

PLUTONIUM

CREDIBLE OPTIONS ANALYSIS (Gate A)

2010

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Plutonium Credible Options Analysis (Gate A) 2010

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Reasoning Behind the 2010 Update to this Paper

In the period since our original credible options paper was published in January 2009, there have been a number of new developments. We have updated our credible options to incorporate this new information into our assessment of the options. The key changes are given below.

Since 2008, UK Government has published an Energy National Policy Statement¹, in which several statements on Nuclear Power Generation are made which indicate a commitment towards new nuclear build in the UK over the coming 10-15 years. This policy position is more definitive than that available when the initial version of this paper was written in 2008. As such NDA has added a further option of reuse of plutonium as MOX fuel in UK new nuclear power stations for consideration, even though NDA recognises that Justification and the Generic Design Assessment have only been carried out on a uranium oxide fuel basis.

Additionally at the 2010 Washington Nuclear Security Summit 47 nations committed to advancing nuclear security goals, and US President Obama outlined how global cooperation will combat the threat of nuclear terrorism and safeguard nuclear material. Specifically it was formally recognised that separated plutonium requires special precautions and the nations agreed to promote measures to secure, account for, and consolidate these materials, as appropriate². Immediately prior to the Summit, US Secretary Clinton and Russian Foreign Minister Lavrov concluded the U.S.-Russia Plutonium Disposition Agreement, which was initially reached in 2000. The pact commits each country to eliminating 34 metric tons of weapons-grade plutonium, by recycling as MOX fuel.

Since 2008, there have been improvements in performance and a new contract put in place for MOX fuel manufacture in the Sellafield MOX Plant (SMP). The SMP continues to be used to manage overseas owned plutonium. The performance of the SMP will be monitored against current contractual commitments. Its longer term future requires a sustained production rate and further commercial contracts.

Since 2008, NDA has been working hard to better understand and underpin the options for plutonium management, such as by undertaking a more detailed review of plutonium physical and chemical data records. As such the process flowcharts for each of the options (see appendix A) are better understood and have been modified. Additionally, it is now anticipated that a small proportion of the plutonium inventory, classed as residue material, will be immobilised using Hot Isostatic Pressing technology to produce a durable ceramic wastefrom. This process has been factored into the process flowsheets.

¹ <https://www.energynpsconsultation.decc.gov.uk/docs/AnnexestoEN-6-RevisedDraftNuclearNPS%28VolumeII%29-October2010.pdf>

² <http://www.america.gov/st/texttrans-english/2010/April/20100413171855eaifas0.6155773.html#ixzz1814L4iLg>

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In NDA's published draft Strategy II³ the principle of co-location of plutonium from sites across the UK to one central site was proposed, and for the purposes of this study, all the credible options now consider the possibility of the relatively small amount of plutonium (around 2% of the total inventory) stored at Dounreay being managed at Sellafield. However the option to manage plutonium at Dounreay still remains. Another development since 2008 has been the improved understanding of long term costs of facilities management at Sellafield, as given in the recently updated Sellafield Lifetime Plan (LTP). Since these financial changes have a potentially large impact, the costs used in the earlier paper have now been updated.

NDA received a wide variety of comments from the previous study concerning the use of proliferation resistance analysis tools to better understand plutonium management options. Following those comments, the NDA, working with the National Nuclear Laboratory, has commenced work on proliferation resistance analysis methods (considering state-sponsored proliferation as well as plutonium theft/diversion). This work is presented, at an early stage of development, in this updated report to inform on proliferation and security aspects of the ten plutonium management options.

Document Revision Record

Version	Stage	Record of Change	Author	Date
1.0			Paul Gilchrist	2008
2.0	A	Update	Paul Gilchrist	2010

	Name	Signature	Date
AUTHOR:	Paul Gilchrist		
CHECKED:	Clive Nixon		
APPROVED:	Adrian Simper		

³ <http://www.nda.gov.uk/documents/upload/Draft-Strategy-published-September-2010-for-consultation-full-colour-version.pdf>

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1 Introduction

1.1 Purpose

The purpose of this report is to outline the credible options for a future management strategy for the UK civil stockpile of separated plutonium. The report assumes a degree of familiarity with the NDA operating model and its Strategy Management System. This updated report will be presented to Government with the aim of informing their consideration of the future policy frameworks which will facilitate decision making in this area. A redacted version of the report will be published on the NDA website.

1.2 Context of the UK civil owned Plutonium

As a result of historic reprocessing operations since the 1950's the UK has generated a stockpile of separated civil plutonium (Pu) in the form of plutonium oxide, scrap mixed oxide fuel and miscellaneous residues, which will grow to just over 100te at the completion of currently planned reprocessing. This will represent the largest civil plutonium inventory of any country. The most appropriate policy for managing the civil plutonium stockpile is an important issue to be determined by Government with assistance from the NDA. To support Government in this regard, the NDA has developed what it believes to be the credible options for the future strategy. These have been summarised as a range of potential strategy options for this paper.

The scope of the analysis is the interim management and future disposition of the UK owned civil separated plutonium and planned future arisings from the completion of the Sellafield reprocessing plan. Included within this definition is the material owned by the NDA and British Energy (BE). It is noted that there may be changes to the scope in the future. For example, (i) if BE chose a different route for their material, (ii) if MOD-owned material was to be included in the inventory at any point in the future or, (iii) an alternative strategy for foreign owned material were to be adopted by the overseas utilities.

1.3 Background to the formation of the UK Separated Plutonium Stockpile

In the 1950's the separation of plutonium was carried out primarily for defence purposes. During the 1960s the developed nations recognised that fossil fuels would eventually run out and that alternative energy sources would be required. This alternative was considered by many (including the UK) to include nuclear power, initially *via* conventional thermal reactors and subsequently *via* fast reactors.

