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TECHNICAL NOTE

IMPLICATIONS OF DECLARING UK URANIUM STOCKPILES AS WASTE

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PROVISONAL or INTERIM status means this Technical Note is 'work in progress' and has been prepared to facilitate Nirex's work programme and does not necessarily reflect the company's final position.

TECHNICAL NOTE

This Technical Note is part of an ongoing programme of research conducted by Nirex and its contractors. It is a component of the research into options for the long-term management of radioactive waste in the UK.

Nirex want to develop the thinking outlined in this Technical Note through discussions with others. Therefore, this Technical Note should be viewed as 'work in progress' and Nirex would be grateful for any comments on the ideas put forward. Nirex recognises that the Technical Note only outlines our view and that others may have different views on the issues.

Conditions

Bibliography

A complete bibliography of Nirex publications is available at the Nirex website, www.nirex.co.uk, or from Nirex Corporate Communications at the address below or e-mail: info@nirex.co.uk.

Feedback

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TECHNICAL NOTE

PREFACE

Nirex produces a number of Technical Notes, on a variety of subjects, to inform the debate on what the UK should do with its radioactive waste. These are often accurate at a particular point in time and will change as a result of further thinking, comments from other interested parties and the results of further research. They are thus regarded as ‘work in progress’, but we feel that given the nature of the debate that it is beneficial to release them at this stage. It must be recognised that they may be updated and amended over time.

This Technical Note has been prepared by Nirex to provide information on a specific question raised by the DEFRA and Devolved Administrations Consultation Paper on the policy to be adopted for the long-term management of UK stockpiles of uranium, including whether some of the stock should be considered as waste. The aim of this report is to provide information on the implications of declaring the UK separated stockpiles of uranium as waste.

TECHNICAL NOTE

Executive Summary

This Technical Note has been prepared by Nirex to provide information on a specific question raised by the DEFRA and Devolved Administrations Consultation Paper on the policy to be adopted for the long-term management of UK stockpiles of uranium, including whether some of the stock should be considered as waste. The aim of this report is to provide information on the implications of declaring the UK separated stockpiles of uranium as waste.

The House of Lords Select Committee on Science and Technology recommended that the Government should develop a comprehensive and integrated strategy for the management of all long-lived wastes and that decisions are needed soon on which materials are to be declared as wastes. This Technical Note therefore discusses depleted uranium, but also all other sources of uranium such as: commercial spent fuel; research spent fuel; defence spent fuel; low enriched uranium and highly enriched uranium. However, in order to highlight key issues for this spectrum of materials this report focuses on depleted uranium and spent fuel, that are also the two largest volumes of uranium.

This Technical Note does not provide a comprehensive list of long-term management options for uranium or make any recommendations on whether uranium should be declared a waste. It does, however, highlight that it is important to ensure that there will be a comprehensive and integrated strategy for all materials (including uranium), in order that:

- public concerns can be addressed at an early stage;
- late/additions/changes to the range of wastes included in the developing strategy are minimised;
- any future programme will not be delayed by revisions to decision-making.

If declared a waste, key issues for the long-term management for uranium are similar to those raised by other radioactive wastes/materials and could be managed as part of an integrated approach to waste management. Key issues that would need to be considered include: long and short term safety; cost; availability of technology; public perception; retrievability; safeguards and avoidance of nuclear criticality.

Nirex has performed scoping studies to determine the implications in the event that the UK's depleted uranium were to be disposed of in an adaptation of the Nirex Phased Disposal Concept and that commercial spent fuel were disposed of in a bentonite-lined HLW repository concept. If some of the UK uranium stockpile were declared a waste to be disposed of, a suitable wasteform, packaging design and repository concept would need to be determined. This would be addressed through a programme of research and development that includes clear steps for consultation and decision-making.

Based on the assumptions made for this scoping study the inclusion of depleted uranium in the Nirex Phased Disposal Concept would exceed risk targets. However, the results of these risk calculations are sensitive to some of the assumptions made (including parameters) and are subject to some uncertainty. Hence, more work is required to determine whether it would be feasible to include depleted uranium in the Nirex Phased Disposal Concept or whether a separate repository would be required.

The inclusion of commercial spent fuel in a bentonite-lined repository with HLW is not expected to have an unacceptable impact on safety, although detailed studies have not been performed.

Contents

1 Introduction

1.1 Background

The Department of the Environment, Food and Rural Affairs (DEFRA) and the Devolved Administrations [1] recently launched a Consultation paper titled Managing Radioactive Waste Safely (here on in referred to as the Consultation paper). This Technical Note has been prepared by Nirex to provide information on a specific question raised in the Consultation paper on the policy to be adopted for the long-term management of UK stockpiles of uranium, including whether some of the stock should be considered as waste. The aim of this report is to provide information on the implications of declaring the UK separated stockpiles of uranium as waste.

The House of Lords Select Committee on Science and Technology recommended that the Government should develop a comprehensive and integrated strategy for the management of all long-lived wastes and that decisions are needed soon on which materials are to be declared as wastes [2]. This report therefore discusses not only depleted uranium, but also other sources of uranium such as: commercial spent fuel; research spent fuel; defence spent fuel; low enriched uranium and highly enriched uranium. However, in order to highlight key issues for this spectrum of materials this report focuses on depleted uranium and spent fuel, that are also the two largest volumes of uranium.

This report does not provide a comprehensive list of long-term management options for uranium or make any recommendations on whether uranium should be declared a waste. It does, however, highlight that provisions should be made in case some forms of uranium are declared as waste, in order that there can be an integrated strategy for all wastes.

The Consultation Paper [1] states that:

"There are two main forms of uranium which may be surplus to requirements. Depleted uranium in the form of uranium hexafluoride tailings is a by-product of fuel fabrication and enrichment. Reprocessed uranium (drummed uranium oxide) is derived from reprocessing irradiated fuel and represents 96% of spent fuel from which plutonium and waste materials have been separated".

In view of the large stock of uranium from reprocessing and enrichment processes (referred to from here on in as depleted uranium) existing in the UK, the question arises whether this material should be retained for possible re-use in the future or if some should be considered as a waste. If it were decided that the uranium is not going to be used in the future it would be appropriate to treat the material to put it in a form where it is unavailable for use [1].

There are also other sources of uranium in the UK, these include: low enriched uranium, highly enriched uranium, commercial spent fuel, defence spent fuel and research spent fuel. The House of Lords Select Committee on Science and Technology recommended that there was an integrated waste management strategy for all these materials and that any radioactive materials that could be declared as waste should be declared as such soon, so that they can be considered at the planning stage [2].

