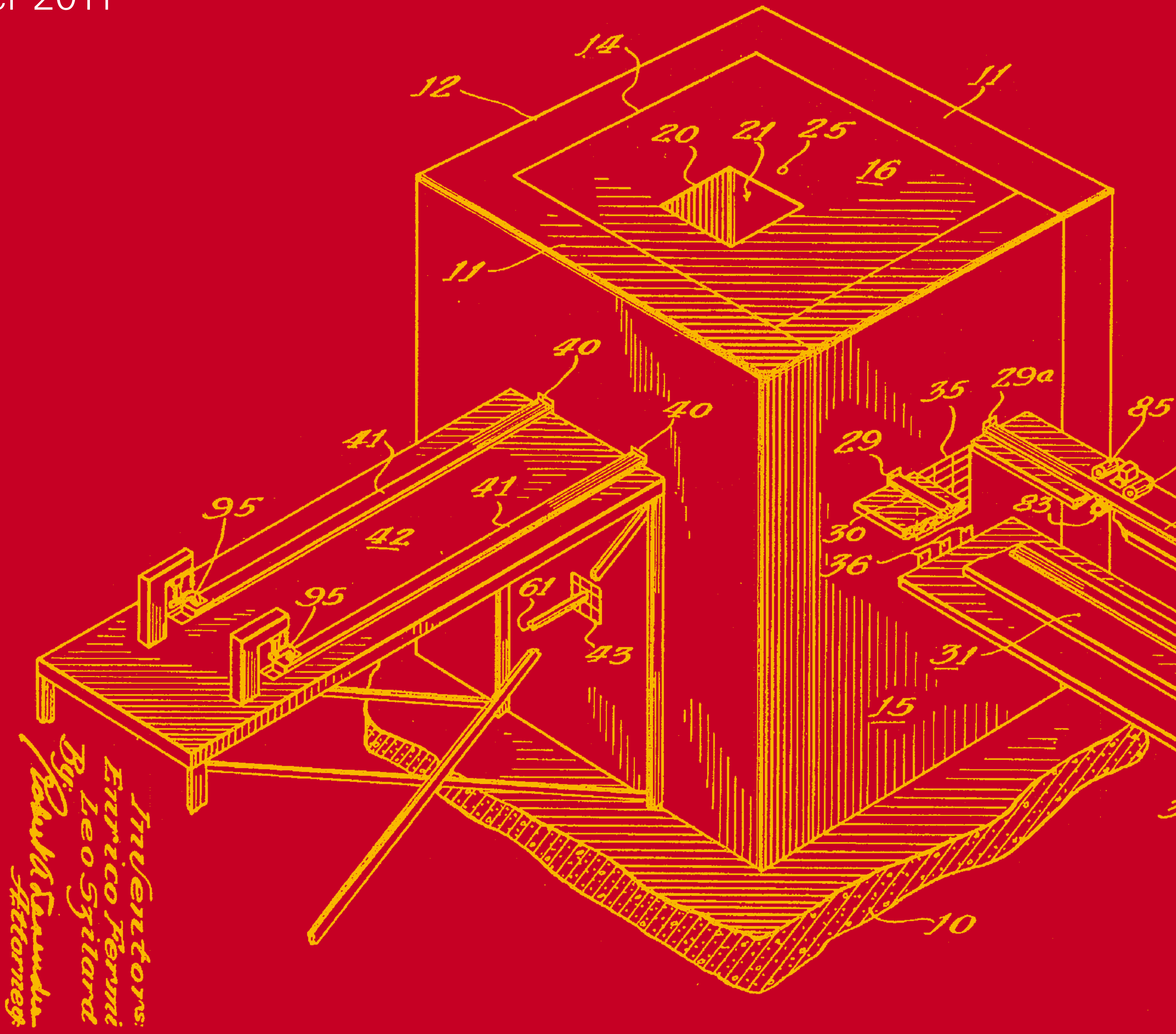
Fuel cycle stewardship in a nuclear renaissance

October 2011



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Fuel cycle stewardship in a nuclear renaissance
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Cover image: Enrico Fermi, a Nobel Laureate and Foreign Member of The Royal Society, was a giant in 20th century physics making major contributions in quantum mechanics, statistical mechanics, and nuclear and particle physics. A theorist and experimentalist he gave his name to the prolific family of fundamental particles which have a spin of ½, the fermions. In 1942 he demonstrated the first nuclear chain reaction in Chicago, under the University Football Stadium, paving the way for nuclear reactors and nuclear weapons. The cover illustration contains the design of an atomic pile, known today as a nuclear reactor, taken from his and Leo Szilard's 1944 patent for the 'Neutronic Reactor'.

Contents

Summary

Many countries worldwide are considering expanding their civilian nuclear power programmes or even embarking on civil nuclear power for the first time to help meet their climate change and energy security needs. Before the earthquake and tsunami hit the Fukushima nuclear power station in Japan, the nuclear industry projected the world was about to enter a period of global expansion in nuclear power. Post-Fukushima, this may still remain valid, although the rate at which nuclear power expands globally may slow.

This so-called 'nuclear renaissance' has renewed debate about the relationship between civil nuclear power and the proliferation of nuclear weapons, as well as other security risks. Although civil nuclear power has its history in nuclear weapons, its future is not. In some countries with nuclear weapons, the civil nuclear industry has become solely a provider of electricity. The good track record of international non-proliferation safeguards suggests alternative pathways may be more likely sources of proliferation than the diversion of nuclear material from civil nuclear power programmes. In many countries, the industry has moved from being purely state-run, national companies into multinational enterprises. This increases the transparency of civil nuclear power programmes and this multinational practice should continue. A fully internationalised nuclear fuel cycle and thoroughly multinationalised global nuclear industry may be part of the solution to proliferation, rather than the problem. A World Nuclear Forum is now timely so that CEOs and government leaders can explore their respective views on the future development of nuclear power and responsibilities for non-proliferation and nuclear security.

There is no proliferation proof nuclear fuel cycle. The dual use risk of nuclear knowledge, materials and technology and in civil and military applications cannot be eliminated. The technical expertise of the International Atomic Energy Agency plays a central role in managing this dual use. Improving the efficiency and effectiveness of international safeguards remains a Research and Developement (R&D) priority. It is difficult to assess and easy to exaggerate dual use risks. Risk assessments must be based on a sophisticated understanding of proliferation that appreciates the wider geopolitical system in which nuclear technology is embedded. Assessing what level of risk is acceptable remains ultimately a policy judgment, not a technical one.

Major security incidents, involving non-state individuals or groups, such as criminal networks and terrorist organisations, have been rare. As demonstrated by the attention to nuclear safety post-Fukushima, avoiding complacency is vital to maintain confidence in a nuclear renaissance. An integrated approach to risk assessment and management needs to feature more prominently at all levels of nuclear decision making from the design and regulation of nuclear facilities to the corporate governance of nuclear organisations.

In the rush to construct nuclear reactors, the management of spent fuel and radioactive waste, including planning for its disposal, must no longer be an afterthought. Currently, there is no operating civil geological disposal facility, although disposal plans are well advanced in some countries. The multi-decade to century timescales involved requires long term, strategic planning. The entire fuel cycle needs to be considered from cradle to grave to reduce proliferation and security risks. Long term R&D programmes should be formulated at the outset so that the capacity to manage spent fuel and radioactive wastes can be delivered in a timely way. Furthermore, R&D provides the contingency to address unforeseen changes in policy by keeping future management options open.

A nuclear renaissance has renewed interest in the potential of offering cradle to grave fuel cycle services that couple the supply of fresh fuel with the management of spent fuel and radioactive wastes. Such a comprehensive offer could be attractive to some countries in preference to developing their own national fuel cycle capabilities, thereby providing a key non-proliferation incentive that offers major security benefits. The sensitivities surrounding such arrangements should not be underestimated. This does not mean that governments should reject them. By supporting collaborative R&D to explore these options, governments can keep them open without needing to commit to their implementation at this stage.

The UK's role in the development of nuclear technology has been declining over the last few decades. The UK's long term ambitions for nuclear power need to be clearly articulated and implemented if this decline is to be reversed. Enhanced support for the UK's research infrastructure is necessary if the UK is to remain influential in debates on non-proliferation and nuclear security, and thereby contribute to the responsible stewardship of a global nuclear renaissance.

Recommendations for best practice

Recommendation 1:
Non-proliferation (see chapter 3)

- All states with nuclear weapons programmes should separate them from their civil nuclear power programmes, and then place the latter under international safeguards.
- All non-nuclear weapon states with existing nuclear power programmes or embarking on nuclear power for the first time should adopt and implement IAEA comprehensive safeguards and the Additional Protocol.
- Universities and industry organisations should develop education and awareness raising courses on non-proliferation and nuclear security to be included in the training of personnel in the nuclear industry, including scientists, engineers, technicians and managers.
- Nuclear fuel should be developed and nuclear reactors configured to enable the maximum burn up of fuel, thereby decreasing the attractiveness of plutonium in spent fuel for use in nuclear weapons. To be feasible, this needs to be consistent with efficient and economic operation.

Recommendation 2:
Nuclear governance (see chapter 5)

- At the national level, regulation of nuclear power programmes should be based upon an integrated approach to nuclear safety, security and safeguards.
- At the international level, in the absence of a specific Convention on nuclear security, appropriate security information could be included on a voluntary basis in national reports submitted as part of the peer review process of the Convention on the Safety of Spent Fuel Management and Safety of Radioactive Waste Management, and the Convention on Nuclear Safety. This practice would be promoted by integrating nuclear safety and security into the IAEA's advisory services for member states.
- An integrated approach to industry-led peer reviews should be developed possibly through collaboration between the World Association of Nuclear Operators and the World Institute of Nuclear Security.
- Non-proliferation and nuclear security need to feature more explicitly in corporate governance arrangements with similar status to that given to nuclear safety.

Recommendation 3:
Integrated fuel cycle management (see chapter 6)

Spent fuel should be reprocessed only when there is a clear plan for its reuse. This plan should seek to:

- Minimise the amount of separated plutonium produced and the time for which it needs to be stored.
- Convert separated plutonium into Mixed Oxide (MOX) fuel as soon as it is feasible to do so.
- Identify nuclear power reactors in advance to use MOX fuel and ensure conversion into MOX fuel matches reactors' loading schedules and fuel specifications.
- Transport plutonium as MOX fuel rather than in a separated form.

When planning interim storage:

- The amount of spent fuel stored in ponds in the vicinity of reactors should be minimised by removing spent fuel as early as is feasible for interim storage elsewhere whether onsite (away from reactors) or offsite.
- Interim storage at centralised stores offsite may be more secure than distributed storage at numerous reactor sites.
- If wet storage is to continue in the interim, then sufficient storage capacity should be planned to reduce the need for high density packing and to guarantee continuous cooling.
- Whenever possible, interim storage under dry conditions should be adopted to enhance nuclear safety and security.

To ensure cradle to grave planning:

- Governments should establish a national policy that considers the long term role of nuclear power in the country's energy policy. This national policy should specify the requirements for managing spent fuel and radioactive wastes, including sufficient capacity for interim storage, as well as initiating plans for delivering timely geological disposal from the outset.
- Governments, in partnership with regulators, industry and academia, should develop a long term R&D roadmap to support these management strategies. It should be based on participation in relevant international R&D programmes.
- Operators should formulate spent fuel management strategies that cover the entire lifetime of their reactors. International fuel cycle arrangements should be sought, especially when national capacity is lacking.
- Governments should support collaborative R&D programmes on spent fuel and radioactive waste management. This should include joint studies to explore international fuel cycle arrangements, including geological disposal, although there would be no need for commitments to implement them immediately.

Recommendations to the UK (see chapter 8)

Recommendation 1
Given that the UK government has decided to embark on a new nuclear power programme, the Department of Energy and Climate Change (DECC) should develop a strategy that addressees the future role of nuclear power in the UK's long term energy policy. This could be facilitated by a high level, Civil Nuclear Power Council based in DECC that brings together senior representatives from the UK's nuclear industry and senior officials from government departments and agencies.

Recommendation 2
A long term strategy for nuclear power in the UK would guide a long term Research and Development (R&D) roadmap. It should be based on a review of current UK R&D, relevant international programmes and suitable UK participation in them.

Recommendation 3
The implementation of a long term R&D roadmap will need to be supported principally by government funds but also draw on industry sources. It will involve universities, the National Nuclear Laboratory (NNL) and other relevant research organisations. NNL's facilities must be fully commissioned and suitable access provided to researchers to use them.

Recommendation 4
The National Security Council (NSC) should set non-proliferation and nuclear security policy. Research priorities would be identified by a suitable technical NSC sub-committee. This will ensure co-ordination between the different interests of stakeholders and various implementing bodies. These priorities would then inform the UK's long term strategy for nuclear power and R&D roadmap.

Recommendation 5
AWE's threat reduction research must continue to be well supported. AWE's National Nuclear Security Division should be developed, exploiting the Blacknest model, so that the wider scientific community, including international partners, can engage effectively with this expertise in a non-classified environment.

Recommendation 6
The Foreign and Commonwealth Office (FCO) should set up a Non-Proliferation and Nuclear Security Network chaired by the FCO's Chief Scientific Adviser. The Network should facilitate information sharing between academia, government and industry, as well as fostering collaborations, including with international partners.

Recommendation 7
The UK's civil stockpile of separated plutonium should be reused as Mixed Oxide (MOX) fuel in a new generation of thermal Light Water Reactors. This provides an effective and technically proven management strategy for the stockpile. These reactors need to be suitably licensed and a new MOX fabrication facility now needs to be constructed in the UK.

Recommendation 8
The Department of Energy and Climate Change should carefully consider the long term consequences of its current assumptions that the UK's reprocessing activities should cease. Investment in an operational reprocessing facility and the infrastructure to reuse the UK's stockpile of separated plutonium would allow the UK to continue providing national and international reuse services.

Recommendation 9
The Office of Nuclear Regulation should develop its integrated approach to nuclear regulation by ensuring that security features explicitly in nuclear site licensing conditions. This may require the Government to update the Nuclear Installations Act.

Recommendation 10
The UK government should help to establish a CEO-led, World Nuclear Forum. This Forum would provide an interface between CEOs and government leaders to explore their respective views on the future development of nuclear power and responsibilities for non-proliferation and nuclear security. This Forum could be proposed at the 2012 Nuclear Security Summit and set up thereafter.

Stewardship challenges for a nuclear renaissance

1.1 The changing geography of nuclear power

Many countries have expressed an interest in nuclear power as a major component of their climate change polices and to address their energy security needs. This includes both countries with existing nuclear power programmes, as well as countries embarking on programmes for the first time. The nature of countries' interests in nuclear power varies. In some countries, nuclear power reactors are under construction while in others they are currently being planned and undergoing licensing.

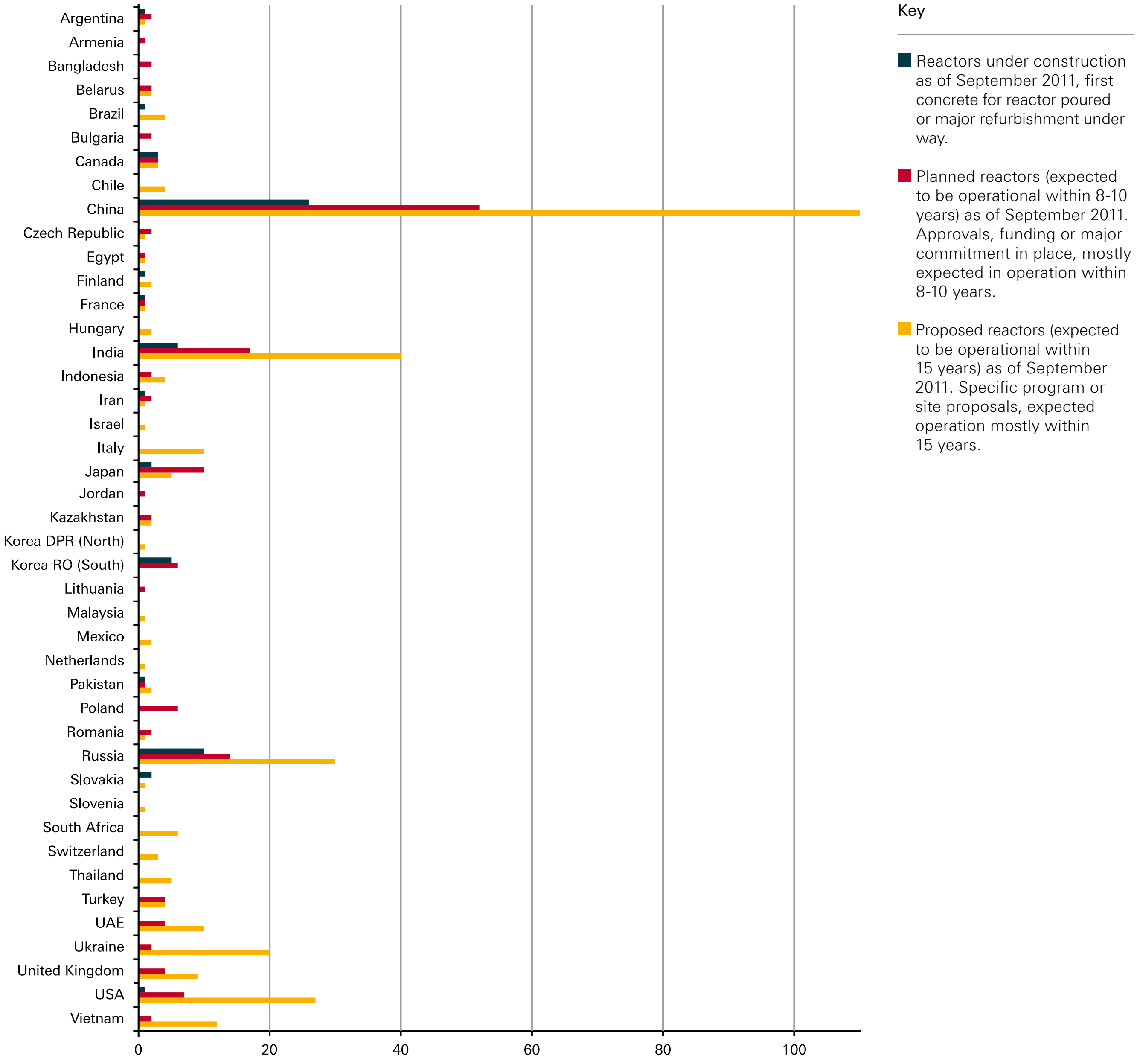
The construction of new reactors is likely to be limited in Europe and USA. The lifetimes of existing reactors, however, may be extended. These reactors may be modified to increase the burn up of fuels so that they can make more efficient use of uranium. These options provide time to resurrect the necessary infrastructure to support the construction of new reactors to replace older ones.

Construction of new reactors is furthest advanced in South and East Asia, especially China, India; and South Korea, as well as Russia (see figure 1). These countries are likely to lead a global expansion of nuclear power: the so-called 'nuclear renaissance'. The Middle East could emerge as the second largest market for new reactors. In 2009, the United Arab Emirates awarded a South Korean consortium the contract to build four nuclear power reactors by 2020. Saudi Arabia recently announced plans to build 16 nuclear power reactors over the next two decades. Kuwait has plans for four nuclear power reactors and Jordan for one reactor.

There could be four or five new nuclear power countries by 2020, including UAE, Vietnam, Turkey and Iran and possibly Belarus. By 2030, there could be up to ten new countries, perhaps including: Egypt, Indonesia, Jordan, Kazakhstan, Kuwait, Lithuania, Malaysia, Nigeria, Philippines, Poland and Saudi Arabia.

Before the earthquake and tsunami hit the Fukushima nuclear power station in Japan, the nuclear industry projected that a nuclear renaissance could take the form of various scenarios (see figure 2). Post-Fukushima, these scenarios may still remain valid, although the rate at which nuclear power expands globally may slow. A few established nuclear power countries are deciding to end their programmes. The German government has announced its plans to phase out all of its nuclear power stations. Switzerland will now be phasing out nuclear power, too. The Italian government is likely to suspend the development of nuclear power following a national referendum less than two years after lifting an earlier ban. Japan may also reconsider its plans to build new nuclear power reactors. Other countries, such as China and India, are likely to continue with their nuclear power ambitions. Despite events at Fukushima, global energy demand and climate change targets still need to be addressed.

Figure 1 **Proposals for nuclear power reactor construction (WNA 2011)**



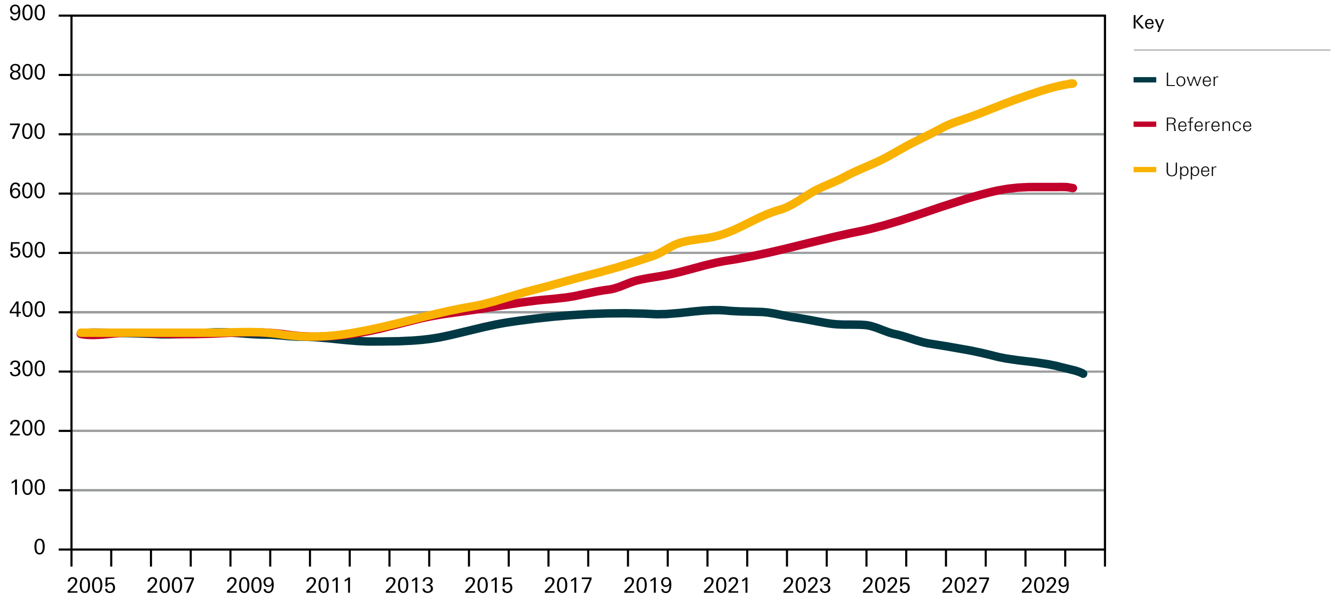
Key

■ Reactors under construction as of September 2011, first concrete for reactor poured or major refurbishment under way.

■ Planned reactors (expected to be operational within 8-10 years) as of September 2011. Approvals, funding or major commitment in place, mostly expected in operation within 8-10 years.

■ Proposed reactors (expected to be operational within 15 years) as of September 2011. Specific program or site proposals, expected operation mostly within 15 years.

Figure 2 **Worldwide nuclear generating capacity scenarios (WNA 2011)**



1.2 The dual use challenge

Anticipation of a nuclear renaissance has renewed debates about the relationship between civil nuclear power and the proliferation of nuclear weapons. Technologies to enrich uranium to fuel reactors can also enrich uranium to higher levels suitable for nuclear weapons use. Nuclear power reactors transmute uranium into plutonium that could be used in nuclear weapons. The dual use potential of nuclear technology in civil and military applications remains. These debates are set within a wider context of the growing international support for multilateral nuclear disarmament (FCO 2009).

Increased attention is being paid to other security threats involving non-state individuals or groups, such as criminal networks and terrorist organisations. States without a suitable security infrastructure may not be able to protect nuclear facilities against attacks or sabotage. These states may not be able to prevent nuclear materials from being acquired by those who could use them in a dispersal device or even an unsophisticated and crudely designed nuclear weapon. The 2010 Nuclear Security Summit emphasised the seriousness of these threats. It convened nearly 50 Heads of State, who committed themselves voluntarily to a four-year workplan to enhance the security of civil nuclear materials worldwide (White House 2010). A follow up summit is scheduled for South Korea in 2012 to assess progress.

There is renewed interest in scientific methods to address the dual use potential of materials and technologies and knowledge acquired through civil nuclear power programmes. Fuel cycles could be designed to reinforce ‘intrinsic barriers’ to proliferation by altering the chemical, isotopic, physical and radioactive properties of spent fuel. Fuel cycles could also be designed to facilitate the implementation of ‘extrinsic barriers’, relating to the political decisions and institutional arrangements governing the fuel cycle. These include international IAEA safeguards, other bilateral, regional or international verification measures, as well as import and export controls.

Set up by the Australian and Japanese governments, the International Commission on Nuclear Non-Proliferation and Disarmament concluded that ‘proliferation resistance should be endorsed by governments and industry as an essential objective in the design and operation of nuclear facilities’ (ICNND 2009). At the Nuclear Security Summit, participating states committed themselves to ‘encourage the use of low-enriched uranium and other proliferation resistant technologies and fuels in various commercial applications’ (White House 2010). When identifying options for the long term management of the UK's stockpile of separated plutonium, the UK's Nuclear Decommissioning Authority (NDA) acknowledged further guidance is needed in areas, 'such as the long term security of materials and to what degree resistance to terrorist threat and proliferation is to be built into disposal waste forms and to what degree it is to be built in through other measures' (NDA 2009).

There is also renewed interest in the potential of international fuel cycle arrangements. In 2004, the International Atomic Energy Agency (IAEA) established an Expert Group on Multilateral Approaches for the Nuclear Fuel Cycle. It concluded that 'a scenario of a strong expansion of nuclear energy around the world calls for the development of nuclear fuel cycles with stronger multilateral arrangements and facilities – by region, by continent or by dedicated cooperation – and for a broader cooperation within the international community' (IAEA 2005).

The IAEA Expert Group was followed by over a dozen proposals from governments, industry and international organisations. There has been limited uptake of these proposals. Most focus on the supply of fresh fuel. Less recent attention has been paid to the international management of spent fuel. This need was highlighted at the 2010 NPT Review Conference when states committed themselves to explore 'the development of multilateral approaches to the nuclear fuel cycle, including the possibilities to create mechanisms for assurance of nuclear fuel supply, as well as possible schemes dealing with the back end of the fuel cycle, without affecting rights under the Treaty and without prejudice to national fuel cycle policies, while tackling the technical, legal and economic complexities surrounding these issues, including in this regard the requirement of IAEA full scope safeguards' (UN 2010).

1.3 Report structure

Chapter 2 introduces the civil nuclear fuel cycle and the major options for managing spent fuel. This depends on the choice of fuel cycle. Under an open fuel cycle, spent fuel is disposed of directly in a Geological Disposal Facility (GDF). Under a closed fuel cycle, spent fuel is reprocessed and then reused in reactors.

Chapter 3 identifies some of the major changes the nuclear industry has undergone over the last 50 years. In particular, the internationalisation of fuel cycle activities and multinational ownership and/or management of facilities have important benefits to address proliferation and security concerns.

Chapter 4 explores the potential of proliferation resistance measures. While it is important to continue research and development (R&D) to ensure the technical feasibility of these measures, political and commercial realities still need to be met if they are to be successfully implemented. Irrespective of a technology's intrinsic proliferation resistance, it will still need to be placed under IAEA safeguards once deployed. Safeguardability remains a R&D priority.

Chapter 5 emphasises the value of an integrated approach to assessing, managing and regulating safety, security and non-proliferation risks. This appears prudent given the complex, interconnected nature of nuclear power (WINS 2011). Synergies between the requirements in these areas should be identified and conflicts resolved. An integrated approach reflects the growing recognition for an 'all hazards approach' to national security that addresses a range of threats from natural disasters to manmade accidents or malicious attacks by states and non-state individuals and groups (Cabinet Office 2010).

Chapter 6 emphasises the importance of cradle to grave planning. Commercial drivers mean the planning of nuclear power programmes tends to focus on short term priorities. This should not be to the detriment of long term considerations. Nuclear power is a major commitment and the century long timescales involved must be fully appreciated. The entire lifetime of the programme must be considered from the outset, identifying requirements for the management of spent fuel and radioactive wastes, including disposal. The management of the large volumes of spent fuel to be generated by a nuclear renaissance must learn lessons from 50 years of operational experience.

Chapter 7 considers international fuel cycle arrangements for the management of spent fuel. Disposal, and to some extent storage, is the last part of the nuclear fuel cycle to be fully internationalised. This is necessary if comprehensive cradle to grave services are to be possible that couple the supply of fresh fuel with the management of spent fuel.

International disposal has received international support (IAEA 2004). The political sensitivities should still not be underestimated. International disposal may become increasingly important since it is unclear if every nuclear power programme will have the suitable geology and resources to construct and operate a GDF nationally. It's in every nation's interests that all countries with nuclear power have access to the capacity to manage nuclear materials safely and securely.