The UK opted for a first generation of metal-fuelled Magnox reactors and a second generation of oxide-fuelled AGR reactors. Two prototype fast reactors were also built at Dounreay. Due to a variety of domestic and international factors, largely connected with the ready supply of fossil fuels, depressed energy prices and public concerns over nuclear power the commercial fast reactor programme was not progressed.

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In the absence of the capability to consume plutonium in either thermal or fast reactors in the UK a stockpile of separated plutonium has been accumulated.

The UK has, up until now, maintained a position of continued safe storage of plutonium as a zero value asset⁴. There is growing national and international pressure to determine the long term management approach of the UK plutonium stockpile and hence determine whether this material should be reused or disposed of. The drivers for proposing change to the current arrangements are described in Section 1.5.

1.4 Worldwide background to Separated Plutonium Stocks and International Strategies

Worldwide, the rate of separation of plutonium significantly exceeds the rate of reuse of plutonium and this has resulted in an accumulated inventory of separated civil plutonium⁵. The declared and estimated national stocks of plutonium held by IAEA member states are shown schematically in Figure 1⁶. It is estimated that there were approximately 500 teHM (tonnes heavy metal) of separated plutonium in 2009. Of the approximately 250 teHM of worldwide separated and safeguarded civil plutonium stored the UK has the largest stockpile, which is estimated to ultimately grow to just over 100 tonnes.

Over recent years there has been growing pressure to reduce worldwide stocks of separated plutonium in order to minimise the risks and hazards associated with separated plutonium. In addition, major international efforts are being made to transfer plutonium out of non-safeguarded military jurisdiction into the safeguarded civil programme, where it can be disposed of or reused in MOX fuel, for example. To date the UK has retained its position of safe and secure storage.

⁴ The concept of a zero value asset means that there are no cost or revenues attributed to the balance sheet, either from immobilisation or from any revenue that may be generated by reuse options

⁵ Status and Advances in MOX Fuel Technology, Technical Report Series No. 415, IAEA, 2003.

⁶ Global Fissile Material Report 2009, from the International Panel On Fissile Materials, <http://www.ipfmlibrary.org/ipfmbriefing091210.pdf>

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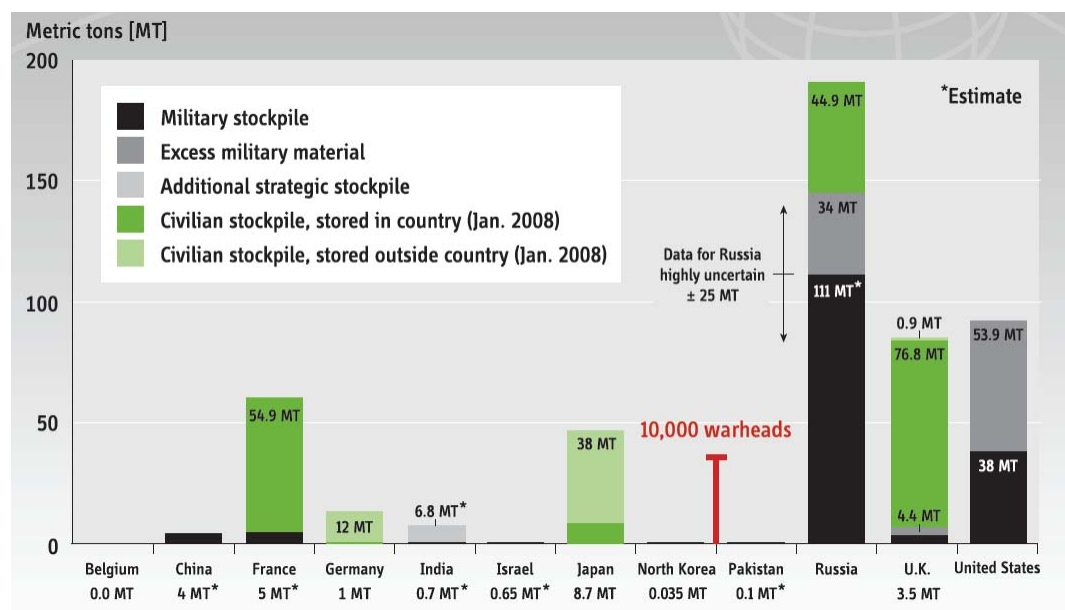


Figure 1: National Stocks of Weapons and Separated Civil Plutonium, (reproduced from Ref Footnote 3)

As shown in Figure 1, separated plutonium stocks are largely held by France, Japan, Russia, UK and USA. Different nation states have and have had quite different approaches to managing their national plutonium stocks, and, while the UK's position has remained relatively static, many countries have been re-evaluating their plutonium management policies over the last 2-3 years.⁷ It should be noted that each of these countries consider management strategies for plutonium stocks of different grade, and as a result one country's solution for plutonium may not be the most appropriate for another due to these differences.

France: France has an established domestic nuclear power industry. Plutonium is separated at the La Hague reprocessing plants and manufactured into MOX fuel at the MELOX plant at Marcoule,

As a result of these efforts France has a declared and safeguarded stockpile of civil plutonium of circa 55 tonnes. In support of long term plutonium strategy the French CEA are undertaking considerable research and development programmes on the use of separated plutonium for energy production in Generation IV reactors including fast neutron and high temperature reactors.

United States: In the 1970s the US Government declared a moratorium on reprocessing. As a consequence of this they have only a small accumulation arising from reprocessing of civil spent fuel. However, a stockpile of ~90 tonnes separated plutonium has been accumulated from military activities. The United States is

⁷ Plutonium Management in the Medium Term, A Review by the OECD/NEA Working Party on the Physics of Plutonium Fuels and Innovative Fuel Cycles (WPPR), NEA 4451, 2003.

