Comparative costs of options 2 and 3

The NDA has performed a valuable public service by publishing the summary report on the comparative costs (ref 86). However it has not published the underlying commercial calculations, or the technical and economic assumptions which are the basis for its conclusion. So it may be premature to take the conclusions drawn from that report in section 3.3 at face value.

The ‘plutonium economy’ argument

The champion has made a vigorous defence of option 3 against the more naïve versions of the ‘plutonium economy’ argument. However not all his arguments are equally strong. His claim that reactor grade plutonium has limited value as a nuclear explosive is rather overstated – the counter-argument is given in section 3.1. The claim that MOX is relatively chemically inert, and in consequence reasonably proliferation-proof, is also overstated. As noted above in the commentary on option 2, incorporation of separated plutonium into MOX pellets or in a ceramic merely increases the difficulty of the chemical task facing a terrorist. Either form can be dissolved by sufficiently aggressive chemical agents, as is demonstrated by the existence of reprocessing facilities which can handle irradiated MOX fuel. The claim that there is widespread interest in the internationalisation of the nuclear fuel cycle is correct, but so is the qualification that there are considerable economic, security and proliferation issues still to be resolved.

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[97] House of Lords Select Committee on Science and Technology, Third Report, Chapter 7, Reprocessing, Plutonium and MOX, 10 March 1999. http://www.publications.parliament.uk/pa/ld199899/ldselect/ldsctech/41/4111.htm

4. Summary and conclusions

This section seeks to pull together the arguments developed in the preceding sections, and identify the areas where further work is required.

This document is basically an exercise in optioneering. It has sought to develop each of three broad options for the management of the UK stockpile of separated plutonium, up to the point at which it should be possible to take a rational decision on the best strategy. It has to be admitted that as such it has failed. Too much essential information is not in the public domain. This is partly for commendable security reasons, and partly for less commendable but understandable commercial reasons. But it is difficult to resist the conclusion that the information has in many places not been published because to do so would draw attention to a series of failures in UK government and public/private sector management. The history of the UK nuclear programme is rather too full of what have proved to be expensive mistakes, and it has been rather too easy to invoke commercial or security considerations to conceal technical, commercial and political mis-judgements. The authors of this report hope that it will assist in the process of achieving a rather greater openness in future.

The three options have been presented above as if they were straight alternatives. However it is clear that the eventual solution may involve a mixture of two, and very possibly all three options. That is primarily because of the timescales involved. Neither option 2 nor 3 can be implemented in full very quickly – option 2 because it involves the creation of a UK repository for nuclear wastes, which has been bedevilled by arguments of the NIMBY (‘not in my back yard’) type for several decades, and option 3 because it involves putting right the technical failures of the past decade in the establishment of a reliable plant for the manufacture of MOX. So in the short run, the UK has no alternative but to make option 1 work, and that is again difficult because of the inadequate protection of our existing plutonium stores against the latest manifestations of the terrorist threat.

The case for option 1 (‘do nothing’) starts with the fact that it has been the *de facto* option for two decades. We have accumulated the stockpile, and we have constructed storage facilities which until recently were judged to be adequately safe and secure. The material in them does not deteriorate very rapidly, so we have, at the least, several decades before we need to worry about that. As the terrorist threat has evolved over the past decade, we have taken vigorous steps to match it with suitable defensive measures. Reading section 3.1, it is difficult to resist the conclusion that that operation has generally been well managed. The weakness in that position lies in the magnitude of the disaster which might arise if a terrorist were to succeed in stealing a significant amount of plutonium, or creating a sufficiently large high-temperature incident in the store – eg by crashing a large airliner on it. The possibility of theft cannot be totally ruled out, but the measures that have been taken against it are such that a rational terrorist would look elsewhere for his fissile material – he would have to be very lucky to succeed in stealing it, and the nuclear weapons that he could create with reactor-grade plutonium would have a much lower chance of working than devices which used U-235. The aircraft crash scenario is also rather remote, but since 9/11 that possibility cannot be ruled out. There are counter-measures, but they involve pouring very large amounts of concrete, which cannot be done overnight, or shooting down civilian airliners which get within a ‘danger zone’, with appalling human cost, and horrendous possibilities of error or misinformation. Having said all that, it remains true that option 1 is not an option which is viable in perpetuity. Eventually, material held in ‘interim’ stores has to be put somewhere more permanent.

