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Strategy options for the UK's separated plutonium

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Plutonium is one of the most radiotoxic materials known and is also fissionable, making it a potential target for illicit nuclear explosive use. UK's civil stockpile of separated plutonium is now over 100 tonnes and has almost doubled since 1997. This plutonium is largely the by-product of commercial reprocessing of spent fuel from UK nuclear power plants. The potential consequences of a major security breach or accidental dispersal are so severe that they justify significant efforts to minimise these risks.

In 1998 we published a report that urged the Government to undertake a comprehensive review of the options for managing the growing stockpile of separated plutonium: unfortunately there has been no such review. Much has changed that makes it all the more urgent to review UK options: the international terrorist threat has increased; climate change is now a significant political and economic issue; nuclear technologies have advanced; other States have developed their nuclear power strategies; and the current review of UK energy policy may lead to a new phase of nuclear energy generation. The Russian Federation and USA have also agreed to dispose of 68 tonnes of their surplus weapons-grade plutonium by converting it to the spent fuel standard, in which the residual plutonium is inaccessible for retrieval and weapon use. The spent fuel standard is now the preferred option for disposing of separated plutonium in a number of countries.

Plutonium is a potential energy source and economic asset. Whether it should in practice be treated as a fuel or a waste product depends on the outcome of a number of decisions the Government will have to make.

Our report outlines the health, environmental and security risks associated with the stockpile and how they might be managed. We suggest actions that the Government should undertake now to reduce the risks and to prepare for the future, as well as making recommendations depending on whether a new generation of nuclear power stations is constructed in UK in the near future. A Nuclear Decommissioning Authority (NDA) economic study has assessed the costs of different management options for UK uranium and plutonium stockpiles.

Our main recommendation is that the Government must develop and implement a strategy for the management of separated plutonium as an integral part of its energy and radioactive waste polices. Failure to do so could result in significant avoidable costs and security risks. The *status quo* of continuing to stockpile a very dangerous material is not an acceptable long-term option.

Immediate priorities

There are a number of urgent actions that the Government and its agencies, such as NDA, should undertake to reduce the security risks posed by the stockpile of separated plutonium:

- The physical security provisions at Sellafield (where the stockpile is stored) must be constantly inspected and reviewed to ensure that they are of the necessary high standard.
- They must stop the stockpile growing. There should be no more separation of plutonium once current contracts have been fulfilled.
- All weapons-grade plutonium that has been transferred to the civil stockpile should continue to be blended down to limit the effects of theft. This provides a way for UK Government to implement the commitments it made in 2000 to irreversible nuclear weapons disarmament.
- The mixed oxide (MOX) fuel fabrication capacity at Sellafield needs to be increased to convert the stockpile from its present state as an oxide powder into MOX fuel pellets, which will make it harder to disperse.

The Government needs to ensure that its strategic thinking about UK energy needs and safe disposal of nuclear waste is informed by a review of the staff and training needs in nuclear science and technology. Such a review is essential, regardless of whether there is new nuclear build, although that decision will alter the detailed nature of the review. The Government needs to know what future options could be missed through skills shortages and whether it would be desirable economically to import these skills from overseas.

The near future

If there is no new build, then the only option available to significantly reduce the risks associated with stockpile is to modify and license Sizewell B to burn a proportion of the stockpile as MOX fuel to the spent fuel standard. Spent MOX fuel is more radioactive than plutonium and cannot be manipulated without considerable shielding, and its pelletised form is harder to disperse than a powder. Converting the stockpile into spent MOX fuel would make it much less of a target for terrorist groups. The remainder of the stockpile could be stored safely and securely as MOX fuel pellets prior to disposal in a deep geological repository.

If there is new build, then the entire stockpile could be burnt as MOX fuel to the spent fuel standard in a new generation of thermal reactors. As the use of MOX fuel might be commercially uneconomic, an assessment is required of the costs and benefits of subsidising the reactor operators to facilitate this. This assessment will need to take into account the investment required in high-specification MOX production facilities, as well as the security benefits of making the resultant material more secure.

The stockpile could also be burnt to the spent fuel standard in future Generation IV reactors. If there is no new build, it seems unlikely that UK would participate in the development and installation of these reactors.

UK's current non-active status in the International Generation IV Forum should be reviewed and its full participation renewed. This would keep open the option of introducing Generation IV reactors in the future.

Long-term solution

The best method of ultimately disposing of the stockpile is likely to be in deep geological repository, whether it is classified as a waste product or has been used as a fuel. It is essential that the Government's strategy for developing a deep geological repository for nuclear waste includes an option for the disposal of both separated plutonium and materials derived from it. The intervening management strategy is crucial as repositories for intermediate-level waste and high-level waste are estimated to be available from 2040 and 2075 respectively.

1 Introduction

1.1 Rationale for the report – the changed context

In 1998, we published a report which expressed concern about the lack of strategy to deal with UK's growing stockpile of separated plutonium (Royal Society 1998). The Government's original intention was to reprocess the plutonium derived from spent fuel from UK's nuclear power stations and then to recycle it as fuel in a new generation of fast reactors. Plutonium separation continued when UK development work on these reactors was halted in 1994, although this strategy could no longer be implemented. We urged the Government to commission a comprehensive, independent review of strategic management options for UK's growing stockpile of separated plutonium. There has been no such review.

Much has changed since 1998, making it timely to re-address the issue. Internationally, extreme acts of terrorism have occurred; climate change has become an increasingly significant political and economic issue; concerns over security of energy supplies have increased; nuclear technologies have advanced; nuclear power strategies of other States have evolved; and the price of uranium on the international market has increased. There have also been agreements between the Russian Federation and USA on the disposition of their large stocks of separated plutonium arising from the dismantling of stockpiled weapons.

The UK separated plutonium stockpile has risen from 53.5 tonnes (1 tonne = 1000kg) in March 1997 to 103.3 tonnes in December 2005 and includes about 27 tonnes that has been separated commercially for overseas owners (IAEA 2006). The Government's May 2007 Energy White Paper discussed building a new generation of nuclear power stations to reduce carbon emissions from energy production to combat global warming and to enhance the security of energy supply (DTI 2007a). A linked process of public consultations has been initiated that, by the end of 2007, should inform the decision to be made by Government on whether energy companies should be encouraged to include nuclear plants in their future generation portfolio (DTI 2007b).

The Nuclear Decommissioning Authority (NDA), a non-departmental public body, has been created to oversee the decommissioning and clean-up of UK civil nuclear sites. NDA undertook a macro-economic study of the costs of three future management options of UK stocks of plutonium and uranium (NDA 2007a). This study classified separated plutonium as an asset of zero value, and did not attempt to attribute financial values for safety or security benefits. The management options assessed did not include possible new nuclear build, which was supported in the 2007 Energy White Paper (DTI 2007a).

Because of these changing circumstances and the continued absence of any published long-term strategy for separated plutonium, the Council of the Royal Society established a working group to review the present situation and to produce a report to contribute to the current discussion of future UK nuclear policy. The working group membership and details of those who gave evidence are given in appendices 1 and 2.

Our report is primarily concerned with the safe and secure management options for the separated plutonium stockpile, and takes into account potentially imminent decisions whether to redevelop the UK's nuclear energy generation capacity. It also aims to identify the issues that need to be addressed if the stockpile is to be managed in the safest and most secure way. The purpose of this report is not to argue for or against a new generation of nuclear power stations, nor for or against an international plutonium market.

Box 1 introduces terminology used in the report about plutonium production, types of nuclear power reactor, the nuclear fuel cycle, radioactivity, nuclear waste and the different grades of plutonium. A list of acronyms is given in appendix 3.

Box 1: Nuclear processes, energy, waste and weapons

Plutonium production

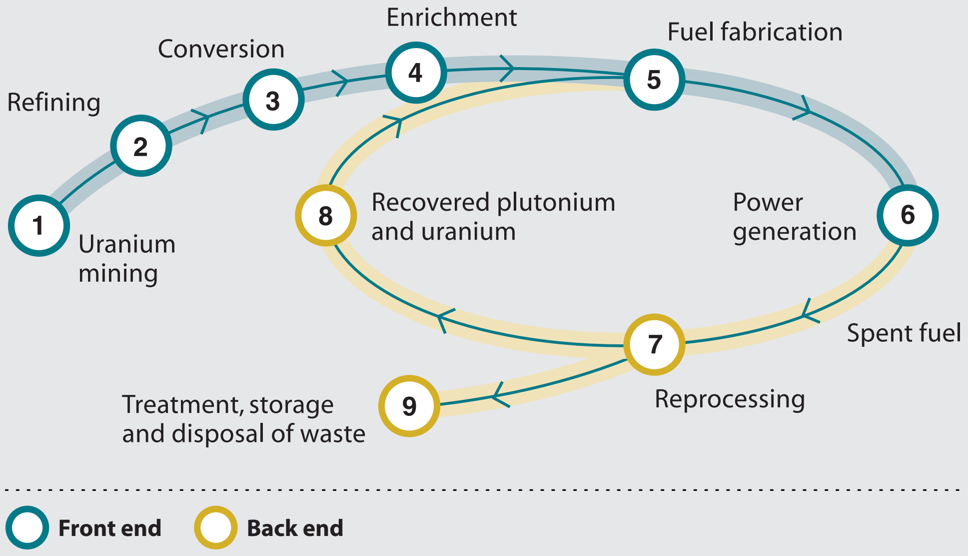
Many nuclear reactors burn or irradiate uranium dioxide powder bombarding uranium nuclei with neutrons. If a neutron is absorbed, a uranium nucleus can split into two fragments, releasing further neutrons and energy. If these free neutrons are absorbed by other fissionable nuclei, these can also split and release more neutrons, and so on in what is known as a chain reaction. Alternatively, neutron capture can take place where neutrons are absorbed without causing fission. Fission and neutron capture facilitate transmutation where atoms of one element are changed into those of another. Uranium can be transmuted into other actinides (radioactive elements with atomic numbers between 89 and 103) such as plutonium (Pu) and americium (Am).