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pursuing a plutonium disposition programme aimed at irradiating excess weapons plutonium as MOX fuel in LWRs. This will modify the isotopic composition of the weapons-grade plutonium to that similar to plutonium in spent uranium oxide LWR fuel thereby minimising the quantity of weapons grade plutonium in existence. Lead test assemblies of MOX fuel have undergone irradiation tests in a Duke Energy PWR and construction started on a new MOX fuel manufacturing plant, the MOX Fuel Fabrication Facility (MFFF) in South Carolina

Russia: A weapons-grade plutonium disposition programme to irradiate plutonium in Russian VVERs (Russian PWR design) is being pursued in parallel to the US programme,

The aim is to achieve parity between weapons plutonium disposition in the US and Russia. A collaborative US/Russia programme is underway in support as experience of MOX in VVERs lags that of MOX in Western PWRs.

Earlier in 2010, the United States confirmed its commitment to financially support Russia's plutonium disposition programme by providing \$400 million in support of a range of activities associated with the programme. These activities include modification of the MOX fuel fabrication facility at RIAR (Dimitrovgrad) to fabricate MOX fuel for the BN-800 reactor. In addition the US has agreed to contribute to the cost of the Gas Turbine Modular Helium Reactor (GT-MHR) research and development programme in Russia. This reactor, if built in time, could be used for plutonium disposition.

In order to reduce plutonium stockpile, The Russian Government announced the shutdown of the ADE-2 reactor in Zheleznogorsk which had been used for the production of weapons grade plutonium over the last 52 years.

Japan: The Japan Atomic Energy Commission states in its 2007 White Paper that "policy is to reprocess fuel and effectively utilise collected plutonium".⁸ Japanese utilities have developed plans for the reuse of plutonium of MOX fuel and have started to irradiate MOX fuel at the end of 2009. In addition, Japan Nuclear Fuel Ltd. started construction on 28th October 2010 in Aomori Prefecture of Japan's first commercial plant to produce MOX fuel, an integral part of the nation's nuclear fuel

⁸ Japan Atomic Energy Commission, White Paper on Nuclear Energy 2007

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cycle aims. The plant in the village of Rokkasho, scheduled to be completed in March 2016

is expected to serve as a key facility in establishing the infrastructure for recycling spent nuclear fuel. It will be able to produce up to 130 tons of MOX fuel a year by changing powdered MOX, extracted from spent nuclear fuel at an adjacent reprocessing plant, into fuel pellets, rods and LWR assemblies.

1.5 The Case for Proposing Change to the Plutonium Strategy

There has been growing pressure nationally and internationally for the UK to more appropriately manage its stockpile of separated plutonium, through the determination of an end state. If this is to be undertaken, credible options for achieving this goal need to be defined and evaluated. By comparing this 2010 update from the original report in 2008, it is clear that France, Russia, USA and Japan have all made strides in managing their surplus plutonium stocks, while the UK has started to consider policy options.

Irrespective of the option(s) to be taken forward, even if decisions were taken today, our initial studies have shown that it will take in the region of 30 – 50 years of continued effort to immobilise for reuse or disposal, the entire UK plutonium stockpile.

For this reason some stakeholders have expressed the view that a strategy does not therefore need to be put in place as a matter of urgency. The NDA believes that there are a number of compelling drivers for developing a reference strategy.

1. Until a clear strategy is decided upon then the Site Licensee Companies (SLCs) cannot plan plutonium management activities and these cannot be prioritised alongside other work, such as operations or decommissioning at NDA sites. This would have the effect of potentially delaying or altering the decommissioning plans at sites such as Sellafield.
2. The cost of the final disposition of the material is not in the current lifetime plans and is likely to significantly increase the extent of the financial liability. Although estimates have already been made of this liability it has not been possible to include them in the formal liabilities estimate figure because of the policy interpretation of treating the nuclear materials as a zero value asset. In order to determine the value to include in the plan, the reference strategy for disposition needs to be articulated. This is required for NDA to meet its obligations under the Energy Act.
3. The current position of treating plutonium as a zero value asset to be stored indefinitely has resulted in plans at Sellafield to store the material until 2120 (the planned end date of the site). Beyond that there are no plans for storage, reuse or disposition. The plans addressing the on-going infrastructure or skills required to safely store plutonium beyond the end of the site - if the material were to be retained – are not fully developed. Unless a strategy is articulated, skills and facilities that are required for the future, and which need planning and investment to put in place, run the risk of not being available.

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4. This also means that the research and development for disposition routes and for the ultimate disposal in a Geological Disposal Facility (GDF) is likely to be deferred in favour of more urgent work. This in fact means the decisions start to be taken by default. If a GDF is not designed to take plutonium, it is likely that a second GDF would ultimately be required to take plutonium. In order to assess opportunities and a full range of options it is necessary to start to review them now.

5. The future strategy may well change over time as external factors and drivers change. In order to evaluate the impact of new strategies it is necessary to have a defined strategy to act as the baseline against which future changes are evaluated.

6. The NDA expects Nuclear Management Partnerships (NMP) to optimise the long term plans for the decommissioning of the Sellafield site. In the absence of sustainable planning assumptions for the materials under their custodianship, optimisation may be compromised. NMP have reviewed and taken ownership of the Sellafield Baseline Plan during 2010. In order for them to plan their activities with respect to plutonium, the stores, the land on the site etc. they need to be given explicit planning guidance, which cannot be given in the absence of a national policy. For Dounreay, plutonium strategy also has the potential to be the constraining factor in the ultimate end date and end state of the site.