Chapter 8 considers the UK's nuclear power programme. Over recent decades, the UK's influence on the development of nuclear technology has been declining. The UK's nuclear industry has become fragmented and each fragment constrained by its particular remit. A more strategic approach is now needed that considers the opportunities and risks presented by a nuclear renaissance nationally and internationally. More active engagement in international R&D programmes is necessary if the UK is to reverse the decline in its influence over the development of nuclear technology, and develop the skills base to support the redevelopment of its industry.

1.4 Acknowledgments

The Royal Society would like to thank the Working Group of experts that was established to oversee this project (see appendix 1). It consulted widely through a series of evidence gathering workshops, meetings with stakeholders, and an open public call for evidence (see appendix 2). Stakeholders included individuals from government, industry, academia, intergovernmental and non-governmental organisations in the UK and other countries. This report was reviewed by a panel of experts and has been approved by the Council of the Royal Society (see appendix 3).

We would like to thank the Atomic Weapons Establishment (AWE), NDA and National Nuclear Laboratory (NNL) for kindly hosting some of the evidence gathering workshops and providing staff at these events.

We would also like to thank the World Nuclear Association (WNA) for invitations to brief its Working Group on Security of the International Nuclear Fuel Cycle.

We are very grateful to the UK's Strategic Programme Fund for its financial support and the Foreign and Commonwealth Office for its assistance.

The nuclear fuel cycle

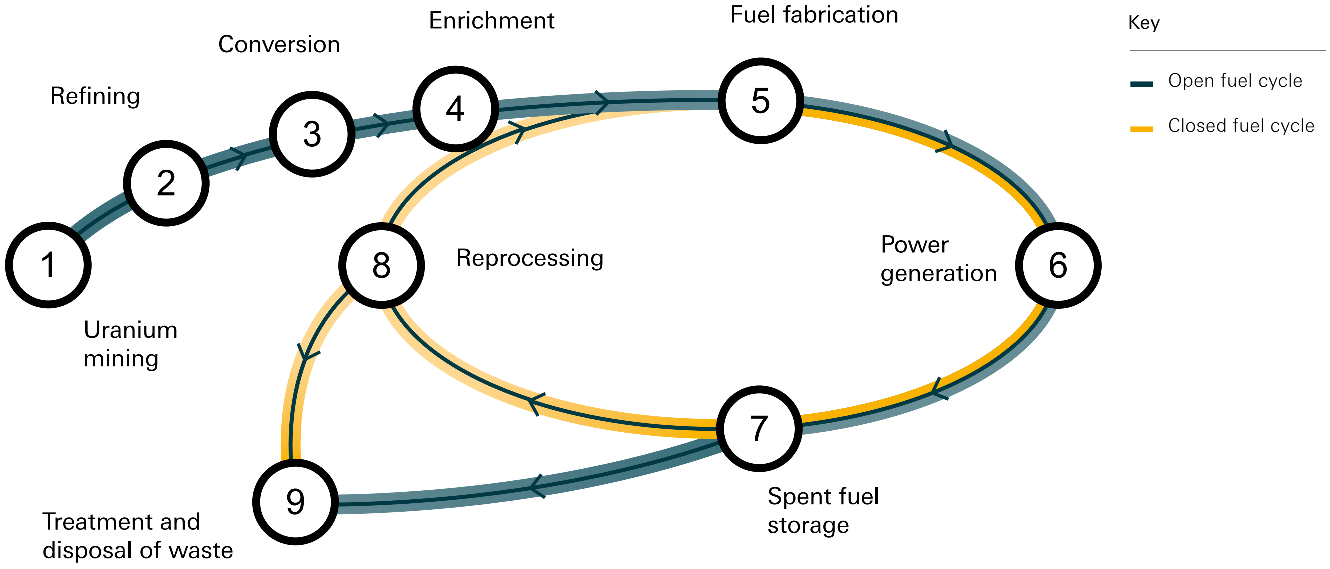
2.1 Reactor basics

The civil nuclear fuel cycle refers to a sequence of processes whereby nuclear fuel is produced and managed before and after its use in a power reactor (see figure 3). For most current power reactors, fresh nuclear fuel consists of fuel pins made out of stacks of cylindrical uranium dioxide pellets, or mixed uranium dioxide and plutonium oxide pellets encapsulated in metal tubes. The fuel pins are bundled together in fuel assemblies that are then irradiated with neutrons in a reactor. If a fissile nucleus absorbs a neutron, it fissions into fragments, releasing further neutrons and energy. If these free neutrons are absorbed by other fissile nuclei, these can also fission and release more neutrons, and so on in what is known as a chain reaction. The reaction can be controlled because neutrons are captured by nuclei without causing fission. Power reactors operate in a steady state. For every neutron consumed in a fission event, exactly one neutron produced in that event survives to propagate the fission reaction.

In uranium, it is the isotope, U-235, that undergoes fission and is primarily responsible for the chain reaction and energy generation. This energy is transferred to a coolant, raising its temperature. Many modern nuclear power reactors, such as Light Water Reactors (LWRs), use ordinary (light) water (H2O) 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 liquid at reactor temperatures. The UK operates a PWR and two types of Gas-Cooled Reactor that use carbon dioxide as the coolant: the Advanced Gas-cooled Reactor (AGR) and the Magnox Reactor.

Over 99% of natural uranium is U-238; less than 1% is U-235. For use in LWRs, uranium needs to be enriched so that its U-235 concentration is increased to approximately 3-5%. This low enriched uranium (LEU) is unsuitable for weapons use unless it is enriched further to become highly enriched uranium (HEU), which is defined to be uranium with a U-235 concentration of more than 20%.

Figure 3 **The nuclear fuel cycle**



2.1.1 Thermal reactors

Nuclear power reactors can be categorised by the neutrons responsible for fission reactions. Thermal reactors, such as LWRs, use ordinary water as not just a coolant but also a moderator to slow down neutrons so that most of the fission is caused by those with relatively low energies, so-called 'thermal neutrons'. Heavy Water Reactors (HWR) use ordinary water as the coolant but heavy water (D2O) as the moderator. They are fuelled by natural uranium, although more recent designs also use slightly enriched uranium.

Whereas LWRs have peak coolant temperatures of approximately 300°C, thermal High Temperature Reactors (HTRs) today have peak coolant temperatures between 700 and 850°C with the long term potential of higher temperatures. HTRs can generate electricity, as well as heat for alternative industrial applications. The traditional coolant to transfer heat from the reactor core has been an inert gas (high pressure helium). R&D is being carried out on the Advanced High Temperature Reactor (AVHTR) that uses low pressure liquid salts as the coolant.

2.1.2 Fast reactors

Fast reactors do not include a moderator, so fission is caused by neutrons with higher energy, so-called 'fast neutrons'. Fast reactors would enable fissile materials in spent fuel to be reused, producing more than 60-70 times the energy per unit mass of original uranium than thermal reactors. Under the Fast Breeder Reactor (FBR) concept, more fissile material is created than consumed. Neutrons generated in the reactor core convert fertile U-238 in the core and the blanket of 'breeder' fuel assemblies surrounding this core into fissile Pu-239. These can be reprocessed to make more fuel. Under the fast burner concept, the blanket can contain radioisotopes encapsulated in an inert material.

2.1.3 Small and medium reactors

The commercial trend has been to deploy large nuclear reactors with power outputs reaching 1,000-1600MWe. Small and medium sized reactors (SMRs) have been developed with power outputs of less than 300MW and between 300-700MW, respectively. Eight SMR designs are available for commercial deployment (NEA 2011). The Canadian CANDU-6 and Chinese QP-300 PWR have already been deployed internationally and there are agreements to build more of these reactors in Romania and Pakistan. The first of a kind Russian barge mounted nuclear power plant with two KLT-40S PWRs is currently under construction and could be deployed in 2013. Approximately twelve advanced SMRs have reached advanced design stages in Argentina, China, India, South Korea and USA, prototypes of which could be implemented before 2020 (NEA 2011). The majority of these advanced SMRs are PWRs, although small and medium fast reactors are also being developed.

2.1.4 Generations of reactors

Nuclear power reactors are also categorised chronologically. Generation I reactors, such as Magnox reactors, refer to early prototype reactors and first designs connected to the grid. Generation II reactors, such as AGR and PWR, are those that are currently operating. Generation III reactors are those that are presently being deployed, for example in South Korea, or are ready to be deployed, such as those under construction in China, Finland and India. They are evolutions of Generation II designs with improved safety, efficiency and economics. Generation IV reactors are currently under R&D and may be available only around 2040 or 2050. They include designs for advanced, thermal VHTRs, as well as fast reactors.

2.2 Management options for spent fuel

Nuclear power reactors are refuelled every 12 to 18 months. Only a quarter to a third of the total fuel is removed as spent fuel. The remainder is moved back into the core at new positions appropriate for its reduced fissile content. The useful life of nuclear fuel in a thermal reactor is usually 3-7 years. By this time it is no longer an efficient energy producer. Its fissile content is either now too low or its content of neutron-absorbing fission products is too high.

Spent fuel is intensely hot and radioactive due to the natural decay processes of the fission products and minor actinides it contains (see figure 4). It is initially cooled under wet conditions in storage ponds located in the immediate proximity of the reactor. Water provides an effective coolant and radiation shielding. With more than 50 years of experience, wet storage is considered to be a mature technology. It requires relatively high maintenance, especially tight control of the water's chemistry to prevent the fuel or its cladding from degrading. The pond is actively cooled. Pumps circulate water from the pool to heat exchanges so that the heat generated by the assemblies is continuously removed. The environment above the pond in the storage facility is carefully monitored and treated, including the detection of hydrogen gas that would indicate overheating.

After 9-12 months, cooling requirements drop sufficiently for alternative management options to be considered. This depends on the choice of fuel cycle. Under the open fuel cycle, it is widely accepted that spent fuel should be disposed of directly in a GDF. Under a closed fuel cycle, spent fuel is reprocessed to separate uranium and plutonium that could be reused as new fuel to generate more energy.

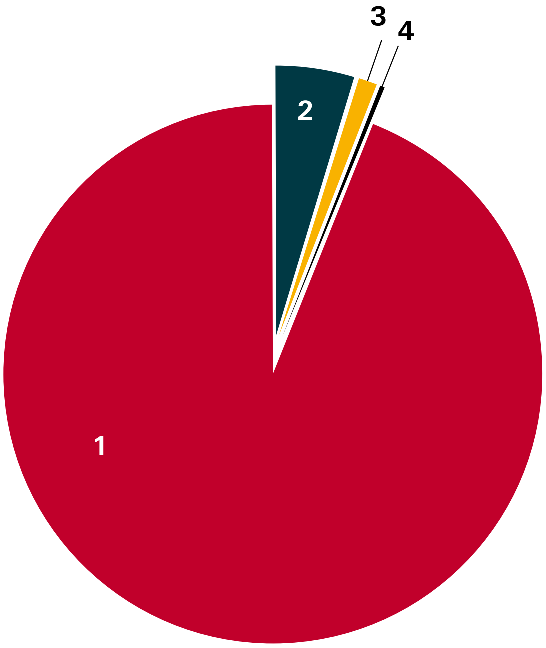
Most current commercial nuclear reprocessing facilities use the Plutonium URanium EXtraction (PUREX) process. Spent fuel assemblies are chopped up and then dissolved in nitric acid. Plutonium and uranium nitrates are separately removed through solvent extraction, and converted into plutonium oxide and uranium oxide products. Fission products and minor actinides that remain in the nitric acid solution are then immobilised as High Level Waste (HLW) by chemically incorporating them into a robust matrix. This commonly involves vitrification into a glass wasteform that is then poured into stainless steel containers for eventual geological disposal.

Separated plutonium dioxide is recombined with depleted or reprocessed uranium dioxide to make Mixed Oxide (MOX) fuel. The fissile content of the plutonium boosts the fissile content of the final fuel to a level where it is usable in nearly all types of thermal reactor. In principle, spent MOX fuel can be reprocessed and the recovered fissile material reused again in LWRs. The number of cycles of reuse is limited by the build up of undesirable plutonium isotopes that will not fission in a thermal reactor. The general expectation at present is that spent MOX fuel is unlikely to be reprocessed but will instead be disposed of directly geologically. The development of fast reactors could support further reuse of spent MOX fuel.

2.2.1 The thorium fuel cycle

Naturally occurring thorium consists almost entirely of fertile Th-232. It does not undergo fission itself but on capturing a neutron it leads to U-233, which is fissile. This is similar to natural uranium, which consists mainly of fertile U-238 that is transmuted to fissile Pu-239 upon neutron capture. Since thorium does not have a naturally occurring fissile isotope, there is no analogue of U-235. Another fissile material, either U-235 or Pu-239, is needed as a 'seed material' to generate the neutrons to start the thorium fuel cycle. The thorium fuel cycle could alternatively be initiated by the neutrons generated by fast reactors or accelerator driven systems. In the uranium fuel cycle, only one neutron needs to be captured to transform U-238 to Pu-239. Multiple neutron captures are required to generate plutonium and other transuranic isotopes from Th-232. Spent thorium fuel poses management problems similar to those arising from the minor actinides in spent uranium fuel because irradiation of Th-232 creates radioactive Pa-231 with a half life of 32,760 years. Spent thorium fuel also contains U-232. Its decay produces intensely radioactive daughter products within a period of a few months after separation, making spent thorium fuel hazardous to handle.

Figure 4 **Constituents of spent LWR fuel**



Spent fuel contains approximately:

1. 94% by mass of uranium (U) with an enrichment level at or slightly above that of natural uranium;
2. 4-5% of fission products, including strontium (Sr), caesium (Cs), iodine (I) and technetium (Tc).
3. 1% plutonium (Pu)
4. 0.1% other minor actinides, such as neptunium (Np), americium (Am) and curium (Cm)

Key

1 Uranium		~94%
U235	0.7%	
U238	93%	
2 Fission Products		~4-5%
Sr-90	0.1%	
Cs-137	0.2%	
I-129	0.03%	
Tc-99	0.1%	

3 Plutonium		~1%
Pu-238	0.04%	
Pu-239	0.7%	
Pu-240	0.3%	
Pu-241	0.2%	
Pu-242	0.1%	
4 Minor Actinides		~0.1%
Np-237	0.07%	
Am-241	0.03%	
Cm-244	0.01%	

2.3 Rationales for fuel cycle choices

2.3.1 Technical needs

The closed fuel cycle could be chosen for technical reasons. Spent fuel from the UK's Magnox reactors, for example, is reprocessed since it corrodes if stored underwater for prolonged periods and being chemically reactive it is unstable for direct disposal.

2.3.2 Waste management considerations

The closed fuel cycle opens up a new set of management options. Instead of needing to store and dispose of the entire volume of spent fuel, reprocessing allows uranium (the major component of spent fuel by volume) to be managed differently. Separated plutonium can be reused as MOX fuel, leaving only a relatively small volume of HLW for disposal. Reprocessing generates a large volume of Intermediate Level Waste (ILW) and Low Level Waste (LLW) but in need of less complicated management. It also leaves large volumes of LEU, which, depending on the economics associated with the price of fresh uranium and enrichment, may itself be economically reused.

2.3.3 Relative fuel cycle costs

The closed fuel cycle has sometimes been presented as cheaper than the open fuel cycle. Over the last few decades, many empirical studies have assessed the relative costs of the open and closed fuel cycle. These studies have varied in quality, methodology and scope and have been published by organisations and experts in different countries, including those that have had pro-reprocessing polices, such as France, Japan and UK. They all conclude that the open fuel cycle currently has cost advantages over the closed fuel cycle.

Key variables affecting the relative costs of the open and closed fuel cycle include:

- price of uranium;
- costs of enriching and preparing uranium fuel;
- costs of reprocessing and preparing MOX fuel;
- costs of storing spent fuel;
- costs of geological disposal.

2.3.3.1 Price of uranium

The closed fuel cycle could provide cost savings because it potentially uses less uranium than the open fuel cycle. To provide a cost advantage, the price of uranium would need to increase significantly and be sustained at this high price for a prolonged period of time. There are differences of opinion about whether uranium will become increasingly scarce, and how price and supply may be affected by discoveries of alternative sources of uranium, the costs of mining and developments in exploitation technology. The price of uranium will be affected by increased demand arising from extra reactor capacity associated with a nuclear renaissance. Many in the nuclear industry and the IAEA assert there will be an adequate supply of natural uranium for many decades to come to cope with this increased demand.

2.3.3.2 Costs of enriching and preparing uranium fuel

Nuclear power reactors operating on either an open or closed fuel cycle require enriched uranium initially. The availability of enrichment and uranium fuel fabrication services on the international market makes these costs comparatively low.

2.3.3.3 Costs of reprocessing and preparing MOX fuel

The market for reprocessing and MOX fabrication is less well developed. It is more difficult to assess the associated costs for these services. The major costs associated with the closed fuel cycle arise from the construction and operation of reprocessing facilities. The construction of the UK's Thermal Oxide Reprocessing Plant (THORP) cost approximately £3 billion, and the Rokkasho Reprocessing Plant (RRP) cost perhaps several times this amount. Should reprocessing facilities already exist, then the operation costs are substantially lower.

2.3.3.4 Costs of storing spent fuel

Storage costs are affected by the volume of fuel to be stored; the duration of storage; and if the fuel is to be stored at reactor sites or centralised stores.

Reprocessed uranium is significantly less radioactive than spent fuel or HLW, potentially reducing storage costs. The total costs of reprocessing are more expensive than interim storage pending final disposal. Should indefinite storage (rather than geological disposal) be the final management option for spent fuel, then reprocessing could be more attractive.

2.3.3.5 Costs of geological disposal

Projections of cost savings for the closed fuel cycle have been presented in term of reduced volumes of HLW in need of disposal. Reprocessing generates other waste streams in need of management, such as ILW and LLW. The costs of managing these materials have to be set against the costs of storing and disposing spent fuel from an open fuel cycle. No GDF for spent fuel or HLW is yet operational, although GDF plans are advanced in Sweden and Finland. The only operating GDF to date is the Waste Isolation Pilot Plant (WIPP) in USA. Located 650 metres below ground, WIPP opened in 1999 and has been disposing of lower activity, long lived waste generated by reactors and other facilities associated with nuclear weapons production. This lack of practical experience in geological disposal creates major uncertainties making it difficult at the present time to estimate the relative costs of geological disposal when comparing fuel cycle choices.

2.3.3.6 Sustainability concerns

In the near term, a nuclear renaissance is expected to be dominated by thermal LWRs operating an open fuel cycle. The closed fuel cycle could become more economically attractive if this places pressure on uranium resources. It is worth noting that China and India are pursuing a closed fuel cycle due to their limited domestic sources of uranium. The option of moving to a closed cycle is kept open in the medium term since LWRs can be designed to irradiate MOX fuel. These LWRs need to be licensed appropriately.

Sustainability concerns are likely to be most acute in the long term, and could coincide with expectations of a possible second wave of nuclear power expansion from 2040 onwards. This could involve the commercial deployment of fast reactors.

The changing nature of the nuclear industry

3.1 Safeguarding civil nuclear power

The dual use nature of nuclear technology and materials is managed through the NPT, which was agreed in 1968 and came into force in 1970. The NPT defines a nuclear weapon state (NWS) as one that has manufactured and exploded a nuclear weapon or other nuclear explosive device prior to 1 January 1967. This includes China, France, Russia, UK and USA. Three other states have exploded a nuclear device, namely India, North Korea and Pakistan, while Israel is also believed to possess nuclear weapons. Non-nuclear weapon states (NNWS) can gain access to nuclear materials and technologies in return for commitments to forsake acquiring or developing nuclear weapons. Under the NPT, all NNWS accept IAEA safeguards on their nuclear activities to verify these commitments not to proliferate are being implemented (see textbox 1).

3.2 Separating nuclear weapons programmes from civil nuclear power

In some NWS, the civil nuclear industry has matured to become solely a provider of electricity. France, UK and USA have fully separated their nuclear weapons programmes from their civil nuclear power programmes. All three countries make specific civil nuclear facilities available for inspections under their IAEA voluntary offer agreements (see textbox 1). Only the UK and France are under specific obligations to place them under safeguards. The European Atomic Energy Community (EURATOM) Treaty requires France and UK to place their entire civil nuclear power programme under its safeguard system, including enrichment, reprocessing and fuel fabrication facilities. All states with nuclear weapons programmes should be persuaded to separate them from their civil nuclear power programmes, placing the latter under international safeguards to verify they do not provide materials for nuclear weapons.

3.3 Universal implementation of international safeguards

The effectiveness of international safeguards depends on the extent of the IAEA's authority, which remains uneven from state to state. Safeguards agreements are in force in the majority of states party to the NPT. IAEA comprehensive safeguards and the Additional Protocol should become the non-proliferation standard for a nuclear renaissance.

The negotiators of the NPT clearly regarded nuclear proliferation as an event, namely the explosion of a nuclear device. Today, proliferation is increasingly being viewed as a process with at least three stages:

Textbox 1 **Nuclear safeguards**

Under the Nuclear Non-Proliferation Treaty (NPT), all non-nuclear weapons states are required to conclude a 'comprehensive safeguards agreement' with the International Atomic Energy Agency (IAEA). This involves declarations of the quantities and location of all nuclear material and facilities within their territories or under their jurisdictions. The IAEA verifies the correctness of these declarations through measures to verify: the design and operation of nuclear facilities; nuclear material accountancy; and the containment and surveillance of materials and facilities through tags, seals and cameras. Nuclear weapon states are not obliged to do likewise. They have concluded 'voluntary offer agreements', choosing to place certain facilities or nuclear material under IAEA safeguards. India, Israel and Pakistan are not party to the NPT but have agreed 'item specific safeguards agreements' with the IAEA whereby they undertake not to use specified material, facilities and some other items to further any military purpose.

Despite its comprehensive safeguards agreement, Iraq had been conducting a clandestine nuclear weapons programme prior to 1993 centred on the same nuclear site where the IAEA conducted routine inspections of declared nuclear material. This demonstrated that IAEA safeguards needed to be strengthened to include assurances of the absence of any clandestine activities at undeclared facilities. This required new legal authority, resulting in the adoption in 1997 of the Model Additional Protocol to Agreement(s) between State(s) and the IAEA for the Application of Safeguards. This has equipped the IAEA with new tools to detect clandestine activities, including environmental sampling, satellite imagery and other novel technologies, as well as nuclear trade analysis and open source information collection.

a political decision to invest in a nuclear weapon capability; the acquisition or manufacture of the necessary nuclear and non-nuclear materials and physical components; and the weaponisation of these materials and components.

Nuclear power reactors and their operation alone are not the primary proliferation risk. It is the material that they use and produce. The historical record shows that IAEA safeguards have proven to be effective to make the diversion of nuclear materials from declared facilities unlikely (APS 2005). Given the likelihood of detection, other proliferation threats may be more likely (see texbox 2).

3.3.1 Clandestine nuclear activities

It remains unclear whether the political, economic and military pressures to sustain the clandestine nature of nuclear weapons programmes have insulated them from civil activities. The A.Q. Kahn network concealed the illicit procurement of technology for nuclear weapons programmes in Pakistan, North Korea, Iran, Libya and possibly elsewhere within an established process. This involved indirect trading companies and a number of middle men, as well as mislabelling of equipment and falsification of end user certificates and final destinations. URENCO now operates its uranium enrichment activities under strict 'black box' arrangements (see textbox 3). It is unclear if a similar arrangement can be applied to reprocessing, especially when the PUREX process is widely documented and accessible if a country wishes to explore reprocessing.

3.3.2 Misuse of dual use know how

It is unclear whether personnel and knowledge gained from civil nuclear power programmes have directly or indirectly assisted nuclear weapons programmes. In some cases, such as in Libya, South Africa and Syria, declared facilities may have helped to train personnel, who were then directed to work on weapons programmes at undeclared facilities (IISS 2008). The USA regarded Iranian attempts to rebuild and operate the civil reactor at Bushehr, after it was attacked by Iraqi air strikes during the Iran-Iraq war in the 1980s, as posing an unacceptable risk. This led to the USA's prolonged (and ultimately unsuccessful) diplomatic campaign to prevent this during the 1990s.

To ensure nuclear skills continue to be used responsibly, education and awareness raising courses on nuclear non-proliferation and nuclear security should be included in relevant university and industrial training courses. As part of their induction, researchers at postgraduate level could be informed about the ethical and legal responsibilities relating to their work. This could be included in existing induction courses that deal with health, safety and other general laboratory training. Outlining the implications for researchers of the NPT and other international treaties would be an integral part of this training. Education may also be needed for established researchers. Training and education have associated costs that need to be factored into organisations' budgets and resource requirements.

Codes of conduct can serve as a valuable education tool to address the risk that scientific research will be misused (Royal Society 2005a). They can remind scientists of their legal and ethical responsibilities, and to consider both the benefits and potential consequences of dual use research. By involving extensive consultation amongst the target groups, the process of producing these codes is itself an important mechanism to raise awareness. Despite some scepticism about the value of such codes, the scientific community and industry could take the lead in creating them to pre-empt their introduction through legislation or other 'top down' approaches (Royal Society 2004).

3.4 The unattractiveness of civil materials for nuclear weapons use

Plutonium used in nuclear weapons has a high concentration of fissile Pu-239. This 'weapons grade' plutonium is produced via very low burn up when fuel is irradiated for a short time, even just for a few weeks. In civil nuclear power reactors, fuel is irradiated over several years to maximise its energy yield for electricity production. This significantly reduces the attractiveness of plutonium in civil spent fuel for nuclear weapons use (IAEA 2010a). Adapting civil nuclear power reactors to lower burn ups would be difficult to conceal due to the safeguards arrangements in place, as well as the observable effects on national electricity generation. Nuclear fuel should continue to be developed and nuclear reactors configured to enable the maximum burn up of fuel consistent with efficient and economic operation (see section 4.1.1.1).

Textbox 2 **Major proliferation threats posed by the management of spent fuel**

Diversion from declared facilities

Spent fuel could be removed from storage ponds and even replaced with dummy material, especially if it had been stored for a long time so that the heat load and radioactivity is reduced. This could make spent fuel assemblies more accessible and easier to handle, although it would still be highly radioactive, heavy and cumbersome to move.

Diverting separated plutonium at a declared reprocessing facility is possible, but would be complicated. Operators could separate extra plutonium dioxide and then falsify the performance records of the facility, as well as the fuel history of the reactor. The facility's design could be modified to allow separated plutonium dioxide to be secretly removed, returning the facility back to its original configuration prior to the next IAEA inspection. This extra plutonium dioxide could be disguised as Material Unaccounted For (MUF). This is the standard accounting term for the difference between the amount of material that is calculated to be present in a facility given its operating records and the amount that actually is present. MUF is inevitable in reprocessing and MOX fabrication facilities due to the uncertainties inherent in measurement systems, as well as accumulation in piping within the facility. Between IAEA inspection visits, the hot cells of a declared facility could be used to develop reprocessing activities to take place on a larger scale at an undeclared facility located elsewhere. Both Egypt and Iran admitted to past small scale reprocessing of irradiated uranium targets but reported this activity to the IAEA many years later (IISS 2008).

Waste packages could be substituted at the surface of a Geological Disposal Facility (GDF) for dummy canisters. Undeclared retrieval of wasteforms from underground vaults is also possible. A waste container could be opened underground and spent fuel assemblies removed and transported to the surface or even reprocessed underground.

Breakout from the NPT

The Nuclear Non-Proliferation Treaty (NPT) allows a state to give three months notice, then legally opt out of the treaty and renounce its safeguards obligations. This is of particular concern when a state has capabilities across the full civil fuel cycle, especially enrichment or reprocessing facilities. Timing would be crucial to maximise the amount of weapons grade plutonium that could be produced before experiencing the economic, political and possible military consequences of breakout. A multi-country breakout scenario is also possible whereby one country could produce spent fuel that is then reprocessed in another (IISS 2008). Given allegations of this type of collaboration between North Korea and Syria, this scenario should not be overlooked.

Clandestine activities at undeclared facilities

The size and complexity of an industrial scale reprocessing plant needed to produce weapons grade plutonium is too large to be easily hidden. A smaller clandestine reprocessing plant could be built. A small research reactor could even be disguised within a non-nuclear industrial complex and use associated hot cell facilities to carry out small scale reprocessing. Facilities could be constructed in advance of any reprocessing, providing a state with a potential break out capability. The US national laboratories have demonstrated the feasibility of small 'quick and dirty' clandestine reprocessing facilities specifically for separating small amounts of plutonium for nuclear weapons use. Studies by Sandia National Laboratory in 1977 and 1996, respectively, have outlined designs that could possibly be built within six months and produce plutonium for nuclear weapons within a few extra months (GAO 1978, DoE 1996). There are some disagreements on the feasibility of these designs and ongoing debate about how technologically advanced a state would need to be to succeed in implementing them (Findlay 2010).

Clandestine tunnels could be excavated into a GDF or out from a GDF to the surface or nearby tunnel system. This would require a determined and sophisticated effort by the state. The drilling, mining and processing involved would produce detectable signals and indicators of diversion (IAEA 2010b).