Box 1 (continued)

Types of nuclear power reactor
A coolant is used to absorb the heat energy produced by nuclear fission and transfer it to drive electricity-generating turbines in a reactor designed to produce energy. Nuclear power reactors are often categorised according to the type of coolant used. A light water reactor (LWR) uses ordinary water as the coolant. A pressurised water reactor (PWR) is a common type of LWR which keeps the water at a high pressure so that it remains in a liquid form at high temperatures. A gas-cooled reactor (GCR) uses a gas as the coolant. The UK operates two types of GCR: the advanced gas-cooled reactor (AGR) and the Magnox reactor, both of which use carbon dioxide as the coolant. Nuclear reactors can also be categorised by the neutrons responsible for fission reactions. Thermal reactors, such as LWRs, are ones where most of the fission is caused by so-called thermal neutrons, which have relatively low kinetic energies. Fast reactors use fast neutrons, which have high kinetic energies. Epithermal reactors use epithermal neutrons that have intermediate kinetic energies. The probability of neutron capture decreases at higher neutron energies so fission tends to be more common in fast reactors. They can therefore burn plutonium and other actinides very efficiently, producing up to 100 times more energy per unit mass of original uranium than thermal reactors.

Nuclear fuel cycle
The nuclear fuel cycle refers to a sequence of processes whereby nuclear fuel is produced and managed before and after its use in a reactor; the front end and the back end of the fuel cycle, respectively. The major processes are summarised in the diagram below. In a closed fuel cycle, irradiated fuel is unloaded from the reactor and this used or spent fuel is reprocessed to separate fissile plutonium and uranium from waste products so that they can be recycled as new fuel. Separated uranium and plutonium can be converted into plutonium dioxide and uranium dioxide, which can be combined to form a mixed oxide (MOX) fuel to be reused as new fuel and produce further energy. Spent MOX fuel can even be reprocessed and recycled again, although the number of cycles is limited by the build up of undesirable, non-fissile isotopes.

Diagram of nuclear fuel cycle ©World Nuclear Transport Institute



Plutonium has fissile isotopes (Pu^{239} and Pu^{241}) and non-fissile isotopes (Pu^{240}, Pu^{238} and Pu^{242}). The isotopic composition of plutonium in spent fuel is controlled by the fuel burn up, the extent to which uranium fuel is irradiated by neutrons in the reactor. The lower burn up of fuel in Magnox reactors achieves a lower energy output and produces a higher proportion of Pu^{239} in its spent fuel. Fuel in AGRs and LWRs is more heavily irradiated to achieve a higher burn up to maximise the energy output. This produces a lower proportion of Pu^{239} in their spent fuels (the spent fuel standard), which diminishes their potential after reprocessing to be reused as a source of energy (see appendix 6).

Spent fuel is set aside in storage areas pending ultimate disposal in a once through cycle. Spent fuel tends to be stored for a short time at the reactor site in water-filled ponds to allow it to cool sufficiently for longer term storage and to shield against its high radioactivity.

Radioactivity
Radioactivity refers to the emission of radiation or energy when unstable atoms spontaneously decay to form more stable atoms. Radiation can take several forms, which interact differently with matter, including the human body. Alpha particles consist of two protons and two neutrons emitted from the nucleus of an atom. They lose their energy very quickly in matter because they are heavy and doubly charged, so are stopped by a sheet of paper or a person's surface layer of dead skin. Beta particles are electrons emitted from the nucleus of an atom. They have negligible mass and only a single charge and so interact less with matter and penetrate further than alpha particles. They are stopped by thin layers of plastic or metal. Alpha and beta particles are considered hazardous to a person's health when they are emitted internally to the body. Beta particles can cause radiation damage to the skin if the exposure is high enough. Gamma rays are a form of electromagnetic wave. They interact lightly with matter and are stopped only, for example, by thick layers of lead or concrete and are hazardous even when emitted externally to the body.

Nuclear waste
Generating electricity by nuclear power reactors creates radioactive waste, which is categorised into three types according to its degree of radioactivity and whether it generates heat: high-level waste (HLW), intermediate-level waste (ILW) and low-level waste (LLW). These categorisations determine how the waste is dealt with. The measure of an element's radioactivity depends both on the amount of the material and its half life (the time required for half of the atoms of the element to decay). HLW tends to contain significant amounts of actinides, which typically have long half-lives and so their radioactivity takes a very long time to decay. ILW tends to be comprised of isotopes with shorter half-lives that decay more rapidly. Spent fuel from commercial nuclear power reactors is classified as HLW and contains roughly 1% plutonium.

Weapons-grade and reactor-grade plutonium
Virtually any combination of plutonium isotopes can be used to make weapons, but not all combinations are equally convenient or efficient. Plutonium with a concentration of over 93% Pu^{239} and correspondingly low concentrations of Pu^{240} and Pu^{241} is suitable for use in high yield nuclear weapons. It is chemically separated from very lightly irradiated fuel specifically for weapons purposes. UK classifies any plutonium with more than 8% Pu^{240} as reactor-grade, and plutonium with less than 8% as weapon-grade (MoD 2000).

Reactor-grade plutonium is separated from heavily irradiated civil reactor fuel and has a lower concentration of Pu^{239} and has a higher concentration of Pu^{240} and Pu^{241}. Reactor-grade plutonium could be used to produce a nuclear device, but is not attractive to weapon designers or military planners. The device would probably have a small and unpredictable yield, reduced reliability, and be unsuitable for long-term storage in an operational condition. More reactor-grade plutonium is required to produce a given yield and the neutrons generated by spontaneous fissions in the material require more advanced and therefore less readily available weapons designs and technologies to prevent the explosion starting at a sub-optimal stage in the explosive process. As a result, reducing the amount of fissile plutonium in spent reactor fuel and controlling its isotopic composition are two ways to increase a reactor's proliferation resistance (IAEA 2002). Minimising the amount of spent fuel makes it more difficult to obtain sufficient quantities of fissile material for weapons.

1.2 The organisation of UK civil nuclear activities

The future structure and nature of the UK nuclear industry will play a key role in determining appropriate strategies for the management of separated plutonium. Currently, the British Energy Group is responsible for nuclear electricity generation in UK. It owns or operates 19 reactors at 10 nuclear power stations with a combined capacity approaching 10,000 megawatts, which provides approximately 18% of UK electricity (DTI 2007c). These include three types of nuclear reactor: 14 advanced gas-cooled reactors (AGRs); UK's only light water reactor (LWR), Sizewell B; and the last four of UK's first-generation Magnox fuelled reactors. The latter are at two sites owned by NDA, Oldbury and Wylfa, and are scheduled to close in 2008 and 2010 respectively. The 14 AGRs are scheduled to close between 2011 and 2023. The large and comprehensive nuclear power capabilities operated by UK over the last 40 years are consequently scheduled to shrink rapidly. Appendices 4 and 5 give the expected lifetimes and locations of these facilities.

NDA has responsibility for the 20 nuclear sites that were previously owned and operated by the British Nuclear Group and UK Atomic Energy Authority (UKAEA) and that are now being decommissioned. NDA is also responsible for ensuring the continued commercial operation of both the Sellafield Thermal Oxide Reprocessing Plant (THORP) and Sellafield MOX Plant (SMP).

Spent fuel from the UK nuclear reactors is stored initially at reactor sites and then moved to large storage ponds at Sellafield in Cumbria. Spent fuel from Magnox reactors has been reprocessed by the B205 reprocessing plant, which has been operational since 1964. Spent fuel from UK AGRs and overseas LWRs has been reprocessed by THORP, which has been operational since 1994. There are no contracts to reprocess LWR fuel from Sizewell B. Ownership of separated plutonium, as well as separated uranium and waste products from overseas reactors, remains with the operating company or State involved. The final disposition of this material is a separate issue from that of the UK-owned stockpile of separated plutonium.

Separated plutonium from the Sellafield reprocessing plants is stored in a number of forms, but mainly in the form of plutonium dioxide powder in stainless steel cans. This is mixed with uranium dioxide powder to form MOX fuel at SMP. None of the present generation of UK nuclear reactors is licensed to use MOX fuel, although worldwide there is both increasing production and use of MOX fuel.

The UK Government has accepted the recommendations of the Committee on Radioactive Waste Management (CoRWM) that the long-term strategy for waste management should be one of deep geological disposal following a period of secure storage (CoRWM 2006). The UK Government announced in October 2006 that NDA would implement geological disposal of intermediate-level waste (ILW) and high-level waste (HLW). UK Nirex Ltd, the body previously having responsibility for this, was absorbed into NDA to form the basis for its new Radioactive Waste Management Directorate. Public consultations have started on selection criteria for disposal locations. The UK Government and the devolved administrations in Scotland, Wales and Northern Ireland were recommended by CoRWM to retain responsibility for working with local communities, on a voluntary basis, to determine the choice from amongst qualified sites. No date has been set for the termination of this process. The Scottish Executive has recently rejected geological disposal as the long-term management option, which poses difficult issues for a UK policy for long-term waste disposal.

