Management of
Separated Plutonium

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The front cover picture shows a nuclear reactor being refuelled

Foreword

Plutonium has been separated from the other products in spent fuel from nuclear reactors since the 1950s in the UK, and this practice means that the UK has a substantial stock of separated plutonium in store. If this practice continues and the plutonium is not used or converted to other forms, the stockpile will continue to grow. Even if the practice of separating plutonium does not continue, the existing stockpile still has to be managed. The need for scientific information to underpin the development of policy for the management of this stock and to inform the choice of options for disposal or use is the subject of this report.

The Council of the Royal Society established a working group in December 1996 to undertake a scoping study on the status of the science needed for management of civil plutonium in the UK. The group, chaired by Sir Ronald Mason, K.C.B., F.R.S., comprised nine individual scientific experts, selected for their ability to provide authoritative advice on the scientific aspects of plutonium management.

This report summarizes current practice with regard to production and disposal of civil plutonium in the UK and reviews the technical options, currently available or under development, for managing or using plutonium separated from spent fuel by reprocessing. The group has identified further work needed to develop these technologies for possible future policy. It was beyond the remit or expertise of the group to comment upon policy decisions that have previously been made, or to recommend policy decisions for the future.

The report was reviewed by a panel drawn from the Council of the Society, and subsequently endorsed by Council. It is being published in order to inform debate among all those with an interest in, or responsibility for, plutonium management.

I am grateful to the members of the working group for their careful assessment of the scientific aspects of a difficult policy issue of major national importance.

Sir Aaron Klug, O.M., P.R.S.
January 1998

Summary

1. In the 1960s the Government committed the UK to a programme of reprocessing spent fuel from nuclear power stations, to separate plutonium for use as a fuel in future reactors. This decision was made in the light of prevailing assumptions about global stocks of uranium ore, the prospects of building a series of fast breeder reactors and the role of nuclear power generally in the national energy programme.

2. These assumptions no longer obtain, but the earlier decision means that the UK now has a major investment in reprocessing technology, binding contracts with several countries for reprocessing work and a stockpile of 54 tonnes of separated civil plutonium oxide from UK power generation. The UK-owned stockpile of civil plutonium is predicted to reach over 100 tonnes by 2010.

3. The existence of plutonium stocks, in whatever form, is of concern on two counts: radiotoxicity and proliferation risk. Whilst not underestimating radiotoxicity risks, the chance that the stocks of plutonium might, at some stage, be accessed for illicit weapons production is of extreme concern. The current stockpiling policy should not be maintained without careful study of alternative policies.

4. The Council of the Royal Society established a working group in December 1996 to undertake a scoping study on the status of the science needed for management of civil plutonium in the UK. The Working Group examined current practice with regard to plutonium production and disposal and reviewed the technical options, currently available or under development, for managing or using plutonium separated from spent fuel by reprocessing.

5. One alternative option is deep disposal of separated plutonium in geological structures. This certainly merits consideration, but, in view of the difficulties currently being experienced by plans for deep disposal of low and medium level radioactive waste, it is hard to imagine deep disposal of plutonium being a viable option even in the medium term.

6. Another option is to form the plutonium into a mixed oxide fuel (MOX) and burn it in existing or specially built UK thermal reactors. This looks like a technically feasible way forward. Whether it is economically feasible may depend on how much we are prepared to pay to get rid of the plutonium stockpile. A large-scale MOX operation may also have security implications, affecting both economics and public acceptability. MOX could also, in principle, be sent to other countries to be used as fuel in their reactors.

7. In the longer term, alternative fuel cycles and advanced reactor designs may make it possible to burn stockpiled plutonium more effectively, or, in some configurations, to generate nuclear energy without producing any plutonium at all. Research and development capabilities should be maintained by the UK to allow evaluation of competing systems and support international collaboration on those likely to be of benefit to the UK.

8. In addition to disposing of some of the plutonium already in the stockpile, steps could be taken to reduce the amount being added to it each year, primarily by reducing the amount of reprocessing carried out. The impact of such a policy on overall costs and proliferation risks would need careful analysis.

9. The present lack of strategic direction for dealing with civil plutonium is disturbing. The Society urges the Government to commission a comprehensive review by independent experts of the options outlined above, covering technical, economic, environmental and security aspects, energy policy issues and taking account of public acceptability and of the opportunity costs of each option.

1 Background

1.1 The issue

A round a quarter of the UK's electricity is generated by nuclear power in thermal reactors. The inevitable consequence of producing power in this way is the conversion of uranium to plutonium. Plutonium can be separated from the other products in spent fuel by reprocessing—a process which was first carried out in the UK in the 1950s for the purpose of producing plutonium for weapons use. In 1964 reprocessing to separate plutonium for future use as a fuel commenced at Sellafield. About 54 tonnes (t) of plutonium have been separated from the other products in spent fuel by reprocessing. This UK stockpile is kept in stores at Sellafield. If no action is taken on these existing stocks, and reprocessing of spent fuel continues as planned, then by 2010 the UK stock of separated plutonium is predicted to increase to over 100 t. There is currently no national strategy to utilize the plutonium in this stockpile.

There are two main concerns about this stockpile. First, plutonium is highly radiotoxic and if it were to be dispersed it could give rise to serious environmental problems. Second, if it is not adequately safeguarded there is a risk of diversion and proliferation of weapons. Whilst not underestimating radiotoxicity risks, the possibility that the stocks of plutonium might at some stage be accessed for illicit weapons production is of extreme concern.

Separated plutonium contains a mixture of isotopes and is therefore not the material of choice for nuclear weapons, which is the fissile isotope ^{239}Pu. However, a nuclear device could be constructed from plutonium that had been recovered from nuclear power reactor spent fuel without the need for additional processing.

