UK PLUTONIUM DISPOSITION OPTIONS

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The UK is currently at a technical and strategic crossroads with regard to disposition of its separated civilian plutonium. 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 below, 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 its contained plutonium) was established at Sellafield in the 1960s, and the separated plutonium has continued to accumulate ever since.

Following the discovery of North Sea oil & 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 (uranium and plutonium) 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 that was eventually incorporated into the design of a new fully-automated production facility, the Sellafield MOX Plant (SMP), which started commissioning in 2001.

The design 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). For various reasons, however, mostly unpublished, SMP has never achieved its design throughput, and in the most recent year for which figures are available (2006/7) it only produced 2.6 tons of finished fuel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 an embarrassing 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 the government-owned company British Nuclear Fuels Limited (BNFL), which had built the

THORP (Thermal-oxide Reprocessing Plant) and SMP MOX-fuel-fabrication plant at Sellafield, 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, undertook a series of option studies on the way forward for managing the plutonium stockpile.

In parallel with these developments within 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 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. In 2006 it set up a second working group on the subject, chaired by Prof Geoffrey Boulton, whose report was published in September 2007. That report prompted the British Pugwash Group (BPG) to take over where these two reports left off, and to set up its own working group. The questions 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.

During the period over which the BPG Working Group operated, there were a number of further developments. Most notably, the UK Government published its Energy White Paper in January 2008[2], in which it committed itself (with some qualifications) to a substantial program of new Nuclear Power Plant construction in the UK. This decision substantially altered the relative credibility of the various options for managing the stockpile. In August 2008, following the completion of its option studies, the NDA published a report entitled "NDA Plutonium Options"[3] , and this was followed by a public consultation exercise in October/November 2008, in which BPG participated. Since then, the NDA has published a set of four documents outlining their conclusions[4]. 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 Her Majesty's Government (HMG) to consider, but they left a number of very significant gaps. They contain no quantitative information about costs. At all the points where the argument involves cost information, the actual figures are replaced by "xxxx." The studies also provide almost no new scientific data, or information about the security situation. They give indicative timescales for various options, but these are in most cases not explained, and the timescales tend to be extremely long. So it seems that there is still a place for further public debate on this issue.

The BPG report took the view that a rational strategy for the management of the UK's stockpile needed to be set in the context of a broader policy addressing two objectives that are not always readily reconciled:

1. The need for the UK 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 need for the international community to create and sustain a nuclear security regime, in which threats from rogue states and terrorist groups can be contained, if not eliminated.

In relation to objective 1, the BPG noted that historically, the UK has for some decades relied upon nuclear energy to provide a significant part of its energy mix. Nuclear power currently accounts for about 18% of UK electric power production. The 2008 Energy White Paper[2] proposes that this fraction should at least be maintained if not increased, notwithstanding the fact that nuclear reactors of the present generation are coming to the end of their design lives. More recently, on 14 July 2008, Prime Minister Gordon Brown indicated that he would wish the fraction to increase.[5] To meet this objective, in the short term, the UK will be obliged to build advanced thermal reactors of non-UK design, since it allowed its domestic nuclear power supply industry to wither away during the years of North Sea oil and gas plenty. However the UK Government is in a good position to influence decisions on the type of nuclear fuel that the next generation of reactors should be able to burn, and could seek to ensure that at least some of them could burn MOX fuel.

In relation to objective 2, the BPG Working Group noted that the international situation was far from satisfactory. The number of countries owning or believed to own nuclear weapons has risen to nine, with a number of other countries approaching the nuclear threshold. Although 187 countries have now signed the NPT treaty, this is no longer seen as a guarantee of good behaviour, and the last quinquennial review of that treaty in 2005 ended badly. Reports to the IAEA of thefts of nuclear materials continue.[6] Although none of the reported thefts has yet involved a sufficient quantity to permit the construction of a terrorist bomb, some of them have allegedly been samples. 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 a "plutonium economy" involving the separation and recycle of plutonium. 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 are guaranteed supply of their nuclear needs by a few international suppliers. The existing international regime still falls considerably short of this objective.