The case for option 2 (‘bury it’) is that it gives a definite end date, after which there will no longer be any separated plutonium at ground level in the UK, except for such plutonium as we choose to keep for military reasons. It would all be 500 m below the surface, and quite difficult to access, and could perhaps also be made self-protecting by mixing it with some highly radioactive material, such that anyone who tried to handle it would die rapidly. This would perhaps be an attractive option if it could be achieved quickly, but unfortunately it cannot. The UK does not possess a repository for high-level radioactive waste, and its attempts to create one have been stalled for decades by essentially political obstacles, in many cases of the NIMBY variety. Faced with this history of failure to reach agreement on a site, the UK government has understandably taken the view that it will take a considerable time to reach agreement. Even when a site has been found, there will be administrative constraints on acceptable ‘wasteforms’ to go into it, and it is far from obvious what wasteform would be appropriate for separated plutonium. However the experts are agreed that that is a soluble problem, though converting the stockpile into that form will take time and cost money. If the wasteform does not include some high level radioactive waste, there is room for argument about how ‘proliferation-proof’ the material will be, either while it remains in interim storage on the surface, or even after disposal in what might eventually become a ‘plutonium mine’. The good news is that, given adequate engineering of the repository and containment, the risk of plutonium migrating with ground water back up to the surface and causing radiation doses to future generations is very low. A further consideration in favour of option 2 is that for some fraction of the existing stockpile, option 3 may not be economically viable, because its isotopic mix or americium content is too unfavourable. So a solution will have to be found for the eventual disposal of this material. Equally, after one (or perhaps several) rounds of recycling as MOX, the spent MOX will become uneconomic to recycle further, so it will require permanent disposal.

The case for option 3 (‘burn it’) is that that was always the intention, when the stockpile was created in the first place, and that in the long run, if mankind is going to rely on nuclear energy as a major source of energy, it is going to have to learn to use more than 1% of the energy in the uranium which it mines. So the ‘once-through’ fuel cycle which it currently operates is going to have to be replaced by a cycle involving reprocessing – in the short-to-medium run using MOX fuel and in the long run, fast breeders or accelerators that may also be able to transmute other radwaste to less problematical materials. Once that has been accepted, the plutonium which we have already separated becomes a major asset, and could generate electricity with a value of at least £27b [66] at current prices. Burning the stockpile will be part of a much larger programme, in which plutonium will eventually be bred and consumed in a balanced way, with no large stockpiles accumulating. The UK nuclear industry has, over the past three decades, been trying to move in this direction, but has been beset by a mixture of political and technical misfortunes. These were briefly rehearsed in our introduction – technical difficulties with our early prototype fast breeder reactors, the discovery of North Sea oil & gas, which temporarily made the UK energy-self-sufficient, and removed the economic pressure to maintain our nuclear industry, the accidents at Three Mile Island and Chernobyl, the breakup of the Soviet Union, and the consequential nuclear disarmament treaties, leading to stockpiles of surplus fissile material, and last but not least the technical problems with both THORP and SMP, which have bedevilled our attempts to make the MOX fuel cycle work.

The case made above for option 3 is based on the premise that the time and expenditure required to solve the problems facing THORP and SMP are relatively small, and that this is the cost-effective direction in which to go. However it is recognised that there are difficulties:

- The UK's stockpile is ageing, and the in-growth of americium (from the decay of Pu-241) will progressively increase the cost, and decrease the attractiveness of this option as a means of disposing of the stockpile, even if the reprocessing route is eventually established as the way forward. To avoid this decisions and actions are needed quickly;

- The situation on SMP is frankly scandalous. A plant which had a design throughput of 120 tons/year, and was fully constructed in 1996 is still only operating at ~2% of its design throughput, and is beset by technical problems. Until the reasons for this are published it will be impossible to have an informed view about how best to remedy the situation;

- The UK currently has no reactors capable of burning MOX, though Sizewell B could be converted to do so, and the 'new build' reactors could be specified to fulfil this role. In either case it will be some years before this could make much impact on the stockpile.

It can be argued that for the UK to adopt the MOX cycle now would represent a move in the direction of the 'plutonium economy', and that concerns over non-proliferation and nuclear terrorism ought to take precedence over arguments about energy supply and economics. The champion of option 3 has sought to counter this argument. However not all his arguments are equally strong.

In the last resort, economic arguments may well prove decisive in this debate. However it is still far from clear which of the options (or what combination of them) will eventually win in strictly financial terms. The NDA, which is responsible for advising HMG on this matter, has commissioned a very interesting study, in which all three options are analysed rather carefully, and its conclusions are rather supportive of option 3. However the detailed assumptions and economic calculations which underlie their conclusion have not yet been published, so it is not easy to validate them. Other authors have published conclusions which contradict theirs, and it is clear that more work remains to be done in this area. It is important to stress that the UK economic calculation is, by its nature, different from that elsewhere in the world, since we have made very considerable investments in the reprocessing route, which must now be regarded as sunk costs, but can operate to our benefit if we move wisely.