If uranium were declared a waste to be disposed of, consideration would need to be given to whether one or more repositories would be required. The following issues would need to be addressed:

- Radiological implications of concentrating increased inventory of different wastes in the same repository;

- Chemical and thermal interactions between different wasteforms and associated barriers;
- Equity issue - if the wastes were disposed of at one site, as one community would be seen as having the entire burden;
- Resource issue - if wastes that were previously considered a resource were disposed of alongside wastes that have been historically considered as such, what would be the implications of an attempt to retrieve this waste if a future generation tried to retrieve wastes that they considered a resource.

1.2 Scope and Purpose

The owners of the UK uranium stocks currently consider the majority to be a resource. This includes commercial and defence spent fuel for which the plan is to store spent fuel indefinitely with the option to reprocess to recover uranium and plutonium for future use [1]. If some of the UK stocks of depleted uranium and plutonium were declared as wastes, this would require the rationale for storing spent fuel to be revisited.

This report focuses on the implications of declaring the two largest volumes of UK stocks of uranium as waste (i.e. depleted uranium and commercial spent fuel). These two sources of uranium cover the key issues for other sources of uranium. However, the high fissile content of highly enriched uranium means that plutonium is also a useful analogy for determining the key issues for declaring this source of uranium a waste.

Presented in this report are some of the suggested options for the management of uranium, these include:

- Continued surface storage;
- Reuse of uranium as fuel;
- Transmutation of long-lived fission products and actinides present in spent fuel;
- Deep Geological Disposal (including immobilisation of depleted uranium);
- Disposal in deep boreholes.

In Section 2 the options that are being investigated internationally for the long-term management of uranium are described.

In Section 3 some of the key issues for the long-term management of uranium are discussed.

In Section 4 the implications for the disposal of depleted uranium as cemented ILW and the disposal of spent fuel with HLW are described.

In Section 5, conclusions are presented.

1.3 Material arisings

In this section, for each source of uranium the estimated future total stocks, material characteristics and potential future uses are discussed. This information has been obtained from published references. It is interesting to note that the House of Lords Select Committee on Science and Technology also recommended that an inventory that covers all radioactive materials in the UK is produced [2].

1.3.1 Depleted Uranium

Estimated Future Stocks: It is estimated that the combined stocks of depleted uranium could reach around 106,000 tU by 2020, although this quantity could be reduced according to use. These stocks are thought to roughly consist of depleted uranium from the enrichment of natural uranium (40%), enrichment of reprocessed uranium (20%), reprocessing of spent fuel (25%) and military stocks (15%) [3, 4, 5].

Characteristics: Depleted uranium has a smaller percentage of uranium-235 than the 0.7% content found in natural uranium.

The majority of tailings from the enrichment of natural uranium will therefore be uranium-238, with residual uranium-235 at about 0.3%. Tailings from the enrichment of reprocessed uranium additionally contain small amounts of uranium-236 and is stored as uranium hexafluoride [3,6].

Depleted uranium from reprocessing of spent fuel will have a similar composition, but will also contain small quantities of americium, curium, neptunium and plutonium. This material is stored as uranium trioxide [3,6].

Potential Future Uses: Suggestions made in the Consultation paper [1] include: the manufacture of new AGR fuel using reprocessed uranium; enrichment of uranium tailings to produce new fuel; mixing depleted uranium with plutonium to make Mixed Oxide Fuel (MOX fuel); mixing depleted uranium with highly enriched uranium formerly used in military applications (a process known as downblending) and use in a fast breeder reactor to generate additional fuel. However, for the manufacture of new uranium fuel the low cost of fresh uranium could make this option economically unfavourable. Radiation shielding applications and other industrial applications make use of specific properties of the material.

1.3.2 Low Enriched Uranium (LEU)

Estimated Future Stocks: Low enriched uranium is recovered from reprocessing spent fuel. The future UK stocks of LEU are uncertain, but could be of the order of 10,000 tU. However, the quantities that may be declared as waste will depend on future demand for spent fuel reprocessing and recycled uranium.

Characteristics: In LEU the content of uranium-235 is increased from natural level of 0.7% up to 20%.

Potential Future Uses: Low enriched uranium with a uranium-235 content between 3 and 5% can used to fabricate oxide fuel for Advanced Gas Cooled Reactors (AGR) and Light Water Reactors (LWR) nuclear power stations. This material is regarded as commercially valuable by its owners, and is not currently considered a waste.

1.3.3 Highly Enriched Uranium (HEU)

Estimated Future Stocks: Military stocks of HEU are 21.9 tU [4]. A significant portion of this material is likely to be in the form of spent submarine fuel. There are 51 spent submarine cores that contain HEU and these are stored at Sellafield [2]. Based on information in Reference [3], the 51 cores in stock could hold about 3.9t of HEU. By 2020, used cores could number about 90, and contain about 8.5t HEU.

At the end of 1998, civil stocks of HEU were 1.66tU [7]. However, at the present time it is not possible to predict how much highly enriched uranium may be declared as waste. The potential quantities involved will depend on the size of the UK's nuclear defence capability.

Characteristics: In highly enriched uranium the content of uranium-235 is increased to greater than 20%.

Potential Future Uses: This material is regarded as commercially valuable by its owners, and is not currently considered a waste.

1.3.4 Commercial Spent fuel

Estimated Future Stocks: The 1998 Inventory indicates that the eventual unreprocessed spent fuel masses will be of the order 2,900 tU from the AGR stations and 1,200 tU from the Pressurised Water Reactor (PWR) Sizewell B [5]. However, the actual inventory will depend on the operational lifetime of the reactors.

Characteristics: In AGR and PWR spent fuel, uranium is in the oxide form and the cladding for the fuel is made of steel or zircaloy. A typical PWR spent fuel inventory can be found in Reference [8].

Potential Future Uses: Current policy is that the decision to reprocess or hold AGR and PWR spent fuel in long-term storage pending direct disposal is a matter of commercial judgement for its owners (BNFL and British Energy, respectively).

1.3.5 Research Spent Fuel

Estimated Future Stocks: About 25 civil research, test and training reactors have been constructed in the UK over the past 50 years. All except the Imperial College Reactor at Sillwood Park have been shutdown. The defence research reactor Vulcan STP at Dounreay, and the test reactor Viper at Aldermaston are operating; the Vulcan DS/M P is shutdown. Most research reactors utilise very small quantities of specialised fuel.