1.3 Developments in nuclear power technologies

1.3.1 Generation III reactors

Development of new Generation III designs of thermal reactors has been progressing slowly but steadily since the major worldwide phase of nuclear power-reactor installation in the 1970s. Internationally, orders are now being placed for Generation III reactors as part of the so-called renaissance of nuclear power. Design objectives for this new generation of thermal reactors have included more robust safety precautions, greater proliferation resistance and greater energy efficiency due to enhanced fuel burn-up.

1.3.2 Generation IV reactors

Design work has now started on Generation IV reactors optimised to further minimise waste, improve safety and proliferation resistance, as well as decrease the building and running costs of nuclear energy systems. Some of these reactors (notably the fast reactors) could have the capability to burn the long-lived actinides present in spent fuel. This would leave fission products as their only HLW and would eliminate stockpiles of separated plutonium more efficiently than current thermal reactors. Adopting a MOX fuel cycle in thermal reactors does not preclude the eventual future use of reprocessed plutonium from their spent MOX fuel in Generation IV fast reactors.

The Generation IV International Forum (GIF) is currently considering six reactor types, all of which can burn plutonium-based MOX fuel. One is a thermal reactor, three are fast reactors, one can be a fast or thermal reactor and one is an epithermal reactor. GIF membership comprises: Argentina, Brazil, Canada, China, EU via the European Atomic Energy Community (EURATOM), France, Japan, Russia, South Africa, South Korea, Switzerland, UK and USA. These GIF reactor designs will not be fully operational for several decades. French and Japanese energy policies assume that fast reactors will not be deployed until 2040 at the earliest (NDA 2007a). India is not a GIF member but is constructing a prototype 500 Megawatts sodium-cooled fast breeder reactor, which is scheduled to be commissioned by 2010, and which will be followed by construction of two, twin 500 Megawatts units during the period 2010-2020.

In October 2006, the former Department of Trade and Industry (DTI) withdrew from active membership of the GIF charter, although it still retains ‘non active’ status. This action reflected a refocusing of DTI’s priorities following the Energy Review towards near term objectives, and means that the new Department for Business, Enterprise and Regulatory Reform (BERR) will no longer provide the annual funding of up to £5 million for UK researchers to participate in GIF. EURATOM is an active member of GIF, so UK researchers could participate through the EU Framework Programme 7. This will require researchers to find up to 50% of the required funding for the research either from their own resources or by obtaining a customer that is willing to provide these funds (Nuclear Safety Advisory Committee 2007).

The decision whether to build Generation IV fast reactors in the UK when they come on stream around 2040 will depend upon the contemporary economics;

energy security; national and international climate policy; and public acceptability. Public attitudes will be influenced by the history of any Generation III reactors, particularly their safety record and any controversy surrounding them.

The change in the UK's GIF status and the loss of direct involvement with these developing technologies will affect the UK's capacity and willingness to implement Generation IV reactors, as the necessary nuclear engineering skills would have to be imported. A lack of indigenous technical skills will mean that the UK would not be an intelligent consumer as economic, technical and security judgements might be flawed. It would also make any assessment whether Generation IV fast reactors should be used in future to dispose of the separated plutonium stockpile much harder to undertake.

1.3.3 Proliferation-resistant fuel recycling technologies

Concern about nuclear weapons proliferation led the US Government in 2006 to announce a Global Nuclear Energy Partnership (GNEP), where it would work with other countries to develop new proliferation-resistant fuel recycling technologies and global fuel-cycle standards. In December 2006 the US Government published a nuclear energy cooperation plan based on GNEP and in January 2007 announced the construction of a fuel recycling centre including reprocessing and fuel fabrication plants, an advanced fast recycling reactor, and an advanced fuel cycle research facility. Cooperation agreements for the construction of new nuclear power plants were made with Russia in December 2006 and with Japan in April 2007, whilst negotiations have started on a similar agreement with France (US DoE 2006 & 2007).

GNEP recipient countries (in particular new entrants into the nuclear power field) must commit to forgo enrichment and reprocessing activities. In exchange GNEP partner countries will provide guaranteed supplies of nuclear fuel to recipient countries at economic prices. They will also develop and provide advanced proliferation-resistant reactors to new entrants and others, appropriate to their power grids and under enhanced safeguards. There is the implication that used nuclear fuel will be returned to the existing supplier states, so that any future reprocessing will occur only in supplier states. GNEP is therefore seen as a commercial complement to the Nuclear Non-Proliferation Treaty (NPT). It aims to remove separated plutonium from international commerce as well as to offer incentives to States not to construct their own enrichment and reprocessing facilities. The UK's world-leading capability in the reprocessing and fabrication of fuel (including MOX fuel) means it could play an important role in GNEP.

Any fast reactors built as part of the GNEP process could, in principle, be a means of burning the UK's separated plutonium stockpile.

1.4 The new security environment

The threat of releases of radiotoxic material after a military attack on the plutonium (and HLW) stored at Sellafield largely disappeared with the dissolution of the USSR in 1991. However, the mass-casualty attacks on US targets on 11 September 2001 brought with them fears that global terrorist networks would engage in attacks using other methods. Concerns initially focused on suicide attacks on toxic and radiotoxic production and storage facilities. Following the overthrow of the Taliban regime in Afghanistan in 2002, and information found in facilities used by the Al Qaeda network in that country, concerns also emerged about terrorists stealing (or otherwise acquiring) relevant nuclear materials to construct and detonate nuclear or radiological devices. The detection, prevention and consequence management of such threats became a high priority security concern for the UK.

It also became apparent to the western intelligence community that procurement networks that had previously been used by States clandestinely to acquire weapon-usable technologies and materials, at least in the case of the A Q Khan network based in Pakistan, had been operating as global commercial entities. This network had offered procurement opportunities to a number of potential proliferators, including Libya and Iran. It remains unclear whether the Khan network was also prepared to provide similar services to global, non-State terrorist networks, such as that responsible for the 11 September 2001 attacks.

The existence of UK's separated plutonium stockpile offers encouragement by example to States that may wish to reprocess nuclear fuel for weapons purposes. This risk is reflected in the international community's problems in persuading a reluctant Iran and other States not to construct indigenous nuclear reactors and reprocessing plants, and not to store separated plutonium.

2 Stockpiles, reprocessing and MOX fuel production

2.1 UK stockpiles of separated plutonium

The UK civil stockpile of unirradiated separated plutonium on 31 December 2005 totalled 103.3 tonnes, of which about 75 tonnes is UK-owned and the rest is from foreign sources (IAEA 2006). It is estimated that this stockpile will be about 133 tonnes after completion of the current reprocessing contracts around 2012. Approximately 100 tonnes will be UK-derived, the majority owned by NDA and the rest by British Energy. 33 tonnes will be from foreign sources. The UK civil separated plutonium stockpile is by far the largest in the world, primarily because it is not recycled as is done in France. The international holdings of civil plutonium are given in appendix 7.

At least 4.4 tonnes of the current civil stockpile is of military origin. 3.21 tonnes of separated plutonium remains under Ministry of Defence (MoD) ownership, either in weapons or in reserve stocks. This figure, about 3% of eventual total UK stocks of separated plutonium, is unlikely to increase, as all the military reactors have closed and there are no obvious substitutes. See Box 2 for details on UK stocks of weapons-grade plutonium.

Data on the quantities or locations of plutonium in weapons and reserve stocks is not publicly available. The 2006 MoD White Paper announced that an additional 40 warheads were to be retired and dismantled (MoD 2006). This will lead to additional separated plutonium material being either moved into military storage or transferred to the civil stockpile and placed under international safeguards.

2.2 Reprocessing and MOX fuel production

UK is committed to maintaining reprocessing and MOX fuel production at Sellafield to fulfil existing contracts to reprocess spent fuel from overseas LWRs. THORP will require approximately three years of operating time to complete these contracts but is not currently operating due to waste discharge problems. The re-start is scheduled for late 2007 and closure for 2010. Reprocessing in the Magnox plant is scheduled to end in 2012, after which the UK will have no capability to separate additional plutonium, thereby placing a cap on the size of the stockpile (NDA 2007a). The Government has concluded that waste management plans and financing for any new nuclear power stations that might be built in the UK should be based on a once-through cycle in which spent fuel will not be reprocessed (DTI 2007b). The stockpile of separated plutonium should therefore slowly decrease after 2012 as its overseas-owned material is converted into MOX fuel and repatriated to its owners.

SMP was built to convert the plutonium separated by THORP into MOX fuel. All plutonium from overseas reactors is scheduled to be returned in this form. The first MOX fuel was returned to overseas clients in Switzerland in 2005. SMP was designed to produce approximately 120 tonnes of MOX a year, but is not expected to achieve a production rate of over 40 tonnes. As a result, conversion of plutonium into MOX for foreign customers may continue until around 2022-2023 (NDA 2007a).