Best practice for non-proliferation

- All states with nuclear weapons programmes should separate them from their civil nuclear power programmes, and then place the latter under international safeguards.
- All non-nuclear weapon states with existing nuclear power programmes or embarking on nuclear power for the first time should adopt and implement IAEA comprehensive safeguards and the Additional Protocol.
- Universities and industry organisations should develop education and awareness raising courses on non-proliferation and nuclear security to be included in the training of personnel in the nuclear industry, including scientists, engineers, technicians and managers.
- Nuclear fuel should be developed and nuclear reactors configured to enable the maximum burn up of fuel, thereby decreasing the attractiveness of plutonium in spent fuel for use in nuclear weapons. To be feasible, this needs to be consistent with efficient and economic operation.

3.5 The internationalisation and multinational nature of nuclear power

At the start of the Atomic Age and during the time of NPT negotiations, energy markets were generally directed by governmental monopolies and nuclear power programmes driven by national energy planning. This implied that each country needed to develop its own national industry. Recommendations at the time for new multinational practices could be prompted by intergovernmental agreements, domestic legislation and licensing arrangements, but commercial considerations complicated their implementation.

Today, globalisation and the liberalisation of energy markets provide an economic infrastructure that has facilitated the internationalisation of the nuclear fuel cycle. Countries now look to the international market for both the supply chain (including technological components and human resources), as well as services, including uranium enrichment, fuel fabrication, reactor construction and reprocessing.

Due to concerns about security of supply, further incentives may be necessary to supplement these international services. Customers could be offered a direct stake in the ownership and/or management of the facilities providing the fuel cycle service through various types of multinational arrangements. This could make financing easier when it may be difficult to mobilise enough capital nationally. Risks could be shared, as well as financial losses in case of technical or market failure. There is no single formula to satisfy all states' needs, whether service provider or customer (Scheinman 2004). Different models of multinational arrangements may be necessary (see textbox 3).

Multinationalisation could be considered alongside moves in many countries of national nuclear facilities from state-run enterprises to privately owned and operated, multinational companies. Globalisation and the liberalisation of energy markets have also provided the conditions that support competition, leading to the merging of nuclear power companies. This reflects practices already well established in many other high technology industries that are simply not sustainable at an individual state level given the high costs involved with development.

3.5.1 Benefits for non-proliferation

3.5.1.1 Increased transparency of national programmes

Multinational companies owning and/or operating fuel cycle facilities could be less vulnerable to a state's desire to proliferate than a single state owned and operated nuclear organisation. Overt or covert diversion would be more difficult. A thoroughly interconnected global nuclear industry could allow earlier warning and 'whistle blowing' of suspicious activities. International professional networks could maintain greater awareness of colleagues' activities.

Multinational arrangements could serve as a confidence building measure. If a country's desire to proliferate is due to concerns that another country may do so too, then they could both voluntarily choose to participate in an arrangement that constrains their independent national capabilities to develop sensitive dual use technologies (Smart 1980). A country could participate in a similar arrangement to demonstrate its clear intentions not to proliferate, thereby gaining political legitimisation to participate in certain fuel cycle activities. NWS may need to be willing to restrain their national capabilities to avoid accusation by NNWS that multinational arrangements are discriminatory.

Textbox 3 **Models of multinational fuel cycle arrangements**

Eligibility for services

Commercial enrichment services are provided by the European Gaseous Diffusion Uranium Enrichment (EURODIF) company and URENCO. EURODIF was set up in 1973 by France, Belgium, Italy, Spain and Sweden to provide enrichment services to these countries. Sweden withdrew in 1974 and in 1975, its 10% share in the company was passed to Iran through the establishment of a joint French-Iranian enterprise. Today EURODIF is a subsidiary of AREVA and operates an enrichment plant at the Tricastin nuclear site in France. URENCO was founded in 1971 by the Treaty of Almelo, signed by the governments of Germany, the Netherlands and the UK. Whereas EURODIF provides enriched uranium to its members only, URENCO provides enrichment services for its members and others outside the company.

Different degrees of joint ownership

Joint ownership of fuel cycle facilities need not be proportionate. Shares in EURODIF correspond to the level of its member's investment. Initially, URENCO facilities were to be built with equal ownership and investment by the three partners (the UK government, Dutch government and German utilities, EON and RWE), regardless of location. No single country would then have a majority of shares in the company to prevent dominance in decision making.

Different degrees of joint operation

Joint ownership does not necessarily entail joint operation. A facility can be under multinational ownership yet nationally operated, as long as national decision making is subordinate to the decision of the group of owners (Scheinman 2004). The operation of EURODIF's enrichment facilities remains a responsibility of the host state, France. The French Commissariat à l'énergie atomique (CEA) proposed that the new Georges Besse II facility to replace EURODIF should be open to international partnerships.

Different degrees of access to technology

EUROCHEMIC provided direct access to reprocessing technology. Set up in 1957 by thirteen OECD member governments, EUROCHEMIC acted as a training centre to develop industrial experience of reprocessing. A pilot reprocessing plant in Belgium was commissioned in 1966, as well as facilities for nuclear chemistry research. It was not set up as an alternative to national reprocessing efforts. Due to competition from the latter, however, operations ceased in 1974 and EUROCHEMIC's installations were progressively taken over by the host country, Belgium.

In contrast, France provides and controls the sensitive technology used by EURODIF. Other non-sensitive technology is shared. After the revelations about A.Q. Kahn, URENCO placed stricter controls on its technology. In 2003, URENCO was divided organisationally into Enrichment Technology Corporation (ETC) and URENCO Enrichment Company Ltd (UEC). ETC is a joint venture between URENCO and the French company, AREVA. It provides enrichment technology to UEC, AREVA and, soon, to the National Enrichment Facility currently being constructed in the USA. ETC develops centrifuge technology, designs centrifuge enrichment plants and manufactures centrifuges. UEC owns and operates enrichment plants. Centrifuges are provided under a 'black-box' arrangement whereby they are supplied, complete and ready assembled by ETC. The operator has no access to the centrifuges directly but only ever interacts with the outside of the black box. The black box remains the property of ETC and must be returned to ETC for repair or disposal when no longer needed. In a break out scenario, the facility operators could decide to misuse and modify it to produce highly enriched uranium. Whilst a team of ETC engineers may perhaps need approximately three months, other engineers without any experience of the technology within the black box would need 12 months or more to carry this out. This could provide extra time for the international community to take action.

3.5.1.2 Proactively assisting the IAEA

Trade analysis has become an important aspect of the new State Level Approach to safeguards, especially in light of the A.Q. Khan network (see textbox 1). Yet the IAEA's powers are constrained by its state-centric Statute. The IAEA can only gain export and import data through the voluntary support of member states. Multinational companies may have a greater awareness than national governments about the global circulation of materials, technologies and personnel. They may be less constrained to proactively provide trade information directly to the IAEA, as well as informing the IAEA about technology relevant to safeguards being developed outside of member state support programmes and national government laboratories.

3.5.1.3 Reinforcing safeguardability

Internationalisation can help to reduce the number of facilities in need of safeguarding, thereby allowing the IAEA to focus its resources more effectively. This is particularly important for spent fuel management since this is one aspect of the fuel cycle that every nuclear country, however small, must address.

Many countries recognise the economic benefits of seeking international fuel cycle services rather than developing national commercial fuel cycle facilities. The national rights of states 'to develop research, production and use of nuclear energy for peaceful purposes without discrimination and … participate in the fullest possible exchange of equipment, materials and scientific and technological information for the peaceful uses of nuclear energy' remain central to the NPT (UN 1970). Pilot research facilities may still be sought to maintain a national skills base in case the international market should fail. R&D activities can be prone to unauthorised or unreported experiments (see textbox 2). Pilot research facilities still need to be fully safeguarded. Consideration should be given to offering some countries a direct stake in the ownership and/or management of research facilities elsewhere. Carrying out R&D on dual use technology through an international framework increases transparency and maintains confidence that there are no clandestine nuclear weapons programmes. Knowledge could still be misused, as the case of A.Q. Khan demonstrates.

3.5.1.4 Increasing the costs of break out

Even if certain arrangements do not limit the development of fuel cycle facilities, multinational ownership and/or management maintains the transparency of these activities. This does not eliminate proliferation risks. The host country could still expel multinational staff and break out of the NPT, although the involvement of other countries in this multinational arrangement would significantly increase the political costs of doing so.

3.5.1.5 Addressing country breakup

Internationalising the management of nuclear materials could mitigate the consequences of any future breakup of countries or collapse of their political regimes. Thousands of scientists involved with nuclear weapons programmes were left unemployed or underemployed following the dissolution of the USSR. There were concerns that they could be tempted to sell their expertise on the black market, leading to initiatives in 1990s to redirect former weapons scientists into civil employment. A loss of control over nuclear materials also raised concerns about the illicit trafficking in these materials that could aid countries of proliferation concern and even non-state groups.

3.5.1.6 Spreading best practice

The opportunity for technology transfer, or at least hands on training, may be an important attraction of multinational arrangements. While the scientific principles of enrichment and reprocessing may be well known, the ability to operate a commercial enrichment or reprocessing facility successfully presupposes operational experience of the technology. Such arrangements could help to spread best practice, especially from countries with experience of nuclear power to those embarking on nuclear power for the first time.

3.5.2 Benefits for nuclear security

Internationalising the management of nuclear materials would help countries that lack the national infrastructure to do so securely. This could help address security threats affecting the management of spent fuel.

3.5.2.1 Theft of material during reuse

The likelihood that a sufficient amount of spent fuel could be stolen for use in a radiological dispersal device is small (NAS 2006). According to the US National Academies of Science (NAS), the high radioactivity and sheer bulk of spent fuel assemblies means 'that the removal of a spent fuel assembly from the pool or dry cask would prove extremely difficult under almost any terrorist attack scenario. Attempts by a knowledgeable insider to remove single rods and related debris from the pool might prove easier; but the amount of material that could be removed would be small. Moreover, superior materials could be stolen or purchased more easily from other sources' (NAS 2006). The protection of spent fuel rods not contained in fuel assemblies, especially in facilities where individual fuel rods or portions of rods are being stored, should not be overlooked (NAS 2006).

3.5.2.2 Use of separated civil plutonium in a dispersal device

The theft of separated plutonium is a major security concern at reprocessing and MOX fabrication facilities. Because it emits alpha but almost no beta or gamma radiation, separated plutonium could be relatively safely handled by those who access it provided precautions are taken to limit exposure. If stolen, separated plutonium may be more easily be used in a dispersal device. As a powder, separated plutonium could be toxic if ingested or inhaled.

3.5.2.3 Use of separated civil plutonium in an improvised nuclear weapon

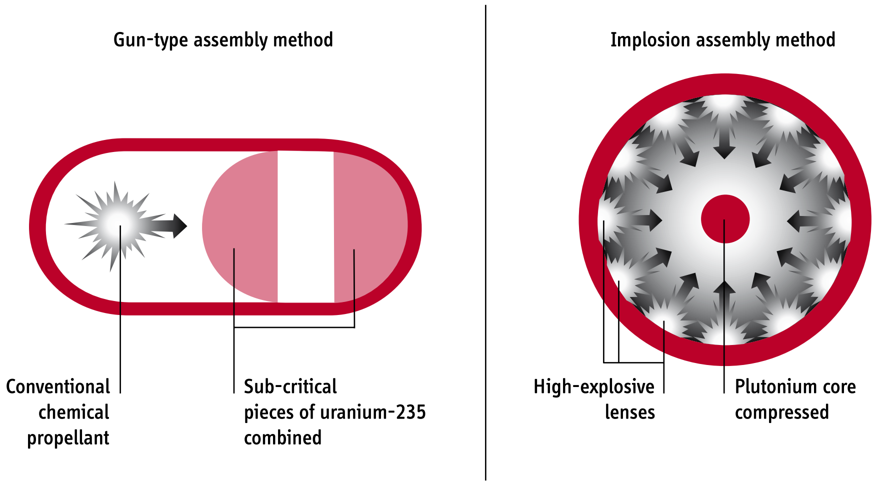
There are debates about whether separated civil plutonium could be used in an unsophisticated and crudely designed nuclear weapon. If HEU is not easily accessible, then plutonium from civil nuclear power programmes could be sought. This would pose a set of major technical challenges:

- Spent fuel contains a number of intrinsic barriers to proliferation. Having been irradiated and removed from a reactor, the intense heat and radioactivity of spent fuel makes the plutonium it contains highly inaccessible.
- Spent fuel needs to be reprocessed to access the plutonium it contains, presupposing (access to) major industrial capabilities. Similar capabilities are also necessary to separate plutonium from unirradiated MOX fuel. This would be easier than reprocessing spent fuel since fresh fuel does not contain highly radioactive fission products.
- Plutonium dioxide needs to be converted into a plutonium metal to be used easily in a nuclear weapon. Various techniques to reduce plutonium dioxide to plutonium metal are already available in the public domain.
- The design of plutonium based nuclear weapons is more technologically demanding than HEU based, gun assembly designs (see textbox 4). Sophisticated metallurgical and machining expertise is needed to manufacture plutonium metal into a suitable geometry with a highly uniform density and composition, and to shape the component parts. Advanced physics and engineering expertise is needed to ensure the assembly's components are accurately aligned, and that the functioning of the detonators is highly synchronised.
- The isotopic quality of plutonium from civil nuclear power programmes complicates its use in a nuclear weapon. Advanced nuclear weapon states may have the technical capability and knowledge of sophisticated nuclear weapon designs to use reactor grade material to produce reliable explosive yields comparable to those made from weapons-grade plutonium. A technologically advanced, proliferating state could use less sophisticated nuclear weapon designs to produce less reliable explosive yields, although greater than one or a few kilotons, the so-called 'fizzle yield'. A less technologically advanced, proliferating state could possibly use reactor grade plutonium in nuclear weapon designs no more sophisticated than those used in first-generation nuclear weapons to produce a fizzle yield (DoE 1997).

There are differences in expert opinion about whether non-state groups could access the extensive scientific expertise and technical infrastructure required to overcome these challenges. Nonetheless, complacency must not be introduced into the management of plutonium (see section 6.1).

Textbox 4 **Nuclear weapons basics**

In a nuclear explosion, a mass of fissile material has to be transformed from a subcritical to critical state to sustain a 'run away' chain reaction. The simplest design to produce a critical mass is to fire one subcritical mass of highly enriched uranium (HEU) down a gun barrel at another subcritical HEU mass, using conventional explosives. The reliability of the nuclear explosion depends on the initiation of the chain reaction. An initiator produces a timed burst of neutrons to trigger the reaction. The spontaneous production of neutrons in the fissile material also needs to be considered. The spontaneous fission rate of U-238 is 14 neutrons per kilogram per second (n/kg/s). For U-235, it is less than 1 n/kg/s. 100 kg of HEU produces approximately 100 neutrons per second. The critical mass therefore needs to be assembled within approximately 1 millisecond so that the number of spontaneous fission neutrons produced has a negligible effect on initiation. The two sub critical masses could be brought together over a distance of several tens of centimetres within this 1 millisecond period. This is comparable to the typical velocity of a gun shell, and is the basic principle behind nuclear weapons based on the 'gun assembly design'. One drawback of the gun assembly design is its vulnerability to background neutrons, as well as the relatively large amount of fissile material required. A plutonium based weapon, using Pu-239, may be more attractive. An alternative design is necessary due to the larger spontaneous fission rate of Pu-240, which produces approximately 50,000 n/kg/s. To ensure these neutrons do not affect initiation, 10 kg of weapons grade plutonium would need to be assembled into a critical mass within 1 microsecond. This is much faster than a gun shell, so a plutonium based weapon is based on an 'implosion design'. A subcritical shell of plutonium is surrounded by conventional explosives that cause it to implode and achieve a critical mass. HEU can also be used in an implosion designed nuclear weapon.



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3.5.2.4 Attack on, or sabotage of, storage facilities

An attack on storage facilities and/or sabotage of their cooling systems could take various forms (Beach *et al* 2009). The vulnerabilities of these facilities around the world are site specific. They will each be affected by a range of external factors, such as the nature of the attack; the layout of other structures on site; and the surrounding terrain that could make certain types of attacks more difficult to carry out. Nonetheless, ponds are designed with high structural integrity. Most ponds are semi-embedded in the ground to address vulnerabilities to line of sight attacks and aeroplane crashes.

Post-Fukushima, moving spent fuel once it has sufficiently cooled from ponds close to, or integral with, reactors to alternative storage elsewhere is likely to become standard practice. Robust arrangements for continuous and back up cooling and onsite power are essential to guarantee security (and safety) over the long term (see section 6.2).

3.5.2.5 Multi-barrier concepts

Disposal concepts for spent fuel and HLW are still under R&D. The majority of GDF concepts involve a set of surface facilities to receive, treat, package and temporarily store wastes before they are transferred to a series of deeply excavated chambers, caverns or vaults at depths of several hundred metres underground. There is a consensus that best practice should involve a multi-barrier approach, incorporating combinations of engineered and natural barriers. Wastes may first need to be reconditioned into stable and durable wasteforms. They are then to be immobilised so that radionuclides cannot move and leach into the surrounding groundwater. In the case of spent fuel, the fuel material itself and the cladding provide the first barrier. The second barrier is provided by packing the waste into containers that can provide mechanical stability and protection from corrosion. The third barrier is provided by emplacing these containers in the GDF and backfilling the void around. The host rock itself provides a fourth barrier. Finally, the GDF will be closed to limit groundwater, and eventually waste movement, when the integrity of the canisters finally breaks down.

Geological disposal offers a high degree of security. Underground arrangements reduce the risks of unauthorised access and make the GDF less vulnerable to attack. Wasteforms are already in an immobilised and packaged, non-dispersible form, which reduces risks further. Should an attack take place, the release of radiological material can be contained.

According to best practice, physical protection measures should apply to all nuclear material in use, storage and during transport at all nuclear facilities (IAEA 2011). These measures should also extend to the disposal of nuclear materials and decommissioning of nuclear facilities. Security considerations should also factor in decisions about the retrievability of GDFs (see section 4.4.2.3).

3.5.3 A World Nuclear Forum

Global governance does not reflect the internationalisation of the nuclear fuel cycle and multinational reality of the nuclear industry. This has important consequences since the nuclear industry has a supranational interest in non-proliferation and nuclear security. An act of proliferation from a single civil facility or major nuclear security incident would affect the credibility of the entire industry worldwide.

A World Nuclear Forum is now timely, providing an interface between CEOs and government leaders to explore their respective views on the future development of nuclear power and responsibilities for non-proliferation and nuclear security. This Forum must consider the changing geography of nuclear power. It should engage leaders in countries at the forefront of a nuclear renaissance and other countries embarking on nuclear power for the first time (see section 1.1). These countries may have ambitions to provide fuel cycle services to other countries at some stage themselves, and so should be engaged on how they can help to promote and international and multinational practices.

The proliferation resistance of spent fuel management

4.1 The potential of intrinsic proliferation resistance barriers

The chemical, isotopic and radioactive properties of spent fuel present various intrinsic barriers to proliferation that reduce the accessibility of civil fissile materials and their attractiveness for use in nuclear weapons. Various international R&D programmes are developing measures that enhance these barriers (see textbox 5). These programmes need to ensure such measures are not only technologically feasible, but also politically acceptable and economically attractive.

Textbox 5 **International R&D programmes for non-proliferation and nuclear security**

The US-led Generation IV International Forum is a leading R&D collaboration on six advanced reactor systems and associated fuel cycles. These include: the Very High Temperature gas reactor, sodium cooled faster reactor, supercritical water cooled reactor, gas cooled fast reactor, lead cooled fast reactor and molten salt reactor.

The IAEA-led International Project on Innovative Nuclear Reactors and Fuel Cycles is developing high temperature reactors, fast reactors and accelerator driven systems, as well as small and modular reactors.

The US-led Next Generation Safeguards Initiative is one of the leading international programmes developing the safeguards infrastructure for the next 25 years. This includes developing safeguards concepts for new reactor types and their associated fuel cycles.

Set up in 2006 under the Bush Administration, the Global Nuclear Energy Partnership (GNEP) envisioned a consortium of technologically advanced nuclear power countries providing international fuel cycle services to other countries. The Obama Administration cancelled the domestic aspect of GNEP, which sought the near term deployment of fast reactors and construction of a reprocessing plant in the USA. In 2010, GNEP's international component was renamed as the International Framework for Nuclear Energy Cooperation with a renewed mission and more inclusive approach. There are 25 participating countries, three permanent international observers (IAEA, Generation IV Forum and EURATOM) and 31 observer countries. Its Executive Committee consists of Ministerial officials, and two Working Groups have been set up. France chairs a Working Group on Reliable Nuclear Fuel Services with a remit that includes the legal, political and commercial conditions for international fuel cycle arrangements. The UK chairs a Working Group on Infrastructure Development, focusing on the management of spent fuel and radioactive waste, as well as safety, security and non-proliferation aspects of nuclear power regulation.

The Global Initiative to Combat Nuclear Terrorism (GICNT) was launched by Russia and USA in 2006. By 2010, there were around 80 participating countries, and the IAEA and EU are observers. GICNT convenes counter proliferation and counter terrorism experts to foster best practice in a legally non-binding environment through various meetings and workshops, as well as in-field demonstrations and table top exercises. GICNT fosters collaboration between academia, government and industry. GICNT's research priorities include nuclear forensics and the detection of special nuclear material, as well as developing national regulatory and legal infrastructures to address nuclear terrorism.

Under the Global Threat Reduction Partnership (GTRP) launched by the G8 in 2002, the USA committed $10 billion over 10 years to be matched by the other G8 partners. GTRP is working to improve nuclear security globally in collaboration with the International Atomic Energy Agency (IAEA) Office of Nuclear Security through contributions to the IAEA Nuclear Security Fund. GTRP was not extended for another 10 years at the recent G8 meeting in Canada. Given current financial problems, countries were reluctant to make commitments when it is unclear what exactly the funds would be spent on. With better clarity on its future role and geographical focus, GTRP could be extended beyond 2012.

4.1.1 Enhancing isotopic barriers

4.1.1.1 Denaturing plutonium in standard LWRs

The 'reactor grade' plutonium in civil spent fuel has a lower fraction of Pu-239 due to the high levels of burn up in civil nuclear power reactors. It has a greater quantity of undesirable isotopes of plutonium that would complicate the use of civil nuclear materials in nuclear weapons, decreasing the reliability of a nuclear explosion (see figure 5). Pu-238 decays relatively rapidly, generating significant amounts of heat. Pu-240 could set off the chain reaction prematurely, substantially reducing explosive yield as the weapon may blow itself apart and cut short the chain reaction. Pu-241, although fissile, decays to Am-241, which absorbs neutrons and emits intense gamma radiation. These isotopes require careful management and extensive shielding to protect personnel when handling these materials, and they could damage other components in a nuclear weapon. There is no well defined threshold for this higher 'burn up' above which plutonium becomes unusable for weapons, so the working hypothesis is that all reactor grades of plutonium pose a proliferation risk (IAEA 2010a).

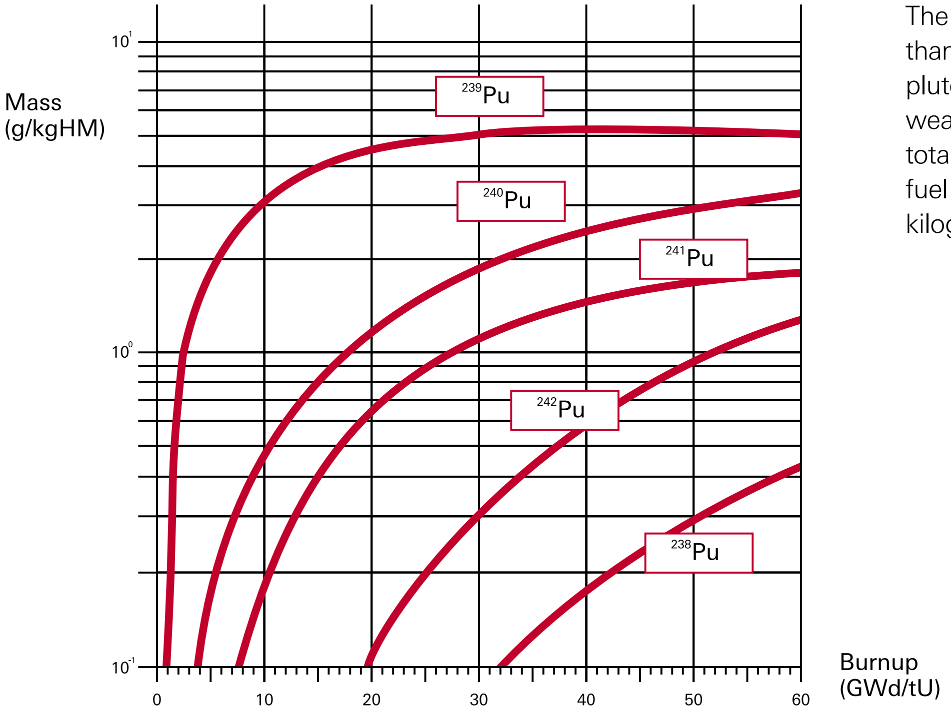
There are practical limitations on the level of burn up that can be reached in current LWRs. Higher burn ups require fresh fuel to be enriched to higher levels of fissile U-235, which would increase costs. A balance would need to be struck between the extra electricity that can be generated and the extra costs of fuel manufacture, especially when it would entail redesigning fuel fabrication facilities. Currently, this balance is around 55 GigaWatt days per tonne of uranium (GWd/tU). The maximum enrichment currently permitted by regulators is 5% due to handling constraints and proliferation concerns. An enrichment of 5% would allow burn ups of around 65 GWd/tU to be achieved.

The behaviour of fuel at increasingly high burn ups would have to be tested. As the fuel is irradiated increasing quantities of fission products are formed, creating greater internal pressures within fuel rods that can affect their integrity. Rod failure can result in the release of fission products into the coolant and core and is to be avoided. The international OECD Halden reactor project has been leading collaborative R&D to increase the burn up limits of the fuel in line with economic performance. This is necessary to provide more reliable and accurate assessments of fuel performance to satisfy regulators that the fuel can be safely taken to high burn ups.

The additional irradiation of plutonium in MOX fuel further reduces the isotopic quality of plutonium in spent MOX fuel. If MOX fuel is used, fuel fabrication costs do not vary significantly with burn up while the amount of electricity generated increases proportionally. This creates an incentive to increase the burn up of MOX fuel beyond those for uranium fuel. Instead of requiring higher enrichment levels, a greater content of plutonium would be necessary. In a core that contains both uranium dioxide and MOX fuel assemblies, this difference in burn ups would disrupt the reload schedules and probably give rise to greater down time that would be unsatisfactory for the reactor operator. In a reactor core designed for 100% MOX fuel, there would be no such limitation. Burn up levels would be determined by the fuel's performance in the reactor and the limitation of plutonium content that can be handled in the MOX fabrication facility.

Higher burn up is achieved by creating more fissile material in the reactor during its operation. FBRs have higher burn ups because they have a higher 'conversion ratio' (which signifies the relationship between the rates at which fissile material is produced and consumed in a nuclear reactor). FBRs have a conversion ratio of unity or higher: they produce fissile material as fast as it is consumed. Thermal LWRs have conversion ratios between 0.5 and 0.6. The reduced reactivity limits the level of burn up. It may be feasible to operate a closed fuel cycle using advanced hard spectrum LWRs to produce conversion ratios nearer to unity if an epithermal (between thermal and fast) spectrum is possible. This could be achieved by reducing the moderator to fuel ratio and/or using heavy water as a coolant since it is a less efficient moderator. R&D to demonstrate the technical, safety and economic viability of high conversion LWRs has not been carried out (MIT 2011).

Figure 5 **This graph illustrates how the fraction of plutonium isotopes in spent fuel changes as a nuclear power reactor is operated at higher burn ups (note that the scale of the vertical axis is logarithmic).**



The build up of isotopes other than Pu-239 makes civil reactor plutonium less attractive for nuclear weapons use. At high burn up, the total mass of plutonium in spent fuel is approximately 10 grams per kilogram of heavy metal (g/kgHM).

4.1.1.2 Thorium

Alternatives to uranium or plutonium fuels, such as thorium, have been advocated because the thorium fuel cycle produces less plutonium in its spent fuel (see section 2.2.1). There is an emerging consensus that the thorium cycle may be no more proliferation resistant than uranium or plutonium based fuel cycles. An open thorium fuel cycle will generally require U-235 or Pu-239 fuel to initiate it. Spent thorium fuel that contains fissile U-233 can be reprocessed and the U-233 used to initiate the cycle instead. U-233 could be used in nuclear weapons.

The thorium fuel cycle is not considered to be mature in any area but could potentially be used in LWRs (NNL 2010). The experience of using thorium in a LWR on a near-commercial scale is now dated and not adequate to meet current licensing requirements (NNL 2010). There has been no experience of using thorium in HWRs, although much of the technology is demonstrated at a laboratory scale. Thorium could be used in fast reactors and accelerator driven reactor systems, but these remain viable only in the longer term.

4.1.2 Enhancing radiation barriers

4.1.2.1 Co-processing plutonium

Plutonium in spent LWR fuel operating on an open fuel cycle is protected by the radiation of spent fuel (at least in the near term). When operating on a closed fuel cycle, this radiation barrier decreases during reprocessing when fission products are extracted and the plutonium nitrate stream is separated from the uranium.