Characteristics: The majority of these materials are included in the 1998 inventory [5].

Potential Future Uses: A number of research reactors have been decommissioned, most are undergoing decommissioning. Some spent fuel has already been reprocessed. It is likely that these wastes will be disposed of after suitable conditioning.

2 Long-term management options for uranium

In this section only the options that are currently being investigated internationally for long-term management of the depleted uranium or spent fuel are described.

2.1 Surface and underground storage

Depleted uranium arising from reprocessing is stored as drummed uranium oxide and is already regarded as passively safe. Uranium from the enrichment of natural uranium is stored as uranium hexafluoride (UF_6) at BNFL sites [3]. This could be treated to put it in a similar passive form for long-term storage pending a decision on future options. The Consultation paper [1] highlights that although this could be achieved the costs would be significant (as discussed in Section 3.4.1).

Many countries currently safely store spent fuel and HLW in surface (or near surface) storage [9]. A period of interim storage allows for radioactive decay and reduction in the heat generation of the materials. In the UK spent nuclear fuel from Sizewell B PWR is stored at the reactor site. AGR spent fuel that is not currently designated for reprocessing is stored at the Sellafield site.

In the short term, safe storage in surface or near-surface facilities can be achieved by packaging spent fuel and HLW in suitably engineered structures or robust containers to assure that radioactive materials will not be released. The security of surface or near-surface storage can be achieved by restricting access of individuals and groups that might divert fissionable material for weapons use or use radioactive materials for acts of terrorism [9].

The advantages of surface stores (and underground stores) are that they allow the uranium to be monitored and potentially retrieved. If the stores themselves were required to operate much beyond their design lifetimes, then refurbishments or even new stores would be required.

The consideration of surface or underground storage as a long-term waste management strategy should address the effectiveness of controls to restrict and assure containment integrity and the degree of confidence that can be placed in these controls [9].

2.2 Re-use

Separated uranium could be recycled in various ways to produce new fuel (including mixed with plutonium to make mixed oxide fuel (MOX) [3]. The possible future implications of declaring MOX spent fuel a waste is discussed in Reference [10].

2.3 Transmutation

Transmutation is the changing of one type of atom to another as a result of a nuclear reaction; usually as a result of bombardment with neutrons from a nuclear reactor or, in more recent schemes, from a particle accelerator. In the context of radioactive waste management, the aim is to produce shorter-lived or stable nuclides and so eliminate or reduce the need for disposal or other form of isolation from the biosphere.

Various proposals have been made for the application of transmutation to spent fuel, where the long-lived fission products and actinides are first separated (or partitioned) from uranium (as covered in a recent review by Bush [8]). In these schemes separated uranium is either re-used for fuel fabrication or declared as waste.

When actinide elements are irradiated by neutrons they either fission, or capture a neutron to transmute into a higher isotope. Hence, in order to produce a stable or short-lived product (not leading to a decay chain that contains long-lived radionuclides), for actinides transmutation means fission. Most proposals for fission of uranium are for the use of uranium as fuel in a reactor.

Transmutation of spent fuel is often claimed as providing a large reduction in the volume of waste requiring deep disposal. However, this is based on the assumption that separated uranium would have future uses or is declared as waste and placed in stores for low-level nuclear wastes [11].

Although partitioning and transmutation could reduce the inventory of some long-lived radionuclides present in spent fuel, it is not feasible for all the long-lived radionuclides. In addition, the process would create secondary wastes that would also require long-term management [8]. Hence, partitioning and transmutation would not eliminate the need for deep disposal or other form of isolation from the biosphere.

Although there has been considerable progress in partitioning and transmutation development over the last ten years, it remains a long-term venture. Further development is required to confirm technical, safety, proliferation and economic aspects.

2.4 Deep Geological Disposal

There is no current strategy in the UK for the disposal of high-level waste, spent fuel, HEU and depleted uranium, and detailed design and feasibility studies have not been performed. Although the disposal of spent fuel in a bentonite lined HLW/SF repository concept was suggested as an option in a recent report published by the DETR [12], this report did not provide any specific details on the repository design (i.e. layout and canister spacing). In order to perform scoping studies to determine the safety issues and provide cost estimates for the disposal of depleted uranium and commercial spent fuel in the UK it was necessary to make some assumptions about the immobilisation, packaging and repository concept. Key issues for the disposal of highly enriched uranium (such as immobilisation and waste loading in a package) are similar to those for plutonium, as discussed in Reference [10], hence are not discussed in detail in this report.

For the purposes of this study Nirex has used the disposal concept for HLW/SF in crystalline rock developed as part of a European Commission Study [13]. This information has been used to generate an illustrative concept for disposal of spent fuel with high-level waste in the UK.

Information is therefore provided in this report for the disposal of depleted uranium on the basis of the Nirex Phased Disposal Concept for ILW/LLW as described in [14] and the disposal of spent fuel in a bentonite-lined HLW/SF repository concept [described in Annex 1].

2.4.1 Immobilisation

Depleted uranium

Sixty percent of the UK stockpile of depleted uranium is estimated to be in the chemical form uranium hexafluoride (UF_6). This compound is highly reactive and not considered to be suitable for very long term storage or disposal [3,15]. In order to proceed it will be necessary to convert it to another chemical form. The potential conversion forms include the tetrafluoride (UF_4), oxide (UO_2 or U_3O_8), or metal [3, 15].

The United States Department of Energy (US DOE) is in the process of converting about 700,000 tonnes of depleted uranium hexafluoride (containing 475,000 metric tons of depleted uranium) to a stable form more suitable for long-term storage or disposal. If worthwhile beneficial uses cannot be found for the depleted uranium product form, it will be sent to an appropriate site for disposal [15].

A study performed by Oak Ridge National Laboratory noted that each form of depleted uranium has a degree of uncertainty regarding acceptability for disposal with the uncertainty decreasing in the following order: uranium metal, UF_4, UO_2, U_3O_8. A preference was expressed for uranium oxides over the metal due to the potential for oxidation and hydriding the metal in the presence of water and the resultant potential for radiological and environmental consequences [15].

It is worth noting that if in the oxide form there would be a preference for uranium in the U(IV) form rather than U(VI) form in order to maintain the overall redox potential in the Nirex Phased Disposal Concept.