The BPG Working Group chose to structure the available plutonium management options under three broad headings:

1. **Do nothing** other than ensuring that the risks involved in storing the plutonium are kept at an acceptably low level by an appropriate combination of physical protection and security measures;
2. **Bury it**, i.e. put it into a form that makes it safe for disposal as a waste material in some suitably designed repository at some future date and that immediately makes it difficult for a malefactor to recover the plutonium for malign purposes).and
3. **Burn it**, i.e. convert it into a nuclear fuel that is suitable for use in existing or reasonably foreseeable future reactors, either in the UK or elsewhere, and burn it in such reactors, producing spent nuclear fuel that then meets the "spent fuel standard" for disposal as a "self-protecting" waste.

Option 1 "Do nothing"

There are three classes of domestic U.K. plutonium stored at Sellafield. Ultimately, they will amount to:[7]

- Magnox-derived, i.e. produced in the first-generation UK power reactors (≈83 tons),
- Thorp-derived, i.e. produced in the second-generation UK Advanced Gas Reactors (AGRs) (≈15 tons if reprocessing stops with the base-load contract) and
- Residues transferred from the Atomic Weapons Establishment at Aldermaston and other military locations (≈3 tons).

This combined stockpile is the largest single accumulation of plutonium in the world (France comes second with 65 tons).

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" (three-layered containers) 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. There are currently two plutonium stores at Sellafield, one for Magnox plutonium, which has recently been extended to have a capacity of 80 tons, and one for Thorp material, with a capacity of approximately 45 tons.[8] The total number of cans is about 17,000, and the cans are aircooled, to remove the heat generated by radioactive decay (about 125 watts/can). The radiation hazard within each store is increasing with time as a result of the in-growth of Americium-241 from the decay of 14.4-year half-life plutonium-241.

The main problem with this arrangement is the vulnerability of the stores to theft or malicious damage, particularly by some action that could disperse the plutonium as a fine aerosol – for example an aircraft crash or rocket attack. In recent years, BNFL was very aware of this problem, and it (and its successor the NDA) are engaged in building a new store,the so-called Sellafield Product and Residue Store (SPRS), which has been engineered to address these problems. However SPRS has not been designed to accommodate the entire stockpile immediately. Its nominal design capacity is only 9600 cans, and in any case it is not yet available.

These stores of separated civilian plutonium at Sellafield are subject to international safeguards administered by the International Atomic Energy Agency (IAEA) and by the European Atomic Energy Community (Euratom). Both IAEA and Euratom inspectors and facilities are installed at Sellafield. Compliance with this international regime is ensured by the UK Office for Civil Nuclear Security (OCNS), which requires the site operator to submit a site security plan, covering 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, Information Technology systems and Personnel Security. The OCNS requires the operator to hold exercises at regular intervals, to test counter-terrorist procedures and responses to serious breaches of security. These exercises are based on scenarios approved by OCNS that take account of the malicious capabilities that could be deployed against a nuclear site, and the security measures that have been devised to protect against these, including precautions against car and truck bombs and individual suicide bombers, as well as attacks by aircraft. At Sellafield eight such exercises are completed each year, involving every officer of the force in at least one exercise.

All of this is encouraging as far as it goes, and suggests that a terrorist (or even a determined group of terrorists) would be ill-advised to try to steal significant quantities of plutonium from Sellafield. However the risk of a 9-11 type of attack cannot so easily be dismissed, and until an SPRS-type store has been built, and extended to accommodate *all* the plutonium, there is no complete protection against that threat other than taking extreme measures against all aircraft within some exclusion zone around the store (an approach that the BPG study dismissed as unrealistic).

Option 2. "Bury it"

This option consists in burying the whole of the UK stockpile of separated plutonium as soon as possible in a suitably designed deep geological repository. Unfortunately no such repository exists at present, but 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 here to be shorthand for the interim storage of plutonium, followed by deep geological disposal as soon as a suitable repository becomes available. This is, of course, the inevitable ultimate option: even if all the separated plutonium were initially to be recycled, using reprocessing and plutonium-burning reactors, this recycling could not be continued indefinitely, so eventually the spent fuel would have to be dispatched for deep geological disposal.