Box 2: Stocks of weapons-grade plutonium

UK nuclear weapons production was formally sanctioned in January 1947. Separated plutonium for UK military purposes arose from the operations of two small dedicated reactors at Windscale on the Sellafield site, and four small dual-purpose power / plutonium reactors at each of two further locations, Calder Hall on the Sellafield site and Chapel Cross in south-west Scotland. Reprocessing of fuel to produce metallic plutonium also took place at Sellafield before transfer to Aldermaston for fabrication into weapons. Initially, both civil and military nuclear activities were the responsibility of UKAEA. More powerful Magnox reactors using similar design concepts started to operate for civil power production from 1961 onwards. A much larger B205 reprocessing plant came into operation in 1964 to reprocess fuel from military and civil reactors in UK. It was announced in 1995 that production of weapons-grade plutonium for defence purposes had ceased. An audit of the military stocks of fissile material in the UK was announced in the Strategic Defence Review (SDR) in 1998 (MoD 1998). This was completed in 2000 and covered the period through to 31 March 1999. It was initially based on paper records rather than physical audit. It concluded that 16.83 tonnes of plutonium had arrived at Aldermaston, mainly for military purposes, and 13.61 tonnes of plutonium had been transferred from Aldermaston to other sites. This left 3.22 tonnes of plutonium either in weapons at Aldermaston and elsewhere or in store. However, the audited military stockpile in these locations was 0.29 tonnes higher at 3.51 tonnes. 0.3 tonnes of the audited weapons-grade plutonium was then declared excess to military requirements in SDR and transferred to the civil stockpile. It was moved to Sellafield and stored under EURATOM and IAEA safeguards. SDR also listed 4.1 tonnes of non weapons-grade plutonium stored at Sellafield under MoD ownership (MoD 2000). This too was transferred to the civil stockpile and placed under safeguards. The UK military plutonium holdings and details of transfers to and from Aldermaston are given in appendix 8.

3 Risks associated with the stockpile

There are three key risks associated with the stockpile: health, environmental and security, of which the latter are of greatest concern.

3.1 Health risks

Plutonium emits alpha radiation making inhalation the most important pathway of occupational exposure. Lungs, bone and liver receive the largest doses from inhaled plutonium for both humans and animals (National Research Council 1988; National Council of Radiation Protection and Measurements 2001).The dose to the lung following deposition depends on the physical and chemical properties of the plutonium compounds that have been inhaled. These properties determine how long the plutonium stays in the lung before it clears and is transferred to the blood. Once in the bloodstream it is preferentially deposited in the liver and on bone surfaces and eventually in the volume of the bone. Animal experiments show that plutonium can cause cancers of the lung, liver and bone. It may also cause leukaemia but the evidence is less clear.

Strict precautions against the possibility of accidents that could cause exposure, particularly via inhalation, must be enforced at all stages of plutonium handling. These are implemented through relevant UK regulation. On the basis of laboratory data, the International Commission on Radiological Protection (ICRP) has drawn up protection guidelines for radiation workers. They are based on the best available data and are calculated using mathematical models of the behaviour of radioactive isotopes in the body. New guidelines will be issued by ICRP in 2007 but they will not affect the situation with regard to plutonium.

Plutonium can be handled safely wherever it is possible to maintain appropriate control of air quality and strict safety procedures are followed, as in most industrial operations. Under such conditions, human exposure to this potential radiation hazard to workers or the general population has been insignificant. However, if plutonium is released as a powder or vaporised it would constitute a major health hazard. Human health impacts on plutonium workers are discussed in more detail in Box 3.

3.2 Environmental risks

Relevant data for estimating the environmental effects of a catastrophic event at the separated plutonium store at Sellafield is likely to be found in studies of the Windscale fire in 1958; Chernobyl; and the potential effects on the local population of discharges from the reprocessing plants at Sellafield and, to a lesser extent, at Dounreay. Discharges to the air consist of gaseous and some volatile fission products and fine dust particles. Dilute washing liquids from the chemical processes are up to 1000 times more radioactive than discharges to the air. These liquids are discharged into the sea, where more than 90% of the plutonium discharge is incorporated into sediments close to the point of release. Plutonium and other actinides are converted to insoluble forms, which are precipitated or deposited on suspended solid material. These insoluble plutonium compounds are slow to disperse and could be deposited on salt marshes or sea-washed pastures, or dispersed in marine sediment during storms.

Box 3: Human health impacts on plutonium workers

Although many epidemiological studies have been carried out on humans exposed to radiation from plutonium most of them have not been robust enough to give useful quantitative information. There have been a number of studies examining cancer rates and radiation exposures, including Pu^{239}, for workers at the Sellafield plant, UK Atomic Weapons Establishment, UK Atomic Energy Authority, as well as the Los Alamos Laboratory and Rocky Flats reprocessing plant in USA. They show no evidence of radiation-induced cancer of the lung or liver but the level of exposure of these workers was relatively low.

Recently data have become available on the health impacts due to plutonium exposure of workers at the Russian Mayak plant in the South Urals. This was a reprocessing facility for the Soviet nuclear weapons programme. Poor working conditions posed severe health hazards. Although studies are still in progress, some preliminary conclusions are available (Shilnikova *et al* 2003; Harrison and Muirhead 2003; Gilbert 2004). Risk estimates for lung and liver cancers are in good agreement with those derived for exposure to external radiation. The results are consistent with a linear relationship between dose and the occurrence of lung cancer (Kreisheimer *et al* 2000). The results are also consistent with previous estimates of risk from earlier studies. There is also an elevated risk of both liver and bone cancer at body burdens greater than 7.4kBq but sufficiently reliable estimates of doses to these workers are not yet available and it is not possible to calculate risk estimates for these cancers.

It is unlikely that anyone will receive a radiation dose greater than 1mSv per annum (the limit set for public exposure) from this source but the monitoring of relevant coastal regions will have to be continued. Soluble radioactive isotopes, such as caesium, are dispersed in the sea and have been found in low concentrations throughout the Irish Sea and beyond. Discharges to the environment and their associated radiation doses are discussed further in Box 4.

3.3 Security risks

The UK stockpile of separated plutonium poses three types of security risk:

- proliferation of nuclear weapons to other States through theft or illicit transfer of separated plutonium;
- construction of nuclear or radiological explosive devices by terrorists following the theft of separated plutonium;
- terrorist attacks on storage sites to disperse contained materials.

The first and second are both remote risks as agents of potential proliferating States or terrorist groups would have to steal plutonium from the well-guarded Sellafield site. Separated plutonium stores in some other countries are less secure and would be much easier to divert. It would appear that all of the separated plutonium at Sellafield is of reactor-grade, which poses design problems if used in stockpiled nuclear weapons.

The third probably offers the greatest risk to the current storage arrangements, provided precise knowledge of the location of the materials is available. Plutonium poses a toxic threat if dispersed in a fire or explosion, particularly whilst it remains in a powder form. Although a direct or indirect attack with explosives or aircraft on the plutonium store at Sellafield could release separated plutonium into the atmosphere, a precise attack or a large explosion would be required to disperse the material. It will remain a potential but remote risk as long as the material remains in its current powdered form and location, and no long-term policy for its disposition is agreed.

The risks of terrorist attack or theft are difficult to estimate but they must be taken with the utmost seriousness. The potential consequences of a major security breach are severe, and justify a strong and sustained policy to minimise risks.

Box 4: Discharges to the environment and radiation doses

Discharges from Sellafield have been much reduced since the early 1970s by the introduction of new effluent treatment practices and plants. The Food Standards Agency (FSA), Environment Agency (EA), Scottish Environmental Protection Agency (SEPA) and the Environmental and Heritage Service of Northern Ireland monitor radioactive discharges from Sellafield and produce annual reports on the Radioactivity in Food and the Environment (RIFE). This monitoring and reporting is independent of any monitoring carried out by site operators. The most recent report is RIFE 11 that provides the discharges for Sellafield and other installations for 2005. In the years 2003, 2004 and 2005 the ‘total alpha’ activity discharged to the Irish Sea was 0.291 TBq, 0.248 TBq and 0.174 TBq respectively (SEPA 2003, 2004, 2005). This compares with the discharge limit of 1TBq set by the environment agencies. Similarly the ‘total beta’ activity discharged in these same years was 73.3 TBq, 42.9 TBq and 85.9TBq respectively, against an authorised limit of 400 TBq. The largest part of these discharges arises from the reprocessing of UK civil spent fuel. In the case of Pu241 the amounts discharged were 10.1 TBq, 8.1 TBq and 5.5 TBq against authorised limits of 27, 27 and 25 TBq. It is worth noting that the authorised limits have essentially remained unchanged over the last 10 years and the discharges are well within these limits.

For the years 2003-2005, RIFE reports also provide average radiation doses for groups whose exposure is liable to be above average because of their location, lifestyle or diet. The critical groups around Sellafield were those who ate molluscs and infants who lived locally and obtained their milk and other food from local farms. In both cases the average exposures included the doses from all possible radiation pathways. In the case of adult consumers of molluscs the assessed doses in 2003, 2004 and 2005 were 0.71 mSv, 0.60 mSv and 0.41 mSv respectively, of which 60% came not from Sellafield but from a chemical phosphate processing works near Sellafield. In the same three years, the assessed doses to one year-old infants were 0.026 mSv, 0.024 mSv and 0.019mSv respectively. All of these doses are below the limit set in 1995 for the overall exposure to the general public, which is 1mSv per annum. They may be compared with the average annual doses to the public from sources of ionising radiation in UK of 2.23 mSv from all natural sources of radiation and 0.42 mSv from all non-natural sources of radiation, mainly from medical uses (Watson *et al* 2005).