Maintenance and growth of the stockpile of separated plutonium could be seen as contra to the spirit of national and international policies for anti-proliferation. The USA and Former Soviet Union (FSU) intend to reduce excess military plutonium to the 'spent fuel standard', meaning that it is made to be 'as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in spent fuel from commercial reactors' (US Department of the Environment). Separated civil plutonium does not conform to this standard.

1.2 The UK nuclear industry

The UK nuclear industry is divided into a number of component parts. There are two nuclear power generating companies: Scottish Nuclear Limited and Nuclear Electric Limited. These companies constitute British Energy plc. British Energy owns eight Advanced Gas-Cooled Reactor (AGR) stations and the UK's only Light Water Reactor (LWR), the Pressurised Water-cooled Reactor (PWR) Sizewell B. The other eight nuclear power stations operating in the UK are Magnox (magnesium-clad gas-cooled) reactors operated by the government-owned Magnox Electric. In addition, British Nuclear Fuels plc (BNFL) operates two small Magnox stations at Calder Hall and Chapel Cross. It is planned that BNFL and Magnox Electric will merge over the coming year.

The UK Atomic Energy Authority (UKAEA) was formed in 1955 with responsibility for carrying out a national programme to develop all aspects of nuclear technology, for both civil and military applications. Following a series of reorganizations between 1970 and 1996, it now has the residual responsibility for managing the Authority's sites and associated nuclear liabilities.

Spent fuel from UK nuclear reactors is sent to Sellafield for storage and reprocessing under contract to BNFL. A Magnox reprocessing plant has been operating since 1964; the plant is expected to continue operation through to the end of the Magnox programme. The Thermal Oxide Reprocessing Plant, THORP, for the reprocessing of AGR and LWR fuels, also operated by BNFL at Sellafield, commenced operation in 1994. This is a commercial operation and approximately two-thirds of its existing contracts are with overseas customers. Contracts are already in place for the first ten years of THORP's operation. For both THORP and the Magnox reprocessing operation, plutonium is recovered and stored in the form of plutonium oxide. There are currently no plans to reprocess spent fuel from Sizewell B, which has its own spent fuel storage pond with capacity to accommodate spent fuel for about half of the life of the station.

Reprocessing involves dissolving the spent fuel and separating the re-usable plutonium and

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uranium content from the residual waste fission and actinide products. The separated uranium may then be re-enriched prior to re-use and the separated plutonium can be used as the fissile component of MOX (mixed oxide: uranium dioxide and plutonium dioxide) fuel which can be loaded back into nuclear reactors. BNFL's Sellafield MOX Plant is under construction and due to start operating within the near future, subject to regulatory approval. A MOX Demonstration Facility started operation at Sellafield in 1993 and already produces MOX fuel.

Despite operating one of the world's two major reprocessing plants at Sellafield, the UK has no national strategy at present concerning its recovered plutonium. None of the present generation of UK nuclear reactors is licensed to use MOX fuel and there are no facilities for the final disposal of plutonium. Historically, the UK policy on plutonium utilization was based on an assumption of commercial use in fast reactors. However, in 1990 the UK government decided to phase out its support for the European Fast Reactor Project, and in 1994 it withdrew all financial support for the UK prototype fast reactor at Dounreay. This has effectively postponed any deployment of fast reactors in the UK indefinitely. Furthermore, the existing stock of separated plutonium is far larger than would be needed to initiate any advanced reactor programme which might be developed within the next few decades.

1.3 The Royal Society study

In view of the absence of a UK strategy for plutonium management, a Working Group of the Royal Society Scientific Aspects of International Security Group (SAIS) was established late in 1996 by the Royal Society Council to undertake a scoping study on the status of the scientific basis for management of civil plutonium in the UK. The terms of reference of the group were to summarize current practice with regard to plutonium production and disposal in the UK and review the technical options, currently available or under development, for managing plutonium separated from fuel by reprocessing, in order to identify research needs for further examination.

Members of the working group, chosen for their ability to provide authoritative advice over all the scientific aspects of plutonium management, are listed below. The members of the group joined it as individual scientists, not as representatives of organizations.

Sir Ronald Mason, K.C.B., F.R.S. (Chairman). Chairman of the Royal Society SAIS group. Chairman of UCL Hospitals NHS Trust and formerly Chief Scientific Adviser to the Ministry of Defence.

Dr B. Eyre, C.B.E., F.Eng. Formerly Deputy Chairman and Board Member of UKAEA, AEA Technology.

Professor A.J. Goddard. Professor of Environmental Safety and Deputy Director of the Centre for Environmental Technology at the Imperial College of Science, Technology and Medicine with responsibility for the safety of Imperial College's research reactor. A member of the Nuclear Safety Advisory Committee (formerly Advisory Committee on the Safety of Nuclear Installations, ACSNI).

Sir Francis Graham Smith, F.R.S. Emeritus Professor in the University of Manchester. Former Astronomer Royal and Physical Secretary of the Royal Society.

Professor C.R. Hill, F.R.C.R. (Hon). Emeritus Professor of Physics as Applied to Medicine at the Institute of Cancer Research and Royal Marsden Hospital, University of London. Formerly a Visiting Reader in Radiation Studies at the University of Surrey with a substantial research interest in the behaviour of radioactive materials in humans and the environment. Currently Secretary to the British Pugwash Group.

Dr R.S. Pease, F.R.S. Former Director of the UKAEA Culham Laboratory and of the UKAEA Fusion Research Programme. Currently Chairman of the British Pugwash Group.