Internationally, there are three national programmes that are making significant progress towards providing a deep disposal facility, in Sweden, Finland and France. The Sweden and Finland repositories (and indeed the planned UK repository) envisage placing spent fuel assemblies inside high integrity containers made from a combination of steel (for strength) and copper (for corrosion resistance). These are to be buried 500 m underground, surrounded by buffer of swelling clay. France proposes to use thick walled steel canisters placed in horizontal boreholes drilled from the underground galleries in a rock repository. The safety of all these disposal concepts has been extensively investigated, and the doses to individuals on the surface have been shown be acceptably low even on a million-year timescale. The principal doses turn out to come from iodine-129, chlorine-36, technetium-99 and uranium-238. In no case has plutonium been found to make a significant contribution, because its compounds have low solubility and a high retardation coefficient. However the currently proposed repositories do not envisage the disposal of bulk quantities of plutonium, and the design of a repository which could do so would have to take account of the fact that plutonium-loaded waste generates a significantly greater amount of heat than conventional spent fuel.

A crucial issue in deep disposal of plutonium will be the design of a suitable waste form that will permit a good post-closure safety case to be made. The main issues are the leachability of plutonium out of the waste form by groundwater, and possible instability of the waste form due to radiation damage. Possible waste forms may include cement grouts, borosilicate glass, or a ceramic matrix such as Synroc. There is a high probability that one of these waste forms could safely be used for plutonium, but the necessary research to prove this has not yet been done.

A problem with this option is that (in the view of the NDA) it will be 30 years at least before a UK repository could become available, so there will be a need for an interim storage solution. This might be the option 1 ("do nothing") solution, or it might involve some pre-processing of the PuO_2 powder into a less easily dispersed form which is compatible with the planned long-term disposal waste form (to avoid expensive double-handling). Among the various pre-processing options, four are being considered further:

1. *Convert the stockpile to 'low-specification' MOX* – i.e. mix the plutonium with depleted uranium oxide and convert it to pellet form, but without seeking to meet the rigorous specification that would be required if this MOX were to be used in a reactor. 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.
2. *Mix the plutonium into vitrified high-level waste.* This would bring it up to the 'spent fuel standard' of inaccessibility, and it could be stored with relatively little risk of diversion until a repository became available, because the high radiation level from the cesium-137 fission products with which it was mixed would make it "self-protecting." This waste form would almost certainly be technically suitable for deep disposal – probably using the same high integrity containers as are proposed for spent fuel. This measure would require significant R&D, and perhaps modification of the Sellafield waste vitrification plant (or construction of a new one) that could have significant cost implications.
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 waste form in the form of simulated fuel pellets contained within tubes (similar to fuel rods) which are then placed in a larger container. The gap between the rods and the surrounding container would then be filled with vitrified high-level waste. Clearly, this option requires the prior identification of a suitable waste form. A variant of this scheme has intermittently been under development at Savannah River.

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, forming a block with a weight of approximately 20 kg. This technique is already being developed at Sellafield for the immobilisation of plutonium-containing residues. It has been established that the product is stable at temperatures of up to 1350 °C. However, the technology has so far only been demonstrated with up to ten grams of plutonium.

There is room for debate about the extent to which Option 2 achieves proliferation-resistance. Proponents claim that once the plutonium, in a suitable waste form, has been deposited in a well-designed repository, and that repository has been closed (with all the access tunnels back-filled in the manner required to make it safe on a geological timescale) then subsequent "plutonium mining" would be a very expensive and easily-detected activity, so a would-be proliferator would preferentially seek other alternatives. That argument does not apply, however, during the 30+ years in which the material is being kept in interim storage above ground, During that period, its proliferation-resistance would be lower.