7. Continued storage over time requires new stores, infrastructure and potentially repackaging facilities to maintain the material in a safe and secure condition. This is not a low cost option, [REDACTED] The NDA believe that these costs should be taken into consideration when assessing alternatives to indefinite storage. In order to estimate these costs a defined strategy is required.

8. The prolonged storage of plutonium results in gradual conversion into different isotopes as the plutonium progresses along the radioactive decay sequence. As a result, for some options, there may be additional effort required in order to undertake subsequent management steps. For example, the in-growth of americium over time means that some of the options become more difficult to execute. The current baseline strategy does not include plant to separate americium from plutonium. Therefore it is assumed that stocks could be blended to allow reuse, if that were a preferred solution. This assumption is progressively challenged over time. In order for reuse to continue to be an option, additional costs may have to be incurred and the option would become less attractive as time progresses.

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2 Current Baseline Strategy

The current lifetime plans treat plutonium as a zero value asset which is planned to be stored. No ultimate disposition route is yet developed. The material is currently stored at two locations, Dounreay and Sellafield. Both sites have defined end-points and so their plans only progress as long as activity is maintained on the sites. The Dounreay plan shows the material being stored until 2075. The Sellafield plan shows material being stored until the site end-point in 2120, the assumption is that the material will remain in place beyond that date. No costs are included for the subsequent storage of the material. In addition the long term plans are not fully developed and it is believed that some of the support and infrastructure required to maintain the storage of the material in a safe and secure condition until 2075/2120 is not currently in the plan.

The design life of the new stores which are being built is estimated to be between 50 and 100 years. They are likely to be adequate up until the end of the current site plans, but should a decision be taken that storage should be continued beyond that point provision would need to be made for replacements.

Storage as PuO₂ powder is not considered by the regulators as a passive form for long-term storage. Their advice in 2008 was should very long term storage up to 2120 be contemplated it is likely that at least a proportion of the plutonium would have to be converted into a more passive form well before 2120. Should that be the case the expense incurred in such a treatment process might dictate that it be converted into a form suitable for either reuse or disposal. Once the material is converted to a passive form, it would likely involve significant cost to make it suitable for reuse in the future. This has now been at least partially mitigated by the planned Heat Treatment Facility and as such NDA considers long term storage to be technically viable.

The non inclusion of retrieval, treatment and disposal costs for the lifetime plans is a significant omission. Presently the plans for the management of plutonium at Dounreay and Sellafield have not been optimised. In optimising the plans for the future, the differing radioactive waste policies in Scotland and England is an important consideration.

In the short term the sites are undertaking a programme of review of the current storage arrangements and a phased build programme to replace the older stores, replacing them with stores built to current standards, for the longer term interim storage. This is required to manage in the longer term, the safety and security hazards associated with this material.

Summary: Anomalies in the Current Position:

Current strategy assumes extended storage but no costs or infrastructure is provided beyond 2075 (Dounreay) or 2120 (Sellafield).

The management arrangements for the storage of material at Sellafield and

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Dounreay are not yet optimised, although co-location of plutonium has been proposed in the NDA draft strategy⁹

The requirements for the support facilities to ensure the long term safe and secure storage of plutonium are not fully developed

The final treatment and disposition route and resulting cost provision requires definition and inclusion in the lifetime plans for Sellafield and Dounreay, as only long term storage is included in the Lifetime Plans.

⁹ NDA Draft Strategy II (2010). <http://www.nda.gov.uk/documents/upload/Draft-Strategy-published-September-2010-for-consultation-full-colour-version.pdf>

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3 Plutonium Topic Strategy Objectives

3.1 Objective of the Plutonium Topic Strategy

The objective of the Plutonium Topic Strategy is to ensure the safe management then ultimate disposition of UK owned plutonium.

To achieve this, a project has been initiated to define the options available and to progress the development of the strategy, using the NDA Strategy Management System (SMS). Further details of the SMS system can be found on the NDA website.

The project is currently in Stage A of the Strategy Management System where credible options are defined.

3.2 Objective of the Current Phase

There are three objectives of this stage:

- The definition of credible options
- The recognition of areas where more work is required to identify the preferred option and
- The identification of the relevant policy areas where guidance is required from government to enable the political acceptability of options to be assessed.

The process of development of the credible options, the options themselves and the implementation routes are identified in Sections 3, 5 and 6 of this paper.

3.3 Focus of the Current Phase

The principle areas that require further work to underpin decision making are largely identified in the sensitivity analysis section of this report in section 6.8 and centre around:

- Incorporation rate
- Waste form acceptability
- Waste form durability
- Characterisation of the feedstock
- Revenue variability
- Degree to which costs of spent fuel disposal should be considered off-set by the fuel that it effectively replaces from an existing a uranium oxide fuel load.

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The areas where further guidance is required to make a decision are identified in this paper in the future work section. Briefly they include issues 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.

Other key attributes in the NDA's Value framework will be evaluated during the next phase of this project, in line with the requirements of the Strategy Management System

Several stakeholders in the 2008 comment period made the statement that the future strategy for plutonium needs to be formulated in the context of energy policy. Since then, it has become more clear that other nations such as Russia, USA and Japan have all considered their plutonium management strategies and are moving towards the implementation of a reuse policy in domestic energy programmes. In the UK, reuse of plutonium in UK nuclear power plants and national energy policy are a matter for Government and NDA is working with them as they determine policy guidance. For this 2010 update, a new option of domestic reuse of plutonium has been added (option 10).

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4 Process for Developing Credible Options

The NDA has developed an approach for progressing the development of strategic options, and this is called the Strategy Management System. It has several stages to it, termed Reconnaissance, Credible Options, Preferred Option, Approvals and Implementation. Strategy development takes place in a methodical manner as it progresses through the stages.