<u>Spent fuel</u>

In countries such Sweden and the United States, where spent fuel is not reprocessed, it is currently planned to directly dispose of spent fuel.

2.4.2 Packaging Options

<u>Depleted uranium</u>

Following consideration of other options, for the purposes of this study it was assumed that depleted uranium to be included in an adaptation of the Nirex Phased Disposal Concept is:

- Conditioned in cement in an oxide form as this offers advantages over other chemical forms in terms of long-term passive safety. For this particular study depleted uranium is assumed to be U_3O_8.
- Packaged in 2-metre box (50 tU per box), as this gave the best packaging efficiency.

However, these assumptions were made in order to perform scoping studies to determine the key issues for uranium disposal and is not an attempt to present an optimised packaging option.

<u>Spent fuel</u>

There are potential advantages of including depleted uranium in a HLW/SF repository concept; such as acting as a neutron poison, assisting the maintenance of reducing conditions and uranium saturation in groundwaters thus retarding dissolution of spent fuel [6]. The use of depleted uranium as a neutron poison by mixing it with plutonium [16] or as an overpack material [6] has been suggested. In order to determine the feasibility of these options a programme of research and development would be required.

In the EC concept adapted for this study the spent fuel disposal container is carbon steel [13]. However, a range of materials has been suggested internationally for SF disposal containers as discussed in a recent study performed by the DETR [17]. These include: copper, stainless steel, titanium, carbon steel and ceramics. The selection of disposal container material would depend on the containment time required for SF, which in turn would depend on the geological environment being considered and the relative role of the near-field and far-field containment which underpin the conceptual safety case for the disposal system [17]. In addition, cost implications of utilising different materials would need to be considered.

2.5 Deep boreholes

Another form of geological disposal is disposal in deep boreholes at depths between 2 and 5km’s. The concept of deep borehole disposal received significant research in the 1970's and 1980’s for disposal of HLW and SF. This option has been investigated in several countries, including Australia, Italy, Russia, Sweden and Switzerland [9]. The borehole option has also been investigated for low-level and intermediate-level waste by Nirex in the 1980's [18].

However, several limitations in the concept led a number of nations to drop deep borehole disposal in favour of a mined geologic facility [19]. The issues that would need to be considered are:

- socio-political factors (decreased retrievability and easily grasped procedures) [20];
- heat generation of waste would limit hole capacity;
- surface area requirements (dependent on spent fuel loading per borehole and separation between boreholes, this could be 500m) [21];
- cost of disposal;
- criticality (an assessment of the possibility of gravity induced accumulations would need to be performed);
- limitations of drilling technology (but the technology has improved greatly in recent years);
- buffer material (bentonite may not be the best choice for deep boreholes) [22].

3 Key issues for Long-term Management of Uranium

3.1 Criticality

Nuclear criticality is a sustained nuclear chain reaction, in which the fissioning of atoms releases neutrons that induce further fission reactions. The reactions produce radiation, heat and fission products. In order to occur, criticality requires sufficient quantities of fissile isotopes in a suitable geometry and neutrons of appropriate energies. The principal fissile isotopes present in spent fuel are uranium-235 and plutonium-239, which are present at levels that may be sufficient to obtain criticality [23].

The post-closure criticality safety assessment for the Generic Performance Assessment for the Nirex Phased Disposal Concept examined the potential for a criticality. It was concluded that the potential for a criticality would be low and that, even if it did occur, its impact on repository performance would not be significant [24]. The low content of fissile uranium-235 relative to uranium-238 means that the inclusion of depleted uranium would not change this conclusion. In fact, uranium-238 is a good neutron poison and could be used to reduce the likelihood of a criticality event (as discussed below).

There are no detailed designs for the disposal of HEU or spent fuel in the UK, hence, the assessment of criticality in this section is largely qualitative and comparative in nature.

The disposal of HEU or spent fuel in a HLW disposal concept would require the potential for the accumulation of a critical mass of fissile material occurring to be assessed. The accumulation of a critical mass is primarily dependent on container failure and the plutonium or uranium from many containers joining [25]. The design of containers for the spent fuel or immobilised HEU to be placed in a repository would be optimised taking into account the need to prevent or minimise the possibility of criticality. If necessary, this could be achieved in a number of ways, including the use of:

- Limiting the mass of fissile material per container;
- High integrity containers, to increase the reliability/longevity of the spent fuel containers and allow more time for radioactive decay.
- Separating fuel assemblies, or the fuel pins from dismantled assemblies, in crates made of iron, steel or possibly other materials of high integrity.
- Filler materials to prevent water access and reconfiguration [26].
- Neutron poisons - such an approach requires consideration given to the impact of dissolution and transport of the materials, which could lead to non-uniform distribution of the neutron absorber [27].
- Dilution of the fissile mass of uranium-235 by the addition of uranium-238, hence utilising stockpiles of depleted uranium [27].

It is worth noting that criticality safety assessments for irradiated fuel operations have historically assumed the fuel to be unirradiated [28]. In other words, the spent fuel is assumed to have its original content of fissile material. The "fresh fuel" assumption is conservative since the potential reactivity of the nuclear fuel is substantially reduced after being irradiated in the reactor core. The concept of taking credit for this reduction in nuclear fuel reactivity due to burnup of the fuel, instead of using the fresh fuel assumption in the criticality safety analysis, is referred to as "Burnup Credit" [29]. Burnup credit uses the actual physical protection of the fuel and accounts for the net reduction of fissile material and the build-up of neutron absorbers in the fuel as it is irradiated. The use of burnup credit in the design of criticality control systems enables more spent fuel to be placed in a package. This is also has economic benefits [28,29].

3.2 Safeguards

Nuclear materials are kept under safeguards, to provide assurance that the materials designated for peace purposes are not used to further any military purpose. There are two organisations responsible for the implementation of safeguards in the UK – the International Atomic Energy Agency (IAEA) and Euratom. Each organisation uses a series of measures to ensure that nuclear material from the civil cycle (i.e. safeguarded material) is not diverted for weapons use.

<u>Application of safeguards to surface stores</u>

Safeguards regimes for nuclear materials including uranium are well established in the UK for surface stores. Both Euratom and the IAEA have developed safeguards and verification strategies [30].

For depleted uranium, in some cases, exemptions from safeguards can be accepted where the material is used exclusively in non-nuclear activities e.g. ballast.