Option 3 "Burn it"

This option involves 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 has neither a properly operational MOX plant, nor a reactor licensed to burn MOX, nor a fast reactor programme, nor a suitable accelerator facility. It could, of course, seek to sell its plutonium to other countries that do have such facilities. The UK does have a semi-operational MOX plant (SMP at Sellafield), however, and the UK Government White Paper on energy policy[9] 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. So the proponents of option 3 claim that the UK should have the courage of its convictions, and gear up to 'burn' its plutonium as MOX. This would involve implementing a two-stage process: i) establishing and operating a fuel production facility with the required throughput to convert most or all of the plutonium stockpile into MOX on a reasonable timescale, and ii) constructing or modifying sufficient reactors to burn this fuel at a suitable rate. The variants of this option involving fast breeder reactors or accelerator-driven sub-critical assemblies are not altogether excluded, but are generally judged to be too far from commercial implementation to be a realistic solution for the existing stockpile.

The case made by the advocates of option 3 is essentially the same as that which led to the creation of the stockpile in the first place - that existing thermal reactors only extract about one percent of the energy contained in uranium mined from the ground, i.e. 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. This will necessarily involve reprocessing, and it is arguable that implementing the MOX fuel cycle in light water reactors, which reduces natural-uranium requirements by about 15 percent, is a sensible first step in the use of the separated plutonium, with a fast breeder reactor programme as a longer-term 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 is appropriate for it to implement these technologies. Reprocessing and plutonium recycle in light-water reactors is not economic today but France has adopted this approach rather than abandon the reprocessing program that it originally launched to provide startup plutonium for a breeder reactor program. Japan also is pursuing this route because local governments have refused to permit expansion of spent-fuel storage at its reactor sites. China has built a pilot reprocessing plant. India and Russia are reprocessing and building demonstration fast-neutron breeder reactors in which they plan to recycle the separated plutonium. A dozen countries that used to send their spent fuel to France, Russia and the UK for reprocessing have not renewed their contracts, however.[10]

The UK decision to construct the SMP MOX plant at Sellafield was a step towards implementing a plutonium-recycle policy, and proponents argue that it would be sensible to continue that approach today, notwithstanding the difficulties that it is currently experiencing. It is recognised that it will require a major act of public policy, and a considerable further investment, to get this approach back on course. If the UK did so, however, it could become a major supplier of MOX to its own internal and/or the international market.

To give a clear account of the steps that would be required to implement this approach, it is first necessary to know the reasons why SMP has hitherto failed to achieve even a small fraction of its design throughput. Unfortunately, most of the necessary information is not yet in the public domain. The decision to build SMP was taken in 1991, planning permission was granted in 1994, and construction was completed in 1996. Because of a political crisis involving the quality assurance (QA) system on the previous MOX plant at Sellafield, it took the UK government until 3 October 2001 to decide to give the go-ahead for SMP operation, and commissioning of SMP started on 20 December 2001. A series of technical problems were then encountered. Details of these technical problems have never been published in full, although a 'redacted' version of a review by Arthur D Little, dated 21 July 2006, has been released.[11] It is reported that the underlying problem was that SMP sought to introduce new technology on a large scale without having previously tested it at the pilot-plant scale. Equipment repeatedly failed to perform to specification. The magnitude of these problems can be inferred from the figures given to Parliament by the Minister for Business, Enterprise and Regulatory Reform (BERR) for SMP output during the past five years (tons of heavy metal as finished fuel assemblies):[12]

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

There is as yet no published information on the NDA's plan to recover from this situation. Given the success of the French Melox MOX-fuel-fabrication plant at