There is ongoing international R&D to avoid the separation of pure plutonium, instead co-processing it with more radioactive materials This R&D involves both aqueous techniques, such as co-extraction of actinides (COEX) and uranium extraction (UREX), as well as non-aqueous techniques, such as pyroprocessing (PYROX). Developed in France, COEX extracts plutonium together with uranium. A French-Japanese-US research programme is also developing processes involving the separation of longer lived minor actinides, such as americium and curium. This could even be implemented with COEX so that the uranium, plutonium and minor actinides are kept together and used as fuel for fast reactors. RRP in Japan uses a modified PUREX process that recombines some uranium with the separated plutonium so that the final product is a mix of plutonium and uranium oxides. Research in France has shown that UREX can be supplemented to recover the fission products iodine and technetium. Further research has demonstrated the separation of caesium. The US Department of Energy (DoE) has been supporting R&D of a UREX+ process to recover uranium for reuse. The residual solution is treated to keep plutonium with other transuranics, whilst separating this mixture from the fission products so that the high level waste contains only the latter. Several variations of UREX+ have been researched. The main differences lie in ways in which the plutonium is combined with the minor actinides and fission products are separated. For example, UREX+1a combines plutonium with three minor actinides but this gives rise to problems in fuel fabrication. UREX+3 leaves only neptunium with the plutonium and the result is closer to a conventional MOX fuel. PYROX involves dissolving spent fuel into a molten salt mix, and separating uranium through electrolysis. Plutonium remains mixed with actinides and fission products. This mixture is then fabricated into fuel for reuse in fast reactors.

Many of these alternative reprocessing techniques are not yet ready for more than laboratory testing. There are significant challenges relating to the reliability and availability of the proposed facilities and the generation of secondary wastes. PUREX remains cheaper, simpler and is widely documented. With many years of industrial experience, it is likely to be a more attractive choice for countries wanting to explore reprocessing.

South Korea is an exception. It has been unable to operate a closed fuel cycle because reprocessing its spent fuel nationally or internationally is constrained by agreements with USA. An open fuel cycle may not be feasible as South Korea's high population density and mountainous topography create difficulties for a suitable GDF site. South Korea is reaching the limit of current capacity to store spent fuel. To help solve these problems, South Korea announced in 2008 its plans to deploy a demonstration FBR by 2030 to close the fuel cycle. South Korea is undertaking R&D on pyroprocessing that it argues do not constitute conventional reprocessing since it does not separate pure plutonium. South Korea is considering deploying pyroprocessing on an industrial scale in the medium term. Other countries, such as Russia, are looking to deploy it in the longer term (2040 at the earliest).

4.1.2.2 Spiking nuclear materials

Fresh fuel could be spiked with small amounts of minor actinides, such as Np-237, to enhance the production of Pu-238 in spent fuel, further complicating the use of civil plutonium in nuclear weapons. Since Np-237 is itself fissionable, the use of separated neptunium would itself introduce new risks, and neptunium may need to be co-processed with other minor actinides (IAEA 2010a). Radionuclides could be added to increase the radiation barrier of fresh fuel, especially those with low chemical or isotopic barriers, such as MOX fuel. It is unclear how new signatures could feasibly be introduced that met key operational criteria (see section 4.4.3.1).

4.1.2.3 Optimised system design

The proliferation resistance of these techniques may be limited. They do not eliminate the attractiveness of plutonium for nuclear weapons use. Some of the radioisotopes that plutonium is mixed with are fissile, resulting in a material that a technologically advanced state could use in a nuclear weapon (Bathke *et al* 2009). All isotopes capable of being assembled into a critical mass are potentially weapons usable and are of proliferation concern (IAEA 2010a).

Proliferation vulnerabilities could be more effectively addressed by optimising the design of the wider system in which reprocessing takes place. Chemical barriers are increased once plutonium is fabricated into solid MOX fuel. Irradiation in a LWR increases the isotopic and radiation barriers. Attempts to access it once in a reactor would be easily detectable. Spent MOX fuel is highly radioactive and inaccessible with a higher intrinsic proliferation resistance than spent uranium dioxide fuel. Facilities could be co-located with other facilities to limit the need for transporting sensitive materials. This system could be optimised to minimise the amount of plutonium and time for which it is present at fuel cycle facilities (see section 6.1).

4.1.3 Enhancing chemical barriers

4.1.3.1 Inert Matrix Fuel

The difficulty of extracting plutonium is affected by the manufacture of fresh fuel. MOX fuel is currently the most widely used and proven plutonium bearing fuel. Plutonium dioxide could be mixed with a non-fertile ceramic carrier to produce an Inert Matrix Fuel (IMF). While irradiating MOX fuel creates new plutonium, IMF offers the possibility of generating electricity from a plutonium-bearing fuel whilst producing no additional fissile material. The remaining plutonium is of even less desirable quality for nuclear weapons use. Further irradiation is possible in fast reactors, which could also transmute the plutonium into isotopic forms that are even less attractive for weapons use. Matrix materials could be chosen that are optimised for different behaviour, such as stability during long term storage and disposal. IMF can be designed so that plutonium would be more difficult to extract compared with conventional MOX fuel (IAEA 2010a). If spent IMF is to be reused, however, spent IMF would need to be leachable, if possible in the same reprocessing conditions as for spent uranium fuel. Higher burn up would be less attractive to retain fissile material for new fuel (IAEA 2006). IMF is currently an unproven technology. There are some international IMF research programmes, such as those currently being funded by the European Union.

4.1.3.2 High Temperature Reactor fuel

The chemical form of the fissile materials in spent HTR fuel makes recovery of plutonium more difficult than compared to spent LWR fuel. Unlike LWRs, the fuel and moderator are combined together in a HTR fuel assembly. HTR fuel consists of small particles of uranium or plutonium oxides or oxycarbides surrounded by layers of carbon based materials and silicon carbide (or sometimes zirconium carbide). These coated particles are embedded in a graphite matrix that can take several geometric forms, such as pebbles the size of tennis balls or hexagonal blocks. The burn up of spent HTR fuel may be 50% higher than spent LWR fuel (MIT 2011). The Pebble Bed Modular HTR had a target date of deployment in South Africa for 2013. This was stopped in 2010 when the vendor and operator suffered financial difficulties. Continued R&D is necessary on the engineering and economic aspects of HTRs (MIT 2011).

4.1.4 The spent fuel standard

The ‘spent fuel standard’ was specifically proposed in the context of disposing of weapons grade plutonium from nuclear weapons by making it as inaccessible as spent fuel. This has become a de facto best practice for the management of separated civil plutonium, and can be achieved by burning MOX fuel in a LWR to produce spent MOX fuel (Royal Society 2007).

Others propose that the spent fuel standard could be achieved through immobilisation of the stockpile with HLW. Vitrified HLW could be poured around the outside of plutonium wasteforms or separated plutonium could be incorporated directly into vitrified HLW. The solubility of plutonium in glass is low so this latter option would be inefficient. The long term proliferation resistance it provides is debatable. The majority of the fission products in HLW have half lives less than 30 years, offering only short term intrinsic proliferation resistance. After 200-300 years this option would offer no higher proliferation resistance than any other management option (Royal Society 2008).

This is not a practical option for the management of the UK’s civil stockpile of separated plutonium. It would require both complete redesign of the current vitrification facility and also liquid HLW to be retained at Sellafield for many decades until a GDF was designed and constructed. The early vitrification of HLW stocks must be one of the NDA’s highest security priorities (Royal Society 2008). This option could become more attractive if reprocessing were part of a long term UK nuclear power strategy. Additional liquid HLW generated by future reprocessing could then be transferred directly to a vitrification plant for immobilising the stockpile. Significant technical and engineering challenges would still have to be overcome before this option could be implemented.

Some commentators propose that the spent fuel standard should underpin the wider civil management of spent fuel. There is an emerging consensus that this may not be a practical standard. It is ill defined without any specification of the minimum radioactivity required to make plutonium inaccessible.

4.2 Limitations of intrinsic proliferation resistance barriers

4.2.1 Technical feasibility

Many initiatives on proliferation resistance over the years have concluded that there is no technological 'silver bullet' solution to proliferation, yet great promise was still placed in such solutions. There is an emerging consensus that some measures to increase the intrinsic proliferation resistance of spent fuel may have been oversold. They cannot physically prevent a technologically advanced state from acquiring nuclear weapons if it decides that they are in its interests.

4.2.2 Political acceptability

Even if deployed in less technologically advanced states, the training of individuals to implement proliferation resistance measures could inadvertently lead to the spread of sensitive nuclear knowledge that could be misused to reverse engineer them. As the capabilities of these states continue to advance, their ability to overcome the barriers to proliferation are likely to increase. The effectiveness of any intrinsic proliferation resistance measure is likely to decrease with time (IAEA 2010a).

Less technologically advanced states could interpret the adoption of these measures as discriminatory and reinforcing a systems between 'haves' and 'have nots'. To avoid these accusations, technologically advanced states would need to constrain their technology choices and adopt these measures, too. As the UK Government recognised, 'over the long term, delivering proliferation resistant nuclear technology will require rethinking and reshaping of the way multilateral mechanisms for global nuclear security work' (Cabinet Office 2009). A system perceived to be discriminatory could foster resentment and undermine the enforcement process. The non-proliferation regime is affected not just by the ability of the international community to detect acts of proliferation, but also its ability to respond once they have been detected.

4.2.3 Economic attractiveness

Governments would need to convince industry that existing technologies are not adequate to address vulnerabilities of the fuel cycle. Some new measures may have adverse impacts on commercial aspects of fuel cycle performance, including operational efficiency and operating costs. Notwithstanding significantly increasing the costs, modifying fuel cycles to increase the radiological hazard of nuclear materials, for example, creates extra safety and environmental risks that pose extra regulatory burdens. Since many of these measures are not mature, industry is likely to use existing and less expensive technologies where there is significant experience of deploying them at the industrial scale. In an era when nuclear power in some states is no longer heavily subsidised, governments would need to identify and provide the incentives necessary for industry to adopt these measures.

4.3 An improved framework for assessing proliferation resistance

4.3.1 The need for comprehensive threat analyses

4.3.1.1 State versus non-state threats

State based threats need to be distinguished from non-state threats. Responses to both types of threat may overlap, drawing on similar measures, such as computer security and personnel vetting. 'Proliferation resistance' should be restricted to measures responding to state-based threats, as in the IAEA's definition: 'that characteristic of a nuclear system that impedes the diversion or undeclared production of nuclear material or misuse of technology by states in order to acquire nuclear weapons or other nuclear explosive devices' (IAEA 2010a). 'Physical protection' should be used when responding to non-state, nuclear security threats. Blurring this distinction could convey a misleading message about the potential benefits of a particular proliferation resistance measure (Bathke 2010). Measures to manage non-state threats may have a low impact on managing state level threats given the difference in their nature.

Textbox 6 **The case of North Korea**

North Korea embarked on an national nuclear research and reactor development programme in the 1970s and 1980s. Its planned power reactors were to be graphite moderated and gas cooled, as they did not have access to enriched uranium fuel. Its fuel fabrication and reprocessing facilities were not declared or inspected by the International Atomic Energy Agency (IAEA) since North Korea was not a state party to the Nuclear Non-Proliferation Treaty (NPT). In 1985, the USSR agreed to build LWRs in North Korea to meet its energy needs on condition that the USSR provided fresh fuel and North Korea repatriated it once spent, and that North Korea became party to the NPT. North Korea acceded to the NPT in 1985, but the arrangements for the USSR to supply North Korea with Light Water Reactores (LWR) and their fuel collapsed after the dissolution of the USSR in 1991. Lengthy negotiation between North Korea and the IAEA secretariat over the wording of its safeguards agreement took place through to 1992. This delayed the start of IAEA inspections. Verification of its initial declaration of plutonium uncovered discrepancies in accountancy, which had the consequence that safeguards could not be fully implemented. This stand-off was terminated by the negotiation of an Agreed Framework with USA in 1994. North Korea halted its national fuel fabrication and reprocessing activities in return for the funding and building by South Korea, Japan and other states of two large LWRs. Building started on these, and in parallel the IAEA monitored the cessation of operations of its prototype reactor and the building of additional power reactors. Following US accusations in the early 2000s of clandestine uranium enrichment activities, North Korea declared in 2003 that it would withdraw from the NPT. IAEA inspectors were expelled and spent fuel from its indigenous reactor was reprocessed. Two plutonium-based nuclear tests were carried out in 2006 and 2009.

4.3.1.2 Spectrum of nuclear weapon capabilities

Nuclear weapons capabilities range from highly advanced nuclear weapons capable of being carried by, and associated with, missile delivery systems of considerable range; through to simpler weapons with an associated delivery system of lesser military capability; and much cruder devices without highly predictable and reliable yields. Whereas advanced nuclear weapons are likely to require the acquisition of weapon grade uranium or plutonium, especially if a reliable and predictable yield is sought, acquisition of weapon grade materials may not be necessary for the construction of less advanced nuclear weapons. It should not be assumed that proliferators will necessarily seek the most advanced capabilities (see textbox 6).

4.3.1.3 Supply vs demand sides of proliferation

Threat assessments should not focus solely on capabilities, proliferation pathways and barriers to them. The motivations for choosing each of them, as well as the economic, political and military consequences of doing so, must also be considered.

4.3.2 The importance of sophisticated risk assessments

4.3.2.1 Methodologies to assess proliferation risk

The development of suitable methodologies is important to allow the unbiased and systematic comparison of different fuel cycle systems. Previous attempts were criticised for failing to do so, partly due to a lack of internationally accepted definitions and a common set of analytical tools. This has been addressed over the last decade by various national and international programmes, especially the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and the Generation IV International Forum (GIF). INPRO and GIF draw on previous US work, especially studies by NAS in the mid-1990s on the disposal of plutonium from nuclear weapons, as well as US DoE taskforce on the Technical Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS). More recently, the IAEA has published a TOPS-based framework to assess proliferation resistance (IAEA 2010a). This is important because it provides the basis for an international consensus on the attributes to guide proliferation resistance assessments.

Both INPRO and GIF frameworks support qualitative assessments. INPRO's Proliferation Resistance Acquisition and Diversion Pathway Analysis is still under development. GIF's Proliferation Resistance and Physical Protection methodology provides a more complete framework. There is growing interest in the possibility of quantitative assessments. Neither framework prescribes what analytical technique should be used. Different techniques, broadly based on either decision analysis or probabilistic methods, are being developed as part of national programmes, for example in France, Japan, UK and USA (see textbox 7).

4.3.2.2 Proliferation resistance as risk management

There is no proliferation proof fuel cycle. Proliferation risks can be managed, not eliminated. A conclusion of high proliferation resistance should not be interpreted to mean that a nuclear fuel cycle is proliferation proof. Even the term 'proliferation resistant' can be misleading. Proliferation resistance is a relative concept used to compare different fuel cycle options.

4.3.2.3 Systems approach to risk management

Proliferation risk assessments should not assess the proliferation vulnerabilities of specific nuclear technologies in isolation. A particular technology may have proliferation vulnerabilities yet still improve net proliferation resistance when considered as part of a wider fuel cycle. The proliferation resistance of a given fuel cycle option should always be assessed from cradle to grave.

4.3.2.4 The political nature of proliferation

Technological assessments cannot by themselves identify a pass/fail threshold above which a nuclear fuel cycle poses an acceptable level of proliferation risk. To establish such a threshold would ultimately require a political, not a technological, judgment to be made. The proliferation resistance of a nuclear fuel cycle is directly related to the wider political system in which it is embedded. This itself is a dynamic system that can change over time. Technology may not even be the primary contributor to proliferation. As the DoE stresses, 'looking only at how the R&D can improve nuclear technologies without considering who is to use these technologies, and the national and international frameworks under which they are operating, will provide an overly narrow perspective of proliferation risks' (DoE 2010). A failure to appreciate fully the political dimension of non-proliferation makes the concept of proliferation resistance at best irrelevant and at worst counterproductive (Acton 2009). Technological assessments need to be integrated with socio-political ones. This creates an opportunity for collaboration across the natural and social science communities.

4.3.2.5 Communicating results of risk assessments

The results of these assessments, and their uncertainties, need to be capable of being clearly and simply communicated to a variety of audiences, including policymakers, other nuclear decision makers and the public.

4.3.3 Safeguardability as a R&D priority

No matter what fuel cycle technology is developed it will still have to be placed under IAEA safeguards once deployed, irrespective of its intrinsic proliferation resistance. Proliferation resistance assessments could usefully focus on designing fuel cycles to increase their safeguardability so they can be more effectively and efficiently placed under international safeguards, as well as facilitating other extrinsic measures. A robust safeguards R&D programme may be the single most significant technological investment that can be made to improve the proliferation resistance of nuclear power in the near term (APS 2005).

Textbox 7 **Science based approaches to assessing proliferation resistance**

Multi Attribute and Utility Analysis (MAUA) is a leading approach used to assess different engineering options. A utility function, U(x), is assigned to each option in terms of a set of multiple attributes represented by the vector, x. The utility function captures both the intrinsic properties of an engineering component (such as its strength, mass, stiffness and corrosion resistance) and its availability. If a new design for a component involved a material or a manufacturing process that offered technological advantages but was still in need of extensive R&D, then the utility function would be penalised because of its lack of availability. This could be applied to proliferation assessments if the utility function can represent both the intrinsic attractiveness of a nuclear material for nuclear weapons use and its accessibility.

The UK's National Nuclear Laboratory (NNL) has developed a MAUA-based methodology to support a quantitative comparison of different management options for the UK's civil stockpile of separated plutonium management. NNL's methodology draws on the six proliferation measures outlined under the Proliferation Resistance and Physical Protection methodology of the Generation IV Forum (GIF):

1. **Fissile material type.** The attractiveness of nuclear material for nuclear weapons use.
2. **Technical difficulty.** The extent of sophisticated infrastructure needed to overcome barriers to proliferation, (such as criticality hazards, radiation and the need for shielding and remote handling).
3. **Proliferation cost.** The level of resources (money, personnel and equipment) needed to overcome proliferation barriers.
4. **Proliferation time.** The minimum time needed to overcome proliferation barriers to acquire nuclear materials (but not including the time needed for weaponisation).
5. **Detection probability.** The cumulative probability of detecting a proliferation pathway.
6. **Detection resource efficiency.** The level of resource needed to apply international safeguards to the system.

A utility function, U(x), is assigned to a set of multi-attribute parameters, (x), for a particular proliferation pathway in terms of a value function, V(x), and an access function, A(x). The value function, V(x), captures the intrinsic attractiveness of nuclear material in terms of its fissile quality and chemical and physical properties (the first GIF measure, 'fissile material type'). The access function, A(x), captures its accessibility (the other five GIF measures: 'technical difficulty', 'proliferation cost', 'proliferation time', detection probability' and 'detection resource efficiency'). The utility function is the product of the value and access functions: U(x) = V(x).A(x). A low utility function value can be achieved by a small value function (the nuclear material is unattractive for nuclear material use); or a small accessibility function (the nuclear material is not easily accessible); or a combination of both. The definition U(x) = V(x).A(x) reflects a basic principle of nuclear security that the more intrinsically attractive a nuclear material is, the more stringent are the extrinsic security barriers needed to protect it.

Less emphasis should be placed on the absolute values of the numbers generated by this methodology. Instead, the focus should be on how these numbers change as intrinsic and extrinsic barriers are modified. A key finding by NNL has been that the relative rankings of different systems are mostly determined by the access function rather than the value function. This is helpful because it has proved difficult to establish an international consensus as to what value functions to apply. It also underlines the importance of extrinsic measures, such as international safeguards, in proliferation resistance.

4.4 Non-proliferation R&D priorities

4.4.1 Improvements to nuclear material accountancy

Nuclear material accountancy (NMA) will remain central to safeguards activities. Improvements are likely to be more evolutionary than revolutionary. Priorities include:

- **Reducing the impact of a nuclear renaissance on limited resources.** Online, real time data collection, evaluation and reporting capabilities could transmit data to IAEA headquarters and verified remotely at anytime. Secure data transmission and encryption capabilities are crucial. Unattended, automated and remote NMA and containment and surveillance systems need to be cheap and tamper resistant if they are to operate in remote locations worldwide, possibly in harsh conditions. In-situ systems to monitor the long term behaviour of spent fuel could provide further confidence that spent fuel can be stored safely over long timescales, as well as supporting safeguards NMA.
- **Addressing measurement uncertainties.** The plutonium content of spent fuel is presently assessed using operators' reactor burn up codes. There is growing interest in the potential of non-destructive techniques to directly quantify this plutonium content rather than destructive analyses that tend to be expensive, slow and require high activity facilities. Addressing the inherent uncertainty in NMA measurements for reprocessing remains a priority (see textbox 2).
- **Safeguards concepts for next generation reactors and their associated fuel cycles.** Development of safeguards concepts must be integrated into R&D programmes developing advanced and next generation reactors and their fuel cycles.

4.4.1.1 The State Level Approach

The effectiveness of safeguards at each facility in IAEA Member States was traditionally evaluated through the attainment of safeguards goals measured against a strict set of criteria for each type of facility. The effectiveness of safeguards at all facilities was then published in the IAEA's annual Safeguards Implementation Report. The IAEA now seeks a State Level Approach where assurances are sought for the state as a whole rather than for every facility in the state. This is based on 'integrated safeguards' that draws on information gained through traditional safeguards, as well as through the Additional Protocol (see textbox 1). The IAEA now conducts an annual State Evaluation for all countries so that it can streamline its resources and focus on the most pressing proliferation problems and states of concern. While the State Level Approach to safeguards is well accepted, further work is needed to identify internationally accepted criteria on which to carry out State Level assessments transparently.

4.4.2 Safeguards arrangements for geological disposal

4.4.2.1 Safeguards in depth

NMA will be difficult once wasteforms are emplaced. The IAEA's international advisory group on Large Scale Reprocessing was convened in the 1980s to consider similar NMA challenges. It concluded that a combination of different, complementary safeguards techniques could provide the necessary assurances. Such a 'safeguards in depth' approach may be applicable for geological disposal.

Detailed information about the GDF's design will be an important verification tool. This requires a geological and environmental baseline before construction starts that could be informed by the site characterisation for the safety case. Aerial and satellite imagery and geophysics techniques could verify declared excavation activities. Environmental monitoring could detect radioactive material released upon (unauthorised) opening of waste packages or reprocessing. During operation, safeguards will verify declarations on changes to the inventory of nuclear material in the GDF and continue to verify the GDF's design. At this stage, a GDF could be likened to an underground storage facility and perhaps safeguarded in a similar way to a high hazard store. Containment and surveillance systems could be deployed at surface facilities and access points to track waste packages when they are stored or conditioned and then transferred to underground vaults. These systems also need to detect undeclared movement of waste packages in the opposite direction.

Upon backfilling and closure, safeguards may focus on assuring there is no intrusion into the GDF. Aerial and satellite imagery and geophysics techniques could continue to provide assurances of no undeclared intrusion. Based on the NDA's current planning assumptions, the first emplacement of ILW and HLW in a UK GDF will be in 2040 and 2075, respectively. The NDA estimates that a UK GDF for legacy waste will close around 2130. A GDF for wastes from new nuclear reactors will stay open much longer. It is difficult to predict what future technologies might be available at that time.

It is unlikely that a GDF will be constructed in a linear fashion, not least because of the long timescales to prepare all the waste. It is almost certain that vaults will be excavated, filled and monitored simultaneously. Different parts of the GDF will have different safeguards requirements at different stages of disposal. This will be affected by different types of wasteforms. Wastes containing separated plutonium may need to be segregated within particular sections of the GDF and subject to more intensive verification procedures than wasteforms containing spent fuel or only HLW.

4.4.2.2 Geological disposal of plutonium

There is currently no international consensus on best practice for the geological disposal of plutonium. The IAEA provides safety standards for the geological disposal of radioactive waste but these do not explicitly consider the disposal of plutonium. The IAEA has set up a Group of Experts on the Applications of Safeguards to Geological Repositories. International thinking on the safeguards aspects of geological disposal has focused on the disposal of spent LWR fuel. More attention needs to be paid on the disposal of other nuclear materials, such as separated plutonium and spent MOX fuel, as well as spent thorium fuel.

4.4.2.3 Retrievability and safeguards

The 'close and walk away' approach of the safety community requires GDF designs to be passively safe and environmentally sound, needing no active institutional oversight after closure. Yet the safeguards community may require active monitoring and ongoing institutional control for spent fuel and other nuclear materials that cannot be considered to be practicably irrecoverable or otherwise suitable for the termination of safeguards. This is complicated by decisions (that have yet to be made in some countries) about whether wasteforms in GDFs will be retrievable (see textbox 8). Retrievability can be designed into the GDF, the ease of which depends on the GDF concept, timescales during which retrieval may be required and the stage of disposal. It is a major undertaking that becomes more technically complicated and costly as disposal progresses. Delaying emplacement and the closure of a GDF could facilitate further opportunities for unauthorised access to material.

Textbox 8 **Retrievability of geological disposal**

Flexibility can be built into the decision making process so that earlier decisions can be re-evaluated and reversed. This could involve reversing decisions about site selection or choice of disposal concept; or, at later stages, decisions about the construction, operation and date of closure of the Geological Disposal Facility (GDF). Retrievability is a special case of reversibility, namely the potential to reverse the emplacement process so that the waste containers can be retrieved (NEA 2011). Retrievability may be attractive to policymakers so that decisions can be informed by technological developments, new socio-political circumstances, as well as changes to regulation or national policy. Future fuel cycle options are kept open should a decision be made to reuse the spent fuel. Public confidence could be secured by providing reassurance that unforeseen safety problems could be addressed. National governments will need to specify in national policy how reversibility should be implemented and indicate the degree to which retrievability should be considered for different waste types (NEA 2001).

Much of the debate about retrievability concerns the conflict between two important principles: decisions for radioactive waste management should be made now rather than being left for, and imposing undue burdens on, future generations; whilst options should be preserved for future generations to make their own waste management decisions. Retrievability should not be an excuse for indefinite delay of decision making about geological disposal. Nor should it be used to justify an immature programme based on a lower degree of confidence in the safety case (NEA 2011). The safety case for a GDF should not be dependent on the potential of retrieval. If wastes are retrieved, then alternative secure waste management options must already be available to receive the retrieved wasteforms. This could include re-emplacement in the same or in an alternative GDF, or transfer to interim storage at the GDF or elsewhere.

If disposal concepts are to be retrievable, then disposed material will need to remain under safeguards for as long as the state's safeguards agreement is in force. Continuity of knowledge will need to be maintained over very long time periods if the GDF is expected to remain under safeguards. The diversion potential and prolonged inspection effort need to be carefully considered. Delaying closure after emplacement is completed appears to run counter to the desire to minimise the potential for diversion. Maintaining underground inspection and monitoring systems could be a significant burden and prejudice the integrity of the GDF. Prolonged exposure could increase the radiological hazards for inspectors.

4.4.2.4 Deep borehole disposal

Deep borehole disposal (DBD) concepts can be designed to make the retrievability of waste extremely difficult. Like GDF concepts, waste could still be recoverable but only at enormous difficulty and expense. Instead of constructing a GDF, a matrix of boreholes could be drilled either from the surface or from an underground facility to depths of several kilometres. Solid packaged waste containers would be placed into the boreholes of perhaps no more than one metre in diameter, separated from each other by layers of bentonite or cement. The boreholes would not be completely filled with wastes. The top two kilometres would be sealed with materials, such as bentonite or concrete. DBD concepts were proposed in the USA in the 1970s but the necessary drilling technology did not exist at the time. DBD has now become a more realistic option due to recent advances in commercial and scientific deep drilling technology made over the last two decades in the hydrocarbon and geothermal energy industries, although DBD has yet to be demonstrated as a practical option. DBD may not be suitable for disposing of large volumes of spent fuel and waste. It may be more suitable for smaller volumes, especially wastes where retrievability is not desirable or situations where a state has only a few reactors and they are being operated on an open cycle. This could include the disposal of small volumes of plutonium wastes and spent MOX fuels (Royal Society 2006).