The purpose of this section is to present the work completed thus far and highlight areas for further investigation.

4.1 Reconnaissance Phase – Stage 0

NDA has worked on data collection and the reconnaissance phase of the development of a plutonium strategy for around four years.

The starting point of the reconnaissance was to review the work of the BNFL stakeholder dialogue Plutonium Working Group (PuWG)¹⁰ and use the list of options considered by them as the starting point for the reconnaissance phase. The PuWG work had a different scope compared to this current work as it did not consider the asset or liability status of the plutonium. The NDA approach was to take a step back by considering options that were screened out by the PuWG. Where options were screened out a 'benefit of the doubt' methodology was applied and if NDA felt that the options were technically feasible, even though they had some attributes which made them less attractive than other options, they were added back to the list of options under consideration.

The BNFL stakeholder dialogue considered that immobilisation in a ceramic waste form and reuse in UK reactors as the options that required further investigation. It rejected the use of novel fuel types and did not look at reactor systems outside those existing in the UK.

The PuWG report stated that ceramic is preferred to glass, as glass 'is less robust to the extraction of plutonium and expected to be less durable in a GDF environment and likely to involve significantly higher cost'. NDA felt that this statement required further underpinning as a basis for rejecting the option and that the question of 'how good is good enough' needed to be addressed with respect to extraction of plutonium and durability before options were screened out on this basis.

In the same way cement was screened out as a result of the BNFL stakeholder dialogue and although NDA recognise that it is a less durable waste form it is currently in use for low concentration plutonium bearing wastes as an encapsulation technology, has GDF letters of compliance and is a relatively simple and well understood technology. For this reason it has been added back as an option at this stage.

¹⁰ <http://www.the-environment-council.org.uk/bnfl-national-stakeholder-dialogue.html>
Final Plutonium Working Group Report 2003

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The BNFL report¹¹ which was used as the basis for the stakeholder dialogue assumed that the Sellafield MOX Plant (SMP) could be used for fabrication of fuel for reuse options. NDA have reviewed SMP and, despite improvements in performance since 2008, do not believe that it provides either the capacity or longevity to be used for the majority of the UK civil stockpile and the reuse options that NDA has considered assumed that plutonium is either sold direct or that MOX is fabricated in a new plant. There may be an opportunity to utilise the plant in a meaningful manner for the low specification MOX option.

The PuWG report was written assuming that any use of MOX would be in an existing UK reactor. NDA have widened this option to consider utilising MOX outside of the UK as an option. British Energy has shown no interest in licensing their AGR reactors for MOX and the option of reuse in the UK was not been considered in the previous analysis. This update now includes UK burn of MOX fuel in new LWRs; if this were to happen, UK burn would offer a number of advantages over overseas burn; international sea transport would be eliminated, transport security arrangements would be simplified and transport costs would be significantly reduced.

The options outlined above were fed into a macro-economic study for uranium and plutonium which examined at high level the options of store, dispose and reuse. Much of the detail in the main body of the report was security restricted, but a public summary of the document was published on the NDA web-site¹².

Stakeholders, in the form of the Material Issues Sub-group (MIG) of the National Stakeholder Group (NSG) were engaged around this work. The macro-economic report was produced for the NDA by an independent contractor and included authors having a broad cross section of views working in relation to the future direction of the nuclear industry. It is recognised by NDA that two members of the MIG did not agree with the participation of some members of the independent contracting team due to their previous employment in the nuclear industry.

Following publication of the macro-economic report a workshop was held with nuclear experts and regulators to challenge the detailed technical assumptions in the report and to review its completeness as a tool to aid in decision making.¹³

The main outputs from that workshop were:

- An action to re-consider the direct sale of PuO₂ as an option that could be evaluated.

¹¹ The authors have been unable to find a reference to this report although it is frequently cited in the PuWG report

¹² <http://www.nda.gov.uk/strategy/nuclear/plutonium/>

¹³

<http://www.nda.gov.uk/documents/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=8954>

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- An action to assess the disposal costs of different waste forms. The macro-economic study assumed that disposal costs were not sensitive to the waste form and this was challenged. A summary of the workshop output has been published on the NDA website¹⁴.

There has been some interest in recent years on Thorium - Plutonium mixed oxide fuels. The National Nuclear Laboratory have recently published a paper (www.nnl.co.uk) on Thorium fuel cycles and reached the following conclusion:

NNL believes that the thorium fuel cycle does not currently have a role to play in the UK context, other than its potential application for plutonium management in the medium to long term and depending on the indigenous thorium reserves, is likely to have only a limited role internationally for some years ahead. The technology is innovative, although technically immature and currently not of interest to the utilities, representing significant financial investment and risk without notable benefits. In many cases, the benefits of the thorium fuel cycle have been over-stated.

Drawing from the above conclusion, NDA has taken the position that mixed Thorium – Plutonium oxides fuels as a disposition method for UK plutonium is still not credible in the timeframes stated in this document and hence are not considered further at this time.

4.2 Credible Options - Stage A

The credible options phase work to date has concentrated on:

- Defining the strategic objective, as detailed in section 3 of this paper
- Assessing the options generated in the reconnaissance phase against the definition of credible options.
- Developing implementation strategies that would enable definition of the start and end point for the project. This would ultimately assist in the discharge of the NDA liability.
- Starting to develop the criteria by which options could be assessed
- Identification of policy guidance which needs to be provided to support decision making
- Conducting very high level Optioneering to support the credibility of the options which are included
- Identification of areas where more work is required to facilitate decision making

¹⁴ <http://www.nda.gov.uk/news/events/pu-technical-workshop.cfm>

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- Identification of the timescales and resources for the next stage of the project (decision making).