Professor L.E.J. Roberts, C.B.E., F.R.S. Emeritus Professor of Risk Assessment at the University of East Anglia. Formerly Director of the UKAEA Harwell Laboratory.

Professor J. Rotblat, C.B.E., F.R.S. Emeritus Professor of Physics at St Bartholomew's Hospital, University of London. Formerly President of the Pugwash Conferences on Science and World Affairs and winner of the

1995 Nobel Peace Prize for his long-standing activities on nuclear disarmament.

Dr W.L. Wilkinson, C.B.E., F.Eng., F.R.S. Formerly Deputy Chief Executive of British Nuclear Fuels plc and currently chairman of the British Nuclear Industry Forum.

Secretariat: Miss Clare Tenner and Mr John Jackson, Science Advice Section, Royal Society.

2 Production and stockpiles

2.1 Production

Plutonium is produced in nuclear reactors when ^{238}U is irradiated with neutrons. Plutonium 239 is formed and subsequent neutron capture gives ^{240}Pu, ^{241}Pu, ^{242}Pu and ^{243}Pu. Plutonium 239 and ^{241}Pu are referred to as the fissile isotopes because they are the only ones that are fissionable by thermal neutrons.

The isotopic content of plutonium in spent fuel can be controlled by the fuel burnup — the extent to which uranium fuel elements are irradiated with neutrons in the reactor. Fuel burnup is measured in megawatt-days per tonne of uranium fuel (MWd/t). Weapons grade plutonium, which is produced from very lightly irradiated fuel, has very high concentrations of ^{239}Pu, and is defined as containing less than 7% ^{240}Pu (Table 1). Civil nuclear power reactors operate at higher burn-ups in order to maximize the energy output from a given amount of fissile material. This leads to a lower fraction of ^{239}Pu and more of the heavier isotopes ^{240}Pu, ^{241}Pu and ^{242}Pu.

2.2 UK stocks of separated plutonium

Current stocks of separated civil UK plutonium amount to 53.5 t and most of this originates from the Magnox reactor programme (Table 2). The fissile content of the civil plutonium varies according to the burn-up in the nuclear power reactor. Reactors do not always operate at the typical values given in Table 1 and irradiated fuel with up to 85% fissile content has been dispatched from UK civil nuclear power reactors (DTI 1987–1997). The higher fissile content makes this plutonium more suitable for fabrication into nuclear weapons.

Most of the civil plutonium stocks are held at Sellafield. Spent fuel from overseas is also held at Sellafield prior to reprocessing in THORP, but this plutonium will be returned to the country of origin and represents a separate issue from the UK stockpile of separated plutonium.

The UKAEA holds a further 4 t of plutonium in various forms at their sites. Stocks of plutonium in irradiated fuel at reactor sites on 31 March 1997 were:

Table 1. Isotopic concentrations (in %) of weapons-grade and reactor-grade plutonium (Pu), at given burnups
Sources: Albright, Berkout & Walker (1997) and OECD (1989).

Source of Pu (typical burnup)	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Weapons (400 MWd/t)	0	93.0	6.5	0.5	0
Magnox reactors (5,000 MWd/t)	0	68.5	25.0	5.3	1.2
PWR reactors (33,000 MWd/t)	2.0	52.5	24.1	14.7	6.2
AGR reactors (18,000 MWd/t)	0.6	53.7	30.8	9.9	5.0

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Table 2: Stocks of plutonium held by BNFL at 31 March 1997 under international safeguards (units are t rounded to the nearest 0.5t)[1] Source: DTI

OWNER	Magnox Electric	British Energy	UKAEA	BNFL & overseas customers	Total
Spent Fuel in storage ponds	1.0	10.0	0.5	29.5	41.0
Intermediate forms	0.5	0.5	–	1.0	2.0
Plutonium oxide in store	46.0	1.0	1.0	5.5	53.5
Total	47.5	11.5	1.5	36.0	96.5

Magnox	2.5 t
AGR	1.0 t
PWR	0.5 t

DTI annually published plutonium figures state that the civil stockpile of separated plutonium increased by 2.4 t in the year 1996–97.

Magnox Electric estimates that 78 t of separated plutonium will have been generated by the end of the Magnox programme, assuming a 37-year average lifetime for the plant. Under this assumption the last Magnox station (Wylfa) will close in 2006 and all the irradiated fuel will be transferred to Sellafield by 2009. British Energy owns virtually no separated plutonium at present but estimates that 25 t will be created by reprocessing of AGR fuel by 2010. Thus the total UK stockpile of separated plutonium is predicted to reach over 100 t by 2010.[2]

2.3 Global stocks of plutonium

At present, the global total quantity of plutonium, in all forms, is about 1239 t (Table 3). Of this total, approximately two-thirds is contained in stored spent fuel from civil power reactors. The OECD Nuclear Energy Agency (NEA) estimates that 50 t of plutonium are generated world-wide every year in spent fuel. Most of this will be generated in North America, Western and Eastern Europe and Asia. Some countries, such as Japan, are producing spent fuel with the intention of reprocessing to separate plutonium. The increasing numbers of countries producing plutonium is placing growing demands on the safeguards and inspection regimes.

In 1995 the amount of civil plutonium in the separated form, kept in stores, was 140 t. Two industrial factors currently control the transformation of separated plutonium in reactors: MOX fuel fabrication capacity and the number of reactors licensed to use MOX fuels. These parameters will control supply and demand for MOX in the coming years. Since the current capacity of MOX fuel fabrication plants for thermal reactors is limited, the world inventory of separated civil plutonium continues to increase. In 1995 the stock of separated plutonium increased by some 14 t (22 t was separated by reprocessing of which 8 t was used as MOX in LWRs and fast reactor development programmes).