Safeguards apply to spent fuel because it contains fissile material. The presence of an irradiation barrier (due to radionuclides present) will increase the difficulty of extracting fissile material by the potential diverter. However, it depends on the level at which diversion is deemed to take place (e.g. a country without its own significant nuclear programme would find the acquisition and extraction processes more difficult to overcome). Similarly, the value of a significant radiation barrier that poses an imminent threat to health is maximised for a small organisation/group. In safeguards terms the 'value' is recognised in the setting of the timeliness criteria. For example, for spent fuel this is three months, whereas for fresh unirradiated Mixed Oxide (MOX) fuel this is currently one month.

<u>Application of safeguards to a mined geological repository</u>

a) Operation

A repository design will need to be assessed with regard to the appropriate safeguards approach and particular techniques that are required to achieve credible assurance of the lack of diversion of nuclear material. It is possible to safeguard a repository, however, the influence of the design will determine the amount of effort and the degree of intrusion into operations that achieving the required safeguards assurance entails. Ideally the safeguards approach should be designed to minimise the impact on the geological barrier and intrusive surveillance/monitoring should be discouraged with preference given to passive systems in order to not compromise safety.

Important considerations for safeguards include the ability to verify the nuclear material content and to maintain a continuity of knowledge following these verification measurements up to the point of committal for emplacement, irrespective of the point in the process at which this verification is performed.

b) Post-closure

Both Euratom [31] and the IAEA [32] have indicated that safeguards on nuclear material (spent fuel and, by implication, immobilised HEU) disposed of in a geological repository cannot be terminated, not even after the repository has been back-filled and sealed. This could be interpreted as meaning that safeguards would be applied forever. This is clearly not possible over the projected life of the closed repository and an IAEA Advisory Group in 1995 recognised that safeguards should continue to be applied to spent fuel in the repository as long as safeguards apply to nuclear material elsewhere.

3.3 Public perception issues

A co-ordinated approach to handling radioactive wastes will be one of the key requirements for maintaining the confidence and trust of the public. When one group of scientists advocate one solution and another group something else the public lose confidence and trust in those trying to find a solution. This situation is seen with issues such as Bovine Spongiform Encepolopathy (BSE) and Genetically Modified Food, where differing scientific opinion has contributed to undermining public confidence. The approaches to the management of HLW/SF and LLW/ILW are quite different, but this needs to be shown to be a part of larger integrated approach to waste management, which addresses public concerns.

The question of: 'What is a waste?' needs to addressed early in the process. In the United States, Waste Isolation Pilot Plant has been facing problems because there has been an attempt to add more wastes to those originally defined for the repository. This is perceived by the public as changing the goal posts and undermines any agreements that were reached at the beginning of the process, and thus has negative impacts on the public trust and co-operation.

An integrated approach to waste management was recommended by House of Lords Select Committee on Science and Technology (as discussed in Section 3.5) [2]. One means of achieving this would be the combined disposal (co-disposal) of HLW/SF with ILW/LLW within a single facility. However, there is an equity issue if these wastes were disposed of at one site, as one community would be seen as having the entire burden. However, it is important to note that public views on siting do not necessarily differentiate between LLW, ILW, HLW and SF, but may be more concerned with the form of the waste management and other issues. It is also worth noting that the source of waste is significant regarding its acceptability (i.e. acceptability of Ministry of Defence Wastes on moral grounds). These concerns will need to be addressed in public consultation [33].

3.4 Cost

Where possible cost estimates for implementing some of the options discussed in Section 2 are provided to give an indication of the possible economic implications. In the absence of detailed studies (on packaging options and illustrative repository concepts) only highly speculative costs estimates can be provided.

3.4.1 Disposal of Depleted Uranium in ILW/LLW repository concept

<u>Immobilization</u>
The estimated cost for conversion from UF_6 in this study varied widely: UF_4 ($460-740 million); U_3O_8 ($920 million); UO_2 ($1200 million) and U metal ($2400 million) [15]. For this study the cost of conversion made a significant contribution to the estimated total cost (this also included containers, transportation and disposal).
<u>Disposal</u>

As described in Annex 3, it is estimated that for small incremental volume increases emplaced within the same operational regime, the additional cost is of the order £2,000/m^3. The incremental cost of depleted uranium disposal packed in 2-metre box[1] is £440 per tonne. The total cost for the disposal of 106,000 tonnes of depleted uranium is therefore estimated to be of the order of £50 million.

[1] Assumes uranium is compacted in the oxide form (U_3O_8) and the conditioned volume is 11m^3.

This cost estimate does not include the cost for conversion of UF_6 to a suitable waste form for disposal (as discussed above). Hence, the total cost will depend on the chosen method of conversion and the type of Nirex package chosen.

3.4.2 Deep Geological Disposal of Spent Fuel

The information presented in Reference [34] and Annexes 1 and 2 has been used to provide illustrative information on the cost of the disposal in an underground repository of HLW and SF. Based on the assumptions made of the disposal concept the total cost of disposal of HLW (1,250 m^3), AGR SF (2,900 tU) and PWR SF (1,200 tU) would be of the order of £3,900 million. The cost of disposal of commercial spent fuel is estimated to be £1,385 million. This assumes that the same organisation undertakes the development of both the ILW and HLW/SF repository concepts. It should be noted that some of the cost information related to the HLW/SF repository is not at the equivalent level of detail to the ILW/LLW repository concept and estimates should be regarded as relatively approximate. These cost estimates for disposal of spent fuel also do not include the costs of disposal containers[2] [35].

One means of achieving a more integrated approach to waste management is the combined disposal (co-disposal) of HLW/SF with ILW/LLW within a single facility. Nirex has performed scoping studies to investigate the feasibility of co-disposal in the UK [36]. Co-disposal offers potential cost savings over the development of separate facilities for different types of waste; and would involve the development and consequential disturbance of a single site.

3.4.3 Deep borehole disposal of Spent Fuel

A recent review of the Very Deep Hole (VDH) concept by SKB [22] concluded that:

"To develop the disposal concept VDH to attain a level of knowledge equivalent to the one we have today of the KBS-3 (mined repository) concept is expected to take more than 30 years and to cost just over SEK 4 billion".

SEK 4 billion is approximately £300 million.

3.4.4 Partitioning and Transmutation of Spent Fuel

There is limited information available on the cost or time required to develop transmutation of radioactive waste, apart from in the US [37] and European [38] "roadmaps".