The options generated during the reconnaissance phase were reviewed against the definition of credible options which is:

‘those options which could potentially be accomplished, safely, while complying with the law, and using technology which is either available or capable of being developed within the foreseeable future, and which allow decisions to be made on a timescale that is commensurate with any strategic imperatives’.

For plutonium, the timescale is regarded as around 25 years. This timescale is longer than that currently being contemplated for the SMS as a whole and has been chosen as the plutonium topic strategy has a longer time horizon than many of the other topic strategies. It was felt that 25 years reflected timescale beyond which it is difficult to predict the direction future technologies may develop. A watching brief will be maintained with respect to technologies development and if technology does develop faster than predicted other potential implementation routes may be included.

On application of these screening criteria to the options generated by the BNFL Stakeholder Dialogue PuWG, the only option which has been deselected is utilisation of MOX in 4th generation (GEN IV) reactors systems, such as fast reactors or high temperature reactors. This option has been screened out on the basis of NDA judgement and market intelligence suggesting that these reactor systems are unlikely to be available commercially on timescales that allow for their adoption as a method of reuse and the fact that a new build programme which is being embarked is likely to mean that GEN IV reactors would not be developed in the UK for between 40-60 years.

The final output of this phase of work is this paper which details the credible options and provides a high level option assessment.

4.3 Additional Data to Support Reuse and Disposition Option Assessment

In order to gain access to supplementary underpinning data for the potential implementation routes in the macro-economic model and to aid the development of options, contracts were awarded with industrial technology users. Three contracts were let through this process with UKAEA, who have provided advice on cement and cement/polymer technologies, AECL/VT, who have provided underpinning on a CANDU reuse option and AREVA who have provided advice on vitrification, low spec MOX and reuse around an LWR reuse route. The view was taken that, as the ceramic technology process of Hot Isostatic Pressing (HIP) has been developed by NNL and ANSTO, NDA already have access to the data and there was no value to be obtained by placing a separate contract with respect to HIP.

The various companies were asked to provide outline flowsheets including any pre-processing and storage requirements, cost and uncertainty information for the options they covered, their assessment of technical readiness levels, their assessment of the suitability of waste forms for disposability and their views on

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incorporation rates in the waste form. This data has been used to underpin the various options included in the appendices to this report

4.4 Disposability Assessment

As part of the Strategy Stage A work Radioactive Waste Management Directorate (RWMD) were asked to examine all the plutonium waste forms currently under consideration, including the disposal of spent fuel. In addition they also looked at disposal of plutonium powder as a reference position. Their report draws solely from previously undertaken work and seeks to identify any 'show stoppers' around any of the waste forms which would challenge the credibility of the detailed implementation option.

RWMD concluded that the only waste form for which they did not believe a safety case could be made was for disposal as plutonium powder. However, they have indicated that in order to make decisions with respect to the waste form disposability more work is required particularly around the criticality safety case. To take this work forward RWMD are producing pre-conceptual Letter of Compliance cases for all the waste forms as the project proceeds through the decision making phase.

4.5 Modelling

The macro-economic study⁽⁷⁾ was produced using a database to look at a very comprehensive and complex set of data. It models lifecycle impacts across the whole of spent fuel and nuclear materials management, and not just one component such as plutonium. This makes the impact of key uncertainties in one particular area difficult to isolate, although it will be useful to look at the impact of an individual plutonium strategy across the whole of the spent fuel and nuclear materials management area in the future.

To aid understanding of the financial implications of the options a simple model to consider plutonium alone has been constructed. The model is based on the flow sheets for each of the detailed options which are included in the appendices.

This tool has been used to conduct the sensitivity analysis.

In addition the simplified model has been re-created in a software package called GoldSim¹⁵. This is an 'uncertainty-type' model which uses the input data from the option data sheets to assess the uncertainty bounds of each option with a high degree of resolution. A full explanation of the methodology used in the Goldsim model can be found in reference 11.

¹⁵ GoldSim is a commercially available software package that is used to evaluate the cost of strategic options from a probabilistic approach.

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4.6 Stakeholder Engagement

In parallel to work above being conducted, a paper detailing what NDA believe to be the credible options was produced in 2008. This paper is a 2010 update to that original paper. The 2008 paper was published on the NDA website and Stakeholders and Regulators were asked to comment. In particular they were asked their views on the proposed evaluation criteria for both the implementation options themselves and the various waste forms. They were also asked a number of questions about implementation options that in NDA's opinion were on the borderline of being credible. These related to the use of HLW addition within the vitrification options, the use of inert matrix fuel as a means of reuse and the sale of plutonium as a plutonium powder.

In excess of 40 responses were received and these views are reflected in the high level options and detailed appendices of the report. A full list of the comments received and NDA's response to them has been placed on the web-site.

Stakeholder feedback has been incorporated into the production of this paper which has been consequently modified since it was first issued for comment.

4.7 External Review

To facilitate the external review of the modelling and economic analysis a contract was been placed with an independent economic expert who is familiar with the MOX industry. The report detailing the findings of the review for this updated paper is included as Appendix B.

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5 Credible Options

5.1 Options for Future Strategies and Generic Factors for Consideration

At the highest level, the future options are considered to be:

- Store in a time bounded manner
- Disposal as waste
- Reuse, management of the spent fuel followed by ultimate disposal
- Some combination of the three above

These are discussed further in the sections that follow.

We have presented the reasons for proposing a change to the current strategy based upon the balance of arguments. It is the NDA's view that the current storage strategy is not ultimately sustainable; however interim storage is required for any of the future strategies. Depending on the processing route chosen it is the NDA's judgement that this could be of the order of 30-50 years from the date when a decision is made.