4 Minimising the risks associated with the stockpile

If the UK Government is to implement the CoRWM recommendations that HLW should ultimately be disposed of in deep geological repositories, international experience demonstrates that the process of agreeing on an engineering design and a repository site, and then constructing a repository, will take several decades. The NDA study assumed that an ILW repository will be available from 2040 onwards and an HLW repository available from 2075 (NDA 2007a). Prior to geological disposal the key risks are:

- accidental or deliberate releases of plutonium;
- theft of plutonium or diversion for weapons purposes.

We now review the precautions that can be taken to minimise them including:

- safeguards against proliferation;
- safe and secure storage;
- modifying the form of the stockpile.

4.1 Safeguards against proliferation

Anti-proliferation safeguards are implemented by EURATOM and the International Atomic Energy Agency (IAEA) to provide assurances that nuclear material has not been diverted from its declared peaceful purposes. In the UK this includes monitoring the processes for producing separated plutonium from irradiated reactor fuel and its storage. Both the reprocessing plant and the civil store at Sellafield are subject to European and international safeguard systems, with inspectors regularly checking accountancy records and inventories, and movements into and out of the store. This process monitors and seeks to detect any undeclared changes. NDA, which operates the store, also runs its own accountancy and monitoring system for safety, national regulatory and environmental reasons, and because the material could potentially have considerable financial value. All separated plutonium in the UK is therefore under international safeguards, with the exception of the military plutonium either in storage or weapons.

The cornerstone of the global nuclear non-proliferation regime is the NPT, of which IAEA safeguards are a key element. While this has no permanent institutional structures, it does have a Review Conference which meets every five years to consider policy issues connected with the three ‘pillars’ of the treaty: non-proliferation, nuclear disarmament and peaceful uses of nuclear energy. In 2000, the Review Conference agreed a Final Document through a consensus that committed all States to make their steps to nuclear disarmament irreversible (NPT 2000). The isotopic ‘blending down’ of weapons-grade plutonium by mixing it with reactor-grade plutonium in the civil stockpile has been a practical way for UK to demonstrate the implementation of one of its disarmament commitments.

4.2 Safe and secure storage

The physical protection and safety of SMP, THORP and the separated plutonium stores are subject to both domestic and international regulatory regimes. Much of the best practice incorporated into the international conventions negotiated through the IAEA originated in UK’s own national regulatory arrangements. These international conventions include the Convention on the Physical Protection of Nuclear Material and Nuclear Facilities; the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management; and the Convention on Nuclear Safety. The Health and Safety Executive (HSE) is responsible for the domestic regime, more specifically the Nuclear Installations Inspectorate (NII) and Office for Civil Nuclear Security (OCNS) within its Nuclear Directorate.

NDA and BFNL have worked with OCNS to protect against attack on a range of plutonium and HLW facilities, as described further in Box 5. This includes consultations on the design of a new, safer and more secure Special Products and Residue Store, which is being built near SMP and will be commissioned in the near future. Continued upgrading of storage facilities at Sellafield and rigorous inspections need to be given the highest priority since they will minimise the risks of terrorist attacks and security breaches.

Box 5: Security developments at Sellafield

NDA and BNFL have participated in comprehensive Government and industry studies on the security of nuclear sites, exploring how terrorists could carry out attacks; identifying physical vulnerabilities; considering the effects of a terrorist attack; and reviewing personnel working at nuclear sites. Since 2001 security threats to UK civil nuclear facilities, including Sellafield's reprocessing plants and separated plutonium stores, have been assessed by OCNS using the standard planning tool of the Design Based Threat. This aims to outline the possible scale and methods of attack that could be faced at civil sites operated by regulated civil nuclear companies (OCNS 2002).

Inspectors regularly audit sites against OCNS quality standards. 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. A security review in 2003 led to both additional security fencing and a dedicated armed police patrol for the plutonium separation area within the Sellafield spent fuel reprocessing plant, whilst substantial concrete barriers were built at two locations around the Sellafield periphery (OCNS 2004). Other changes have also been implemented, such as establishing large barriers at entry points and keeping fire engines and crews on site as is done at airports.

4.3 Modifying the form of the stockpile

The major safety and security concerns are:

- separated plutonium is stored in a powdered oxide form, which lends itself to widespread dispersal, if released due to accidental leak or deliberate explosive attack on the facility;
- plutonium emits alpha but almost no beta or gamma radiation (see Box 1 for definitions of these terms). Provided that precautions are taken against ingestion and inhalation, it can be relatively safely handled by those wishing to divert it for weapons purposes.

The ideal long-term strategy for safe and secure storage is to store the separated plutonium in a form that limits the human and environmental damage upon dispersal, and that reduces the risk of theft of plutonium or diversion for weapons purposes.

4.3.1 Immobilisation

The safest way of storing nuclear waste to minimise the risks of significant environmental releases of radioactivity is to immobilise it (Royal Society 2002). One option is to immerse HLW in an insoluble matrix and seal it in corrosion-resistant containers, such as stainless steel. Another option is to place solid HLWs in stainless steel drums and pour a cement mix into them so that the waste is encapsulated or embedded in a solid block. A further option is to vitrify liquid HLW by roasting it until it turns into a powder and mixing this with the materials that can be made into glass. This mixture is heated to produce a radioactive glass, which is then poured into heat resistant containers. HLW would then be stored at surface level for 40-50 years so that heat and radioactivity can decay to levels that make handling and storage easier in a geological repository.

Safety assessments for geological disposal facility in the UK assume that groundwater will eventually infiltrate a repository and gain access to the nuclear waste whatever the location. This introduces the potential for radionuclides dissolving in the water, a process known as leaching. Once the radioactivity is in solution it can, over time, be transported through the surrounding geology and could eventually find its way to the human food chain.

The lack of a long-term policy for the future of nuclear energy production and waste management in the UK has inhibited progress on technologies to immobilise the separated plutonium stockpile. NDA is currently exploring immobilisation options, including glass and ceramic matrices, and reconsidering using cement. Research is being carried out on the effects of radioactivity and leaching on these options. However, there are currently no commercially deployable immobilisation technologies. Ongoing research into immobilisation is essential to develop effectively management options for any separated plutonium that cannot be used as a fuel.

There is also no international consensus on immobilisation. USA is considering reprocessing and immobilisation using glass matrices. This is driven by concerns about proliferation and the military interest in reducing both its own and the Russian Federation's stockpile of weapons-grade plutonium in a secure and agreed manner.

4.3.2 Converting the stockpile to MOX fuel

Converting UK's separated plutonium stockpile into MOX fuel has been considered only to date as a precursor to fuel production. However, it also provides a way to increase the safety and security of the stored material. Separated plutonium could be converted into relatively immobile MOX fuel pellets, so would no longer be stored in a mobile powdered form. Belgium, Germany, Switzerland and Japan are moving towards immobilisation of their stockpiles of civil plutonium to achieve the spent fuel standard via conversion to MOX fuel, burning in reactors and eventual disposal in geological repositories.

MOX fuel pellets can be produced to either low- or high-specification. High-specification MOX fuel pellets are normally ground down to the exact requirements for use in a specific reactor and then placed within fuel pins for reactor fuel use. Low-specification pellets are manufactured to lesser standards and in theory could be ground down and fabricated to meet the unique demands of specific reactors if it were later decided to use them as fuel. However, it seems more probable that they would first need to be reground into a powder, then reprocessed and remanufactured.

Converting the UK stockpile of separated plutonium into either type of MOX fuel pellet could only be done by SMP from 2022-2023 when its existing contracts with overseas customers are expected to be completed (NDA 2007a). Consequently, an additional MOX fuel plant would be needed to start converting the stockpile before this date. NII would need to agree the stockpile management options in its role as regulator.

A major advantage of converting the stockpile to irradiated MOX fuel over the direct immobilisation options is that it is proven technically. The technology for recycling MOX fuel through LWRs is well established with about 40 reactors currently licensed for such a cycle in France, Germany, Switzerland and Belgium. It is projected that over the next few years there will be more than 50 thermal reactors recycling MOX fuel based on reprocessed civil nuclear fuel. In addition, USA is currently considering reducing its stockpile of weapons-grade plutonium by adopting a once-through MOX fuel cycle in some of its civil LWRs.

There will always be some plutonium residues from MOX fuel production, so immobilisation and geological waste disposal technologies will be necessary to deal with this excess and any other material that may be difficult to recycle.

4.4 The spent fuel standard

The most effective means of minimising the security risks associated with the stockpile is to convert as much of it as possible into MOX fuel and then burn this in a thermal reactor to the spent fuel standard (US DoE 1996). In this form the plutonium is inaccessible for retrieval and weapons use. Spent MOX fuel is not a powder, reducing the risks of dispersal. It is more radioactive than unirradiated MOX fuel, which reduces the risk of theft or diversion for weapons purposes, although it then requires large facility shielding.

The spent fuel standard has, in practice, become recognised as a *de facto* international standard for the disposition of separated plutonium. This would therefore be the ideal management route prior to final disposal.

5 Management options for the stockpile

Whether the separated plutonium stockpile is classified as a waste or a fuel, it and its derivatives are expected to be ultimately disposed of in a deep geological repository. The NDA study assumed that a repository will be available for ILW from 2040 onwards and for HLW from 2075 (NDA 2007a). There are six options for the stockpile before it reaches a final disposal site:

a safely and securely store the stockpile in an essentially unmodified form;
b safely and securely store the stockpile as MOX fuel pellets;
c burn part of the stockpile as MOX fuel to the spent fuel standard in Sizewell B;
d dispose of the stockpile through an international plutonium or MOX fuel market;
e burn the stockpile as MOX fuel in a new generation of UK thermal reactors;
f burn the stockpile in new Generation IV fast reactors in UK.