In 1999, the Department of Energy prepared a "roadmap" for developing accelerator transmutation of waste in a report to U.S. Congress. The cost of six years R&D was estimated to be about $281 million. The capital and operational life-cycle costs to treat 87,000 tonnes of commercial spent fuel were estimated to be in total around $280 billion ($2 billion R&D, $9 billion demonstration and $270 billion post-demonstrating design, construction, operation, and decommissioning). The total time to implement accelerator transmutation of waste is estimated to be 117 years, of which R&D (initial 8 years) and demonstration comprise the first 27 years, and post-demonstration period activities comprise the following 90 years [37].

It is currently estimated by the European Technical Working Group on Accelerator Driven Systems (ADS) that a prototype ADS for the transmutation of waste could be built by 2040 at a cost of 0.5 billion Euro (excluding fuel and contingencies) [38].

[2] The cost of packaging was estimated in a study by Nattress and Ward to be £2,000 per disposal container at 1991 Money values.

3.5 Integrated Waste Management Strategy

The House of Lords Select Committee on Science and Technology 3rd report recommended that the Government should develop a comprehensive and integrated strategy for the management of all long-lived wastes. It was also concluded that decisions are needed soon on which materials are to be declared as wastes [2].

If some forms of uranium were to be declared a waste, in order to be suitable for disposal issues that would need to be addressed would include the development of a wasteform and packaging, avoidance of a nuclear criticality incident, the application of safeguards to prevent the recovery of material for nuclear proliferation for an appropriate time following disposal and other safety issues. This work could be performed in parallel with other research and development activities in a programme of research and site selection of a repository for an ILW/LLW and HLW repository. A larger inventory of wastes, and issues such as safeguards and criticality for spent fuel, could extend the time taken for consultation, planning applications and planning inquiry processes. However, overall the inclusion of additional uranium is not considered to extend the duration of the programme or change the critical path activities. In addition, the wastes to be considered would need to be identified early in the consultation phase so as not to affect the programme. This was also the conclusion reached in a study of a research strategy for the disposal of HLW and spent fuel undertaken by QuantiSci for the DETR [12].

4 Implications of deep geological disposal

This section describes the key issues identified in the assessment of the implications of including the depleted uranium in cemented packages in the Nirex Phased Disposal Concept in addition to the Reference Case Volume, and commercial spent fuel in a bentonite-lined HLW repository concept.

4.1 Implications of including depleted uranium in the Nirex Phased Disposal Concept

4.1.1 Impact on Generic Repository Design and Transport Design

The 106,000tU of depleted uranium estimated to exist in Section 1.3.1, was assumed to be packaged in 2-metre boxes. Assuming each box could accommodate a loading of 50tU, a total of 2120 boxes would be produced and would require an additional vault in the Nirex Phased Disposal Concept [39]. However, as shown in Reference [10] the Nirex package type chosen can have an impact on the repository volume required.

Including depleted uranium packaged in 2 metre boxes in the Nirex Phased Disposal Concept would not place an additional burden on the transport design if phased over the 25-year period of operation.

4.1.2 Impact on Generic Transport, Operational and Post-closure Safety Assessment

Transport Safety Assessment

The issues for the transport of depleted uranium were estimated using the methodology developed in the Generic Transport Safety Assessment (GTSA) [40]. The results of scoping assessment suggest that the transport operation should be capable of satisfying the Nirex Radiological Protection Policy requirements [41]. However, if the additional wastes were transported contiguous with the Reference Case Volume of ILW/LLW the increase in risk would dictate that risks are reduced as low as reasonably practicable (ALARP).

Operational Safety Assessment

The implications of including depleted uranium in the Reference Case Volume was assessed using the methodology developed in the Generic Operational Safety Assessment (GOSA) [42]. Preliminary scoping calculations, based on what are expected to be conservative assumptions regarding package performance, suggest that deep disposal of depleted uranium packaged in 2 metre boxes would exceed operational safety risk targets.

This assessment showed that the acceptability of depleted uranium packages is dependent on the performance under impact scenarios and the large number of additional packages. More work is required in this area to develop confidence in the optimum packaging options for depleted uranium.

Post-closure Safety Assessment

A scoping study was performed to evaluate the post-closure radiological impacts of including depleted uranium, which considered the groundwater and human intrusion pathways. The work is based on data and models that have been developed for use in the Generic Post-closure Performance Assessment (GPA) [24].

The approach that has been adopted in the GPA utilises a base case model as a basis for packaging advice (for ILW/LLW) which assumes the repository is located at a site that:

- would comply with the annual individual radiological risk target of 10^{-6} per year for the base case[3],
- which could be achieved in environments that may be found in the UK and considered suitable for repository development.

For the combined inventory of depleted uranium and the Reference Case Volume the calculated risk from the groundwater is significantly above the 10^{-6} annual risk target. The leading contributors to risk are the daughters of uranium-238, at times beyond 300,000 years. However, the Reference Case Volume contains organic materials that can form complexants and hence increase the solubility of uranium and decrease sorption. If the depleted uranium were disposed of in vault where it can be assumed with confidence that organics will not affect depleted uranium solubility or sorption, or in similarly conditioned separate repository, the calculated risks do not exceed the risk target.

For the geotechnical worker scenario aspect of the assessment of the human intrusion pathway, the key radionuclides were found to be radon-222, a daughter product from the radioactive decay of the uranium inventory. The calculated annual individual risk for this scenario did not exceed the risk target.

In comparison, for the site occupier scenario the annual risk target is reached for the Reference Case Volume inventory for the GPA (peak risk 10^{-6} occurring at around 300,000 years). However, the calculated peak risk for the site occupier from 106,000 tU of depleted uranium concentrated in one vault was found to be approximately a factor of 20 over the 10^{-6} risk target. A sensitivity study was carried out for the site occupier scenario in which variant waste packaging arrangements were considered. Results indicate that, although dose to the site occupier is affected by alternative waste packaging arrangements, and by how the waste packages are stacked in the repository vaults, annual individual risk in this scenario is invariant to such changes.

The calculated risk is also sensitive to other assumptions such as drilling rate. Sensitivity studies based on alternative drilling rates to those used in the GPA, but arguably reasonable, calculated the risk to be below the regulatory risk target.

Of the materials considered in the GPA [24] to be of concern with respect to the chemical toxicological hazard (beryllium, phenol, benzene, nitrate and vinyl chloride monomer), it is assumed that a significant inventory of these materials would not be present in depleted uranium wastes. For the present it is considered that the most significant contribution to a chemical toxicological impact to humans may arise from the uranium itself, or from lead-206 to which uranium-238 ultimately decays to.