The International Atomic Energy Agency (IAEA) estimates that the separated and stored plutonium inventory will continue to increase up to about 174 t by 1999 and will then decrease slowly for several years as new MOX plants come on line, falling to about 130 t by 2008, and will thereafter increase slowly, reaching about 150 t by 2010. These predictions assume continuation of the existing constraints that spent fuel must be disposed of in the country of origin.

It is worth noting that by 2010 the predicted UK stockpile of separated civil plutonium kept in stores will account for about two-thirds of the predicted global separated plutonium inventory.

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[1] Data are not publicly available that distinguish between plutonium from UK sources held by BNFL and plutonium held on behalf of overseas customers.
[2] The 37-year assumed life of the plant is a notional average figure used for planning purposes. It is possible that the actual life of the Magnox stations will be longer in which case plutonium will continue to be produced from Magnox stations, as well as AGRs and Sizewell B, after 2010.

Table 3: Present and predicted stocks of plutonium globally (units are t)
Source: IAEA Key Issue Paper 5 in IAEA (1997)

	1995	2010
In spent reactor fuel	800	1400
Separated and stored plutonium	140	150
In fast reactor fuel cycle	30	
In thermal MOX fuel cycle	20	550
SUBTOTAL	990	2100
Military Plutonium	249	N/A
TOTAL	1239	

2.4 Military plutonium

The stock of military grade plutonium in the UK has never been revealed but the best estimate based on assumed operation of the Calder Hall and Chapel Cross reactors and the Windscale piles is between 5 t and 11 t. It is unlikely that this will increase in the future since production has now stopped and is not likely to re-start.

World-wide, some 250 t of military plutonium are held, about a fifth of the total plutonium inventory. The largest quantity, nearly 150 t, is in the FSU. Most of the remainder is in the USA (about 100 t) with France and China probably holding less than 10 t each. (Albright *et al.* 1997).

Following agreements between the USA and the FSU to dismantle surplus nuclear weapons, the USA has declared 50 t of weapons grade plutonium as excess to its military requirements. The FSU has also declared that it has an excess of plutonium but has not yet stated a precise quantity. The UK, France and China have not declared an excess of plutonium over their military requirements.

Reduction of the quantity of excess weapons plutonium is generally viewed as a higher priority than plutonium produced by reprocessing from civil nuclear power generation because of its greater potential as a security risk.

3 Risks surrounding the stockpile

Two particular sources of concern should be borne in mind when considering the UK stockpile of separated plutonium:

- Plutonium is one of the most radiologically toxic materials known.

- Plutonium is capable of causing a fissile chain explosion and is thus potentially a target for theft by makers of illicit nuclear weapons.

3.1 The radiotoxicity of plutonium

Through the combination of its properties in emitting alpha particles and in concentrating in a particularly radiosensitive tissue—the periosteum[3]—plutonium is potentially one of the most radiotoxic of materials. However, only some ten parts per million of any ingested plutonium oxide will be taken up into the body via the blood. Whilst uptake following inhalation can be considerably greater than this, such uptake only occurs for a rather limited range of size of dust particle. Thus, where it has been possible to maintain appropriate control of air quality, as in most industrial operations, human exposure to this potential radiation hazard has been quite limited.

There are few data on possible links between pathology and exposure to plutonium in humans, but those from workers at the US

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[3]Periosteum - Connective tissue surrounding the bone.

Hanford plant are the most useful. Even from these data, there is no significant evidence for radiation-induced mortality in the 26 subjects who were studied over periods of up to 42 years.

Administration of sufficiently high doses of plutonium to animals leads to gross tissue damage, with consequent clinical manifestations including shortening of life. Therefore, on the basis of laboratory data, the International Commission on Radiological Protection (ICRP) has drawn up protection guidelines for radiation workers, in terms of 'annual limits on intake' and 'derived air concentrations'.

Under normal operational conditions the production and handling of plutonium does not lead to unacceptable health hazards to workers or the general population, under currently defined standards. However, strict precautions against the possibility of accidents that could cause exposure, particularly via inhalation, must be enforced at all stages of plutonium handling under UK regulations.

3.2 Plutonium in the environment

The most significant environmental exposure to plutonium in the UK, as a result of plutonium separation, is that for the local population arising from 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 discharged to the sea. The radioactive content of liquid discharges are up to a thousand times greater than in discharges to air. Soluble radionuclides, such as caesium, are dispersed in the sea and have been found in low concentrations throughout the Irish Sea and beyond. Plutonium and other actinides are converted to insoluble forms which precipitate out or deposit on suspended solid material.

Discharges from Sellafield have been much reduced since the early 1970s by the introduction of new practices in effluent treatment and of new waste treatment plants. BNFL report that reprocessing of spent fuel resulted in the discharge to the Irish Seas of 0.27 terabecquerel (TBq) of 'total alpha' activity and 140 TBq of 'total beta' activity from Sellafield in 1996. A substantial part of this would be due to reprocessing UK civil spent fuel. These discharges are below the levels authorised by Ministry of Agriculture, Fisheries and Food (MAFF) and Her Majesty's Inspectorate of Pollution (HMIP, now the Environment Agency). It is possible that lower limits will be set in the future.

Extensive surveys of radiation doses along and near the Cumbrian coast have been carried out by MAFF and BNFL. Radiation doses to people have decreased as the discharges have decreased. For purposes of radiological protection, critical groups are defined whose exposure is liable to be above average because of their location, lifestyle or diet. In 1994, the critical groups included people around Seascale who ate local fish and shellfish (0.1 milliSievert, mSv), boat-dwellers in Whitehaven harbour (0.08 mSv) and infants who lived locally and obtained all their milk and other food from local farms (0.07 mSv). These doses are well below the limit set in 1995 for the overall exposure to the general public, which was 1 mSv per annum. The average radiation dose due to discharges to the population around Sellafield was 0.025 mSv in 1989 and is expected to decline if the present emission standards are maintained.