How readily available these options are depends heavily on decisions that are likely to be made in the next year or so about whether to construct a new generation of nuclear power stations in UK. Any economic considerations must be balanced against the human and environmental safety and security risks. The NDA economic study estimated the costs of different management options for UK stockpile of separated plutonium, which is discussed further in Box 6.

Figures 1 and 2 present schematic diagrams of the most viable management options for the stockpile under the scenarios of no new nuclear build and new nuclear build during the coming few years.

5.1 Scenario 1: no new build during the coming few years

Not installing Generation III reactors in this decade will make any UK investment in Generation IV fast reactors problematic. There would be a weak case for retaining the stockpile of separated plutonium as a potential fuel for such future reactors (option f), which would make a strong argument for classifying it as a waste and treating it as such.

The stockpile could in principle be maintained in an unmodified powdered state (option a) until a deep geological repository for HLW is ready to receive the stockpile. This option is unacceptable from a safety and security perspective. Modifying the stockpile by converting it into relatively immobile MOX fuel pellets (option b) is a safer and more secure option. The technology for recycling the stockpile in this way is available and is on a sounder footing than immobilising unirradiated plutonium by other methods. This option also retains the potential for burning the stockpile as a fuel if Generation IV fast reactors were to be developed in the UK in the longer term.

The optimal option is to convert the stockpile into MOX fuel and burn it to the spent fuel standard (option c). This would convert it into the most secure form prior to geological disposal. It would also be possible to reprocess the spent MOX fuel and recycle it as new fuel in Generation IV fast reactors in the unlikely event, under this scenario, that they are installed in UK (option f). Option c has the advantage of generating energy from the stockpile, unlike options a and b that provide no economic benefit.

Box 6: Economics

The NDA macro-economic study estimated the costs of three scenarios for the future management of UK stocks of plutonium and uranium (NDA 2007a):
(1) Processing stocks of plutonium and uranium into forms suitable for geological disposal as waste. This scenario was estimated to cost £1 billion and depended upon the acceptability to the Regulator of the geological disposal of plutonium in the form of low-specification MOX fuel.
(2) Continuing with long-term storage of the stockpile on the assumption that it will have future value. The estimated cost of this scenario was £0.3 billion and depended upon the acceptability of the long term above ground storage of plutonium in an oxide powder form.
(3) Re-using the materials in MOX fuel. This scenario had an estimated cost of £1 billion and depended upon the price of uranium on the international market, with the net cost decreasing by £1 billion for each $25 per pound increase in the uranium price.

The study did not include the specific costs of the UK continuing to meet its national and international security and non-proliferation commitments. The potential risks and costs of accidents or acts or terrorism were also excluded. A specific life cycle assessment of environmental impacts per scenario was undertaken, which examined the carbon footprint and radiotoxic releases to air of each scenario.

Box 7: Consumption of the stockpile as MOX fuel

The NDA study suggests that it would take 1.1 operating lifetimes (66 operating years) to dispose of the UK stockpile if one new 1000 Megawatt thermal reactor capable of operating with a 100% MOX fuel load for a planned lifetime of 60 years became available (NDA 2007a). Current LWRs similar to Sizewell B can run only on a third MOX loading. If it was licensed to burn MOX fuel for 12 years from 2023 until its closure in 2035, then it could eliminate about 6% of the stockpile. It could burn MOX fuel for 32 years and eliminate around 16% of the stockpile if its lifetime was extended until 2055. However, plans exist to increase current LWR MOX full core loading to 50% and Japan has embarked on a program of installing Gen III LWRs and PWRs that have the capability of accepting a 100% core loading of MOX fuel.

In the no new build scenario, the only available reactor for burning the stockpile as MOX fuel is Sizewell B LWR. This poses four problems:

- Sizewell B would need to be licensed to burn MOX fuel, which would almost certainly require incentives to British Energy to do this. Provided that the stockpile was re-classified as waste, a financial incentive could be justified as part of the UK waste management programme without going against the Government's position not to subsidise new nuclear energy production (DTI 2007a).
- Although the UK has the necessary technology for converting the plutonium stockpile into MOX fuel, it does not currently have the capacity to do so. The capacity of SMP will be largely or entirely used to process overseas plutonium into MOX fuel until 2023. Any strategy for MOX fuel production prior to this date would require new production facilities.
- Only about 6% of the stockpile could be burnt in Sizewell B because it is planned to be available only until 2035. Experience with overseas reactors of this type suggests that its lifetime could be extended by 20 years from 2035 to 2055 if key elements of the non-nuclear part of the plant, such as its turbo-generators, were replaced. However, only around 16% of the stockpile could be eliminated with this extension, as described in Box 7.
- Decay to non-fissile isotopes during storage and contamination means that a proportion of the stockpile could not be burnt in this way, which is explained in Box 8.

Even under option c, the majority of the stockpile would remain in its current form. To enhance the security of the MOX fuel inventory that could not be burned in Sizewell B it could converted to a degree of inaccessibility equivalent to the spent fuel standard. One option would be to surround it with HLW to create a radiation barrier around the MOX fuel. Another option would be to immobilise it directly with HLW. In this regard the UK faces a similar challenge in disposing of its civil stockpile of separated plutonium as the Russian Federation and USA face in disposing of their military plutonium stockpiles, which is discussed further in Box 9. Given the current immaturity of other immobilisation technologies, it would need to be stored safely and securely as MOX fuel pellets until HLW disposal is available in about 2075 (NDA 2007a).

Box 8: Problems associated with storing MOX fuel

Approximately 4% of the plutonium in spent fuel derived from Magnox reactors is Pu^{241} whereas 12-15% of the plutonium in AGR spent fuel is Pu^{241} (see appendix 6). Pu^{241}has a short half-life (14 years) and decays to Am^{241}, which has a long half life (approximately 432 years), but it is not fissile in a thermal reactor. After seven years the fissile content of Magnox spent fuel will decrease by approximately 2% and the fissile content of AGR spent fuel will decrease by 6-8%. Plutonium separated from the latter types of spent fuel would need to be converted into MOX fuel a short time before being burnt in a LWR. If such plutonium was stored as MOX fuel for significant periods, it would need to undergo further reprocessing before use as fuel. NDA has commissioned work on the impact of ageing on the feasibility of using AGR-derived plutonium in fuel in LWRs. The longer 'shelf life' of plutonium derived from Magnox reactors, which is responsible for 80% of UK's stockpile of separated plutonium, means that it could probably be stored as MOX fuel pellets for many more years without reprocessing before being used as fuel in a LWR. However, approximately 5% of Magnox derived plutonium is contaminated by chlorine from the early PVC packaging of Magnox derived material, which would need cleaning and decontamination. It is not clear what impact this will have on the ability to recycle it as MOX fuel.

Box 9: US and Russian Federation disposition of weapons-grade plutonium

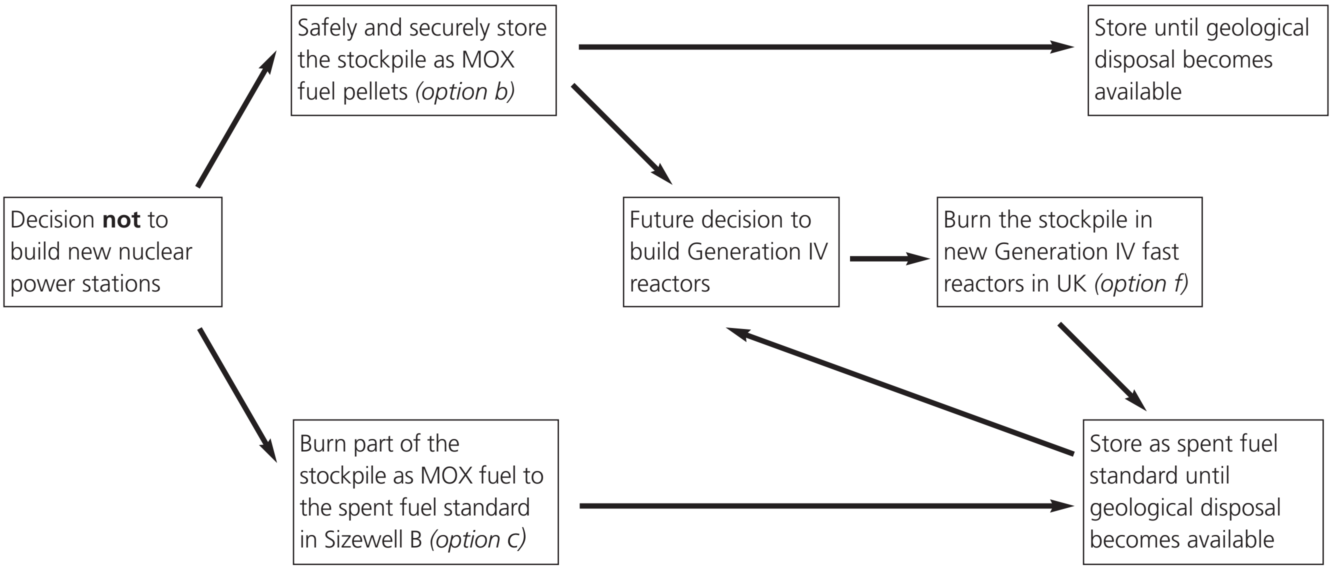
In 2000 USA and the Russian Federation signed the Plutonium Management and Disposition Agreement to dispose of 68 tonnes of weapons-grade plutonium. Both States interpreted the spent fuel standard as involving either converting the plutonium into MOX fuel and then irradiating it as fuel in a nuclear power reactor, or surrounding the plutonium with HLW, and in both cases disposing of it ultimately in a geological depository. Initially, US DoE focused on immobilising plutonium within a glass or ceramic matrix and surrounding it with vitrified glass within large metal canisters. Opponents claimed that immobilisation was a less technically mature option than converting it to MOX fuel, especially since there is large-scale commercial use of MOX fuel in power reactors worldwide. In January 2002 the US Government decided to concentrate exclusively on the MOX fuel option since it was believed it would dispose of the plutonium much faster and more cheaply. A new MOX fuel plant was therefore planned for Savannah River, South Carolina. The Russian Federation had already reached the same conclusion, though more because it regarded plutonium as a valuable fuel rather than a waste. Both Russia and USA initially projected that their full-scale operational MOX fuel conversion plants would be operational in 2007. However, the plant in Russia is not now expected to be operational until 2018, while the opening of the plant in the US is now projected for 2016.