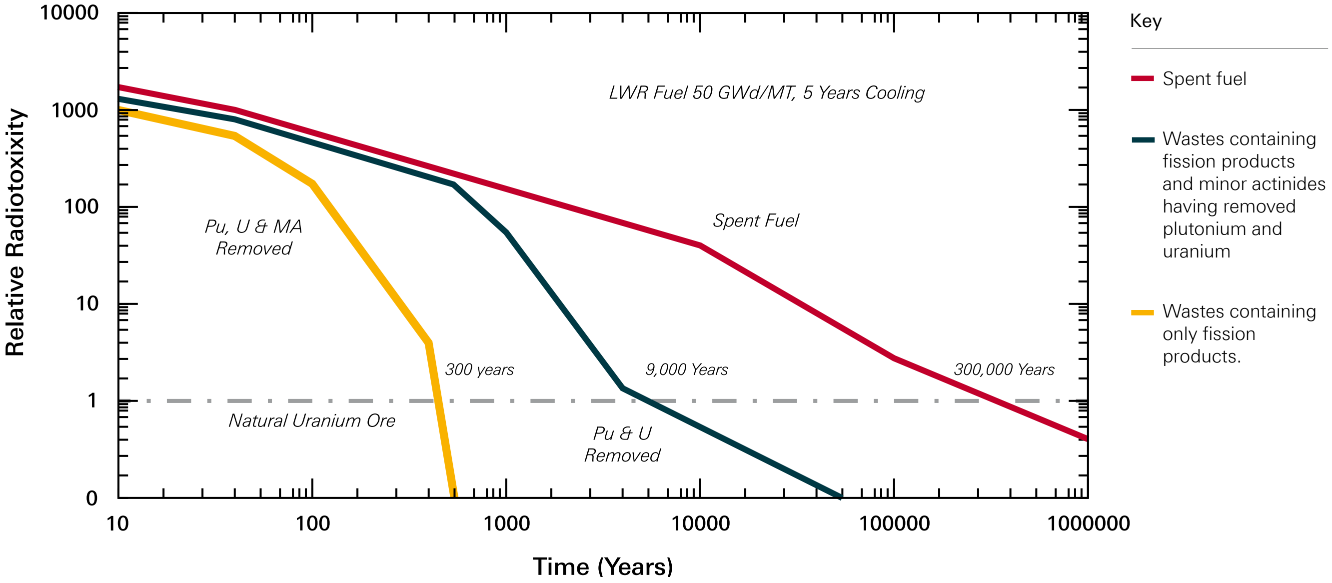
4.4.2.5 Partition and transmutation

Safeguards would be simplified if fissile material could be removed from spent fuel and destroyed through 'partition and transmutation' (P&T) technology. This involves separating out not only plutonium and uranium but also minor actinides and long-lived fission products. Once fabricated into targets for irradiation by neutrons produced by fast reactors or accelerator driven systems, they could be transmuted into less hazardous, shorter-lived isotopes. This could address safety and environmental concerns that radioactive contamination from the disposal of spent fuel and immobilised HLW might eventually leach into the biosphere. The radiotoxicity of the remaining waste would then decline substantially through decay over a timescale of only a few hundred years, rather than hundreds of thousands of years (see figure 6).

P&T is at an early stage of development and not yet deployable at the industrial scale. The infrastructure needed to carry out large scale partition is comparable in scale and cost to a PUREX facility. Application to several different isotopes would require several major facilities. The preparation of targets for transmutation remains highly problematic. Transmutation will also not be completed in a single cycle, so targets will need to undergo further cycles of reprocessing. Fast reactors are still being developed and may only be deployable in the longer term. Transmutation of fission products is an expensive use of neutrons, and reactor fuel will need a higher fissile content to compensate for those absorbed in the transmutation process. Transmutation using accelerator driven systems on an industrial scale would need new accelerator systems.

The timescales for P&T to be technologically feasible and economically attractive remain very long term. Nonetheless, P&T may be a source of future innovations that could address concerns about intergenerational equity so that future generations are not burdened with proliferation vulnerabilities as the radiation barriers of disposed wasteforms decay, as well as indefinite safeguards requirements.

Figure 6 **The relative radioactive decay of spent fuel; wastes containing fission products and minor actinides having removed plutonium and uranium; and wastes containing only fission products.**



4.4.3 Detecting clandestine activities

Under the Additional Protocol, environmental sampling is a powerful technique for the IAEA to detect clandestine activities. Inspectors can take swipe samples from facilities of interest for further particle analysis elsewhere. These techniques could be enhanced by improvements in the following areas.

4.4.3.1 Nuclear forensics

Participating states at the Nuclear Security Summit agreed to cooperate on developing national libraries to improve attribution capabilities (White House 2010). These libraries contain information based on archives of sample materials about characteristic features of civil nuclear material, such as isotopic and elemental composition, geometry, impurities, macroscopic appearance and microstructure (Royal Society 2008). States embarking on nuclear power for the first time could be encouraged to establish national libraries from the outset of their programmes.

Techniques have been proposed to introduce new signatures into nuclear materials to aid their detectability and forensic attribution. Shielded HEU presents major detection challenges, especially at long range, standoff distances. The gamma rays produced by uranium as it decays are not strong and can be shielded, and the neutron production rate is very low and easily lost in background neutrons. The current focus has been on improving the detection of existing signatures by enhancing gamma ray and neutron generation (Royal Society 2008). Alternative signatures could be introduced, although key operational criteria would need to be met:

- **Suitability.** Adding a neutron emitter to fresh fuel would be not feasible since it would undermine the physics of nuclear reactors, so a gamma ray emitter would be more likely. This radionuclide, and its daughter and activation products, would need to avoid increasing safety hazards.
- **Persistency.** New signatures should be good chronometers that are not processed out of the fuel cycle.
- **Deployability.** Safeguards requirements should not be compromised and long term storage and disposal requirements will still need to be met.
- **Consistency.** More reliable attribution signatures should not be impaired.

It is unclear how new signatures could feasibly be introduced that meet these criteria and do not excessively impair economic and safe fuel cycle performance.

4.4.3.2 Nuclear archaeology

There is growing interest in methods to verify declarations of plutonium and HEU production by analysing samples from the structural materials of shutdown reactors (see textbox 9).

4.4.3.3 Long range techniques

Wider area environmental sampling by IAEA within a State is potentially a very powerful technique to help detect undeclared activities. The IAEA has set up a R&D programme to explore laser induced breakdown spectroscopy; optically stimulated luminescence; atmospheric noble gas measurements; antineutrino detectors; remote optical detection of alpha emitters; in field alpha spectrometry; and direction sensitive gamma spectrometry. Techniques require approval of the IAEA Board of governors and could only be implemented in consultation with the State concerned. Non-intrusive techniques, such as satellites, are key. Satellite monitoring can detect the construction of facilities that could be identified by expert analysis, such as nuclear reactors, plutonium production and extraction sites.

Textbox 9 **The potential of nuclear archaeology**

The best established method for nuclear archaeology relies on measuring the build up of transmutation products in the graphite of graphite-moderated plutonium production reactors. This so-called Graphite Isotope-Ratio Method estimates the cumulative neutron flow through the graphite and thereby the cumulative plutonium production in the reactor (IPFM 2009). Even the high purity graphite used as a neutron moderator in most plutonium production reactors contains traces of many different elements, including boron. In natural boron, the isotope ratio of B-11:B-10 is about 4:1 but B-10 nuclei have a greater probability of absorbing neutrons and being transmuted than B-11. Over the lifetime of a reactor, the B-11:B-10 ratio increases. By using computer simulations and many graphite samples, the cumulative production of plutonium in such a reactor could be estimated.

Nuclear archaeology has been used to verify the dismantlement of South Africa's nuclear weapons programme. Its application has also been proposed to verify the elimination of nuclear weapons and related fissile material programmes in North Korea. Nuclear archaeology could be applied to verify declarations of plutonium production in civil nuclear power programmes. The UK has limited and fragmented capability in this area at AWE, the National Nuclear Laboratory and one or two universities. In the university sector, it is largely being developed for other applications but is adaptable to nuclear verification.

Integrated nuclear governance

5.1 Integrated risk management

Nuclear safety and security serve a common purpose, namely the protection of people, society and the environment from large releases of radioactive materials. Many of the principles to provide this protection are common, although their implementation may differ. Both areas are based on a 'defence in depth' approach provided through a number of redundant, diverse and independent controls that prevent or reduce the likelihood of faults from occurring; detect and control them when they do; and mitigate the radiological consequences should these controls fail. Safeguards may also be based on a similar approach (see section 4.4.2.1).

Some actions can serve safety and security functions simultaneously. Security measures can increase safety by making sabotage more difficult. Containment structure of reactors can prevent a significant release of radioactivity, as well as protecting the reactor from attack. Other actions may conflict. Security considerations may need to prevent unauthorised access to certain areas in a facility that may need to be accessed for safety reasons. Emergency planning needs to be well co-ordinated, facilitated by joint exercises (IAEA 2010c). Safety problems could arise from an attack, while security vulnerabilities could be created during a safety accident. Similarly, measures installed for safeguards could improve security. Effective material accountancy and control can assist in detecting theft.

5.1.1 An objective optimisation process to support integrated risk management

An integrated approach could be supported by a holistic optimisation process that objectively evaluates these safety, security and non-proliferation risks together. Each of these areas has its own requirements yet all three need to be considered in the planning, design, construction, operation and decommissioning of nuclear power programmes.

5.1.1.1 Safety by design

'Safety by design' is now standard practice facilitated by a hierarchy of IAEA documents, consisting of Fundamentals, Requirements and Guidance arrived at via intergovernmental consensus, thereby ensuring political buy-in. 'Fundamentals' set out high level principles. 'Requirements' and 'Guidance' documents set out more detailed standards that enable the Fundamentals to be implemented. Although non-binding (except for Member States that accept IAEA support programmes where they are mandatory), these documents are often adopted, especially for the most internationalised aspects of nuclear commerce that require international standards to be implemented.

5.1.1.2 Security by design

No equivalent hierarchy of documents exists for nuclear security (or safeguards), although guidelines for 'security by design' are being developed (WINS 2010). This may require greater information sharing yet there are concerns about inadvertently revealing security vulnerabilities and commercial sensitivities. Transparency was increased following the accidents at Chernobyl and Three Mile Island. Following events at Fukushima, the UK's Office of Nuclear Regulation (ONR) acknowledged 'there must be some limitations, especially with regard to matters of security' but 'such reservations must not stand in the way of our drive for greater openness and transparency', recommending that regulators and the nuclear industry should consider ways to ensure more open, transparent and trusted communications and relationships with the public and other stakeholders (ONR 2011). A major incident should not be needed to catalyse this change for nuclear security. This does not mean all information should be shared. Rather, certain types of information could be shared responsibly even if they begin at first by just focusing on basic, general principles rather than particular site-specific arrangements (WINS 2011).

5.1.1.3 Safeguards by design

Discussions about safeguards by design began in the 1970s and received renewed attention in the 1990s, especially for reprocessing and MOX fabrication facilities. Safeguards by design is not universally implemented. Commitments to safeguards by design are voluntary and vary in priority, although France and UK have to comply with EURATOM safeguards requirements.

No formal international requirements exist for including considerations of safeguardability in the design of a nuclear technology or fuel cycle facility. In some cases, safeguards have been implemented after the design of a nuclear facility has been completed. A set of guidelines for safeguards by design should be developed. Existing procedures and operating experience could be reviewed to identify general principles, as well as principles for specific types of facilities (IAEA 2009b).

Safeguards by design appears to be in the industry's interests. The earlier that safeguards requirements are incorporated into the design of a nuclear technology or fuel cycle facility, the smaller its impact on cost, facility throughput and operational flexibility. The efficiency of implementing safeguards and carrying out inspections could be also improved. The potentially expensive and time consuming retrofitting of a facility once it has been constructed and is operational could be avoided.

5.1.1.4 Integration by design

Just as methodologies have been developed to assess safety risks and inform safety by design, suitable methodologies should be developed upon which to base safeguardability and security assessments and institutionalise safeguards and security by design (see sections 4.3.2 and 4.3.3). These assessments should be integrated into the licensing process for nuclear facilities. This may be complicated by a lack of standardisation in the design of fuel cycle facilities.

The participation of safeguards, security and safety experts in these exercises would identify how measures in all three areas reinforce or conflict with each other, so that optimisations can be considered from the earliest stages of fuel cycle design. This could support more effective and efficient designs. An integrated IAEA hierarchy of documents for safety, security and safeguards may even be possible. The participation of a wide range of stakeholders is important so that the impact on other fuel cycle decision making criteria, such as cost and operational performance, are considered. A high level of industrial participation would also ensure these assessments are of practical benefit. Table-top and on-site exercises designed to assess proliferation and security risks can serve useful heuristic roles. The insights gained from carrying them out may be of value over and above the end results.

5.2 Integrated nuclear regulation

5.2.1 Integration at the national level

Regulation of nuclear safety and security is carried out at the national level. National governments are responsible for setting up a national regulator independent from the nuclear industry and government departments and agencies responsible for promoting nuclear power (IAEA 2007). By implementing a licensing, inspection and enforcement system, regulators can provide national governments with independent assurance that the nuclear industry is operating safely and securely. In some countries the national regulator has consisted of separate bodies with different responsibilities for safety and security. Best practice seeks to integrate these functions into a single regulatory body given the synergies involved and to avoid conflicting regulatory requirements.

Non-proliferation is generally regulated at an international level. It is not the industry per se, but the state in which the industry is based that is primarily the one being regulated. States provide independent assurances to other states, so non-proliferation is inspected by intergovernmental bodies, namely the IAEA (as well as EURATOM in Europe and Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) in Argentina and Brazil). The IAEA has the power to refer non-compliance to the Security Council (and European Court of Justice in the case of EURATOM), which is the ultimate source of enforcing non-proliferation.

National governments still have responsibilities for non-proliferation. It is in their interests to ensure legislation is in place so that industry provides all the support necessary to enable safeguards activities to be carried out effectively, and thereby avoid false accusations of proliferation. Given the synergies with nuclear safety and security, these safeguards responsibilities should be integrated into the national regulatory body. Best practice is to set up a national safeguards office to co-ordinate safeguards activities and act as a focal point for industry and IAEA (and EURATOM).

It could even be possible for a national government to liaise with the IAEA about how its national regulator could act on the IAEA's behalf during the licensing process of a nuclear facility. This would ensure the licensee clearly understands the IAEA's safeguards requirements for the facility, so that the facility design will deliver these requirements and avoid delays and conflicts with other regulatory requirements. The IAEA would need to have confidence in the competence of the national regulator. This would provide the national regulator with powers to not only promote but aslo enforce safeguards by design. The IAEA could prescribe what it requires at a high level but still allow the national regulator suitable flexibility in its implementation. The IAEA could then approve the final arrangements. It would not prevent or replace IAEA inspectors from carrying out safeguards inspections and verifying compliance at the sites.

5.2.2 Integration at the international level

5.2.2.1 Governmental peer review

Global governance of nuclear safety is well developed. Under the Convention on the Safety of Spent Fuel Management and Safety of Radioactive Waste Management ('the Joint Convention'), state parties commit themselves to submitting national reports to peer review every three years to demonstrate how they have each complied with the Joint Convention. This peer review mechanism is vital to ensure best practice is implemented since no intergovernmental verification or enforcement mechanism exists for nuclear safety or security (unlike non-proliferation). As the European Commission recently emphasised, 'peer review could serve as an excellent means of building confidence and trust in the management of radioactive waste and spent fuel in the European Union with the aim of developing and exchanging experience and ensure high standards' (EC 2011).

Global governance for nuclear security is less developed. New international treaties may not be necessary. Weaknesses in those that already exist could be strengthened; for example by ensuring all states become party to them and implement them seriously (Findlay 2010). No formal process of peer review exists for nuclear security. Nuclear security could be introduced into the peer review process for nuclear safety. This need not involve reopening the Joint Convention. Rather, contracting parties could voluntarily include appropriate security information into their national reports. A precedent has already been set for this. France and UK decided to include information about their reprocessing activities in their national reports yet this is not a formal requirement. A truly integrated approach would involve states voluntarily including safeguards in these national reports.

The IAEA's International Physical Protection Advisory Service and International Nuclear Security Advisory Service allow the IAEA to evaluate member states' regulatory infrastructure for nuclear security and compliance with international treaties and best practices. These mechanisms are non-mandatory and made available only upon a member state's request. It is welcome that the UK has invited the International Physical Protection Advisory Service to carry out a review of the Sellafield site. This sets an important precedent for others to follow so that it could become standard practice over time.

These mirror similar review mechanisms for safety, such as the IAEA's Operational Safety Review Team programme and Integrated Regulatory Review Service. These review the safety management at nuclear power stations and compare national regulatory infrastructure against international safety standards, respectively. Over time, nuclear safety and security could be integrated into a single advisory service.

5.2.2.2 Industry peer review

Industry peer reviews for nuclear safety are already standard practice through the World Association of Nuclear Operators (WANO). In light of events at Fukushima, it may be timely for WANO to widen the remit of its peer reviews to include not just reactor operation but also the operation of spent fuel stores. Collaboration with the World Institute of Nuclear Security (WINS) could facilitate integrated safety and security peer reviews (see textbox 10).

5.3 Integrated corporate governance

5.3.1 Nuclear security in the boardroom

In some companies, nuclear security remains a lower priority than safety. This is partly due to an assumption that security is primarily the responsibility of national governments. Some companies are integrating security into the same oversight and corporate governance arrangements they use for safety. This needs to become best practice worldwide. Making security an explicit feature of licensing conditions would make operators aware of their liabilities not just for safety but security too, as well as the reputational risks associated with each (WINS 2011). Engaging industry at the level of the boardroom would help to nurture an integrated safety and security culture that could then filter down through the rest of the company to become embedded in the day to the day operations.

Nuclear companies are aware of their responsibilities for nuclear safeguards. Corporate governance could include implement commitments to best practice, such as safeguards by design; support for the wider adoption of the Addition Protocol; proactive sharing with the IAEA trade information; and technological developments relevant to safeguards.

Textbox 10 **Industry stewardship on nuclear safety and nuclear security**

The World Association of Nuclear Operators (WANO) is a voluntary, membership based organisation established in 1989 in response to the safety accidents at Chernobyl in the USSR in 1986. It is not a regulatory body and is independent of government. WANO is funded exclusively by industry to promote leadership, exchange information, share best practice and conduct peer reviews on safety and operational practices. WANO provides professional development programmes through training workshops, conferences, and training courses to further educate employees in the nuclear industry. In many cases the investment in improved safety has made good commercial sense, as well as increasing confidence that the industry can avoid further nuclear accidents that would impact on the sustainability of the industry worldwide.

The World Institute of Nuclear Security (WINS) is a not-for-profit international NGO established in 2008. It provides an international forum for operators and other practitioners to share and promote best practice to prevent nuclear and radioactive materials from being used for terrorist or other nefarious purposes. WINS publishes best practice guides and organises workshops to allow practitioners to share experience and learn lessons on a wide range of nuclear security issues. WINS believes that security leadership starts in the Boardroom and that practitioners in nuclear security need properly structured professional development and training, as their colleagues in the nuclear safety field receive. WINS will be promoting ‘nuclear security management’ as an accredited, regulated profession.

These efforts could provide commercial advantages by allowing the nuclear industry to respond to societal perceptions that have changed significantly over the last few decades. Integrating security and non-proliferation into corporate governance would allow the nuclear industry to demonstrate greater responsibility as a corporate global citizen, a role emphasised at the 2010 Nuclear Security Summit (White House 2010).

5.3.2 The need for security training

Security training courses are available in many areas of the world for general security guards but there is no international guidance on what constitutes the required competences and capabilities for managers and other personnel that have nuclear security responsibilities. This is in contrast to the structured and accredited training available to nuclear operators and safety managers that have to be demonstrably qualified and experienced. Nuclear security regulators need to review whether their national regulations place any training or education requirements on licensees.

Best practice for nuclear governance

- At the national level, regulation of nuclear power programmes should be based upon an integrated approach to nuclear safety, security and safeguards.
- At the international level, in the absence of a specific Convention on nuclear security, appropriate security information could be included, on a voluntary basis, in national reports submitted as part of the peer review process of the Convention on the Safety of Spent Fuel Management and Safety of Radioactive Waste Management, and the Convention on Nuclear Safety. This practice would be promoted by integrating nuclear safety and security into the IAEA’s advisory services for member states.
- An integrated approach to industry-led peer reviews should be developed possibly through collaboration between the World Association of Nuclear Operators and the World Institute of Nuclear Security.
- Non-proliferation and nuclear security need to feature more explicitly in corporate governance arrangements with similar status to that given to nuclear safety.

Integrated approaches to fuel cycle management

6.1 Best practice for reuse

Civil nuclear power first became a reality in the 1950s. Major investments in reactors began in Europe, Japan, Russia and USA in response to the expectation of increased energy demands. A perceived shortage of uranium led to increasing interest in FBRs. Plutonium is needed to fuel FBRs, so the rationale for reprocessing moved from purely military purposes to civilian ones. By the late 1960s, industrial scale reprocessing plants were operating in France, Germany, Russia, UK and USA.

Several countries began accumulating stockpiles of separated plutonium in anticipation of FBRs. It was soon recognised that this capacity exceeded the requirements of the FBR prototypes then under construction. As an interim strategy to manage growing stockpiles of separated plutonium, studies confirmed the feasibility of reusing plutonium as MOX fuel in LWRs. MOX fabrication plants were built to provide the necessary capacity. In the 1970s, MOX fuel was first irradiated in nuclear power stations in Germany and then Switzerland. The first MOX fuel was introduced into a French LWR in 1987. Other European countries, such as Belgium, Holland and Sweden, have also used MOX fuel in some of their commercial LWRs but on a smaller scale.

UK policy was to reprocess spent fuel from the UK's Magnox reactors and AGRS to provide plutonium for future FBRs. In 1994, the Government stopped funding the UK's FBR research. In 2006, funding was withdrawn completely yet reprocessing continued. Whereas France and Japan manage their stockpiles of separated plutonium by reusing them as MOX fuel in LWRs, the UK now has the world's largest civil stockpile of separated plutonium that is being stored without any long term plan to manage it (Royal Society 2007). The UK has accumulated approximately 112 tonnes (metal weight) of separated plutonium, 84 tonnes of which are UK owned and 28 tonnes of which are foreign owned. The amount owned by the UK is expected to grow to approximately 100 tonnes when existing reprocessing contracts for spent UK fuel are completed (DECC 2011).

Countries differ in their approaches to reprocessing (see textbox 11). Spent fuel should be reprocessed only if there is a clear plan that minimises the amount of time during which plutonium is in a separated form, and converts it into MOX fuel as soon as is feasible thereafter. Reactors should be identified in advance that can irradiate MOX fuel, which, in turn, should be fabricated on timescales that match reactors' loading schedules. This would minimise any risks associated with the stockpiling of MOX fuel. A further advantage is the reduction of the in-growth of americium. This complicates the handling of plutonium and MOX fuel and can affect the performance of the fuel in the reactor. Plutonium should be transported as MOX fuel rather than as separated plutonium.

By co-locating reprocessing and MOX fabrication facilities it may be possible to design a fully continuous process. This may be difficult to achieve in practice. Industrial realities would require some interim storage of separated plutonium to serve as a buffer store so that MOX fuel could still be manufactured in case of any unforeseen interruptions to the operation of the reprocessing plant. The size of this interim store should be minimised and the highest levels of physical protection.

The liquid HLW separated during reprocessing contains highly concentrated fission products. It is among the most hazardous materials in the nuclear fuel cycle. If the containment of the HLW facilities was breached, then radioactive material could be released. An attack on HLW facilities could lead to a loss of coolant incident. If cooling was lost for a prolonged period, liquid HLW storage tanks could overheat, leading to evaporation and release of radioactive material through the ventilation system. If cooling was lost for several days, then the liquid could eventually boil dry, leaving a residue of hot radioactive salts from which volatile elements, such as caesium-137, could be released (POST 2004). HLW should be conditioned as soon as is feasible into forms that are passively safe and robustly stored, requiring minimum active management (Royal Society 2002). This usually involves vitrification into a glass product that is poured in stainless steel containers, solidifying during storage in air cooled vaults. Doing so would convert HLW into a stable solid form less vulnerable to dispersal.

Textbox 11 **International civil reprocessing facilities**

In the UK, the Magnox reprocessing facility reprocesses spent metal fuel from the UK's Magnox reactors. It had an original design throughput rate of approximately 1500 tonnes of heavy metal (tHM) per year. The Thermal Oxide Reprocessing Plant (THORP) was constructed to reprocess the spent oxide fuel from the UK's Advanced Gas Cooled Reactors (AGRs), as well as overseas fuel. UK, Japan and a set of European partners each contributed a third of the required funding. THORP has a throughput rate of approximately 900 tonnes heavy metal (tHM) per year – three times the capacity needed to manage the spent fuel from the UK's AGRs. THORP was commissioned and began operation in 1994. It was planned to operate until 2011 to meet contractual commitments for AGR and overseas LWR fuel. Following problems with its supporting infrastructure in 2005, THORP was shut down for two years and has been operating on reduced capacity since. The Sellafield MOX Plant (SMP) was deliberately built adjacent to THORP to facilitate the automatic transfer of the plutonium dioxide produced from reprocessing to the manufacture of MOX fuel as and when required by the customer. SMP has now been closed, having failed to meet design expectations.

France's nuclear power programme produces approximately 1200 tonnes of spent fuel each year, approximately 850 tonnes of which is reprocessed at La Hague. There are two reprocessing facilities at La Hague: UP2 and UP3. UP2 was originally designed for an annual throughput of 400 tHM per year. This has been upgraded and dedicated to reprocess spent fuel from French LWRs. UP3 is now operational. It was designed with a throughput of 1000 tHM per year. It was initially dedicated to reprocessing spent fuel from overseas customers (in Belgium, Germany, Japan, the Netherlands and Switzerland) but it now also reprocesses spent fuel from French LWRs. Separated plutonium is transported from La Hague to the MOX fabrication plant, Melox, on the Marcoule site in the south of France. At the end of 2008, AREVA and EDF announced a renewed agreement to reprocess and reuse EDF's spent fuel to 2040. This means that EDF could at some point reuse spent MOX fuel.

The Rokkasho Reprocessing Plant (RPP) in Japan has a design capacity of 800 tHM per year. Due to delays in its commissioning, Japan's nuclear industry has experienced difficulties in providing interim storage capacity for spent fuel. In a few years time, on-site storage capacity may reach its limit. Japanese utilities have sought international solutions to this problem, having recently negotiated further reprocessing contracts with UK. These contracts are now unclear in light of the decreased reactor operation in Japan post-Fukushima. Utilities are looking to build off-site storage facilities or to make arrangements with Russia for storage. Ensuring extra storage capacity is likely to be a key part of Japan's spent fuel management plans. RPP is linked directly to a MOX fabrication facility onsite. Japan has adopted a 'no surplus policy'. Since 2003, operators have been required to submit an annual plan about how they are to use their plutonium before any is separated.

While having success with its fast breeder programme with BN-600, commissioned in 1980, still operating today, Russia's progress with reprocessing has been limited. The Mayak RT-1 reprocessing facility was commissioned in 1976 and appears to be confined mainly to processing spent fuel from VVER-440 reactors. The uranium product is recycled in RBMK reactors but the plutonium is currently stored as separated plutonium dioxide powder. There are plans to upgrade RT-1 and the spent fuel storage capacity at the plant is being increased from 6000 to 9000 tonnes. The partly built RT-2 reprocessing facility in Siberia was cancelled but there are plans to redesign it as part of the new Global Nuclear Infrastructure Initiative with operation expected around 2025-30.

Best practice for reuse

Spent fuel should be reprocessed only when there is a clear plan for its reuse. This plan should seek to:

- Minimise the amount of separated plutonium produced and the time for which it needs to be stored.
- Convert separated plutonium into Mixed Oxide (MOX) fuel as soon as it is feasible to do so.
- Identify nuclear power reactors in advance to use MOX fuel and ensure conversion into MOX fuel matches reactors' loading schedules and fuel specifications.
- Transport plutonium as MOX fuel rather than in a separated form.

6.2 Best practice for spent fuel storage

6.2.1 Integrating interim storage into spent fuel management plans

Initially, the USA had ambitions to deploy FBRs as part of its long term energy policy. Following India's nuclear weapon test in 1974, President Carter's Executive Order on Non-proliferation in 1977 postponed government support for civil reprocessing, effectively cancelling reprocessing indefinitely. Since the Carter Administration, plans to manage US spent fuel have been based on the open fuel cycle. R&D was carried out on the suitability of Yucca Mountain as the site of a national GDF. In 2010, President Obama announced that funding for Yucca Mountain was cancelled, although this may be reversed due to legal reasons. A Blue Ribbon Commission on America's Nuclear Future (BRC) has been established to advise the Obama Administration on spent fuel management options. This change of policy has led to difficulties and US utilities may not have sufficient interim storage capacity, risking the shutting down of nuclear power stations. Due to a lack of sufficient storage capacity, ponds at reactor sites in other countries are also quickly filling up. The need for alternative storage capacity is becoming acute in many countries, such as Japan and South Korea.

Interim storage is now being integrated into spent fuel management strategies over periods of 50-100 years to allow cooling prior to geological disposal and to keep other options open. This should not be at the exclusion of pursuing final management options. An interim 'store and see' approach is not a scientifically convincing solution if it leaves waste management issues unresolved and burdens future generations (Royal Society 2006).

One factor complicating events at Fukushima was the amount of spent fuel stored onsite, particularly in the ponds inside the reactor buildings. The nuclear industry internationally is now reassessing its spent fuel management practices. While recognising the need for safety to be improved, security and safeguards considerations should also be taken into account. Moving spent fuel once it has sufficiently cooled from ponds in the vicinity of reactors for longer term storage elsewhere is likely to become standard practice. Minimising the amount of spent fuel stored in ponds in the vicinity of reactors would help to mitigate against the effects of a serious loss of coolant. It would also reduce the need for the high density packing of ponds. This practice has been implemented in some countries to accommodate the larger than expected inventories of spent fuel. High density packing can reduce costs and the risk of leaks (due to the need for smaller or fewer ponds) but places pressure on the reliability of cooling systems and emergency arrangements.

6.2.2 The potential of centralised storage

Interim storage could take place in the immediate vicinity of reactors or away from them. If there are several reactors on the same site, then spent fuel from each reactor could be stored together at a common, centralised store onsite. Alternatively, spent fuel could be stored at centralised stores located offsite, pending reprocessing or disposal. Spent fuel from Swedish nuclear power stations is transported to CLAB for interim storage where it is transferred to an underground complex of five storage ponds 25-30 meters below ground level (EDF 2008). CLAB has been operating since 1985 and its original capacity expanded to cater for spent fuel from all Sweden's current reactors. After interim storage the plan is to encapsulate the spent fuel in copper canisters with cast iron inserts for final disposal in a GDF elsewhere.