More than 90% of the plutonium discharged is incorporated into sediments close to the point of release. This accumulation of insoluble plutonium compounds is slow to disperse and could be deposited on salt marshes or sea-washed pastures, or dispersed through the incursion of marine sediment during storms. It is unlikely that anyone will receive a radiation dose greater than 1 mSv/a from this source, but the monitoring of the coastal regions will have to be continued.

3.3 Proliferation risk

It has already been noted that weapons-grade plutonium contains high concentrations of ^{239}Pu, and less than 7% ^{240}Pu. In contrast, reactor grade plutonium contains high concentrations of ^{240}Pu and ^{242}Pu. The critical mass of fissile plutonium (^{239}Pu and ^{241}Pu) needed to sustain a chain reaction in reactor grade plutonium may be an order of magnitude greater than for weapons-grade plutonium. The reliability and yields of weapons constructed from reactor grade plutonium might also be reduced. However, an experienced weapons designer could have confidence in a weapons system based on reactor grade plutonium with 85% fissile content. Reactor grade plutonium, of known isotopic composition, must therefore be regarded as a plausible target for determined terrorist groups or states wishing to make nuclear weapons.

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The stockpile of separated civil plutonium at Sellafield poses a greater security threat than would spent fuel, which consists of uranium with around 1% plutonium and 3% highly radioactive fission products. The weight of the fuel and its radiation shielding provides a major obstacle to clandestine removal, in addition to the security arrangements for storage. If spent fuel were to be stolen or diverted, the plutonium would have to be recovered by chemical processing carried out by remote handling techniques. In contrast, the plutonium oxide recovered by reprocessing is stored in units small enough to handle (ca 10kg) with low radiation at the surface of the can.

3.4 Safeguards and anti-proliferation measures

The surest anti-proliferation measure is to stop reprocessing spent fuel and to reduce the quantity of separated plutonium in store. However, given that reprocessing is taking place in the UK, safeguards must operate during both storage and reprocessing.

The safety of all nuclear sites in the UK is assessed by the Nuclear Installations Inspectorate (NII), which since 1975 has been part of the Health and Safety Executive (HSE). A nuclear site may operate only if it has been granted a licence by the HSE following approval by NII.

The safeguards and anti-proliferation systems governing plutonium management are administered internationally by the International Atomic Energy Agency (IAEA) and regionally by the European Atomic Energy Community (Euratom). Both IAEA and Euratom inspectors and facilities are installed at Sellafield and at the other UK civil nuclear installations.

As the large throughput, highly automated reprocessing plants, MOX fabrication plants and storage facilities have been built at Sellafield, safeguards and transparency measures have continued to develop. These safeguards arrangements have been developed in an 'excellent spirit of co-operation between BNFL and Euratom' (Kaiser et al. 1996).

Safety features of Sellafield MOX plants include effective shielding and high levels of automation. Plants are designed to be safe against inadvertent criticality. Transparency measures aim to reduce the uncertainty in the quantities of plutonium present in the plants. Such uncertainties could otherwise allow illegal diversion of substances to go undetected. Sophisticated near-real-time accountancy, and systems to reduce process hold up, are complemented by a strong system of physical security and surveillance by IAEA and Euratom.

Separated plutonium stocks are held in custom-built stores that are strictly appraised and approved for safety, security, material control and accountancy (and anticipated safeguards arrangements) at an early design stage. These security arrangements are stringent and under continuous review. However, so long as plutonium separation facilities are operated, and a plutonium store is maintained, there remains a risk of plutonium theft.

4 Management options for separated civil plutonium

Several management options are available to deal with the separated plutonium stockpile. Each option is likely to become available over different timescales so that during the first half of the next century, different options will become more or less appropriate at different times.

4.1 Storage

There appears to be no fundamental technical reason to change from the current practice of storing separated plutonium. Plutonium stores are designed to be safe for 50 years and it is possible that this could be extended. The method is well proven and economic, and facilities are already in place, so this is a pragmatic immediate solution for plutonium that has already been separated. This policy does not prevent any other option being taken up in the future.

However, the FSU and the USA intend to reduce their excess military plutonium to the 'spent fuel standard'. It would therefore be inconsistent with an emerging international consensus to allow a stockpile of separated civil plutonium to accumulate indefinitely. Furthermore, although stores have been designed to contain the civil plutonium for long periods, they are only secure so long as the elaborate security systems and surveillance are maintained. This requires political will and stability. Thus the stockpile can be viewed as a strategic and environmental risk, as well as an open-ended legacy for future generations.

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Given the size and expected growth of the stockpile, storage will necessarily form part of any management policy in the near future. Safeguards and non-proliferation measures should remain under continuous review.

4.2 Utilization as MOX in current reactors

4.2.1 Current experience

Plutonium oxide can be mixed with uranium oxide to form MOX fuel for use in the present generation of thermal reactors. Such use of civil MOX fuel in thermal reactors would reduce the amount of separated plutonium in store and convert it to a form consistent with the spent fuel standard, but would not eliminate it as long as ^{238}U is the main component of the reactor core. This is because, as with uranium fuels, burning of MOX fuels in thermal reactors generates some plutonium from conversion of ^{238}U. Plutonium is also consumed by fission and some undergoes further transmutation into higher actinides. The balance between generation and consumption depends upon the isotopic composition of the plutonium, the fraction of the core loaded with MOX fuel and the burnup of the fuel. To date, loading with MOX has mostly been limited to 30% of the core charge, with fuel burnup of around 35 000 MWd/t, because the characteristics of plutonium fission reduce the efficiency of control rods designed for conventional uranium fuel. Under these conditions plutonium production and consumption are balanced, in contrast to a net production of about 200 kg Pu per annum for the standard uranium cycle in an 1000 MW PWR.