Need for a contingent strategy

As a result of the Stakeholder and Regulatory engagement the need for a contingency plan was highlighted. In the event that no decision is taken on either reuse or disposal, then storage is the option that buys time and allows the plutonium to be maintained safely. It is proposed that a formal contingency option of deferred storage is implemented. This would involve storing the material, prior to conditioning for disposal, to allow material to be moved from the licensed sites at the end of the site life.

Overarching criteria

Stakeholders and Regulators also raised the need to highlight some criteria which apply at the over-arching option level, these included the issues of reversibility and public acceptance of any option and these are discussed under the store, reuse and dispose sections. The section on reversibility addressed the degree to which future options are foreclosed as a result of selecting a given route.

Policy Interaction

In addition a number of policy areas were raised by Stakeholders and Regulators, particularly those surrounding energy policy, sustainability, and security issues around the future protection of nuclear materials from any terrorist threat. NDA are clear that these are issues for Government and not for NDA. However, to the degree to which we are currently able, the policy impacts which result from the selection of a given strategy option, are discussed. Many of these areas require further policy

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development and a programme of work has been initiated to take forward these issues with the relevant Government departments.

Skills

Execution of any of these strategies will require people with a plutonium skill base. The timing of the execution needs to be considered with a view to having key skills available when they are required. Achievement of this requires that the skills base is maintained, such that at least train the trainer type skills are available into the future. This should be a consideration in the funding of future work programmes.

The different options have different implementation timescales and this should to be taken into consideration when deciding upon a skills retention approach. For example if the proposed contingent strategy of deferred disposal were ultimately implemented, a plutonium skill base would be required until 2120.

ALARP

Regardless of the options chosen the execution must consider the principles of ALARP in its execution. If one strategy is shown to have a higher risk profile than another, this must be factored into the decision making process as it is developed for SMS in general and plutonium in particular.

5.2 Store – Proposed Contingency

5.2.1 Outline of the Option

The present plutonium strategy is for extended storage (2075 Dounreay and 2120 Sellafield) after which time no plans are developed. The NDA propose that this strategy is neither prudent nor sustainable in the long-term even if we consider it to be technically viable.

Regardless of what alternative strategies are pursued (either *via* reuse or directly) short-term storage is always an option that buys time in the event of risks to a preferred solution materialising or decisions not being taken. For that reason long-term storage should be considered further as a contingency approach..

For the purposes of planning, this indefinite storage option needs to be time bound. Given that the lifetime plan for Sellafield (the last UK civil nuclear site according to current plans) ends in 2120 it is proposed that the end of storage should be considered as 2120, with disposal facilities provided to allow this end date to be met.

In terms of the disposal method it is not considered to be important to specifically define it, at the present time. Accordingly cost estimates for disposal (following prolonged storage) options should present a bounding range: an estimate based on the cheapest concept envisaged as the lower bound and the most expensive as the upper bound. However it must be stressed that cost is a single component in the overall analysis of lifecycle impact for all the plutonium options under consideration. It is proposed that this approach is modified in the near term and a decision is taken, as

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and when more detailed information becomes available during the next phase of this work programme.

5.2.2 High Level Factors to be Considered

In 2009, after a series of workshops on plutonium management options, DECC published a pre-consultation discussion paper on the key factors that could be used to compare one option for long term plutonium management with another¹⁶. For simplicity, these factors, in bold below, are repeated here and used as a basis for further consideration in this report.

Availability: When can the option be delivered?

Coherent nuclear strategy: Decisions on plutonium needs to be part of a coherent, strategic approach to all matters nuclear

Cost effectiveness: Is this a cost-effective, affordable way forward?

Energy resource: Should the energy value of the plutonium be considered as a valuable resource?

Engineering challenge: Some options present more challenge than others; it's more than technical maturity. Having done something before doesn't guarantee success next time.

Environmental: What effect will the option have on the environment?

Future-proofing: Need to consider how far each option might be affected by foreseeable future energy and waste policy demands.

International best practice: What are other countries doing regarding plutonium? What are the current and emerging technological options? What do other countries around the world feel about what the UK should be doing, including non-nuclear states?

International Conventions/Treaties: What do International Treaties and Conventions require the UK to do.

Practicability: Is this an option that can realistically be employed over a suitable time frame?

¹⁶http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/nuclear/plutoniummanagement/1_20090902105255_e_@@_preconsultationdiscussionpaperplutoniummanagement.pdf

Proliferation resistance: How does the option reduce the value of plutonium to terrorists / proliferators? How easy is it to get to the material in a useful form?

Proliferation: Impact of policy on nuclear non-proliferation policy and materials creation.

Public perception and acceptability.

Reversibility: Does the option foreclose other options?

Safety and hazard: What are the risks / dangers posed by an option? What additional worker dose or risk of public exposure would the option entail?

Security: How well is the material intrinsically protected by this option? What additional levels of protection would be required?

Social factors: Including impact on local communities

Technical maturity: How mature is the technology that the option relies on?

Transport: Plutonium, MOX and spent fuel specific transport issues have to be considered, including environmental, safety and security aspects.

5.3 Disposal

5.3.1 Outline of the Option

Disposal is defined as¹⁷ 'the emplacement of waste in a specialised land disposal facility, without intent to retrieve it at a later time – retrieval may be possible but, if intended the appropriate term for this is storage. The time of emplacement is regarded as the time of disposal, even if the facility is eventually closed many years later.' This paper specifically addresses the inventory of separated plutonium, but it should be noted that it is already planned to dispose of waste bearing small quantities of plutonium, either as plutonium contaminated wastes (mixed with other radioactive elements in waste forms e.g. remotely handled ILW) or bound up within spent fuel.

Disposal could be considered the default option in the event that no decisions are taken over reuse in the next 70-100 years.