Centralised storage introduces regulatory requirements, especially for transport entailed, as well as the need to identify suitable sites. In principle, storage of spent fuel at centralised stores should be more readily secured than multiple stores (Royal Society 2006). Implementing one set of physical protection measures may be cheaper than having to invest in similar measures at multiple stores. Interim storage offsite could decouple the management of spent fuel from the consequences of any major safety accident or security incident onsite, such as an attack on a nuclear power reactor.

Off site, centralised stores could serve as national or international stores. In the UK, for example, spent fuel from the UK's AGRs and Magnox reactors is sent to Sellafield for storage pending reprocessing, reducing the amount of time spent fuel is stored at each reactor site. Moving spent fuel away from nuclear power stations may be important due to environmental changes, such as coastal erosion, or concerns about tsunamis. Consideration is now being given in Japan to constructing a centralised spent fuel store away from the coast (ONR 2011). Centralised storage may be necessary at, and beyond, the end of a reactor's lifetime for the ongoing storage of spent fuel whilst the reactor is shut down and then decommissioned.

Centralised storage could be co-located with reprocessing or disposal facilities. This could reduce waste management costs. Assuring the integrity of spent fuel during interim storage is vital if it is to be transported to another location for reprocessing or geological disposal. If destined for disposal, it may also have to remain intact for a further period before emplacement, final backfilling and sealing of the GDF. If spent fuel has corroded or degraded significantly, then a conditioning and/or repackaging facility may need to be available at each storage site to modify spent fuel into a safer form before being transported. This could add significantly to the logistical difficulties and cost of transport and disposal, and the facilities needed to do this would be expensive. Instead, one conditioning facility could be located at a centralised site.

6.2.3 The resilience of dry storage

If spent fuel is to be stored pending reprocessing, then it would be less complicated to continue to wet store it. Robust arrangements for continuous and back up cooling and onsite power are essential to guarantee safety and security over the long term. If there is no intention of reprocessing, then the high degree of passive safety and security provided by dry storage should be exploited.

Dry storage involves surrounding spent fuel assemblies with inert gas inside a large cask, typically a steel cylinder that is welded or bolted closed. This inner canister is surrounded by an outer cask made of steel, concrete or other material to provide extra radiation shielding. Cooling channels in the outer cask allow air to circulate naturally around the inner canister so that heat is removed by natural convection processes. In some cases, the casks are stacked vertically or horizontally in concrete vaults to provide further radiation shielding.

Although wet storage allows greater heat dissipation, dry storage is considered to be a safer long term management option due to its simpler, passive cooling systems. Unlike wet storage, dry storage does not necessarily rely on the intervention of an operator or mechanical control. Casks are considered to be highly robust to various attack scenarios. Casks may be easier to access than spent fuel in wet stores but their sheer size and bulk makes handling and movement of them highly difficult. Dry storage may be more expensive than wet storage, requiring extra space to store the same amount of spent fuel. Several casks are needed for each reactor discharge, thereby dividing up the inventory of spent fuel into a large number of discrete containers.

One R&D priority is to design casks that allow spent fuel to be removed from ponds after one to two years following initial cooling rather than the standard five years, although this may require active cooling. Further R&D may be necessary in the drying process, especially for damaged spent fuel.

Casks can be either single or dual use depending on whether they are to serve as the storage container only or also as the transport container. Other options are being explored, including multipurpose designs that can function as the storage, transport and waste container for disposal deep underground. This practice should be encouraged since it builds in contingency should spent fuel need to be moved or alternative management options pursued. Continued R&D can help provide confidence that spent fuel can be storable, transportable and disposable in the long term (CoRWM 2009b).

Best practice of storage

When planning interim storage:

- The amount of spent fuel stored in ponds in the vicinity of reactors should be minimised by removing spent fuel as early as is feasible for interim storage elsewhere whether onsite (away from reactors) or offsite.
- Interim storage at centralised stores offsite may be more secure than distributed storage at numerous reactor sites.
- If wet storage is to continue in the interim, then sufficient storage capacity should be planned to reduce the need for high density packing and to guarantee continuous cooling.
- Whenever possible, interim storage under dry conditions should be adopted to enhance nuclear safety and security.

6.3 Best practice for cradle to grave fuel cycle planning

6.3.1 Long term national policies for nuclear power

National policy needs to consider the long term role of nuclear power in energy policy. A nuclear power programme will almost certainly extend over 100 years, involving approximately: 10 years to plan, license and construct nuclear reactors; 60 year reactor lifetimes; and 50-100 years of spent fuel storage before reprocessing or disposal. Policymakers need to be made aware of the implications of departing from, or modification to, national policy on the capability to manage spent fuel and radioactive waste over these long timescales.

6.3.2 Planning for timely geological disposal

A GDF does not need to be available before nuclear power stations can be constructed. Rather, a dedicated Waste Management Organisation (WMO) should be created to ensure this capacity is delivered in a timely way. An agreed funding scheme for the capital investment that will be required needs to be identified and then implemented as soon as nuclear power stations begin operation. Storing spent fuel for decades provides time for the WMO to develop and implement long term waste management strategies, including for disposal (see textbox 12).

Textbox 12 **Spent fuel management in Scandinavia**

In 1977, legislation was passed in Sweden to ensure plans were formulated to manage spent fuel arising from its nuclear power programme. Responsibilities were clearly defined and financial arrangements put in place. The Swedish nuclear utilities set up the Swedish Nuclear Fuel and Waste Management Company (SKB) to develop a comprehensive spent fuel management programme. The utilities pay a fee determined by the government to a state fund to cover spent fuel and waste management, as well as decommissioning costs.

In the late 1960s, Finland embarked on a nuclear power programme and by 1980 two Soviet VVERs and two Swedish BWRs were in operation. Spent fuel was transported from the two VVER reactors to the Russian Mayak reprocessing facility. This was halted in 1994, after which Finland amended the Nuclear Energy Act to ensure that spent fuel would be managed nationally based on an open fuel cycle. This is managed by Posiva Oy, which was set up in 1995 as a joint venture company with TVO and another nuclear power company, Fortum (FPH).

Key responsibilities for the WMO include:

- Identify through international collaboration the capacity needed to deliver long term waste management, including disposal.
- Formulate a long term R&D plan to deliver this capacity when required. This could include acquiring intellectual property from other more advanced nuclear power programmes.
- Initiate a public and stakeholder engagement process, based on international best practice, on the long term management of waste, including disposal.
- At a later date, identify a suitable site and construct and operate a GDF.

6.3.3 The importance of public and stakeholder engagement

The importance of meaningful public and stakeholder engagement (PSE) in nuclear decision making must not be underestimated. A PSE process should be implemented from the outset and continue throughout a country's nuclear power programme (IAEA 2007). Public views and values must be listened to and considered even if government determines overall national needs and priorities (Royal Society 2002).

This PSE process should be:

- **Deliberative.** The starting point should not be to elicit responses to a predefined issue since the definition of an issue by experts may not be shared by the public. PSE should start by determining the issue itself and then framing the debate accordingly (Royal Society 2002).
- **Participative.** It should allow, and take account of, feedback from a wide range of local and national stakeholders, such as the government, regulators, industry and public, as well as neighbouring countries and the wider international community.
- **Inclusive.** A diversity of views should be encouraged and aired so that individuals can understand each other's viewpoint and build trust over time.

The institutions facilitating PSE need to command public confidence. An independent and credible advisory body could be set up independent of industry, government or regulators. It should reach out to the natural and social sciences, drawing on international experience of PSE processes. It could procure credible technical information and commission independent research and evaluation where necessary. It should also include engineering input to determine the practicality of options evolved. These activities are carried out in the UK by its Committee on Radioactive Waste Management (CoRWM) (see textbox 13).

6.3.3.1 An end to 'decide, announce, defend'

Early attempts to secure geological disposal sites were largely driven by technical considerations. Little effort, if any, was made to engage with host communities and other stakeholders until the process was well advanced. This so-called 'decide, announce, defend' process is no longer viable.

Although the NAS recommended geological disposal of spent fuel and HLW in 1957, it took until 1984 for candidate sites to be identified in the USA. In 1987, the US Congress limited studies to Yucca Mountain in Nevada. The site investigation process proved controversial and was delayed by legal challenges, concerns over the safety case, waste transport and funding shortfalls. In 2010, more than ten years after waste disposal was intended to begin, and with disposal delayed until at least 2020, the Obama Administration decided it no longer wished to pursue the license application. Many objections to the Yucca Mountain project were based on the perceived unfairness of the 1987 decision to limit investigation to Yucca Mountain, and the lack of benefits to the state of Nevada, which has no nuclear power stations.

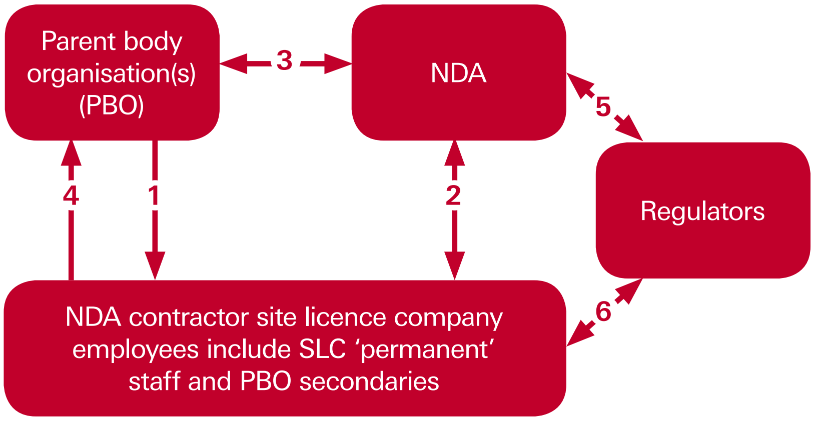
In contrast, recent experience in Belgium, Finland and Sweden has involved engagement with candidate host communities at a much earlier stage. Following early, unsuccessful efforts from the mid-1980s to the mid-1990s, a radically different approach that involved much closer dialogue with potential host communities was adopted in Belgium, initially for lower activity wastes. In Sweden and Finland where spent fuel disposal programmes have made good progress, close engagement with local communities has been essential for success.

Textbox 13 **The UK's approach to spent fuel and waste management**

The independent Committee on Radioactive Waste Management (CoRWM) was set up by the UK government in 2003 with an initial remit to make recommendations on the management of the UK's higher activity radioactive wastes. In 2006, CoRWM recommended geological disposal in the longer term following safe and secure storage in the interim. In 2007, CoRWM was reconstituted with a new remit to provide independent scrutiny and advice to government on these management plans.

The Nuclear Decommissioning Authority (NDA) was created as a Non-Departmental Public Body under the 2004 Energy Act to decommission the historic civil public sector nuclear legacy sites belonging formerly to UKAEA and British Nuclear Fuels Ltd. Whilst the Department of Energy and Climate Change is responsible for deciding policy on the management of the UK's nuclear power programme, the NDA is responsible for implementing it. Under the Energy Act, NDA's remit allows it to operate its reprocessing assets to fulfil existing contracts and earn revenues to help fund its decommissioning activities. This includes contracts to reprocess spent fuel from the UK's spent AGR fuel and spent fuel from overseas LWRs. In 2006, NDA was made responsible for implementing the UK's geological disposal plans. The Nuclear Industry Radioactive Waste Executive (NIREX) was incorporated into NDA's newly formed Radioactive Waste Management Directorate (RWMD), which is charged with executing this responsibility for disposal as outlined in the 2008 White Paper on Managing Radioactive Waste Safely.

Although the legal owner of the UK's civil nuclear sites, the NDA has contracted out work to operate all its sites. The presumption was that reaching out to national and international expertise based on commercially orientated contracts would improve the industry's performance. Under this model, the NDA agrees a contract with a Parent Body Organisation (PBO) to manage a Site Licence Company (SLC) on behalf of the NDA. The SLC is a commercial organisation responsible for delivering an agreed programme of work to schedule within an agreed contract, and for the day to day operation of NDA sites. The PBO may second key personnel into the SLC to provide leadership and management support to ensure successful delivery of the contract. The PBO owns shares in the SLC and dividends are paid to the PBO in light of earnings made by the SLC. Sellafield Ltd is the SLC that manages the Sellafield site, including the Thermal Oxide Reprocessing Plant and Sellafield MOX Plant. The PBO of Sellafield Ltd is Nuclear Management Partners, which is a multinational consortium of French, UK and US companies (AREVA, Amec, and URS, respectively). Both the boardroom and operations on site are multinational.



Key

1	Ownership of SLC shares
2	NDA Contract
3	Parent Company Agreement
4	Payment of dividends generated by SLC
5	Statutory Consultation
6	Regulatory Oversight of SLC/ Licensing/Authorisation

To build the highest level of confidence, the site selection process for a GDF should be:

- **Transparent.** A host site does not need to be initially identified but rather there should be an agreed route for doing so. An agreed set of pre-defined, objective criteria to determine the feasibility of possible options should be sought. These options should be carefully assessed to be demonstrably safe and secure. The premature selection of potential sites must be avoided.
- **Voluntary.** No community should be forced to host a GDF. Interested parties should be solicited voluntarily. They do not need to commit themselves at the outset to hosting the GDF. Even if they are not the eventual hosts, involvement will ensure all parties become informed customers.
- **Multi-staged.** This will allow local input into decision making from the outset and for interested parties to enter at different stages.

6.3.4 The importance of long term R&D

National policies should inform a long term R&D roadmap to develop a highly qualified skills base. Technically informed policymaking will help foster public confidence in the decisions that are made. Long term R&D can support contingency planning by keeping alternative spent fuel management options open.

6.3.4.1 Participation in international R&D programmes

This roadmap should be based on participation in international R&D programmes. This can be a cost effective way to access expertise and infrastructure that may be lacking nationally. It would also allow the policymaking process to remain aware of technical developments elsewhere and learn from experience gained worldwide. For example, there is substantial international research experience for different storage and disposal options given the variety and complexity of wasteforms and climatic and geological conditions.

6.3.5 Long term strategies to manage spent fuel

Operators are now required to develop long term strategies to manage spent fuel and radioactive waste for which they are responsible as part of standard practice for the granting of operating licenses. Different strategies may be necessary for different types of waste or for wastes belonging to different owners. These strategies should identify what capacity will be required and when, including interim storage capacity; the financial, human and technical resources needed to deliver this capacity; and how these resources will be made available.

6.3.6 The potential of international fuel cycle services and multinational arrangements

International fuel cycle services could offer management routes that are economically attractive, environmentally beneficial, and even provide politically helpful solutions to national problems. Facilities providing international reuse services have been available for decades. International storage and disposal services could become feasible, (see section 7.3 and 7.4). Despite the political sensitivities involved, collaborative R&D is still important to keep these international options open and explore their feasibility. There is no reason why these studies should in any way prejudice national approaches to geological disposal, especially those already underway. Governments need not commit to the implementation of these international options at this stage.

Best practice for cradle to grave planning

- Governments should establish a national policy that considers the long term role of nuclear power in the country's energy policy. This national policy should specify the requirements for managing spent fuel and radioactive wastes, including sufficient capacity for interim storage, as well as initiating plans for delivering timely geological disposal from the outset.
- Governments, in partnership with regulators, industry and academia, should develop a long term R&D roadmap to support these management strategies. It should be based on participation in relevant international R&D programmes.
- Operators should formulate spent fuel management strategies that cover the entire lifetime of their reactors. International fuel cycle arrangements should be sought, especially when national capacity is lacking.
- Governments should support collaborative R&D programmes on spent fuel and radioactive waste management. This should include joint studies to explore international fuel cycle arrangements, including geological disposal, although there would be no need for commitments to implement them immediately.

Internationalising the management of spent fuel

7.1 Cradle to grave fuel cycle services

International fuel cycle arrangements that couple the supply of fresh fuel with the management of spent fuel could be a major attraction to countries embarking on nuclear power by allowing them to avoid some of the major uncertainties, costs and complexities involved.

Cradle to grave fuel cycle services are not new. The former USSR leased fresh fuel to customer states for their nuclear power reactors, and spent fuel was repatriated back to the USSR. The USA provided fuel for US-built LWRs in other countries on 30 years contracts, specifying that spent fuel was only to be reprocessed or exported to third parties with US agreement. Contracts for UK designed Magnox reactors in Japan and Italy provided for the fuel to be reprocessed in the UK and HLW to be repatriated. Canada exported CANDU reactors fuelled with natural uranium with no constraints on the management of spent fuel, although spent fuel from one of its reactors was reprocessed to provide the plutonium used in the Indian nuclear test in 1974. This event spurred governments to include constraints on the management of spent fuel in fuel supply agreements through contractual obligations to consult before reprocessing and retransfer of spent fuel.

Cradle to grave services are being considered in the development of SMRs. SMRs could serve remote or isolated areas where electrical grids may be poorly developed or absent. SMRs can be deployed in a distributed or centralised fashion, depending on whether single units deployed at different sites or clusters of SMRs are deployed at a single site. SMRs could even be developed for maritime applications. SMRs could be manufactured and delivered to sites ready constructed, requiring less on-site work and faster deployment. This offers a flexible way to build nuclear generating capacity for a relatively low initial capital expenditure. The longer term economic advantage is unclear and so far there has been limited take up of them from utilities (NEA 2011). Some SMR concepts are based on long life cores so that the reactor does not need refuelling. Fresh and spent fuel management would be limited to the installation and replacement of the entire reactor unit. The storage, reprocessing or disposal of spent SMR fuel would be carried out elsewhere by a company or state with access to these fuel cycle facilities.

A single company could provide commercial services across the fuel cycle from cradle to grave. This could involve fuel leasing arrangements. Currently, an operator buys uranium from a mining company and then has it converted, enriched and fabricated into fuel before irradiating it in its reactors. If a supplier of fresh fuel could retain ownership, it could manage the fuel once spent. Only Russia is prepared to lease fuel and take it back once spent. This has been exemplified by its arrangement with Iran for operating that country’s reactor at Bushehr (albeit arrived at under considerable US pressure). Russia may be negotiating with Vietnam to supply fuel and then take it back once spent for reprocessing. Today, AREVA provides an ‘integrated offer’ whereby it will construct nuclear reactors, provide the fuel for them and reprocess the spent fuel. Arguably, EDF provides a similar service by transmitting electricity generated by reactors in France across its borders to Germany, Italy, Spain and UK, while the spent fuel remains and is managed in France.

Alternatively, several companies could provide fuel cycle services that between them cover the entire fuel cycle. Some companies could provide the same service, which may be more attractive to potential customers by diversifying the supply of services. The grave need not be located in the same country as the cradle.

7.2 Options for international reuse

Not all countries will produce large enough volumes of spent fuel to justify investing in their own reprocessing and MOX fabrication facilities. As a nuclear renaissance takes off, world capacity to reprocess spent fuel is expected to exceed demand.

Commercial reuse services are already provided internationally. Spent fuel from Belgium, Germany, Italy, Japan, Netherlands, Sweden and Switzerland has been sent to France and UK to be reprocessed. Plutonium has been returned as MOX fuel and irradiated in reactors in these countries.

Countries offering reuse services could pay to burn MOX fuel in their own reactors so that only HLW is returned to customer countries. This may be important for some countries with legacy materials that present different challenges, and require different management options, than those embarking on nuclear power for the first time. This option has been suggested in recent proposals to manage stockpiles of separated plutonium internationally (Suzuki *et al* 2009). Utilities could declare some plutonium to be excess in exchange for an energy equivalent of LEU. Reactor operators would bid to irradiate this excess plutonium, having been fabricated into MOX fuel, as part of an international disposition programme funded by the countries that own these stockpiles. The ownership of the resulting spent MOX fuel and responsibilities for how and where it is managed in the longer term (including disposal) would still need to be clarified at the outset.

7.2.1 Comprehensive cradle to grave services

While options exist for international reprocessing, there is a lack of options for international storage and disposal. The recent US Global Nuclear Energy Partnership (GNEP) and Russian Global Nuclear Power Initiative included provisions to lease fresh fuel and then reprocess it once spent. Neither included provisions to dispose of HLW that would arise except by returning it for disposal in the customer country. A comprehensive cradle to grave fuel cycle service that includes disposal could provide a key incentive for countries to decide not to construct enrichment or reprocessing facilities nationally.

7.3 Options for international storage

Access to interim storage provided by third parties could be attractive to countries facing acute problems in storing their spent fuel if national capacity is lacking. Transfer to an international storage facility may be difficult if a final management option is yet to be decided. Returning spent fuel after a period of interim storage could reinstate the national problems that international storage was meant to address. International storage may be perceived to be a permanent rather than an interim solution. International storage could be more politically acceptable if part of an international reuse or disposal arrangement. This is essentially what the UK has provided at THORP for storing then reprocessing spent fuel from international partners.

An international storage facility could be co-located with a reprocessing and MOX fabrication facility or a GDF. This may incentivise the country offering the storage service to ensure these final management options can be delivered when required. Alternatively, stored spent fuel could be sent to a third party for reprocessing or disposal, although this would entail extra transport costs.

7.4 Options for international disposal

Geological disposal is not yet offered internationally. The large volumes of spent fuel arising from a nuclear renaissance, especially if many countries opt for an open fuel cycle, could create a commercial market for disposal services. No country has yet championed international disposal due to concerns that doing so could detract support for the country's own national disposal programme (EDRAM 2011). National programmes must not be hindered since demonstrating progress in disposal is in everyone's interest. This does not mean that governments should reject international disposal outright since they need not commit themselves to implementing it at this stage. Rather, governments should be prepared to engage with it constructively so that even if they are not interested in international disposal themselves, it still remains open for other interested parties to explore.

7.4.1 Demand side considerations

7.4.1.1 Ethical considerations

National approaches to disposal are driven in part by the principle that each country is responsible for ensuring safe and environmentally sound radioactive waste management. The Joint Convention states that 'radioactive waste should, as far as is compatible with the safety of the management of such material, be disposed of in the state in which it was generated' (IAEA 1997). International disposal is not necessarily incompatible with this principle. Every nuclear power programme will give rise to some spent fuels and radioactive wastes to be managed by geological disposal, but not every country may have suitable geology and resources, or a willing host community, to dispose of these materials safely and securely. Under these circumstances, international disposal services could provide the safest and most secure route for a country to manage its spent fuel and radioactive waste responsibly. As the preamble of the Joint Convention recognises, 'in certain circumstances, safe and efficient management of spent fuel and radioactive waste might be fostered through agreements among Contracting Parties to use facilities in one of them for the benefit of the other Parties, particularly where waste originates from joint projects'.

Another important principle is that a strategy to manage radioactive wastes should be identified now with rather than left for future generations. Countries with small nuclear power programmes operating on an open fuel cycle may not produce large enough volumes to justify the significant investment required to construct and operate a GDF. This may require the accumulation of spent fuel (and funds) over very long timescales. Access to a GDF elsewhere would avoid burdening future generations. International options could facilitate early disposal, reducing some environmental impacts associated with decades-long periods of above ground storage. Early disposal would also provide security benefits (see section 3.5.2.5).

7.4.1.2 Economies of scale

The assumption is that international fuel cycle services need to offer benefits at least equal to, or greater than, those provided by solely national means, and must be able to compete commercially. Several international GDFs may be necessary to compete and avoid a monopoly. Disposal services may need to be provided by a diverse group of countries, including NWS and NNWS.

Avoidance of possible political problems affecting national programmes or having a clear and early limit on future liabilities could lead a customer country to pay a premium for international disposal rather than face the uncertain costs of implementing a national solution in the longer term (IAEA 2004).

7.4.1.3 Separating commercial and political decision making

Due to the complexity of multinational arrangements, it may be prudent to seek ways to ensure political differences do not undermine commercial activities. Access to sensitive technology is the major sensitivity for multinational enrichment and reprocessing arrangements. Each of the participating governments in URENCO has equal voting rights on an intergovernmental Joint Committee responsible for the political ground rules for URENCO's activities, such as how the technology is used and transferred and the safeguards and non-proliferation conditions associated with enrichment contracts. This Joint Committee is not responsible for operational commercial decision making. This is the responsibility of URENCO's two business groups (Enrichment Technology Corporation and URENCO Enrichment Company Ltd). Access to sensitive material is likely to be the major source of proliferation and security concerns for an international GDF. This includes not just spent fuels but also plutonium and other sensitive materials. Clear guidelines on the retrievability of wasteforms will need to be discussed from the early stages of design development.

7.4.2 Supply side considerations

The IAEA has identified three types of multinational arrangement (IAEA 2005):

- Type 1 Providing additional assurances for the supply of international fuel cycle services.
- Type 2 Converting existing national fuel cycle facilities into multinationally owned and/or operated ones through partnerships between NWS and NNWS ('add on').
- Type 3 Constructing new fuel cycle facilities to be owned and/or managed on a multinational or even regional basis from the outset ('partnering').

7.4.2.1 Type 1: mulilateral approaches

Type 1 involves a multilateral, rather than multinational, approach. Whereas a multinational approach involves a group of states or companies collaborating on some aspect of the nuclear fuel cycle, a multilateral involves an arrangement involving some form of intergovernmental oversight body, such as the IAEA. This is exemplified in agreements to set up an IAEA owned and managed LEU fuel bank (see textbox 14). A multilateral approach to disposal may be necessary if only to provide confidence that the highest international standards of safety, security and safeguards are implemented (see section 7.5).

7.4.2.2 Type 2: add on

GDFs being developed nationally could eventually offer disposal services to other countries. The host country would need to be politically acceptable, and willing to offer the GDF to some sort of multinational ownership and/or operation at to enhance international oversight. The BRC recommended in its draft report that a capability to take back spent fuel from other countries could be considered in the broader framework for managing and disposing of US spent fuel (DoE 2011).

This option may be a longer term prospect given the political sensitivities involved. National approaches to disposal are driven by perceptions that a country could become an international nuclear waste dump. Originally the providers of international reprocessing services included a disposal service but clauses were later added to contracts to return HLW due to public

Textbox 14 **Assurances of fuel supply**

The World Nuclear Association has proposed a 'guarantee in depth' model to provide greater assurances in the supply of international enrichment services (WNA 2006). It has a three-tiered structure: 1) customers look to the existing commercial market for the supply of enriched fuel; 2) if a company cannot deliver on its contracts for political reasons unrelated to non-proliferation, then other companies guarantee to supply enriched fuel; 3) should this collective guarantee fail, then low enriched uranium (LEU) is made available from a fuel bank under governmental or intergovernmental control. In 2009, the International Atomic Energy Agency (IAEA) approved a Russian initiative to establish a reserve of LEU for the IAEA to supply to its member states. In 2010, the IAEA Board of Governors authorised the IAEA Director General to set up an IAEA owned and managed LEU fuel bank. The IAEA would determine the legitimacy of the customer's claim in light of pre-defined criteria and the events leading up to the contract interruption. The IAEA would then notify the other enrichment companies to fulfil their obligations. International fuel fabrication services would still have to be assured for a fuel bank to be a credible assurance mechanism. An assured supply of nuclear material does not necessarily entail an assured supply of fabricated fuel.

pressures. National stakeholders may need to be convinced that an international GDF sited in their country could first successfully dispose of legacy or new wastes arising from their own nuclear power programmes before accepting wastes from other countries.

7.4.2.3 Type 3: partnering

A second option would be to construct a multinational GDF from the outset. This may be more attractive for countries with smaller nuclear power programmes, although success would be more likely if supported by countries with larger nuclear power programmes.

A group of interested countries could collaborate on a joint waste disposal programme with a view of one of them eventually hosting an international GDF. An international GDF may need to dispose of different types of spent fuel and accommodate a variety of waste types and wasteforms. Alternatively, specialised disposal facilities could be established in different countries for the disposal of specific types of waste. This would help to demonstrate the viability of international GDFs. One country could accept certain types of wastes as part of an arrangement involving the mutual exchange of equivalences of waste. This division into different types of waste is already standard practice in the nuclear industry. Under the Vitrified Residue Returns programme, all the HLW arising from reprocessing Japanese spent fuel in the UK is returned to Japan. The ILW and LLW arising from this reprocessing is substituted for a small volume of radiologically equivalent HLW to minimise the transport of large volumes of radioactive wastes to Japan.

A privatised approach is also possible. In the 1990s, Pangea Resources, a joint venture of British Nuclear Fuels, NAGRA and Golder Associates, carried out research to identify geologically and environmentally suitable sites for the international disposal of HLW and spent fuel. Pangea's initial research was conducted over several years in China, South America, southern Africa and Australia. Australia was the favoured location, but engagement with Pangea was opposed by both Federal and State Governments and no meaningful discussions ensued. Legislation was rapidly passed to prevent Pangea's activities.

7.4.3 Next steps for international disposal

7.4.3.1 A dual track strategy

Interested parties could adopt a dual track strategy (Risoluti *et al* 2008). Countries do not need to decide at the outset between embarking on a purely national or international disposal programme. Should the international route fail, for example, then the country could fall back on the national route as a contingency, having gained invaluable experience from these efforts since national and international options draw on overlapping R&D. To ensure transparency and maintain trust, engagement in any international activity must be clearly communicated to all local, national and international stakeholders.