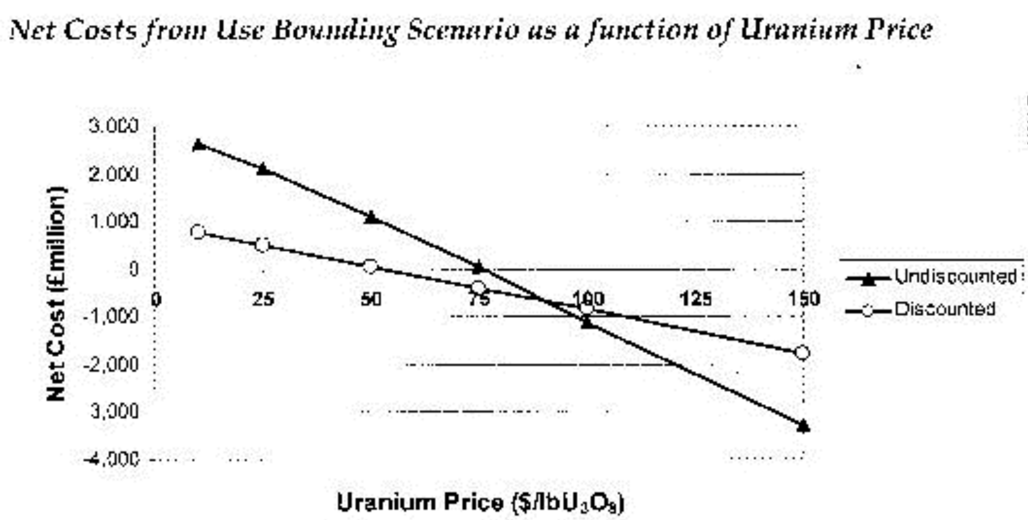
Marcoule, however, there is no obvious reason why Sellafield should not be able to do so. If the UK wishes to convert the whole of its present 100 ton plutonium stockpile into MOX (and thereby create about 1500 tons of MOX), it will need a plant with a throughput of at least 100 tons/year in order to clear the stockpile in a reasonable period of time of 15 years. So if SMP cannot be brought up to something approaching its original design throughput, a new plant will need to be built. A complete replacement for the SMP plant might cost somewhere between the $2 billion estimated cost of the new plant at Rokkashamura in Japan[13] and the $4.9 billion, the cost of the new MOX plant that Areva is building at the US Department of Energy's Savannah River site in the US.[14] Hopefully, the cost of refurbishing SMP would be considerably less than either of these 'new build' figures. Such a plant would not necessarily be able to convert the entire UK stockpile to MOX without some further pre-processing of some of the older material, however, to remove in-grown Americium. This would have cost, waste production and timescale implications.

At present, there is no power reactor in the UK fleet that is licensed to burn MOX fuel. However the changes that are required to enable a modern PWR reactor such as Sizewell B to use MOX fuel are not very great, particularly if only a fraction of the reactor core is charged with MOX: 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 20 PWRs have been modified to permit the use of MOX fuel[15], and there 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 that is foreseen in the latest UK government White Paper, are capable of being specified to include full-core MOX-burning capability. Now that EdF has purchased British Energy[16], 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 a full core of MOX.

A typical light water reactor will burn about 25 tons of MOX fuel each year[17], 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, encourage EDF or other new operators to ensure that the new build reactors are able to operate with MOX fuel, and that some will actually use at least a proportion of MOX 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 and uranium can again be used to make reactor fuel. It is recognised that the cost of reprocessing spent MOX fuel is higher than that of normal spent fuel and that it would require more space in an underground repository, because of the somewhat higher radiation levels, and higher levels of after-heat. Also, the plutonium in spent MOX fuel contains a smaller fraction of the odd-numbered plutonium isotopes, Pu-239 and Pu-241, that can be efficiently fissioned in light water reactors. This is why France has chosen to store its spent MOX fuel indefinitely at its La Hague reprocessing plants until the hoped for date when fast-neutron reactors, which can fission the even plutonium isotopes, Pu-238, Pu-240 and Pu-242, more efficiently will eventually be commercialized.