This option is well proven technically, with experience of loading MOX fuel into a thermal reactor dating back to 1963 (BR-3 reactor, Belgium). Large-scale use commenced in Germany in 1981 and the government-owned French utility started to recycle plutonium in thermal reactors in 1985.

The plutonium content of spent MOX fuel will be greater than that of ^{235}U enriched spent fuel, and there will be a continuing requirement for facilities to dispose of the high level waste and spent fuel. Repeated recycling could lower the fissile content but significant technical issues are encountered in attempting this procedure, notably the increased proportion of higher actinides.

The economics of MOX recycling in thermal reactors are controversial. Reprocessing of spent fuel solely to produce plutonium for recycling as MOX is not economic. But given that reprocessing has been carried out and the plutonium is available, then the extra cost of fabricating MOX fuel (as compared with enriched uranium fuel) might be justified in view of the savings in uranium and enrichment costs. Today MOX fuel fabrication costs are higher than for conventional uranium fuels because of the shielding required, but increased MOX utilization, and the associated economies of scale, should reduce these additional fabrication costs.

A safety case for the use of MOX fuels in UK reactors would have to consider the risks that could arise during transport and storage of the fuels, and during operation of the reactors. The NII would have to consider what variations to site licences would be required. The use of MOX in place of ^{235}U will raise the level of security necessary at reactor sites where fresh fuel is stored. Fresh MOX fuel could be a target for illegal diversion since the plutonium could be recovered relatively easily, particularly as the levels of penetrating radiation will be less than those from spent fuel. However, these problems have been successfully overcome in other countries.

4.2.2 MOX utilization in the UK

At present no UK reactors are licensed for burning MOX. Sizewell B, the LWR operated by British Energy, could utilize MOX fuel. Since the balance between plutonium consumption and generation depends on the isotopic composition of the plutonium, the fraction of the core loaded with MOX fuel and the burnup of the fuel, it is difficult accurately to estimate the possible rate of transformation of separated plutonium to the spent fuel standard. Estimates range between 0.5 to 0.7 t of separated plutonium per annum. This means that Sizewell B would need to run a standard MOX fuel cycle for *35–50* years to transform the 25 t of separated plutonium which British Energy expects to generate by 2010, although this timescale could be shortened by non-standard fuel cycles giving lower burnup to MOX fuel.

While there do not appear to be any insurmountable technical difficulties with loading MOX into AGRs, doing so would present a number of practical difficulties such as operator dose and modification to the stations' fuel routes. The safety case for a new fuel would need to be

established and station output might be adversely affected. However, it is estimated that a single AGR could transform 0.4–1.2 t per annum of separated plutonium depending on the fraction of the core that could be loaded with MOX and the plutonium content in the MOX fuel. The economics of burning MOX in AGRs will be less favourable than in LWRs because MOX fabrication costs per unit of electrical energy output are greater.

Magnox reactors have metallic fuel and incorporation of plutonium into them would present formidable technical and licensing difficulties which would not be worthwhile pursuing for a reactor system of such limited remaining life.

If a new UK LWR reactor designed for burning MOX fuel was to be built, it could convert 1.2–2.1 t plutonium per annum to the spent fuel standard.

4.2.3 Utilisation of UK MOX fuel in overseas reactors

Even if these options were brought into use in the UK, a substantial plutonium stockpile would remain. UK plutonium could also be 'leased' or sold to overseas utilities as MOX fuel. World-wide, 34 LWR reactors are currently licensed for 30% MOX core loading, but only about half of them are currently being used in this mode. The MOX would be under international safeguards and under Article 4 of the Non-Proliferation Treaty it would be subject to end-use restrictions, meaning that it could not be used for the development or production of nuclear weapons. The USA is generally opposed to a 'plutonium economy' and so may not be willing to take part in such transactions. However, France, Germany, Belgium and Switzerland all have reactors licensed for MOX, with spare capacity. Belgium in particular has reactors licensed for burning MOX, but has a moratorium on MOX production in place and so spare capacity for burning MOX would appear to exist.

An alternative option based on thermal reactors is to recycle plutonium in CANDU (Canadian Deuterium-Uranium Reactor) type reactors, mostly available in Canada. CANDU reactors have a higher rate of consumption of plutonium than other thermal reactors, so overall consumption of plutonium, recovered uranium and the minor actinides is possible. It is estimated that recycling MOX from reprocessed LWR fuel in a CANDU reactor could consume the minor actinide content from three to four LWR reactors in a year. A disadvantage of using CANDUs is that they require significantly lower levels of enrichment and therefore correspondingly greater MOX fabrication capacity.

The overseas market for MOX fuel manufactured from UK reactor plutonium appears limited for the foreseeable future because of the desire by other states to use their own separated stocks and of the preference to consume weapons grade plutonium from the US and FSU. This means that an economic agreement would need to be reached between the UK and the recipient country. Further agreements would need to determine, for example, which country gets the benefit of the energy gained and which country deals with the spent fuel created.