7.4.3.2 An international siting process

The siting of an international GDF would in time need to be addressed. Concerns about 'not in my backyard' are already experienced in national programmes. Yet this has not prevented local communities in some countries agreeing to host a GDF due, in part, to successful PSE.

A focus of PSE in this area would need to facilitate a deeper discussion about the global benefits of these arrangements for non-proliferation and international security. Lessons could be learned from international programmes involving the take back of spent research reactor fuel since they provide similar benefits. In the 1960s, the USA exported research reactors fuelled with HEU to approximately 40 countries, mainly as part of the Atoms for Peace programme. Security and non-proliferation concerns have led to efforts to promote the reduction and phase out of HEU for civilian uses, and to return nuclear materials from vulnerable sites worldwide. In 1986, the DoE extended its 'Off Site Fuels Policy' to include the acceptance of foreign spent research reactor fuel. This programme expired in 1988 for HEU fuels and in 1992 for LEU fuels. In 1996, the US Foreign Research Reactor Spent Nuclear Fuel Acceptance Programme began whereby the USA would take back certain types of spent fuel from US supplied research reactors, serving as an incentive for countries to convert their research reactors to use LEU. This programme was subsumed in the Global Threat Reduction Initiative, which was launched in 2004 by the DoE. Russia has also taken back research reactor fuels.

Successful national approaches could be used to identify best practice for engaging international partners, as well as national and local stakeholders (McCombie and Chapman 2008). These models cannot be translated blindly to other nations, cultures and systems of government but they may be useful to establish some general principles (see section 6.3.3.1):

- Interested parties should participate voluntarily. Participation is not premised on any commitment to host an international GDF. No country at any stage will be compelled against its will to accept foreign wastes. Even if they are not the eventual hosts, involvement will ensure all partners become informed customers.
- A host site does not need to be initially identified. Instead, an agreed route for doing so should be established, including a set of pre-defined, objective criteria to determine the feasibility of possible options. These options should be carefully assessed to be demonstrably safe and secure.
- This process should be multi-staged. Interested parties should be able to enter at different stages. Only once the largest nuclear power programmes likely to participate are engaged can the scale of benefits and impacts to the host country and community be estimated confidently. This will help ensure that potential sites are not identified prematurely.
- The involvement of credible international bodies could build confidence. Engagement of the IAEA and/or EURATOM could ensure that international standards are met at each stage of the process.

7.4.3.3 International transport of nuclear materials

There is a strong public antipathy to the transport of nuclear material and radioactive wastes yet the statistics of incidents during transport over several decades imply a very low risk (Royal Society 2006). To date, many thousands of tonnes of spent fuel have been transported safely and securely. The transportation of nuclear materials provides a good example of how a thoroughly internationalised fuel cycle activity can be carried out through high levels of physical protection and operational best practices (see textbox 15).

Textbox 15 **Secure transport of nuclear materials**

The transport of nuclear materials is governed by various international regulations underpinned by the UN Model Regulations on the Transport of Dangerous Goods. As Class 7 Dangerous Goods, the most highly regulated category of transport, the transport of nuclear materials is subject to various international safety and security regulations. Nuclear material is transported by road, rail and sea in highly robust transportation casks designed to provide radiation shielding and high levels of physical protection. Spent fuel, MOX fuel and HLW are transported using purpose built transport vessels. Cargo areas are surrounded by double hulls filled with structures highly resistant to impact. Redundant navigation, communications, cargo monitoring and cooling systems are deployed, as well as twin engines. Satellite navigation and tracking is employed to monitor movements. Shipments have also involved deck mounted naval guns, an armed escort and escort by a second identical vessel. Should the ship and container be breached upon attack, spent fuel and vitrified HLW remain highly insoluble in water. If Category 1 materials, such as plutonium, are transported, armed guards accompany the shipment so that the cargo is under surveillance at all times.

Best practice for transport includes (IAEA 2011):

- receiving authorisation for transport from the national regulator based on current threat assessments and intelligence information available relating to the particular transit route;
- minimising the total time nuclear material is in transit and the number and duration of transfers;
- avoiding predictable and regular use of transport schedules, routes and bottlenecks, as well as routes that involve areas of natural disasters, civil disorder or with a known threat;
- restricting advance knowledge of transport, including the date of departure, route and destination, to the minimum number of designated individuals on a 'need to know' basis.

IAEA safeguards inspectors verify the loading of transport containers of nuclear materials onto ships, which are then sealed. IAEA inspectors are on-hand at the receipt of the container to verify the integrity of seals and witness the unloading. If the shipment is not sealed, then the shipper and receiver both make an estimate of the content of nuclear material and report it to the IAEA. The IAEA allows a limit on differences in these measurements, depending on the type and nature of the material. If differences are too large, then the IAEA may need to investigate further and establish the cause for the discrepancy. Where discrete items are shipped, the items have to correspond.

7.5 Regional approaches to spent fuel management

A multilateral approach to disposal could be developed regionally. As the previous UK government recognised, 'developing regional perspectives that build trust between those who have and those who seek nuclear power is absolutely crucial to the development of multilateral approaches' (Cabinet Office 2009).

EURATOM may provide the best exemplar of a regional approach to fuel cycle management (see textbox 16). EURATOM provides a mechanism to promote and implement the highest standards of safety, security and non-proliferation. EURATOM applies regional oversight, including safeguards inspections, of all contracts for nuclear materials through formal ownership of nuclear material produced or used within the European Union. Similar arrangements could compliment the IAEA and help address political problems in other regions by involving inspectors from neighboring states rather than from outside of the region (Mallard 2008). EURATOM supports R&D and mechanisms exist for regional collaboration. For example, the EC Technology Platform Implementing Geological Disposal brings together national Waste Management Organisations from across the EU to develop collaborative R&D on geological disposal. EURATOM also facilitates the development of dual use technologies, although doing so solely within a regional framework is not mandatory. If other countries want to develop sensitive technologies, then doing so within a regional framework could help to build trust.

Textbox 16 **A European framework for nuclear power development**

Signed in 1957, the European Community of Atomic Energy (EURATOM) Treaty provided a legal and political framework to develop nascent European nuclear power industries. Security of supply was at the heart of EURATOM due to concerns at that time about possible uranium scarcity. The EURATOM Treaty created the European Supply Agency (ESA) as a regional procurement agency to ensure member states had access to fuel, especially for those that do not themselves have national enrichment facilities. This provided a collective assurance of fuel supply. If a major exporter of fuel was to stop exporting fuel to a EURATOM member state for reasons unrelated to the behaviour of the importing state, then exports to all other member states would be stopped. The Euratom Control Agency (ECA), also established under the Treaty, would investigate this misbehavior to verify the legitimacy of the exporting state's claim. EURATOM requires all uses of nuclear power to be reported to, and verified by, the ECA. ECA has the powers to trace and inspect the circulation and use of fissile materials within the European Union since fissile materials are formally the property of EURATOM rather than nation states and industries. ECA has no effective rights during normal times. The ECA cannot redistribute, sell or confiscate material unless companies that use it are found guilty of misusing it.

There are emerging signs of regional developments elsewhere. The bilateral Agreement for the Exclusively Peaceful Use of Nuclear Energy created the ABACC that supports bilateral safeguards inspections in Argentina and Brazil. Should ABACC develop with an increasing regional membership (as EURATOM did), then it could provide a similar oversight framework. The African Commission on Nuclear Energy (ACNE) was established under the African Nuclear Weapon Free Zone Treaty that entered into force in 2009. As of 1 March 2011, all 53 members of the African Union are signatories. ACNE promotes cooperation in civil nuclear power and verifies civil nuclear activities to ensure compliance with the treaty. The African Regional Cooperative Agreement for Research, Development and Training related to Nuclear Science and Technology seeks to make the best use of expertise and infrastructure. The Forum of Nuclear Regulatory Bodies in Africa was recently created to facilitate the exchange of best practice among national regulatory bodies in the region. Proposals have been made for a EURATOM-like concept for the Association of Southeast Asian Nations (ASEAN). Little progress has been made to date, although an ASEAN Nuclear Energy Cooperation Sub Sector Network was set up following the 2007 Regional Energy Summit to assist member states' nuclear power programmes. An Atomic Energy Agency was set up under the auspices of the Arab League to oversee nuclear power development in the region.

With over 50 years of operation, the strengths and weaknesses of EURATOM should be assessed so that lessons could be applied to other regions. Any new regional arrangement will need to secure the confidence of the IAEA and international community, especially in their ability to exercise independent legal enforcement. The EURATOM Treaty created the Euratom Commission responsible for developing civil nuclear power projects that first needed to be approved by the Council of Ministers. The European Court of Justice has the judicial power to litigate conflicts between member states, industrial companies and EURATOM Commission. A similar underpinning governance structure may be a prerequisite, the culture for which may not exist in all regions (Mallard 2008).

Whilst EURATOM provides a regional approach to the supply of fresh fuel, a multilateral mechanism for a European approach to geological disposal does not yet exist. European governments are starting to taking this option seriously. A recent Directive of the European Commission requires all member states to submit a report to the European Commission by 2015 on their national plans to manage spent fuel. As the Directive recognises, 'sharing of facilities for spent fuel and radioactive waste management, including disposal facilities, is a potentially beneficial option when based on an agreement between the Member States concerned' (EC 2011).

The 'partnering' option for disposal could be amenable to a regional approach. The Support Action: Pilot Initiative for European Regional Repositories finished in 2008. Funded by the European Commission, this project explored the feasibility of shared storage and disposal solutions for some countries in the EU. It made proposals for a staged strategy to implement a European Development Organisation that would carry out the preparatory work up to the siting of a regional GDF (Risoluti *et al* 2008). In 2009, a Working Group of interested countries was set up, in which ten countries have participated, including Austria, Bulgaria, Ireland, Italy, Netherlands, Lithuania, Poland, Romania, Slovakia and Slovenia. These efforts provide a model that could be applied to other regions (see textbox 17).

Textbox 17 **A regional approach to geological disposal** (based on Risoluti *et al* 2008)

A Regional Development Organisation (RDO) could be set up to carry out preparatory work up to the siting of a regional Geological Disposal Facility (GDF) and secure acceptability in potential user and host countries. This would begin as a non-governmental activity given the political sensitivities involved. The RDO could be a voluntary network or association of interested parties, such as national Waste management Organisations and relevant regional and international bodies, such as the International Atomic Energy Agency. The RDO could develop into a more formal organisation with a legal status over and above its individual members, such as a co-operative or consortium. Cooperatives tend to be equally owned by their members and controlled with equal voting rights. Members of consortia participate in a common activity or seek to pool their resources for an objective beyond the means of any one member. Both types of organisation would demonstrate the commitments of the RDO's members to seek a common waste disposal solution.

Joint studies could explore:

- flexibility of geological disposal concepts to accommodate different types of wastes;
- contractual and financial arrangements between host and customer countries;
- benefits and risks of international disposal options and how they are to be shared among partners;
- responsibility for liabilities, including the ownership and retrievability of spent fuel and HLW;
- compatibility of national laws, not least definitions of radioactive waste;
- consent of third parties, especially if nuclear material is to be transported across their territories or jurisdictions;
- condition of wastes and any need for reconditioning upon arrival in the host country.

In the longer term, these partnerships could build trust to foster more integrated polices and even collaborative infrastructure. The RDO could evolve into an intergovernmental organisation. An intergovernmental treaty between participating states would be necessary given the long timescales involved. Collaborative disposal programmes will need to endure many political election cycles. The various governmental organisations or industrial companies involved at the start may no longer exist at the end of the project.

Once the RDO has achieved its objectives, it could evolve into or separately set up a Regional Repository Organisation (RRO) responsible for constructing and operating the regional GDF. Various arrangements for the management and/or operation of the RRO are possible, drawing on models used for other fuel cycle facilities (see textbox 3). Shares could be apportioned between the RDO's members according to level of investment made, possibly reflecting the size of each partner's planned waste inventory to be disposed of in the GDF. Whereas the RDO can be located anywhere (so as not to prejudice the siting of the GDF), the RRO must be based in the country where the GDF will be implemented. The government of the host country may need to distance itself from the ownership of the RRO to demonstrate there is no conflict of interest with its regulatory functions. Once built, however, the host country could be largely responsible for the operation of the GDF. The RDO could remain a purely intergovernmental organisation. Alternatively, the RRO's members could decide to transform it into a commercial company.

The UK's role in the development of nuclear power

8.1 A long term strategy for nuclear power in the UK

The government has reaffirmed its support for the construction of new nuclear power stations in the UK (DECC 2010a). Over the next decade and half, all but one of the UK's reactors are scheduled for closure and decommissioning. Current plans are for new thermal LWRs to replace existing capacity. The current assumption is that geological disposal will be the ultimate, long term management option for spent fuel arising from the UK's new nuclear power stations preceded by interim storage until a GDF is ready. The NDA is developing a strategy to manage spent oxide fuel for which it is responsible (see textbox 13). NDA's current assumption is to complete these contracts as soon as reasonably practicable and then cease reprocessing at THORP.

The UK's electricity generation, including nuclear power, is open to the market. The UK government has not set specific targets for the contribution that nuclear power may make to meet future demand since this is for the market to determine. The government sees its role as catalysing private sector investment in the UK's energy infrastructure by developing a clear and long term policy framework (DECC 2010a).

A long term strategy for nuclear power was developed at the very start of the UK's nuclear power programme. The 1955 White Paper entitled 'A Programme of Nuclear Power' identified nuclear power as a major source of diversifying the UK's supply of energy. The Department of Energy and Climate Change (DECC) similarly needs to articulate the future role of nuclear power in the UK's long term energy policy to achieve its energy security, climate change and stated carbon reduction goals. This could be facilitated through a high level, Civil Nuclear Power Council. Set up in DECC, this Council would bring together senior representatives from the nuclear industry and senior officials from key government departments and agencies to provide coherence and set strategic direction. This Council would advise Ministers, making its advice public and transparent. The participation of senior officials would be of benefit to Ministers by providing institutional memory and longevity.

Recommendation

Given that the UK government has decided to embark on a new nuclear power programme, the Department of Energy and Climate Change (DECC) should develop a strategy that addressees the future role of nuclear power in the UK's long term energy policy. This could be facilitated by a high level, Civil Nuclear Power Council based in DECC that brings together senior representatives from the UK's nuclear industry and senior officials from government departments and agencies.

8.2 A long term R&D roadmap

A long term strategy for nuclear power should inform a long term R&D roadmap to be developed by DECC in partnership with industry and academia. Nuclear R&D currently focuses on supporting the existing and decreasing fleet of nuclear power stations, including life extension, safety and waste management and decommissioning (ERP 2010). It may be short-sighted to foreclose options early given the uncertainties inherent in the long timescales of a nuclear power programme. Appropriate investment needs to be made in the infrastructure, R&D and the skills base to keep future options open.

8.2.1 Reinvigorating UK participation in international nuclear R&D programmes

A priority for re-engagement is GIF. The UK's current non-active status in GIF should be reviewed and its full participation renewed. A modest investment, even of the order of £1 million a year, would facilitate re-engagement and provide the UK with significant leverage (EPSRC/STFC 2009).

The UK is not an active member in INPRO and any contribution is made through the European Commission's membership. The proliferation sensitivities of the technologies being developed under GIF and INPRO directly affect the UK's strategic interests. The UK can only assert influence through active participation in the development of these technologies. The UK is recognised as having unique industrial experience of fast and gas cooled reactors, as well as industrial scale reprocessing, that would be of significant value to GIF and INPRO.

The UK has the opportunity to shape the direction and activities of the International Framework for Nuclear Energy Cooperation (IFNEC), not least through NDA's chairmanship of one of IFNEC's Working Groups. IFNEC need not be viewed as a competitor to other international bodies, such as the IAEA. IFNEC could promote the implementation of best practice identified by these bodies. A greater industry lead on IFNEC's activities would provide a source of new funding, as well as helping to distinguish IFNEC from other government-led bodies. Whereas nuclear newcomers approach the IAEA for assistance through governmental routes, IFNEC could allow them to interface directly with the international nuclear industry. IFNEC should foster collaborations to explore the potential of various international fuel cycle arrangements. UK industry's unique experience of such arrangements reinforces its leadership potential in this area.

The UK is not a member of the Next Generation Safeguards Initiative (NGSI) (see textbox 5). The UK's practical experience of safeguarding spent fuel and plutonium other non-uranium materials provides it with an opportunity to be a leading international partner.

Recommendation

A long term strategy for nuclear power in the UK would guide a long term R&D roadmap. It should be based on a review of current UK R&D, relevant international programmes and suitable UK participation in them.

8.3 A global R&D hub

The implementation of a long term R&D roadmap will involve universities, the National Nuclear Laboratory (NNL) and other relevant research organisations. It will need to be supported principally by government funds but also drawing on industry sources. This is necessary to deliver the comprehensive research portfolio necessary to develop a high quality skills base to support a growing nuclear industry in the UK. There are important historical lessons to learn. The UK was a world leader on fast reactor R&D, having built and operated the Dounreay Fast Reactor and the Prototype Fast Reactor. Without government support, the UK lost its leadership and its skills base in this area quickly dissipated.

8.3.1 The role of the National Nuclear Laboratory

NNL was created from the R&D Division of British Nuclear Fuels Ltd. NNL was launched in 2008 on a Government Owned Contractor Operated model. The UK government owns NNL's facilities while external customers pay to use them. NNL receives no direct government funding and undertakes work for customers, although the majority of its customers are government departments or agencies, especially the NDA. NNL was not given a R&D remit. Annual profits are returned to government rather than invested in longer term R&D. This business model means NNL delivers on customers' short term needs rather than long term R&D and strategic needs. It is difficult for NNL to participate in some international R&D programmes since it is difficult to find a customer to fund their participation.

NNL operates the only high activity civil R&D facilities in the UK. This is based around The Central Laboratory, a £260 million state of the art research facility which is only partially commissioned. At the time of writing, the Plutonium Development Laboratory awaits government approval to complete its commissioning. NNL's high activity facilities are yet to be commissioned. Both sets of facilities need to be fully commissioned if the UK is to have a world leading capability to undertake spent fuel management R&D. If this was successfully applied to the UK's stockpile of separated plutonium, it could also be applied to help other countries manage plutonium materials, too. The only R&D that can be carried out at NNL's facilities is that funded by NNL customers. NNL's management wishes to open its facilities to external researchers. Discussions are underway to develop an access model to give academic and other external users the ability to undertake research.

Recommendation

The implementation of a long term R&D roadmap will need to be supported principally by government funds but also draw on industry sources. It will involve universities, the National Nuclear Laboratory (NNL) and other relevant research organisations. NNL's facilities must be fully commissioned and suitable access provided to researchers to use them.

8.4 Co-ordinating non-proliferation and nuclear security

A long term nuclear power strategy would need to be informed by national policy for non-proliferation and nuclear security. This should be set by the UK's new National Security Council (NSC). Similarly, a long term R&D roadmap would need to be informed by R&D priorities in these areas. These could be identified by a suitable technical NSC sub-committee on which relevant governmental departments and agencies should be represented. Publicising the membership and terms of reference of this sub-committee would increase the transparency of nuclear decision making.

Although centrally co-ordinated, the implementation of non-proliferation and nuclear security research could be implemented in a distributed fashion. The best use must be made of limited resources and complementary expertise, especially when basic R&D cuts across many stakeholders' interests, including AWE and NNL.

Recommendation

The National Security Council (NSC) should set non-proliferation and nuclear security policy. Research priorities would be identified by a suitable technical NSC sub-committee. This will ensure co-ordination between the different interests of stakeholders and various implementing bodies. These priorities would then inform the UK's long term strategy for nuclear power and R&D roadmap.

8.4.1 The role of AWE

The majority of the UK's expertise in threat reduction research resides in AWE's National Nuclear Security Division. It must continue to be well supported. Civil nuclear organisations, such as NNL, have an important role to play to complement AWE's expertise. To facilitate engagement with the wider scientific community, full advantage should be taken of AWE Blacknest. Blacknest provides an exemplar for effective interaction between classified and non-classified environments. The Eskdalemiur seismic array in Scotland relays information to the UK's National Data Centre at AWE Blacknest as part of the international monitoring system for the Comprehensive Test Ban Treaty. This has enjoyed successful engagement with the British Geological Survey in particular.

Recommendation

AWE's threat reduction research must continue to be well supported. AWE's National Nuclear Security Division should be developed, exploiting the Blacknest model, so that the wider scientific community, including international partners, can engage effectively with this expertise in a non-classified environment.

8.5 Capacity building for non-proliferation and nuclear security

8.5.1 A Non-Proliferation and Nuclear Security Network

A Non-Proliferation and Nuclear Security Network should be set up by the Foreign and Commonwealth Office (FCO). By facilitating information sharing, academia and industry would remain knowledgeable about government policy whilst policymakers would be networked with experts to draw on for advice. The network would allow academia and industry to be more effectively integrated with the UK's Member State Support Programme to the IAEA. They would be informed about the IAEA's requirements whilst reciprocally identifying relevant R&D of benefit to the IAEA. Chaired by the FCO's Chief Scientific Adviser, the network would allow participants to advise on non-proliferation and nuclear security priorities, and how they impact on long term nuclear power strategy and R&D.

Relevant government departments and agencies, including DECC, FCO, Ministry of Defence and Research Councils, should brief the network about funding sources so that they can then collaborate outside of it. During FY2010-2011, the UK Government spent over £40 million on nuclear non-proliferation and nuclear security programmes (see textbox 18). The costs of the network are unlikely to be significant and could probably be accommodated within this spend and other industry budgets. To ensure wider impact, the results of these collaborations should be profiled at major diplomatic initiatives, such as NPT Preparatory Meetings and Review Conferences, Nuclear Security Summits, as well as IFNEC and GICNT meetings. By reaching back into university departments, the network should stimulate student interest in career paths as safeguards and nuclear security professionals.

Textbox 18 **UK spend on nuclear non-proliferation and nuclear security**

The Counter Proliferation Programme (formerly known as the Strategic Programme Fund) is administered by the Foreign and Commonwealth Office (FCO). It has a budget of £3 million for 2011-2012. It funds projects to encourage priority countries to strengthen their capacity to secure nuclear materials and expertise and strengthen export control regimes. This programme also supports the UK government's preparation for the 2012 Nuclear Security Summit and the next Nuclear Non-Proliferation Treaty Review Conference in 2015.

UK Contribution to the Global Initiative to Combat Nuclear Terrorism (GICNT) has consisted primarily of expert support and advice to the GICNT Implementation and Assessment Group in the areas of nuclear detection and forensics. UK officials and experts have contributed to various GICNT exercises and workshops during 2010-2011. The UK has developed a specialist training programme for GICNT members to improve their capabilities to mitigate and investigate acts of terrorism involving nuclear or radioactive material. This programme was funded by FCO (£25,000) and run by AWE. The Ministry of Defence (MoD) hosted a GICNT conference on nuclear detection in partnership with FCO in 2010 at a cost of £25,000.

The UK has committed $750 million over ten years during the 2002-2012 lifetime of Global Threat Reduction Programme (GTRP) (approximately £40 million per year). GTRP is jointly managed by the Department of Energy and Climate Change (DECC), FCO and MoD. DECC manages the nuclear related programmes of the UK's contribution to GTRP. Approximately £32 million was spent on these nuclear programmes in 2010-2011 (DECC 2010b). These focus on assistance to improve nuclear security in Russia and help Russia manage its submarine spent fuel legacy. It also includes scientist redirection programmes for former nuclear weapons workers in the former Soviet Union.

The UK Safeguards Support Programme is funded by DECC and is administered on its behalf by the National Nuclear Laboratory. It has an annual budget of approximately £1.5 million, the majority of which is spent in support of the International Atomic Energy Agency's (IAEA) Department of Safeguards. From 2009-2010, UKSP contributed to 25 active tasks across the Department of Safeguards R&D programme (Tushingham 2010). The UK provided support to inspection activities through the analysis of 63 environmental swipe samples and assisted the IAEA to develop its Network of Analytical Laboratories.

The RCUK Global Uncertainties Programme was launched in 2008 with a ten year lifetime. Current activities are running at a level of approximately £50 million per year. It has six core themes, one of which considers chemical, biological, radiological and nuclear issues, including non-proliferation and nuclear security. The Global Uncertainties Programme provides a mechanism to ensure co-ordination in these areas among the relevant research councils given the interdisciplinary approach required.

8.5.2 A global training hub for best practice

8.5.2.1 Regulation

The UK's expertise on nuclear regulatory frameworks is internationally recognised. Given the diversity of its legacy inventory, the UK has unique expertise to share on the management of various radioactive wastes, spent fuels and other nuclear materials. No longer a reactor vendor, the UK may be perceived as a more independent source of regulatory advice than those countries who sell reactors. The UK is well placed to develop the regulatory frameworks for new reactors, including fast reactors and SMRs based on its operational experience of the Dounreay Fast Reactor and submarine reactors, respectively.

8.5.2.2 Education

There is no formal security training for nuclear professionals or international system for security accreditation (see section 5.3.2). Building on the UK's extensive experience of training safeguards inspectors across the entire nuclear fuel cycle, the network could help to co-ordinate activities in the UK that are developing educational and training courses on non-proliferation and nuclear security.

An International Nuclear Security Education Network was set up by the IAEA following the 2010 Nuclear Security Summit. UK members include Kings College London and the University of Central Lancashire. The University of Central Lancashire has developed a MSc in Nuclear Safety, Security and Safeguards. The University of Manchester is part of a consortium of five or six European universities developing a MA in nuclear security led by the Delft University of Technology in the Netherlands. In collaboration with WINS, these activities could develop a comprehensive training programme and offer it for international participation.

8.5.3 International partnerships on non-proliferation and nuclear security

The network should meet on a non-nuclear site to allow ease of access to national and international participants. Partnerships with individuals and organisations in other countries, especially those that will be leading a nuclear renaissance and are embarking on nuclear power for the first time, would allow the UK to tap into the growing scientific expertise in these countries and encourage the implementation of best practice.

Recommendation

The Foreign and Commonwealth Office (FCO) should set up a Non-Proliferation and Nuclear Security Network chaired by the FCO's Chief Scientific Adviser. The Network should facilitate information sharing between academia, government and industry, as well as fostering collaborations, including with international partners.

8.6 Reusing the UK's civil stockpile of separated plutonium

The UK's civil stockpile of separated plutonium undermines the UK's credibility in non-proliferation debates given this stockpile is the largest in the world and poses a serious security risk (Royal Society 2007). As recognised in the run up to the 2010 NPT Review Conference, 'to build confidence in the safe expansion of civil nuclear power, the UK itself needs to demonstrate that, as a long established nuclear energy producer and consumer, we can act as an exemplar in managing our nuclear fuel cycle' (Cabinet Office 2009). A PSE consultation process is currently underway (DECC 2011). The Government's recognition that the status quo of continuing to store stockpile indefinitely is not an acceptable long term option is welcome.

8.6.1 Reusing the stockpile in a new generation of LWRs in the UK

The Government's preliminary view is that the best long term option is to reuse the stockpile as MOX fuel in either the UK or overseas (DECC 2011). A proposal to sell the stockpile overseas would be deeply controversial and would face significant economic and political challenges. There are currently no technically proven and commercially deployable immobilisation technologies that the UK could use to dispose of the stockpile other than reusing it as MOX fuel (Royal Society 2008).

The management of the stockpile must be integrated into the UK's energy and radioactive waste policies (Royal Society 2007). NDA's remit does not extend to the consideration of new nuclear power stations, yet this opens up a new set of management options. The UK's new nuclear power programme creates the possibility of burning the stockpile as MOX fuel in a new generation of LWRs in the UK (Butler *et al* 2011). New LWRs need to be suitably licensed. A safety case would be needed to demonstrate the reactor operations met the appropriate safety requirements. It would not need a new licence as such.

Reuse of the stockpile will depend on the willingness of operators to irradiate MOX fuel. Reusing the stockpile could be considered as a waste management option (Royal Society 2007). If MOX use in new reactors were part of a least cost route for the long term management of plutonium but represented a higher cost to reactor operators than using uranium-only fuel, the NDA could offer a financial incentive to operators to use MOX fuel. It would not breach the spirit of the Government's principle that operators of new reactors should not be subsidised, provided that the incentive did not reduce the overall cost of the fuel below that of uranium-only fuel (Royal Society 2008).

8.6.2 The need for a new MOX fabrication facility

The NDA has recently announced that the Sellafield MOX Plant (SMP) will be closed. A new MOX fabrication facility is now needed. Given the throughput problems experienced by SMP, the design of new MOX fabrication facility would benefit by learning from the successful operation of the MOX fabrication facility, Melox, in France.

Recommendation

The UK's civil stockpile of separated plutonium should be reused as Mixed Oxide (MOX) fuel in a new generation of thermal Light Water Reactors. This provides an effective and technically proven management strategy for the stockpile. These reactors need to be suitably licensed and a new MOX fabrication facility now needs to be constructed in the UK.

8.7 The UK's reprocessing capabilities

NDA makes it clear that its strategy for managing spent fuel from the UK's AGRs will be considered in isolation from a decision about the UK's civil stockpile of separated plutonium since the latter is the responsibility of the UK government (NDA 2010). The Government must adopt a broader, integrated view not constrained by such boundaries.