The methodology used in the GPA study to estimate the toxicological impact of the disposal of the Reference Case Volume was applied to the inclusion of depleted uranium in the Nirex Phased Disposal Concept. It was found that the inclusion of uranium would not affect the conclusions of the GPA study concerning the chemical toxicological impact of the disposal of uranium and daughter products.

4.2 Implications of deep geological disposal of SF with HLW

This section presents the results of scoping studies to determine the implications of including commercial spent fuel in the same repository as HLW.

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[3] By choice of the three key site-specific hydrological properties that are known to have a direct impact on performance, namely the groundwater flux through the engineered barrier system (Q = 300 m^3/year), groundwater travel time from the repository to the surface (T = 100,000 years), and the groundwater mixing flux (F = 300,000 m^3/year) in any overlying rocks into which groundwater leaving the repository may eventually discharge.

4.2.1 Impact on HLW/SF Repository Design and Transport Design

A description of the illustrative repository concept for the disposal of SF in the same repository as HLW is given in Annex 1. The repository footprint would depend on the repository design, the design and thermal loading of the disposal canister and the total quantity of waste for disposal.

There is currently no design for the transport of HLW/SF to a repository, but the following factors will need to be considered:

- Rail Gauge - The flask and its canopy must fit within the UK rail gauge.
- Axle Weight - heavy loads (i.e. greater than 22.5 tonnes) are likely to restrict their suitability on the rail network.
- Flask length - longer flasks (i.e. 20m) can not negotiate tight bends and could only be used on selected routes

4.2.2 Operational, Transport and Post-closure Safety

Transport and Operational Safety Assessment

A quantitative assessment of the operational and transport safety for HLW and SF was beyond the scope of these studies and is not timely at this stage. The key issues for operational and transport safety are likely to be:

- behaviour of the waste form and package under impact and fire conditions;
- identification of hazards through the handling and transport of these wastes (these can be considered in the development of a detailed repository design and transport design);
- criticality and safeguards (these issues are discussed in Sections 3.1 and 3.2 respectively).

Post-closure Safety Assessment

A scoping study was performed to evaluate the post-closure radiological impacts of a HLW/SF repository that considered the groundwater and human intrusion pathways. The work is based on data and models that have been developed for use in the 'Generic Performance Assessment' (GPA) for the disposal of ILW [24]. These models have been extended to consider a generic concept for the disposal of HLW/SF. Over the timescale of interest (1 million years post repository closure) the calculated radiological risk from the groundwater pathway remains below the 10^{-6} risk target. The important radionuclides that contribute to risk were found to be selenium-79, caesium-137, iodine-129, radium-226, thorium-230 and uranium-233

For the human intrusion pathway the key radionuclides were found to be plutonium-239, plutonium-240 and americium-241 at times up to 100,000 years post-closure, and radon-222 at times beyond this time. However, the annual risk target of 10^{-6} is only exceeded for the site occupier scenario[4] for SF waste. The calculated peak risk is 2 10^{-6} occurring at about 200,000 years following repository closure. As the risk is related to the concentration of radionuclides in a package, this issue that would need to be considered in the design of the disposal canister and of the repository concept.

Hydrogen is the principal gas of interest for the assessment of the gas pathway for an HLW/SF repository. It is generated mostly through anaerobic corrosion of the carbon steel waste containers in the HLW/SF tunnels and a relatively small volume due to the radiolysis of water [13]. Gases released from spent fuel (such as helium,

[4] This scenario addresses the risks to a group of individuals who inhabit land that may have been contaminated by materials discarded after earlier borehole drillings that penetrated the repository.

krypton and radon) are considered to be of minor importance compared to the generation of hydrogen [13].

5 Conclusions

Options for the long-term management of uranium have been investigated in other countries. There is a need to establish the criteria for assessing the long-term management options and through consultation decide on the option(s) to pursue further. It is important to ensure that there will be a comprehensive and integrated strategy for all materials (including uranium), in order that:

- public concerns can be addressed at an early stage;
- late/additions/changes to the range of wastes included in the developing strategy are minimised;
- any future programme will not be delayed by revisions to decision-making.

Scientific, technical, ethical and social research and development would be required, which includes clear steps for consultation and decision-making.

If declared a waste key issues for the long-term management for uranium are similar to other radioactive wastes/materials and could be managed as part of an integrated approach to waste management. Key issues that would need to be considered include: long and short term safety; cost; availability of technology; public perception; retrievability; safeguards and avoidance of nuclear criticality.

Nirex has performed scoping studies to determine the implications of the deep disposal of the UK's depleted uranium in an adaptation of the Nirex Phased Disposal Concept and commercial spent fuel in a bentonite-lined repository concept. If some of the UK uranium stockpile were declared a waste to be disposed of, a suitable wasteform, packaging design and repository concept would need to be determined. This would be addressed through a programme of research and development that includes clear steps for consultation and decision-making.

Based on the assumptions made for this scoping study if depleted uranium were included in an adaptation of Nirex Phased Disposal Concept:

- The cost of disposal has been estimated based on the assumption that depleted uranium is included in the same operational phase and did not include the cost of conversion to a different chemical form suitable for disposal, packaging or containers. More detailed studies are required to consider the uncertainty and risk associated with these figures.
- The impact on repository footprint would not be significant.
- However, both cost and footprint would depend on waste form and Nirex package type chosen.
- At least 60% of the stockpile would require conversion to a more passively safe chemical form, which could have a significant impact on cost.
- Scoping calculations suggest that deep disposal of depleted uranium with the ILW/LLW in the Nirex Phased Disposal Concept exceeds risk targets for operational and post-closure safety. However, acceptable level of risk may be achieved for:
    - Operational safety by appropriate choice of package design and/or extending the operating period.
    - Post-closure safety for groundwater pathway by disposing of depleted uranium in a separate repository or in vault where it can be assumed with confidence that organics will not effect depleted uranium solubility or sorption.

- However, the risk target was exceeded for the site occupier scenario of the human intrusion pathway. The calculated risk is sensitive to drilling rates, but not to packaging design or waste packaging arrangements in the repository.

These scoping studies show that inclusion of depleted uranium is sensitive to assumptions made in order to undertake the safety assessments. Hence, more work is required to determine whether it would be feasible to include depleted uranium in the Nirex Phased Disposal Concept or whether a separate repository would be required.