4.3 Disposal

It could be possible to dispose of separated plutonium, after suitable pre-treatment, by mixing it with highly radioactive waste and either converting the mixture into glass by the vitrification process or immobilizing the plutonium in ceramic pellets. This process does not extract useful energy from the plutonium and does not destroy it, but renders it relatively inaccessible. The product could be disposed of in geological structures. Such technologies exist for immobilization of high level wastes (HLW) but different equipment designs and materials formulations will be required because of chemical differences between plutonium and high level waste, which may affect the stability of the glass or ceramic matrix. More research and development would be required to understand how the technology could be adapted to plutonium. This procedure is currently being considered in the USA alongside the MOX route for disposal of military stocks of plutonium.

While preliminary work has started on the needs for geological disposal of HLW and spent fuel, no work has yet been done on direct disposal of separated plutonium. In addition to the technical uncertainties, geological disposal calls for a new approach to safeguards. A major quantity of plutonium would be underground and require long-term safeguards maintenance. It is not clear how the financial and legal arrangements for such permanent supervision can be established. A disadvantage of disposal is the waste of a potential fuel resource.

4.4 Limiting further growth of the separated plutonium stockpile

It is possible to limit further growth of the stockpile of separated plutonium by stopping reprocessing and instead making arrangements to dispose of the spent fuel from nuclear reactors directly. This is known as the once-through cycle. The plutonium is protected from illicit actions for many tens or even hundreds of years by the high amount of radioactivity, due to fission products in the spent fuel.

At present the UK does not have disposal facilities for HLW or spent fuel, although the Department of the Environment, Transport and Regions has begun to look into the criteria for repositories of these substances. This means that the spent fuel would need to be stored for some time pending the development of a repository.

In the case of AGR reactors, storage of spent fuel for long periods is technically possible. However, existing spent fuel storage facilities would not be adequate to handle all the AGR fuel without reprocessing. Licences and planning permission would be required to build new storage facilities on AGR sites.

Storage of Magnox spent fuel pending development of a repository poses more problems: Magnox fuel rods cannot be wet stored for long periods because the cladding on them corrodes under water. Therefore fuel for direct disposal would need to be dried and put into store while a disposal site was developed. No dry stores exist although Magnox Electric does have some experience in the dry storage of Magnox fuel at its Wylfa Power station. The spent fuel can be made suitable for storage and ultimate disposal by oxidizing the fuel prior to disposal. This technology has been developed in France but a number of technical problems remain. A potential alternative is to convert spent fuel into uranium and a waste stream containing the plutonium and fission products. This process has the advantage of not separating the plutonium, and gives rise to waste in a form suitable for disposal. The technology has already been developed for the Integral Fast Reactor metal fuel in the USA, but it is at an early stage of development and has not yet been proven for magnesium and aluminium clad fuels.

Given the technical and economic difficulties described, and the short time left before the Magnox programme is due to end, it seems unlikely that it will be possible to reduce significantly the predicted production rates of Magnox separated plutonium without closing Magnox reactors earlier than is planned. There are currently no plans to reprocess spent fuel from Sizewell B which is stored on site. This spent fuel could be disposed of in the same way as AGR spent fuel in a deep repository.

The once-through cycle has been adopted by several countries including the USA, Sweden, Finland and Canada. Internationally controversy remains over whether it has lower costs and proliferation risks than reprocessing and recycling spent fuel. A study performed by the OECD Nuclear Energy Agency (1994) concluded that the monetary cost differences between the reprocessing option and the direct disposal option are uncertain (direct disposal being about 10% cheaper in power generation costs).

4.5 Alternative fuels and reactor designs

Conversion of separated plutonium to the spent fuel standard by use as MOX fuel, or disposal, cannot be regarded as optimum long-term solutions as the plutonium remains for future generations. A long-term strategy should close the fuel cycle. In the long-term it is likely that plutonium could be used in alternative fuel cycles or in different reactor configurations to provide energy more efficiently while simplifying ultimate disposal arrangements. As with the use of MOX fuel in current reactors, the use of plutonium fuels will raise the level of security required at reactor sites.

4.5.1 Alternative fuels

In order to go beyond the spent fuel standard, and eliminate the plutonium, matrices other than uranium for the burning of plutonium are required. This avoids the production of plutonium which takes place by neutron capture in fertile matrices. Fuel matrices for plutonium that do not contain uranium which have been tested include spinel, silicon carbide and thoria. The use of new fuels in existing types of reactor, such as CANDU or possibly PWR, might be easier than designing and proving new types of reactor. However, tests of fuel performance as well as safety analyses and studies of waste disposal would be required.

4.5.2 Fast neutron reactors

The most developed of the 'advanced reactor

designs' is the liquid-metal cooled fast neutron reactor. This would provide a much more effective way of burning plutonium, while minimizing the production of minor actinides. Fast reactors can be used in a 'destructive mode', meaning plutonium is burned up almost completely. The design of the planned European Fast Reactor could burn up to 70 kg Pu per terrawatt hour of electricity (TWh).

4.5.3 CANDU

In addition to once-through MOX fuel cycles, CANDU reactors can in principle be adapted to CANDU-LWR tandem cycles using partially reprocessed LWR fuel as a direct source of fissile material for CANDU reactors. This process should be able to extract further energy from the fuel without the need for conventional reprocessing, but would require expensive re-canning of fuel and is principally of interest to South Korea, which has both reactor types. The process is known as DUPIC (Direct Use of spent PWR fuel In CANDU) and can reduce the total quantity of spent fuel produced by a factor of about three.

4.5.4 High temperature, gas-cooled reactors (HTGRs)

The helium cooled HTGR, when fuelled with weapons-grade plutonium, can eliminate 90% of the initial charge of plutonium 239 with a high plant efficiency and inherent safety. However, western countries opted out of HTGR several decades ago and the only current development work is in the FSU and China. There is some international participation in Russian studies on this topic.