NDA was set up in an era when government policy was to dismantle the UK's nuclear power industry and there was little prospect of constructing new nuclear power reactors. Given the significant change in government policy and the opportunities provided, and risks presented, by the significant volumes of spent fuel to be generated in a nuclear renaissance, current assumptions that the UK should stop its reprocessing activities once existing contracts have been fulfilled should be revisited. There is a risk of losing a major asset that would allow the UK to participate in a nuclear renaissance. THORP's lifetime would need to be extended and investment made to refurbish it. An operational reprocessing facility, a new MOX fabrication facility and LWRs licensed to irradiate MOX fuel would provide the infrastructure for the UK to manage spent fuel arising from new reactors nationally and internationally.

Economic considerations would play an important role in deciding the scale of this investment since a new reprocessing facility may even be necessary. An analysis of emerging and future market potential and the investment needed for the UK to continue to provide national and international reuse services would be invaluable to explore possible options and inform a long term nuclear power strategy. This analysis should also explore the attractiveness to potential customers of the UK providing long term storage capacity for spent fuel.

It is unclear whether the NDA has the mandate to enter into new commercial contracts (NDA 2010). The NDA should remain focused on delivering its important decommissioning activities, as well as other waste management and disposal responsibilities. If a new reprocessing facility is constructed, then this facility could be owned and operated by a new and separate commercial body.

Recommendation

The Department of Energy and Climate Change should carefully consider the long term consequences of its current assumptions that the UK's reprocessing activities should cease. Investment in an operational reprocessing facility and the infrastructure to reuse the UK's stockpile of separated plutonium would allow the UK to continue providing national and international reuse services.

8.8 Developing the UK's integrated approach

In 2011, the UK government created the ONR as a non-statutory agency of the Health and Safety Executive (HSE). ONR illustrates best practice by integrating into one single body the nuclear safety, security and safeguards responsibilities that previously belonged to HSE, and Office of Nuclear Safeguards. ONR is now also responsible for the regulation of nuclear related transport that was previously the responsibility of the Department of Transport.

Under UK law, employers are responsible for ensuring the safety of their workers and the public from activities on their sites. The primary legislation is the Health and Safety at Work Act (1974) which incorporates the licensing parts of the Nuclear Installations Act 1965 (NIA). Under the NIA no one can construct, commission or operate a nuclear facility without a nuclear site licence. The nuclear site licensing regime is administered by ONR. Its chief executive, HM Chief Inspector of Nuclear Installations, is responsible for licensing the UK's civil nuclear power industry. A nuclear site licence has conditions attached to it and failure to comply with these conditions is a criminal offence. Licence conditions can be attached in the interests of nuclear safety or the management of nuclear and radioactive materials. ONR inspectors check that licensees are complying with the conditions attached to the nuclear site licence. Whilst the UK has robust arrangement for nuclear security which are enforced under the Nuclear Industry Security Regulations, security legislation in the UK has developed separately from this system for site licensing.

Nuclear safety is at the heart of the nuclear licensing regime and its non-prescriptive nature places responsibility for nuclear safety clearly on the licensee. The situation is not so clear in relation to nuclear security since the regulations tend to be prescriptive and hence not as flexible as the licensing regime.

If the Government was to update the NIA to include nuclear security in the nuclear licensing regime, this would make it clear that it is the licensee, and not the regulator, that is responsible for security (see section 5.3.1). Doing so would allow the UK to demonstrate how nuclear security can be integrated in the licensing process of nuclear power programmes without excessive cost or delay.

Recommendation

The Office of Nuclear Regulation should develop its integrated approach to nuclear regulation by ensuring that security features explicitly in nuclear site licensing conditions. This may require the Government to update the Nuclear Installations Act.

8.9 A World Nuclear Forum

A World Nuclear Forum could be proposed at the next Nuclear Security Summit in 2012 (see section 3.5.3). The UK Government is well placed to do so given its experience of international fuel cycle arrangements and its thoroughly multinationalised nuclear industry (see textbox 13). This Forum could ensure the momentum generated by the Nuclear Security Summit process is sustained. Wide consultation, especially with industry, will be necessary.

Recommendation

The UK government should help to establish a CEO-led, World Nuclear Forum. This Forum would provide an interface between CEOs and government leaders to explore their respective views on the future development of nuclear power and responsibilities for non-proliferation and nuclear security. This Forum could be proposed at the 2012 Nuclear Security Summit and set up thereafter.

List of acronyms

ABACC	Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials
AGR	Advanced Gas-cooled Reactor
APS	American Physical Society
AWE	Atomic Weapons Establishment (UK)
BNFL	British Nuclear Fuels Ltd
BRC	Blue Ribbon Commission on America's Nuclear Future
BWR	Boiling Water Reactor
CANDU	Canada Deuterium-Uranium reactor
CBRN	Chemical, Biological, Radiological and Nuclear
CEA	Commissariat a l'Energy Atomique (France)
COEX	Co-extraction of actinides
CoRWM	Committee on Radioactive Waste Management (UK)
DBD	Deep Borehole Disposal
DECC	Department of Energy and Climate Change (UK)
DoE	Department of Energy (USA)
EA	Environment Agency (UK)
EC	European Commission
ECA	Euratom Control Agency
EDF	Électricité de France
EDRAM	International Association of Environmentally Safe Disposal of Radioactive Materials
EPR	European Pressurized Reactor
EPRI	Electric Power Research Institute
EPSRC	Engineering and Physical Sciences Research Council (UK)
ESA	European Supply Agency
ESRC	Economic and Social Research Council (UK)
EUROCHEMIC	Reprocessing plant in Dessel
EURODIF	European Gaseous Diffusion Uranium Enrichment
ETC	Enrichment Treatment Company
EURATOM	European Atomic Energy Commission
FBR	Fast Breeder Reactor
FCO	Foreign and Commonwealth Office (UK)
GDF	Geological Disposal Facility
GICNT	Global Initiative to Combat Nuclear Terrorism
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
GTRP	Global Threat Reduction Partnership
HEU	Highly Enriched Uranium
HLW	High Level Waste
HSE	Health and Safety Executive (UK)
IAEA	International Atomic Energy Agency
ICNND	International Commission on Nuclear non-Proliferation
IFNEC	International Framework for Nuclear Energy Cooperation
ILW	Intermediate Level waste
IMF	Inert Matrix Fuel
INPRO	Innovative Nuclear Reactors and Fuel Cycles
INSAG	International Nuclear Safety Group
IPFM	International Panel on Fissile Materials
LEU	Low enriched Uranium
LLW	Low Level Waste
LWR	Light Water Reactors
MAUA	Multi Attribute and Utility Analysis
MOX	Mixed Oxide fuel
MUF	Material Unaccounted For
NAS	National Academy of Sciences (USA)
NDA	Nuclear Decommissioning Authority (UK)
NIA	Nuclear Installations Act
NIREX	Nuclear Industry Radioactive Waste Executive (UK)
NMA	Nuclear Material Accountancy
NNL	National Nuclear Laboratory (UK)
NPT	Nuclear Non-Proliferation Treaty
NNSA	National Nuclear Security Administration (USA)
NNWS	Non-Nuclear Weapon State
NWS	Nuclear Weapon State
NSC	National Security Council (UK)
OECD	Organisation for Economic Co-operation and Development
ONR	Office of Nuclear Regulation (UK)
PBO	Parent Body Organisation
POST	Parliamentary Office of Science and Technology (UK)
PSE	Public and Stakeholder Engagement
P&T	Partition and Transmutation
PUREX	Plutonium URanium EXtraction
PWR	Pressurized Water Reactors
PYROX	Pyroprocessing
RCUK	Research Councils UK
R&D	Research and Development
RPP	Rokkasho Reprocessing Plant (Japan)
RWMD	Radioactive Waste Management Directive (UK)
SLC	Site Licence Company
SMP	Sellafield MOX Plant (UK)
tHM	tonnes of heavy metal
THORP	Thermal Oxide Reprocessing Plant (UK)
TOPS	Technical Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems
UEC	Enrichment Company Ltd
UKAEA	UK Atomic Energy Authority
UREX	Uranium EXtraction
VTHR	Very High Temperature Reactors
WANO	World Association of Nuclear Operators
WINS	World Institute of Nuclear Security
WIPP	Waste Isolation Pilot Plant
WMO	Waste Management Organisation
WNA	World Nuclear Association

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Appendix 1: Working group of experts

Professor Roger Cashmore FRS (Chair)
Principal of Brasenose College at University of Oxford. He is a former Director of Research and Deputy Director General of the European Organisation for Nuclear Research (CERN) where he was responsible for the experimental programme at the Large Hadron Collider (LHC). Currently his research interests focus on the LHC using the Atlas detector in which University of Oxford is involved, and the search for dark matter in underground experiments. Roger is Chairman of the Ministry of Defence's Nuclear Research Advisory Council.

Professor Jonathan Billowes
Head of the Nuclear Physics Group in the School of Physics and Astronomy at the University of Manchester and Director of Education at the Dalton Nuclear Institute. His research interests are in laser spectroscopy of radioactive atoms. Jon is the course director for the MSc in Nuclear Science and Technology run by the UK university Nuclear Technology Education Consortium, and is Principal Investigator for the university consortium delivering the Nuclear Engineering Doctorate programme.

Professor Wyn Bowen
Director of the Centre for Science and Security Studies in the Department of War Studies at Kings College London. His research interests include nuclear proliferation, non-proliferation and counter-proliferation. Wyn served as a Specialist Advisor to the House of Commons' Foreign Affairs Committee for inquiries into 'The Decision to go to War with Iraq,' (2003) and 'Weapons of Mass Destruction,' (2000).

Dr Christine Brown
Consultant on variety of nuclear energy issues since retiring in 2006. Christine began her professional career with the United Kingdom Atomic Energy Authority where her work included the use of plutonium containing fuels in fast reactors. By the late 1980s, she led the UK contribution to the European Fast Reactor Fuels and Materials programme. In 1995, she joined the British Nuclear Fuels Ltd (BNFL) Thermal MOX team at Sellafield to lead the technical development work required to support this part of BNFL's business. In 2002, Christine joined the US Department of Energy Blue Ribbon Panel formed to advise its Nuclear Energy Research Advisory Committee on the Proliferation Resistant Characteristics of Recycle Fuels.

Professor Robin Grimes
Professor of Materials Physics at Imperial College London. His research interests include radiation damage, nuclear fuels and waste form behaviour, ionic conductivity and defect processes for fuel cell materials, surface structural processes and interfaces between glass and ceramic. He was recently appointed Principal Investigator of the Research Councils multi-university initiative 'Keeping the Nuclear Option Open'.

Dr Roger Howsley
Director of the World Institute for Nuclear Security. Previously he was the Director of Security, Safeguards and International Affairs for BNFL. He led BNFL's response to the terrorist attacks of 9/11, assessing and leading the programme of security enhancements at BNFL sites and interacting with Government at all levels. Since 2001 he has served on the IAEA Director-General's Standing Advisory Group on Safeguards Implementation.

Professor Francis Livens
Director of the Centre for Radiochemistry Research in the School of Chemistry at the University of Manchester. His research interests include actinide chemistry, contamination and decontamination processes in both natural and engineered environments, and isotopic fingerprinting of trace radionuclides. He is a member of the Committee on Radioactive Waste Management.

Professor John Simpson
John Simpson recently retired as the Director of the Mountbatten Centre for International Studies at the University of Southampton. His research interests include the evolution of the Nuclear Non-Proliferation Treaty (NPT) and other international mechanisms to prevent nuclear proliferation. John has been an advisor to the UK delegation to NPT Preparatory Committee Sessions and Review Conferences (1999-present). He is also a principal researcher in a consortium tasked from 2008 onwards by the UK Engineering and Physical Sciences Research Council to produce an integrated Approach to a Sustainability Assessment of Nuclear Power.

Professor Peter Styles
Professorial Research Fellow, and Head Applied and Environmental Geophysics Research Group, Keele University. Peter is currently a member of the Nuclear Decommissioning Authority's Geosphere Characterisation Panel looking at repository site selection, characterisation and construction of a geological radioactive waste facility. A former President of the Geological Society of London, Peter is a Board member of the British Geological Survey. Peter is also Chair, Stoke and Staffordshire Local Enterprise Partnership Low-Carbon Group.

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Appendix 2: Details of evidence gathering

1 Evidence Call

The following organisations and individuals provided written submission to the call for evidence:

- Dr Irma Arguello, Chair, Non-proliferation for Global Security Foundation (NPSGlobal).
- Dr Godric Beresford-Jones.
- Professor Gregg Butler, Director IDM and Professor of Science in Sustainable Development, University of Manchester.
- Dr John Carlson, Director General, Australian Safeguards and Non-Proliferation Office.
- Professor Trevor Findlay, Director, Canadian Centre for Treaty Compliance, Carleton University, Canada.
- Mr Peter Friend, Head, Security and Safeguards, URENCO Limited.
- Professor Fergus Gibb, Professor of Petrology and Geochemistry, Department of Engineering Materials, University of Sheffield.
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- Professor Frank Von Hippel, Professor of Public and International Affairs, Princeton University, Co-chair, International Panel on Fissile Materials.
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- Professor Juan Matthews, Visiting Professor London Centre for Nanotechnology, UCL.
- Mr Sean Morris, Secretary, Nuclear Free Local Authorities UK and Ireland.
- Professor Clifford Singer, Professor, Departments of Nuclear, Plasma, and Radiological Engineering, and of Political Science, University of Illinois at Urbana-Champaign.
- Dr Rachel Western, Nuclear Researcher, Friends of the Earth groups in Cumbria.
- Dr William Wilkinson FRS, Former Director, British Nuclear Fuels Ltd.
- Dr Michael Zentner, Scientist, Pacific Northwest National Laboratory, USA.

2 Evidence gathering events

We are very grateful to everyone who participated in the following evidence gathering events: The papers and presentations from the workshops and evidence call are available on the Royal Society's website: royalsociety.org/policy/projects/nuclear-non-proliferation

2.1 Seminar held on 22 April 2010 at the Nuclear Decommissioning Authority, (NDA) Daresbury Park.

Non-proliferation and spent fuel management

- Clarifying the concept of proliferation resistance and its implementation.
- Technical issues affecting the management of the UK's stockpile of separated plutonium.
- Decision making about the geological disposal of spent fuel.
- Lessons to be learned from the UK's experience of spent fuel management.
- Internationalising nuclear decision making.

2.2 NGO roundtable on held on 4 May 2010 at the Royal Society.

Non-proliferation priorities

- Internationalising the nuclear fuel cycle.
- Closing the fuel cycle and an international plutonium economy.
- Engaging the nuclear industry on non-proliferation.
- Engaging national laboratories to support non-proliferation.
- Nuclear non-proliferation and disarmament.

2.3 Workshop held on 18 May 2010 at the National Nuclear Laboratory (NNL) Birchwood Conference Centre, Risley.

Nuclear strategy to support proliferation resistant fuel cycles

An overview of nuclear fuel cycle studies at the National Nuclear Laboratory.
- Dr Graham Fairhall, Chief Science and Technology Officer, NNL.

What are the most useful ways to think about nuclear non-proliferation and assess proliferation resistance?
- Mr Kevin Hesketh, Senior Fellow in Nuclear Systems Analysis, NNL.

How should we think about nuclear security and proliferation resistance norms?
- Mr Roger Blue, Manager for Safeguards and Non-Proliferation, NDA.

What are the technology options for storing and disposing spent fuel over the near, medium and long term?
- Dr Richard Taylor, Chief Engineer, NNL.

What is the UK's strategy for the design and operation of a geological repository?

- Dr Brendan Breen, Head of Engineering, Radioactive Waste Management NDA.

What are the technical challenges facing MOX use in the UK?

- Dr Paul Gilchrist, Head, Fuel Cycle Technology, NDA.

What are the technology options for reprocessing spent fuel over the near, medium and long term?

- Dr Robin Taylor, Senior Fellow in Actinides, NNL.

What are the opportunities for the developing fast reactors over the near, medium and long term?

- Mr Kevin Hesketh, Senior Fellow in Nuclear Systems Analysis, NNL.

What opportunities are there for the UK to develop the thorium fuel cycle over the near, medium and long term?

- Dr Andrew Worrall, Technical Authority (Reactors and Fuels), NNL.

What would be the domestic and international drivers for the UK to close the fuel cycle?

- Dr Andrew Worrall, Technical Authority (Reactors and Fuels), NNL.

2.4 Workshop held on 10 and 11 June 2010 at the Royal Society.

Building proliferation resistance into the nuclear fuel cycle

What are the possible proliferation pathways posed by civilian nuclear power programs and research reactors? What is the evidence that they have been a source of proliferation?

- Dr Mark Fitzpatrick, Head, Non-Proliferation and Disarmament Programme, International Institute of Strategic Studies, UK.

How has the concept of proliferation resistance been used in nuclear debates since the start of the atomic age? On what evidence was the use of this concept in each of these debates based?

- Dr Joseph Pilat, Senior Advisor, National Security Office, Office of the Director, Los Alamos National Laboratory, USA.

Seeking the proliferation resistant fuel cycle: what lessons that can be learned from the International Nuclear Fuel Cycle Evaluation?

- Dr Mike Lawrence, Managing Director, NNL, UK.

What fuel cycle options are being considered by USA over the near, medium and long term to manage spent fuel?

- Dr Phillip Finck, Associate Laboratory Director for Nuclear Services and Technology, Idaho National Laboratory, USA.

What fuel cycle options are being considered by France over the near, medium and long term to manage spent fuel?

- Dr Bernard Boulis, Head, Fuel Cycle Research, Nuclear Energy Division, Atomic Energy Commission (CEA), France.

What fuel cycle options are being considered by Japan over the near, medium and long term to manage spent fuel?

- Dr Tatsujiro Suzuki, Vice Chairman, Atomic Energy Commission, Japan.

What fuel cycle options are being considered by India over the near, medium and long term to manage spent fuel?

- Dr Anil Kakodkar, former Chairman, Atomic Energy Commission, India.

What are the most promising technologies to improve the proliferation resistance of the fuel cycle? What incentives are required for industry to adopt these technologies?

- Mr Jean-Noël Poirier, Vice President External Relations, AREVA, France.

What might be the unintended consequences of adopting proliferation resistant technology?

- Dr James Acton, Associate, Non-Proliferation Program, Carnegie Endowment for International Peace, USA.

What are the major safeguards challenges facing the management of spent fuel under open and closed fuel cycles?

- Mr Brian Burrows, Safeguards and Nuclear Materials Accountancy Manager, NDA.

What are the current safeguards developments and future challenges for spent fuel management?

- Mr James Tushingham, Manager, Safeguards Programme, NNL.

New and emerging technologies to support non-proliferation and nuclear safeguards.

- Dr Said Abousahl, Joint Research Centre, European Commission, Belgium.

Safeguards by design: how can fuel cycle facilities be made more safeguards enhancing and proliferation transparent?

- Dr Randy Beatty, Group Leader, International Project on Innovative Nuclear Reactors and Fuel Cycles, International Atomic Energy Agency, Austria.

Designing nuclear facilities in a proliferation resistant way: lessons learned from the Rokkasho Reprocessing Plant

- Ms Shirley Johnson, former Head of the JNFL Project, Department of Safeguards, IAEA.

2.5 Workshop held on 28 and 29 June 2010 at the Royal Society.

New governance practices for the civil nuclear fuel cycle

What are the various models for placing the nuclear fuel cycle under international control? What benefits for non-proliferation do they provide?

- Mr Bruno Pellaud, Swiss Nuclear Forum; Chairman, IAEA Expert Group on Multilateral Approaches to the Nuclear Fuel Cycle.

If the nuclear fuel cycle was placed under international control, then what would be required to make it genuinely non-discriminatory?

- Dr Tom Shea, Director, Nuclear Consulting, USA; former Director, Defence Nuclear Non-proliferation Programme, Pacific Northwest National Laboratory.

The potential of internationalising the nuclear fuel cycle: a view from outside the Nuclear Non-Proliferation Treaty.

- Dr Ravi Grover, Director, Strategic Planning Group, Department of Atomic Energy, India.

What lessons can be learned from URENCO for the management of spent fuel?

- Dr Pat Upson, Chief Executive, Enrichment Technology Company, URENCO, UK.

Options for international storage and take back of spent fuel.

- Mr Mark Jervis, Managing Director, International Nuclear Services, UK.

Options for international reuse.

- Mr Stuart MacVean, Executive Director, Sellafield Ltd

Options for international geological disposal?

- Dr Charles McCombie, Executive Director, Arius Association, Switzerland.

The international legal regime for transporting nuclear materials.

- Mr Lorne Greene, Secretary General, World Nuclear Transport Institute, UK.

The economics of the open and closed fuel cycle?

- Dr Gordon MacKerron, Director, Sussex Energy Group, Science and Technology Policy. Research, University of Sussex, UK.

What role do non-proliferation considerations play in decision making about nuclear power programs?

- Lady Barbara Judge CBE, Chairperson, Industry Advisory Board, National Nuclear Centre of Excellence, UK.

What fuel cycle options are being considered by South Korea over the near, medium and long term to manage spent fuel?

- Dr Keun Bae OH, Vice President, and Director, Department of Nuclear Policy Development, Korean Atomic Energy Research Institute, South Korea.

How can nuclear non-proliferation and nuclear security norms become more embedded within project management and corporate governance?

- Miss Martine Letts, Deputy Director, Lowy Institute for International Policy, Australia.

How can a nuclear security culture be further developed within the nuclear industry?

- Dr Michel Debes, Head, International Relations, EDF.

2.6 Workshop held on 7 July 2010 at the Atomic Weapons Establishment (AWE), Aldermaston

Opportunities for threat reduction to support nuclear non-proliferation

Overview of AWE's capabilities relevant to non-proliferation

- Dr Daryl Landeg, Chief Scientist, AWE.

What criteria should be used to assess the proliferation resistance of the civil nuclear fuel cycle?

- Professor Peter Roberts, Head of Plasma Physics, AWE.

Overview of AWE's National Nuclear Security programme.

- Dr Graeme Nicholson, Director Science and Technology Programme, AWE.

What are international community's nuclear security capabilities?

- Dr Bryan Wells, Head, Strategic Technologies, MoD.

How feasible is it to add signatures to the fabrication of nuclear fuel to improve the detection and forensic attribution of nuclear materials?

- Mr Ian Smith, AWE.

What is the current role of the IAEA in detecting and verifying declared and clandestine activities?

- Mr Stephen Francis, NNL.

What are the most promising technologies in the near, medium and long term to detect fuel cycle activities?

- Mr Paul Thompson, Principal Scientist, AWE.

What is the role of satellite monitoring to detect fuel cycle activities?

- Dr Pat Norris, Manager, Space and Defence Strategy, Logica.

What are the key technologies to verify nuclear disarmament?

- Dr David Bowers, Principal Scientist, AWE.

What are the prospects for the UK to become a Non-Proliferation and Disarmament Laboratory?

- Mr Peter Sankey, Director, Strategic Technologies, Ministry of Defence.

2.7 Roundtable held on Monday 23 May 2011 at the Royal Society

Best practices in light of the events at the Fukushima nuclear power station

Prospects for a nuclear renaissance: the future of nuclear power globally.

- Mr Steve Kidd, Deputy Director, World Nuclear Association.

Best practice for securing spent fuel storage and fuel cycle facilities.

- Mr Peter Wylie, Head of Strategy Development, Sellafield Ltd.

Building safeguards and security in a nuclear renaissance: best practice for nuclear regulation.

- Professor Laurence Williams FREng, Head of uclanNUCLEAR and Professor of Nuclear Safety, University of Central Lancashire.

Strengthening the international governance regimes for spent fuel management.

- Professor Laurence Williams FREng, Head of uclanNUCLEAR and Professor of Nuclear Safety, University of Central Lancashire.

3 Participants at evidence gathering events and other experts consulted

- Professor Tim Abrams FREng, Professor of Nuclear Fuel Technology, University of Manchester.
- Mr Peter Adsley, Principal Scientist, AWE.
- Dr Peter, Ainscough, Office for Security and Counter Terrorism, Home Office.
- Professor Robert Ainsworth FRS, BNFL professor of structural integrity, University of Manchester.
- Dr Keith Baker, Research Fellow, Mountbatten Centre for International Studies, University of Southampton.
- Dr Zara Banfield, Signature Research Programme for Spent Nuclear Fuel, NNL.
- Dr Andrew Barlow, Head, Arms Control and Disarmament Research Unit, FCO.
- Ms Kat Barton Research Associate, Acronym Institute for Disarmament Diplomacy.
- Dr Mike Beamen, Head, UK Safeguards Office, HSE.
- Dr Norman Bird MICE Technical Lead Manager, Nuclear Security, Assurance and GIS Homeland Security and Non-Proliferation Team, NNL.
- Professor John Brewer, Visiting Professor, Centre for Science and Security Studies, Kings College London.
- Dr Alex Burkhart, Bureau of International Security and Non-proliferation, Department of State, USA.
- Mr Brian Burrows, Manager for Safeguards and Nuclear Materials Accountancy, NDA.
- Dr John Carlson, former Director General, Office of Safeguards and Non-Proliferation, Australia.
- Dr Jean Marc Capdevila, Nuclear Adviser, French Embassy.
- Mr Burrus Carnahan, Bureau of International Security and Non-proliferation, Department of State, USA.
- Professor David Clary FRS, Chief Scientific Adviser, FCO.
- Mr Bob Cockrell, Company Secretary, WANO.
- Mr Adrian Collings, Director of Policy Development, WNA.
- Professor Paul Dorfman, Co-ordinator, Nuclear Consultation Group.
- Dr Stephen Elsby, Senior Sector Manager (Energy), EPSRC.
- Dr Jeremy Edwards, Environmental Management and Homeland Security, NNL.
- Professor Steve Fetter, Assistant Director, Office of Science and Technology Policy, Executive Office of the President, USA.
- Dr Paul Gilchrist, Head, Fuel Cycle Technology, NDA.
- Professor Frank von Hippel, Co-Director, Programme on Science and Global Security, Princeton University.
- Dr Ian Jackson, Associate Fellow, Energy, Environment and Development Programme, Chatham House.
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- Mr Neil Longfellow, Director, Springfields Fuels, UK.
- Dr Micah Lowenthal, Director, Committee on International Security and Arms Control, NAS, USA.
- Professor David MacKay FRS, Chief Scientific Adviser, DECC.
- Dr Bill McCarthy, Head, Nuclear Safeguards Policy, DECC.
- Mr Ed McGinnis, Deputy Assistant Secretary, Corporate and Global Partnership Development, Department of Energy, USA.
- Dr Alistair Manning, Met Office.
- Mr John Mathieson, Head, International Relations, NDA.
- Mr Julian Miller, Director for Defence and Foreign Policy and Assistant National Security Adviser, Cabinet Office.
- Professor Bill Nuttell, Senior Lecturer Technology Policy, University of Cambridge.
- Mr Martin Oliva, Marketing Director, Rio Tinto Uranium Ltd.
- Dr Bob Page, Chief Technical Officer, VT Services.
- Mr Bevis Parker, Team Leader Computational Physics, AWE.
- Dr Stuart Parkinson, Director, Scientists for Global Responsibility.
- Mr Simon Parsons, Cabinet Office.
- Dr Andreas Persbo, Director, Verification Research, Training and Information Centre.
- Dr Rhydian Philips, Head, Counter Proliferation, DECC.
- Dr Robin Pitman, Associate Director, Institute for Security Science and Technology, Imperial College London.
- Mr John Roberson, Distinguished Scientist, AWE.
- Dr Nick Ritchie, Peace Studies Department, Bradford University.
- Mr Graham Sedge, Office for Nuclear Development, DECC.
- Dr Philip Sharp, President, Resources for the Future; Member, Blue Ribbon Commission on US Nuclear Future.
- Ms Jane Simmonds, Head of Environmental Assessments Department, Centre for Radiation, Chemical and Environmental Hazards, Health Protection Agency.

- Dr Lawrence Scheinman, Distinguished Professor, James Martin Center for Nonproliferation Studies, USA.
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- Ms Zoe Smith, Nuclear Issue Group, Counter Proliferation Department, FCO.
- Professor Peter Storey, Professor of nuclear policy, regulation and safety, University of Manchester.
- Dr Daniel Thomas, Team Leader & Project Manager Nuclear Forensics, AWE.
- Mr Peter Thompson, Distinguished Scientist, AWE.
- Ms Zaneta Ulozeviciute, RCUK Global Uncertainties Programme.
- Mr John Wand, Theme Leader, ESRC.
- Dr Christopher Western, British Pugwash Group.
- Mr Jeremy Watson, Director for Special Projects, EDF.
- Dr Richard White, Capability Assessment Manager, AWE.
- Professor Laurence Williams FREng, Head of uclanNUCLEAR and Professor of Nuclear Safety, University of Central Lancashire.
- Ms Charlotte Wood, Nuclear Issues, Counter Proliferation Department, FCO.
- Ms Frances Wood, Head (Nuclear Issues), FCO.

Appendix 3: Review panel

The Royal Society gratefully acknowledges the contribution of the review panel, members of which were not asked to endorse the conclusions or recommendations of this report.

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Executive Director Emeritus, Sigma Xi.

Professor Robert Ainsworth FRS
BNFL professor of structural integrity, University of Manchester.

Professor John Pethica FRS (Chair)
Vice President, Royal Society.

Professor Ekhard Salje FRS
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We would also like to thank the following individuals for providing comments on previous drafts:

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