An important and perhaps determining factor in the decision between options 2 and 3 will be a cost comparison. This subject is bedevilled by arguments about the correct treatment of historically-incurred costs and uncertainties about the future cost of uranium. Most accountants would take the view that in the UK, the historically-incurred costs of reprocessing and constructing the SMP plant should be treated as 'sunk costs'. It is also significant that the uranium market is very volatile - the spot price of uranium on the international market that was about $10 per pound of uranium oxide from 1990 till 2003, climbed to $136 per pound in January 2007, and then declined to about $50/lb in the first half of 2009.[18]

The only 'official' estimate of the economics of the three options 1, 2 and 3 is the study commissioned by NDA, and undertaken by Environmental Resources Management and Integrated Decision Management Limited in 2007.[19] On their assumptions, option 2 (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 option 3 (the so-called 'use' bounding scenario) would have a cost or net benefit depending on the price of uranium as shown:



It will be seen that on these assumptions, the net cost of option 3 is less than the cost of option 2 for almost any uranium price, and becomes negative (i.e. 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 van der Zwaan[20] that 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 assumes that the capital cost of SMP is regarded as a sunk cost, and that the spent fuel has already been reprocessed to produce separated plutonium, so neither the capital nor operating costs of the Thorp reprocessing plant feature in the calculation at all. By contrast, the report by Bunn et al compares the cost of two different commercial operations, both aimed at generating power from uranium. 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, their 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. In the NDA-commissioned report, the capital cost of the Thorp reprocessing plant is irrelevant, and the capital cost of the SMP is regarded as a sunk cost, and does not feature in the calculation at all. Of course, if a new MOX plant has to be built to replace the SMP or if it costs a comparable amount to make the SMP operative, the cost of the MOX option would be increased correspondingly and the choice between options 2 and 3 would become less clear.

One variant of Option 3 which could be considered would be for the UK not to attempt to manufacture MOX fuel itself, but to ship its plutonium to another country which could do so, and sell the MOX as fuel. The commercial terms under which it would do so are a matter for speculation. The country concerned would clearly need to be trusted to use the plutonium as fuel and not to use it for military purposes. These requirements are arguably satisfied by France, which has 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. This variant 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 and secure interim storage (France also has only limited storage capacity). There also would be the question as to how much it would cost France to expand its MOX-fuel fabrication capacity to accommodate both its own plutonium-recycle program and the UK plutonium disposition program and how much France would charge the UK for disposing of its plutonium. Finally, there would the UK political problem of loss of control over the future of its plutonium.

It would be a natural (but not inevitable) consequence of taking option 3 that the UK would continue with a nuclear power program in which reprocessing and the conversion of the resulting separated plutonium into MOX fuel would be carried out on an ongoing basis. This is precisely the outcome which some opponents of this option fear, on the grounds that it would make the UK part of a world-wide "plutonium economy" instead of being one of the nations leading the movement to eliminate plutonium separation altogether. It is recognised that there are hazards associated with a nuclear power programme that involve the creation and use of plutonium on a multi-ton scale.

Summary and conclusions

This document is a summary of an options exercise undertaken by the BPG. 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 three options for the disposition of UK plutonium 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 that has been bedevilled by arguments 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, and the creation of (or getting access to) a cohort of reactors capable of burning 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.

<u>The case for option 1</u> ('do nothing') starts with the fact that it has been the *de facto* option for two decades. The UK has accumulated the stockpile, and constructed storage facilities that, 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. 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 that 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, for example 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. 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 that 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.

<u>The case for option 2</u> ('bury it') is that it gives a definite end date, after which there will no longer be any separated plutonium above ground in the UK, except for such plutonium as we choose to keep for military reasons. It would all be 500 meters 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 a number of obstacles, many of them essentially political and 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 regulatory constraints on acceptable "waste forms" to go into it, and it is far from obvious what waste form would be appropriate for separated plutonium. The experts are agreed, however, that this is a soluble problem, though converting the stockpile into that form will take time and cost money. If the waste form 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.

<u>The case for option 3</u> ('burn it') is that this 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. To do this, the 'once-through' fuel cycle which it currently operates would have to be replaced by a cycle involving reprocessing – in the short-to-medium run using MOX fuel in light-water reactors and in the long run, fast breeders or accelerators that may also be able to transmute other radioactive waste to less problematic materials. Under this option, burning the stockpile could evolve into a much larger program, in which plutonium would 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, which have been briefly rehearsed above.