In this scenario, none of these options above could be achieved unless extra MOX fuel production capacity is created during the next 15 years. Without that, there is no alternative to the current policy of storing the separated plutonium in a powdered form and accepting the security and environmental risks involved.

Another possibility would be to burn the stockpile overseas in current and Generation III thermal reactors or future Generation IV fast reactors (option d). This would require an international plutonium or MOX fuel market, which has many associated uncertainties. France has stated openly its desire for more plutonium for its future nuclear energy systems. The development of such a market would depend upon the global market prices for uranium, which it would also influence, and the acceptability of international trading in plutonium and MOX fuels. The acceptability of such a market would depend on the development of an international consensus and rules about trading; the risks entailed by a plutonium market; other governments' policies; and public attitudes. The possibility of diversion to State proliferators would become a particularly important consideration. Export rules would need to include an embargo on selling MOX fuel to a country where its use is not established because of uncertainty about diversion to possible weapons use. It is unclear at this stage if and how an international plutonium market might be facilitated by the further development of GNEP.

Disposing of the stockpile in this way would not remove the need for ultimate geological disposal, as the UK would probably have to take back the spent fuel for ultimate disposal. Plutonium should be transported in the form of MOX fuel pellets, not in its present powdered form. The UK capacity to fabricate these would become a key issue, as would the issues surrounding transportation, and possible ethical objections to the export of risks the UK has itself created.

Figure 1: Schematic diagram of the most viable options based on no new nuclear build decision



5.2 Scenario 2: new build during the coming few years

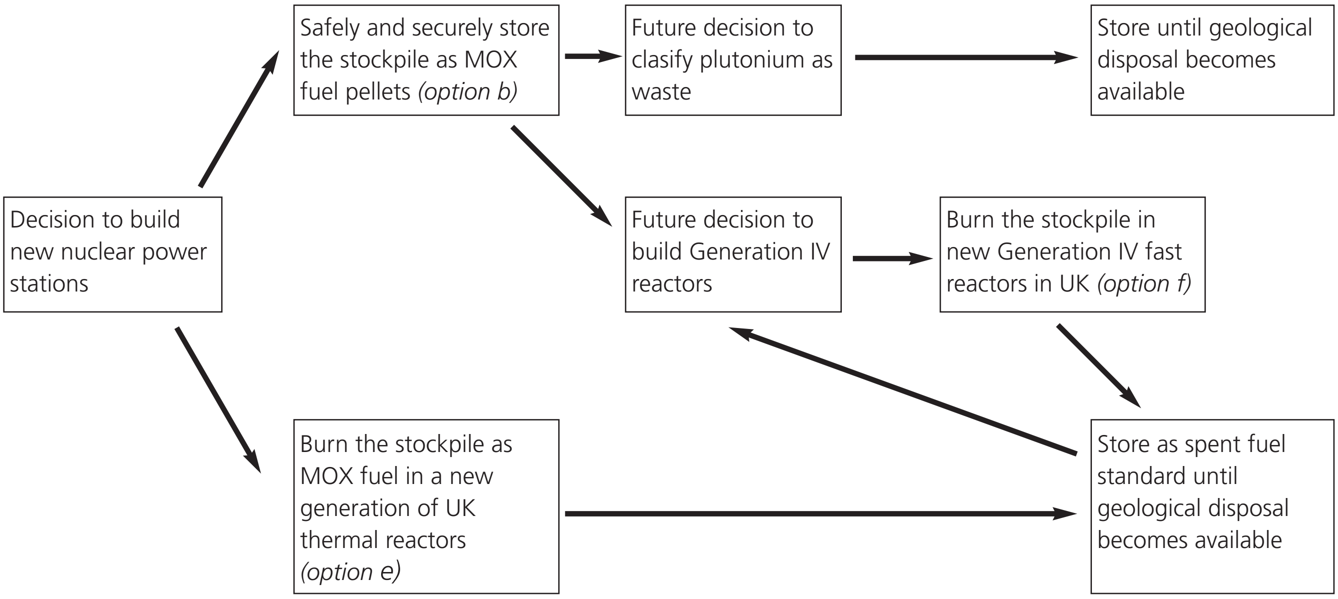
The development of a new generation of thermal reactors would open up further management options in addition to those considered in the 'no new build' scenario. It creates the possibility of burning the stockpile as MOX fuel to the spent fuel standard in a new generation of thermal reactors as part of a once-through cycle (option e). In the short term, this option would also depend on additional high-specification MOX fuel production capacity being made available in the UK. It is not clear whether MOX fuel would be a commercially viable fuel for reactor operators, so the Government and NDA need to assess whether the associated security benefits would justify such a subsidy.

Whether the entire stockpile could be converted to the spent fuel standard in a new build of thermal reactors would depend on the numbers built. If there were insufficient reactors to eliminate the entire stockpile and Generation IV reactors were built in the UK after 2040, then option f could become viable. This would transform the stockpile into a substantial energy asset. Whether Generation IV reactors will be constructed is highly uncertain, even if new thermal reactors are built in the coming years.

In the longer term (around 2040), the stockpile could be eliminated if there were to be construction of Generation IV fast reactors (option f). The problem of isotopic decay in AGR derived separated plutonium could preclude the use of ageing stocks from this source as part of options e and f (as discussed in Box 8). An intermediate course could be pursued where only the Magnox-derived part of the stockpile is converted into MOX fuel pellets to be burned in Generation III reactors. An economic analysis would be required at this point to determine whether Government incentives might be required that would need to take into account the enhanced stockpile security.

New nuclear build that redevelops the UK nuclear power capacity and nuclear engineering skills base would increase the possibility of Generation IV reactors being introduced in the UK in the long term.

Figure 2: Schematic diagram of the most viable options based on decision to build new nuclear reactors



6 Recommendations

6.1 Irrespective of whether there is new build

Recommendation 1: A strategy for the management of separated plutonium must be considered as an integral part of the current processes of policy formulation for energy and radioactive waste. Failure to do so could result in significant avoidable costs and security risks. Indefinite storage in its present form is not an acceptable long-term option.

Recommendation 2: It is essential that the strategy for developing a deep geological repository for nuclear waste includes options for both the disposal of separated plutonium and new materials derived from it.

Recommendation 3: Physical safety provisions for areas where separated plutonium will be held at Sellafield must be constantly reviewed and inspected, and adequate resources provided to the Health and Safety Executive and Nuclear Decommissioning Authority (NDA) to enhance them to the highest possible standards.

Recommendation 4: A cap should be placed on further separated plutonium production in the UK once fuel from the decommissioned Magnox reactors has been reprocessed, by storing all non-contracted irradiated advanced gas-cooled reactor (AGR) fuel and light water reactor (LWR) fuel for geological disposal.

Recommendation 5: All weapons-grade plutonium and any similar material arising from normal start-up and close-down operations of the UK's Magnox reactor fleet should continue to be blended down or converted to mixed oxide (MOX) fuel by mixing with reactor-grade plutonium to limit the effects of theft. Down-blending this weapons-grade material is a way for the UK Government to implement the political commitment it made in 2000 to engage in irreversible disarmament.

Recommendation 6: The Government and NDA need to increase MOX fuel fabrication capacity at Sellafield to allow the stockpile to be converted into MOX fuel pellets.

Recommendation 7: Part of the present strategic thinking about UK energy needs and safe disposal of nuclear waste must include a review of the staff, training and research needs in nuclear science and technology. This review will need to determine what future options would become impossible due to the loss of skills and whether it would be possible (and economic) to import these skills from overseas. This review is essential, regardless of the decision on new nuclear build, although that decision will alter the focus of the review.

6.2 Options contingent on no new build

Recommendation 8: The UK Government should take the only option available to make the stockpile more secure by licensing and modifying Sizewell B to burn MOX fuel. This would enable at least some of the stockpile to be converted to the spent fuel standard.

6.3 Options contingent on new build

Recommendation 9: The stockpile should be burnt in the form of MOX fuel to the spent fuel standard. The Government and NDA should consider helping to fund this because of the associated security benefits, if this would make MOX fuel an economic prospect for reactor operators. It would also require investment in additional high-specification MOX fuel production facilities.