4.5.5 Accelerator-driven reactors

Various proposals have been made to eliminate plutonium and other actinides in an arrangement of fuel and coolant that is driven by neutrons produced by a powerful proton accelerator. The fuel/coolant arrangement is designed to be sub-critical (thus not requiring conventional control rods), but would be so close to criticality that the substantial neutron multiplication leads to the possibility of electric power generation (energy amplification). Studies initiated by CERN employ a fast reactor-like core in which plutonium and other actinides may be transmuted. Other studies suggest that reactors using slow (thermal) neutrons would have significant advantages. Such systems need a great deal of further development to confirm technical, safety, proliferation and

economic aspects but they might be important in the future.

5 Recommendations

1. The current stock of civil separated plutonium in the UK is about 54 t and is forecast to rise to over 100 t by 2010. There is a growing international consensus that a large stockpile of separated plutonium may pose a significant environmental and security (proliferation) risk.

   We recommend that the Government reviews the strategy and options for stabilizing and then reducing the stockpile.

2. Safeguarded storage represents the only short term (*ca.* 4–5 years) option for dealing with the separated civil plutonium. In the medium term (2010–2015) the opportunities for stabilizing and reducing the stockpile include:
   - Once-through cycle
   - Recycling as MOX fuel in current reactors in the UK.
   - Use in a new LWR, designed for MOX burning, built in the UK.
   - Burning UK MOX fuel in overseas reactors.

   The need for a repository for HLW and spent fuel will remain alongside each of these options.

   Options for the medium- to long-term (2015 and beyond) include:
   - Disposal of separated plutonium in geological structures.
   - Use in an advanced reactor whose fuel cycle could eliminate plutonium.

   We recommend that all these options be subjected to independent review with comprehensive terms of reference.

3. If advanced reactors or fuel cycles are to remain as a long-term element in UK energy policy, **we recommend the maintenance of research and development capabilities that will allow the evaluation of competing systems and support international collaboration on those likely to be of benefit to the UK.**

11

Glossary

Actinide
A group name for the series of elements of atomic number 89 (actinium) to 103 (lawrencium). Uranium and Thorium occur naturally in the Earth's crust, but plutonium and the other higher actinides are produced by irradiation. The term 'minor actinide' denotes certain actinides other than plutonium.

Becquerel
SI unit of radioactivity, one Becquerel is the activity of a quantity of radioactive material in which one nucleus decays per second.

Burnup
The total energy released per unit mass of nuclear fuel, commonly expressed as MWd/t or GWd/t.

Criticality
State when a chain reaction in fissile materials is self-sustaining and therefore does not require an external neutron source.

Critical mass
The minimum mass required to sustain a chain reaction. The exact mass varies with many factors such as the particular isotope present, its concentration and chemical form.

Enrichment
Raising the proportion of ^{235}U fissile nuclei in reactor fuel above that for natural uranium.

Fission
The physical process whereby the nucleus of a heavy atom is split into two nuclei with masses of equal order of magnitude whose total mass is less than that of the original nucleus.

Isotopes
Nuclides having the same atomic number but different mass numbers.

Moderator
A component (usually water, heavy water, or graphite) of some types of nuclear reactor that slows neutrons, thereby increasing their chances of fissioning fertile material.

Non-Proliferation Treaty
Multilateral agreement to prevent the spread of nuclear weapons signed by over 140 nations. The treaty requires non-nuclear states not to develop, manufacture or acquire nuclear weapons and to accept full IAEA safeguards on all of their nuclear facilities. In turn, the nuclear weapons states agree to share 'the applications of nuclear energy for peaceful purposes' with non-nuclear weapons signatories on a 'non-discriminatory basis' and to negotiate in good faith an end to the arms race and toward nuclear disarmament.

Reprocessing
The chemical and mechanical processes applied to fuel elements discharged from a nuclear reactor in order to remove fission products and recover plutonium, uranium and other valuable material.

Sievert (Sv)
A measure of the biological effect of radiation. It expresses an amount of radiation that may have been received over any period of time. The measure takes into account differences in the radiobiological effectiveness of different types of radiation, to ascertain the total biologically effective dose.

Spent Fuel
Nuclear fuel removed from a reactor following irradiation. The fuel elements are removed from the reactor when they contain too little fissile and fertile material and too high a concentration of unwanted radioactive by-products to sustain reactor operation.

Spent Fuel Standard
Plutonium which is roughly as inaccessible for weapons use as that in spent fuel from commercial reactors.

Acronyms

AGR	Advanced Gas-cooled Reactor	LWR	Light water reactor
BNFL	British Nuclear Fuels plc	MAFF	Ministry of Agriculture, Fisheries and Food
CANDU	Canadian Deuterium-Uranium reactor: a type of heavy water reactor	MOX	Mixed Oxide (uranium dioxide and plutonium dioxide) fuel.
DTI	Department of Trade and Industry	mSv	Millisievert
DUPIC	Direct Use of spent PWR fuel In CANDU	MWd/t	Megawatt-days per tonne of uranium fuel
EURATOM	European Atomic Energy Community	NEA	OECD Nuclear Energy Agency
FSU	Former Soviet Union	NII	Nuclear Installations Inspectorate
HLW	High Level Waste	NRPB	National Radiological Protection Board
HMIP	Her Majesty's Inspectorate of Pollution	PWR	Pressurised Water Reactor
HSE	Health and Safety Executive	SAIS	Royal Society Scientific Aspects of International Security Group
HTGR	High Temperature, Gas-cooled Reactor	t	Tonnes
IAEA	International Atomic Energy Agency	TBq	Terabecquerel
ICRP	International Commission on Radiological Protection	THORP	Thermal Oxide Reprocessing Plant
		UKAEA	UK Atomic Energy Authority

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