The case 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 stockpile is ageing, and the in-growth of americium 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, the UK will have to move quickly.
- The situation on SMP is frankly scandalous. A plant that 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 do so. It will therefore 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 a "plutonium economy," and that concerns over non-proliferation and nuclear terrorism ought to take precedence over arguments about energy supply and economics. The champions of option 3 have sought to counter this argument, but not all their 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 Her Majesty's Government (HMG) on this matter, has commissioned a very interesting study, in which all three options are analysed rather carefully, and its conclusions are apparently 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, many of the issues raised above will be discussed publicly. A few cannot, for obvious security reasons, and these will have to be taken into account in reaching the final decision. It would be very good, however, 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.

[1] This paper is a summary of a report *The Management of Separated Plutonium in the UK* to be published by the British Pugwash Group**.** It was prepared by a BPG Working Group with the following members: General Sir Hugh Beach, Dr Ian Crossland, Prof Roger Cowley, Dr Jack Harris, and Dr Christopher Watson during the period September 2007- April 2009. Responsibility for this summary rests with the author.

[2] http://www.berr.gov.uk/whatwedo/energy/sources/nuclear/whitepaper/page42765.html

[3] [4] www.nda.gov.uk/documents/upload/Plutonium-Options-for-Comment-August-2008.pdf

[4] NDA Plutonium Topic Strategy - Current Position January 2009 (100kb)
NDA Plutonium Topic Strategy - Credible Options Summary January 2009 (63kb)
NDA Plutonium Topic Strategy - Credible Options Technical Summary January 2009 (168kb)
NDA Plutonium Topic Strategy - Credible Options Technical Analysis January 2009 (1.14mb)

[5] http://www.independent.co.uk/news/uk/politics/brown-sets-no-limit-on-number-of-reactors-to-be-built-866896.html

[6] http://www.iaea.org/NewsCenter/Features/RadSources/PDF/fact_figures2007.pdf

[7] U.K. Nuclear Decommissioning Authority, "Plutonium Options for Comment: August 2008 - October 2008," http://www.nda.gov.uk/documents/upload/Plutonium-Options-for-Comment-August-2008.pdf.

[8] Radioactive Waste Management Advisory Committee, "Advice to Ministers on the Radioactive Waste implications of Reprocessing" (2000) Annex 6.

[9] *UK Energy White Paper 2008*, paras 2.188 and 2.221

[10] "Why reprocessing persists in some countries and not in others," Frank von Hippel, in *The Costs and Benefits of Reprocessing in Expanding Nuclear Power: Weighing the Costs and Risks*, Henry Sokolski, ed., Non-proliferation Education Center (2009, forthcoming).

[11] http://www.nda.gov.uk/documents/upload/review_of_the_sellafield_mox_plant_smp_report_2006_redacted.pdf

[12] http://www.publications.parliament.uk/pa/cm200708/cmhansrd/cm080222/text/80222w0002.htm

[13] 190 billion Yen, "Delay to construction of MOX fuel fabrication plant," Citizens for Nuclear Information Center, News Watch, May/June 2009, http://cnic.jp/english/newsletter/nit130/nit130articles/nw130.html

[14] U.S. Department of Energy, *Fiscal Year 2010 Congressional Budget Request*, Vol. 1, p. 427.

[15] http://www.aec.go.jp/jicst/NC/tyoki/chokei2004/chokei19/siryo1.pdf

[16] http://www.world-nuclear.org/info/inf29.html
www.epolitix.com/latestnews/article-detail/newsarticle/mps-urges-scrutiny-of-british-energy-sale/

[17] http://www.publicpolicy.umd.edu/Fetter/2005-NT-repro.pdf

[18] http://www.cameco.com/marketing/uranium_prices_and_spot_price/

[19] http://www.nda.gov.uk/documents/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=13768

[20] *Nuclear Technology* 150 209-230 (2005) available online at http://www.publicpolicy.umd.edu/Fetter/2005-NT-repro.pdf