Recommendation 10: The UK Government should still retain involvement in the Generation IV International Forum. This will keep open the option of using the stockpile as fuel if a decision is taken to build Generation IV reactors in the future. These could convert the stockpile to the spent fuel standard if other methods do not have enough capacity to deal with all the material involved.

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Appendix 1: Working Group

The members of the Working Group involved in producing this report were as follows. They were invited in their personal capacity rather than as a representative of their organisation.

Professor Geoffrey Boulton OBE FRS (Chair)	School of Geosciences University of Edinburgh
Professor Charles Curtis OBE	School of Earth, Atmospheric and Environmental Sciences University of Manchester
Professor Brian Eyre CBE FREng FRS	Department of Materials University of Oxford
Professor William Gelletly OBE	Department of Physics University of Surrey
Professor John Simpson OBE	Mountbatten Centre for International Studies University of Southampton

Secretariat: Dr Nick Green, Richard Heap and Ben Koppelman

This report has been endorsed by the Council of the Royal Society. It was reviewed on behalf of the Council by the Review Group listed below. The reviewers were not asked to endorse the findings or recommendations of the report.

Sir David Wallace CBE FREng FRS (Review Group Chair)	Treasurer and Vice President of the Royal Society
Sir Eric Ash CBE FREng FRS	Emeritus professor of electrical engineering University College London
Professor Gordon MacKerron	SPRU - Science and Technology Policy Research University of Sussex
Professor Stephen Sparks FRS	Department of Earth Sciences University of Bristol
Dr Christopher Watson	Business Consultant AEA Technology

Appendix 2: Individuals and organisations giving evidence

We sought evidence from a variety of organisations and individuals. We are all very grateful to all who contributed to this study.

Evidence submitted at meetings of the working group

Mr David Bonser	Board Director British Nuclear Fuels Ltd
Dr Gordon Bryan	Head of Technology Services Nexia Solutions
Dr Paul Gilchrist	Strategy Manager (nuclear materials, spent fuels and high level waste) Nuclear Decommissioning Authority

Individuals contributing evidence

Dr Sue Ion	UK Representative, Standing Advisory Group on Nuclear Energy International Atomic Energy Agency
Mr Stephen Kidd	Director of Strategy and Research World Nuclear Association
Dr Leslie Mitchell	Independent nuclear energy consultant

Organisations contributing evidence

Department for Business, Enterprise and Regulatory Reform

Appendix 3: Acronyms

AGR	Advanced gas-cooled reactor
BERR	Department for Business, Enterprise and Regulatory Reform
BNFL	British Nuclear Fuels Limited
CoRWM	Committee on Radioactive Waste Management
DoE	United States Department of Energy
DTI	Department of Trade and Industry
EURATOM	European Atomic Energy Community
GCR	Gas-cooled reactor
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
HLW	High-level waste
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LWR	Light water reactor
MoD	Ministry of Defence
MOX	Mixed oxide (fuel)
NDA	Nuclear Decommissioning Authority
NII	Nuclear Installations Inspectorate
NPT	Nuclear Non-Proliferation Treaty
OCNS	Office for Civil Nuclear Security
SDR	Ministry of Defence Strategic Defence Review
SMP	Sellafield MOX Plant
THORP	Thermal Oxide Reprocessing Plant
UKAEA	UK Atomic Energy Authority

Appendix 4: Scheduled lifetime for UK nuclear reactors

A4.1 Operational UK nuclear reactors

BNFL Magnox reactors	Capacity (megawatts)	Published lifetime
Oldbury	434	1967 - 2008
Wylfa	980	1971 - 2010

British Energy	Capacity (megawatts)	Published lifetime
Hinkley Point B	1220	1976 - 2011
Hunterston B	1190	1976 - 2011
Hartlepool	1210	1989 - 2014
Heysham 1	1150	1989 - 2014
Dungeness B	1110	1985 - 2018
Heysham 2	1250	1989 - 2023
Torness	1250	1988 - 2023
Sizewell B	1188	1995 - 2035

A4.2 Non-operational UK nuclear reactors

Nuclear power plant	Capacity (megawatts)	Published lifetime
Windscale	32	1963 - 1981
Berkeley	276	1962 - 1989
Hunterston A	300	1964 - 1989
Winfrith	92	1968 - 1990
Trawsfynydd	390	1965 - 1991
Dounreay	234	1976 - 1994
Hinkley Point A	470	1965 - 2000
Bradwell	246	1962 - 2002
Calder Hall	200	1956 - 2003
Chapelcross	200	1959 - 2004
Sizewell A	420	1966 - 2006
Dungeness A	450	1965 - 2006

Reference

BERR (2007) *Nuclear power generation development and the UK industry*. Department for Business, Enterprise and Regulatory Reform: London
Available online at www.dti.gov.uk/energy/sources/nuclear/technology/generation/page17922.html

Appendix 5: UK nuclear power stations

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NB Calder Hall power station is located on the Sellafield site.

Reference

DTI (2007) *The future of nuclear power. The role of nuclear power in a low carbon UK economy: consultation document*. Department of Trade and Industry: London

Appendix 6: Typical plutonium isotopic variations in different materials

Plutonium source	Typical burn up (megawatts day per tonne)	Plutonium isotope				
		Pu^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}
Weapons-grade plutonium (MoD 2000)	Not applicable	~0	<92	>8	~0	~0
Magnox fuel (Worrall 1999)	~5,000	0.1	70.0	24.9	3.9	1.1
PWR fuel *	~45,000	2.2	54.3	22.4	14.9	6.2
AGR fuel *	~30,000	1.1	53.5	27.9	12.3	5.2

* Derived from the Fission Product Inventory code FISPIN. Data provided by Nexia solutions

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Appendix 7: International holdings of civil plutonium

A7.1 Annual figures for holdings of civil unirradiated plutonium as of 31 December 2005 unless stated otherwise (IAEA 2005, 2006 a-h)

	Amount (tonnes)								
Type of plutonium	Belgium*	China	France	Germany	Japan	Russian Federation	Switzerland	UK	USA*
1 Unirradiated separated plutonium in product stores at reprocessing plants	0	0	49.8	n/a	0.8	40	----	101.1	0
2 Unirradiated separated plutonium in the course of manufacture or fabrication and plutonium contained in unirradiated semi-fabricated or unfinished products at fuel or other fabricating plants or elsewhere	2.1	0	14.4	n/a	3.4	----	----	1.2	<0.05
3 Plutonium contained in unirradiated MOX fuel or other fabricated products at reactor sites or elsewhere	1.2	0	15.9	11.6	1.3	0.3	----	1.7	4.6
4 Unirradiated separated plutonium held elsewhere		0	1.1	0	0.4	0.9	<0.05	1.0	40.3
Plutonium included in lines 1-4 above belonging to foreign bodies		0	30.3	n/a	0	----	<0.05	26.5	0
Plutonium in any of the forms in lines 1-4 above held in locations in other countries and therefore not included above	0.4	0	<0.05	n/a	37.9	0.0009	----	0.9	0.1
Plutonium included in lines 1-4 above which is in international shipment prior to its arrival in the recipient State	0	0	0	n/a	0		----	0	0

* These figures are as of 31 December 2004

1 tonne = 1000kg. Figures provided to IAEA are rounded to the nearest 100kg.

A7.2 Estimated amounts of plutonium contained in spent civil reactor fuel as of 31 December 2005 unless stated otherwise (IAEA 2005, 2006 a-h)

	Amount (tonnes)								
Type of plutonium	Belgium*	China	France	Germany	Japan	Russian Federation	Switzerland	UK	USA*
Plutonium contained in spent fuel at civil reactor sites	25		99.1	58.1	106	61	10	7	420
Plutonium contained in spent fuel at reprocessing plants (but not yet reprocessed)	0		105.9	n/a	14	3	----	27	0
Plutonium contained in spent fuel held elsewhere	0		0.5	8.3	<0.5	34	2	<0.5	12

* These figures are as of 31 December 2004

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Appendix 8: UK military plutonium holdings

A8.1 Acquisitions by Aldermaston

Source	Purpose	Amount (tonnes)
Sellafield (predominantly)	Weapons programme Barter transfer to USA (*) Civil programmes at Aldermaston	15.99
USA	Classified	0.47
Unidentified sites	Unknown	0.37
		Total: 16.83

A8.2 Transfers from Aldermaston

Destination	Purpose	Amount (tonnes)
Sellafield	Return of residues for reprocessing	3.93
Winfrith	Civil programme	2.82
Harwell	Civil and military programmes	0.53
Dounreay	Fast reactor R&D	0.22
USA (Department of Energy)	Classified	0.47
Weapons tests in Australia and USA	Weapons tests	0.20
USA	Barter transfer to USA (*)	5.37
	Discarded, dumped at sea or assigned to waste	0.07
		Total: 13.61

(*) Barter arrangements were made under the 1958 UK/US Mutual Defence Agreement. Plutonium was transferred to the USA in return for tritium and highly enriched uranium for military purposes.

NB 1 tonne= 1000kg

Reference

Ministry of Defence (2000) *Plutonium and Aldermaston: an historical account.* Ministry of Defence: London Available online at www.mod.uk/NR/rdonlyres/B31B4EF0-A584-4CC6-9B14-B5E89E6848F8/0/plutoniumandaldermaston.pdf