It is to be hoped that before the NDA and (eventually) HMG reach a decision on how to move forward in this area, it will satisfy itself that it has answers to the many questions identified in each of the three main sections above (especially those highlighted in the commentaries by the 'devil's advocates'). In our view most of these answers could properly be made publicly available. A few cannot, for obvious security reasons, and this will have to be taken into account in reaching the final decision. However before then, it would be very good if the decision-takers sought to involve the public in their decision to the maximum possible extent, since a positive outcome will depend strongly on public acceptance.

5. Acknowledgements

The authors are very grateful to Dr Jack Harris, whose strong anti-MOX stance provoked the debate within BPG which led us to adopt the ‘champion and devil’s advocate’ approach which we have adopted in this report. His death on 3 February 2009 was a great loss to BPG and all those seeking an informed debate on these topics. We are also grateful to a number of individuals who read the draft report and provided helpful comments: in particular members of BPG, including Robert Hinde, Kit Hill, John Finney, and John Simpson, members of the NDA team, including Paul Gilchrist, Clive Nixon and Nicole Hough, and Frank von Hippel of Princeton University. We also particularly appreciate the help of Sandy Butcher in editing the text for publication.

Annex 1 Membership of the British Pugwash Group Working Party

General Sir Hugh Beach, GBE, KCB, MC

General Sir Hugh Beach, GBE, KCB, MC was educated at Winchester College, Cambridge University (MA 1961), Edinburgh University (M.Sc. 1971). He joined the army in August 1941 in the Corps of Royal Engineers, and served in France, Java and Germany. He was Director of Army Staff Duties at the Ministry of Defence 1971-3, Commandant of the Army Staff College at Camberley 1974-5, Deputy Commander-in-Chief United Kingdom Land Forces 1976-77 and Master General of the Ordnance (Army Board member for Procurement) 1977-81. Since his retirement he has been a member of the Security Commission (1982-91) and Director of the Council for Arms Control 1986-89. He is currently a member of the Board or Executive Committee of the Council for Christian Approaches to Defence and Disarmament (CCADD), the Verification Training and Information Centre (VERTIC) and of the British Pugwash Group. He lectures and has contributed chapters to over two dozen books, and co-authored, with Nadine Gurr, a book on British Nuclear Weapons policy. He holds an honorary Doctorate of Civil Laws from the University of Kent in Canterbury (1990), and is an honorary fellow of Peterhouse, Cambridge

Dr Ian Crossland

Dr Ian Crossland joined the UK nuclear industry on leaving university in 1968. Since then, he has worked on many different aspects of nuclear power specialising, in more recent years, in decommissioning and radioactive waste management. He has taken part in many IAEA projects. These include peer reviews of waste management projects in various countries and efforts to improve the management of disused sealed radioactive sources (eg radiotherapy machines) in countries with minimal nuclear infrastructure. For the past two years, he has been involved with the ongoing cleanup and decommissioning at Chernobyl. He joined British Pugwash in 2008.

Prof Roger Cowley, FRS, FRSE, FInstPhys

Professor Roger Cowley was educated at Cambridge and became a research fellow at Trinity Hall in 1962. In 1964 he moved to Canada where he was employed by Atomic Energy of Canada Limited as a research officer. In 1970 he was appointed Professor of Physics at the University of Edinburgh where he stayed until 1988. He was then appointed Dr Lees Professor of Experimental Philosophy at the University of Oxford where he remained until his retirement in 2007. He has been Chairman of both the Edinburgh and Oxford physics departments and has sat on many national, international and University Committees. His research has used neutron and x-ray scattering techniques as well as theory to study condensed matter physics. He has been elected to the Royal Societies of London, Edinburgh and Canada and has won 3 prizes from the Institute of Physics and one from the European Neutron Scattering Association. He has been a member of Pugwash for 3 years.

Dr Jack Harris, FRS, FREng

Dr Jack Harris was Deputy Chairman of British Pugwash and Editor Emeritus of *Interdisciplinary Science Reviews.* He worked for 35 years in the civil nuclear industry and for his studies of nuclear fuel performance was awarded the Esso Gold Medal for Energy Conservation by the Royal Society.

Dr Christopher Watson

Dr Christopher Watson began his career as a theoretical physicist, as a Junior Research Fellow at Merton College, Oxford. He remained a Fellow at Merton thereafter, but also began working for the United Kingdom Atomic Energy Authority in 1968, initially at Culham Laboratory (on controlled fusion research), then at JET (in the management team), then at Harwell on Offshore Technology and Nuclear Robotics, and latterly on Business Development in Russia for the newly-formed AEA Technology. Since his retirement he has acted as a consultant to AEA Technology and RWE Nukem on problems relating to the nuclear legacy of the Former Soviet Union. He has been a member of the Pugwash movement since 1969, and is currently the Deputy Chair of the British Pugwash Group