The inclusion of commercial spent fuel in a bentonite-lined repository with HLW is not expected to have an unacceptable impact on safety, although detailed studies have not been performed. Based on the assumptions made for this scoping study If commercial spent fuel were be included in a HLW bentonite-lined repository concept:

- The total cost of disposal of HLW/SF was estimated to be approximately £3,900 million; this includes £1,385 million for commercial SF disposal. This cost assumes that the same organisation undertakes the development of both the ILW and HLW/SF repository concepts and would depend on the repository concept developed.
- The total repository footprint for a HLW/SF repository was estimated to be 2.08 km^2; this includes 0.74 km^2 for SF disposal. Hence, the impact on the repository footprint would not be significant, but would depend on the heat output of the SF and the design of the repository concept developed.
- The inclusion of SF in a bentonite-lined repository with HLW is not expected to have an unacceptable impact on safety, however, detailed studies have not been performed.

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Annex 1 – Illustrative Concept for disposal of High-Level Waste, Spent Fuel and HEU

For the purposes of this study Nirex has used the disposal concept for HLW/SF in crystalline rock developed as part of a European Commission Study [A1]. This information has been used to generate an illustrative concept for disposal of HLW/SF in the UK (separate from ILW) and provide estimates of number of disposal canisters, length of emplacement drifts and repository area. These estimates are based on the following assumptions:

1. Disposal canisters are emplaced horizontally in a system of circular emplacement drifts with a diameter of 2.4m. The emplacement drifts are 500m long and spaced 35m apart (Note: the spacing of the drifts will depend on the heat output from the wastes and operational requirements). There are two rows of emplacement drifts separated by 500m. Hence, the repository is 1500m wide and the length is dependent on the number of emplacement drifts required.
2. HLW is packaged in Waste Vitrification Plant (WVP) containers (0.148 m^3 vitrified HLW per container). It is assumed that each disposal canister will contain two WVP containers stacked one on top of the other. The disposal canisters are 3.2m long and 0.9m diameter. These canisters are separated by 2.5m of bentonite [A1].
3. PWR SF disposal canisters contain 4 intact PWR fuel assemblies. The disposal canisters are 4.54m long and 0.9m diameter. These canisters are separated by 1.0m of bentonite [A1].
4. MOX SF disposal canisters contain 1 intact MOX fuel assembly. The disposal canisters are 4.54m long and 0.9m diameter. These canisters are separated by 1.0m of bentonite [A1].
5. The European Study did not investigate the disposal of AGR SF, hence the disposal canister for AGR SF is based on the design for PWR SF. It is assumed that the AGR is dismantled[5] and each disposal canister can contain 8 consolidated fuel bundles (1.03 tonnes AGR SF per canister). The disposal canisters are assumed to be 2.5m long and 0.9m diameter. These canisters are separated by 1.0m of bentonite [A1].

A comparison of the packaging assumptions and disposal concept for HLW and different types of spent fuel is shown in Table 1.

[5] British Energy (formally Scottish Nuclear Limited) have investigated container designs adapted from those developed for the prospective disposal of spent CANDU fuel in Canada. The spent fuel may be in the form of intact fuel elements, or dismantled and consolidated fuel pins [A2].

Table 1: Packaging and Disposal concept assumptions for HLW/SF

Assumptions	HLW	AGR SF	PWR SF	MOX SF
Disposal canister capacity				
SF/HLW (te) per disposal canister	0.200	1.043	2.136	0.534
Disposal canister dimensions				
length (m)	3.2	2.5	4.54	4.54
diameter (m)	0.9	0.9	0.9	0.9
Bentonite between disposal canisters				
length (m)	2.5	1.0	1.0	1.0
500m Emplacement drift capacity				
disposal canisters per emplacement drift	87	142	90	23
SF/HLW (te) per emplacement drift	17	148	192	48

Annex 2 – Cost of HLW/SF repository

In the study performed for RWMAC the total repository area and cost of disposal was estimated for a Reference Case material inventory shown in Table 2.

Table 2: Total number of Emplacement drifts for Reference Case Material Inventory

Waste type	Material Quantities	Number of Disposal Canisters	Number of Emplacement drifts
HLW (m^3)	1,250	4,223	49
AGR SF (te)	2,900	2,805	20
PWR SF (te)	1,200	562	7

Based on the assumptions made of the disposal concept, the material inventory shown in Table 2 would generate a total of 76 emplacement drifts with an associated repository area of 2.08 km^2. The total cost of this disposal concept with 76 emplacement drifts would be of the order of £3,900 million. This assumes that the same organisation undertakes the development of both the ILW and HLW/SF repository concepts and covers:

- Site characterisation;
- Repository operation;
- Repository construction;
- Repository closure;
- Other programme works;
- Institutional costs;
- Internal costs.

This base case value DOES NOT include a cost associated with risk or uncertainty. It is worth noting that due to the preliminary nature of the work, the certainty in the cost for a HLW/SF repository is less than that for the ILW/LLW repository.

The aim of the scoping assessment performed for RWMAC was also to provide incremental costs for disposal of HLW/SF. If the amount of waste for disposal shown in

Table 2 was increased, the cost of each additional emplacement drift is estimated to be £26 million at September 1999 Money Values. This cost estimate is based on the volume dependent costs (such as: repository construction; operation and closure), but assumes the operational period is NOT extended as a result of the requirement to dispose of the larger volume of waste.

Annex 3 - Cost of ILW/LLW repository

Nirex has provided cost estimates for the disposal of 200,000 m^3 of ILW/LLW for the "Base Programme" of the Nirex Phased Disposal Concept for the purposes of providing provisioning advice to its customers [A3]. The total lifetime costs at December 2000 are estimated at £5,082 million without a Care and Maintenance period and £5,738 million with a Care and Maintenance period at September 1999 Money Values [A3]. It is estimated that for small incremental volume increases emplaced within the same operational regime, the additional cost is of the order £2,000 per cubic metre.

These values do not include any costs associated with:

- risk or uncertainty;
- Stage III Decommissioning wastes envisaged to arise after 2100;
- transport costs to the facility from site of arising.

In addition to the base costs for a separate ILW/LLW repository, the cost associated with uncertainty has been estimated by undertaking an analysis of risks. It is estimated that the total cost of this option will be no more than £5,738 million plus £1,532 million (with a likelihood of 75%) at 1999 Money Values.

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