In the event of disposal being chosen as a strategy for plutonium the NDA has, without prejudice to the ultimate technology choice, assessed four high level processing routes which could be used to execute this strategy. These are: encapsulation in cement, vitrification in glass and immobilisation in a ceramic matrix either using the Hot Isostatic Press route or as low specification MOX. Further detail on the key criteria for each of these options is given in Section 6 and Appendix A.

¹⁷ www.defra.gov.uk/environment/radioactivity/mrws/glossary.htm

Plutonium Credible Options Analysis (Gate A) 2010

5.3.2 Consideration of High Level Factors for Disposal

For disposal, a high level analysis of the factors given in section 5.2.2 is presented below.

Availability:

The most robust immobilisation technologies (HIP and vitrification) are the least mature and need considerable development. A large R&D programme would be required to support these options if selected. Low specification MOX immobilisation uses a mature technology and is therefore considered to be relatively available with minimal R&D, although the ceramic wasteform (puck) would benefit from a degree of optimisation (via research and development) for disposal purposes.

Coherent nuclear strategy:

Disposal of plutonium would be contrary to the UK's 50 year old strategy to separate and store the plutonium from spent (immobilised) fuel. The material still has significant energy generation potential and disposal would foreclose that option.

Cost effectiveness:

At this stage in our study, the cost effectiveness is difficult to judge due to the large variance in the economic outputs from this study.

Energy resource:

Disposal of plutonium would, more than likely, foreclose the economic recovery of plutonium as a future energy resource.

Engineering challenge:

Some immobilisation options present more engineering and technical challenge than others; the engineering of any plutonium facility is very challenging, as can be demonstrated by the cost of a modern plutonium store. Adding a large quantity of immobilised plutonium to the Geological Disposal Facility would increase the engineering and technical complexity of that facility.

Environmental:

All of the disposal options require a considerable number of waste stores to safely and securely keep the immobilised products prior to eventual disposal. This requires a considerably more concrete than the reuse options and hence is comparatively disadvantageous. Radioactive discharges from all plutonium disposition options are considered to be very small as non-aqueous processes are almost exclusively used.

Future-proofing:

This will depend on the prevailing energy policy of future UK Governments and is difficult to judge in this study. Immobilisation does foreclose future reuse options

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Plutonium Credible Options Analysis (Gate A) 2010

unless considerable expenditure is undertaken to recover the plutonium from the robust wasteform.

International best practice:

All other countries with separated plutonium now appear to be planning to convert their excess plutonium into MOX fuel for reuse, although some countries are still maintaining a research programme to support immobilisation technologies should they be required. Generally speaking, immobilisation technologies are considered useful for the management of contaminated plutonium materials likely to be uneconomic to recover.

International Conventions/Treaties:

All disposition options described in this study, correctly exercised, would be consistent with International Guidelines for the Management of Civil Plutonium as described on the DECC website¹⁸.

Practicability:

All options are considered practical, however the cement immobilisation is the least practical due to the large number of cement plants and stores required to complete the option (due to the low incorporation rate of the plutonium in the wasteform).

Proliferation resistance:

Generally speaking, as discussed later in this document, immobilisation technologies offer a lower level of proliferation resistance than the reuse options, but are a considerable improvement on indefinite storage.

Proliferation:

This is a measure of the impacts of policy on the options and hence outside the scope of this NDA study. Proliferation resistance measures are being developed and applied against all the options to assist in the development of policy.

Public perception and acceptability.

There are a range of issues surrounding public acceptability as it applies to disposal but the primary issue surrounds the acceptability of placing large quantities of plutonium in a disposal facility.

For stakeholders who would prefer that this material had never been produced in the first place there is generally some acceptance that this is the least bad option. For those who live in the vicinity of a potential host community there is the issue of the

¹⁸<http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/nuclear/issues/plutonium/file26403.doc>

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Plutonium Credible Options Analysis (Gate A) 2010

acceptability of this material as part of a radioactive inventory. This issue needs to be addressed by NDA through close ties to the Geological Disposal Facility programme as it develops.

For stakeholders who see this material as an asset and a future energy source, the disposal option is not readily accepted.

Reversibility:

The intent of the disposal options is not that the material would or could be recovered at some point in the future. Indeed the driver to put materials beyond use is in conflict with the concept of reversibility. The different waste forms which are being explored are designed to bind the plutonium physically and chemically into the immobilisation matrix. For those options that bind the material less tightly, one might consider that in an extreme situation in the future it may be possible to 'mine' these materials. However this would be an expensive and difficult operation. It should be noted that a preference toward a waste form which could be 'reversed' in the future would be in potential conflict with the safety case drivers for a future disposal facility. Consequently, if reversibility was something, that from a policy perspective was felt to be important, then it is important to re-assess whether disposal should proceed or whether the materials should be held in a 'stored' form, until such time as reversibility is no longer important.

Safety and hazard:

Generally speaking, all options must be implemented with due regard to safety and to reduce risk and preferably hazard. This is not a differentiating factor.

Security:

All options (except continued indefinite storage) offer more barriers to material diversion and hence enhanced security.

Social factors:

All immobilisation options require a considerable amount of new construction and a degree of specialist skills to be maintained over time. This should be a socio-economic advantage to local communities.

Technical maturity:

Of all the technologies, HIP and vitrification immobilisation are the least mature and require a considerable amount of development to overcome technical and engineering challenges.

Transport:

For the disposal options, there is a considerable amount of UK transport required although no overseas transport is considered necessary.

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5.4 Reuse

5.4.1 Outline of the Option

The reuse option is being considered as a route for disposing of plutonium in the form of irradiated MOX, *i.e.* as spent fuel. In the US, separated plutonium disposition was proposed to be only appropriate if the wastefrom met the same level of protection as spent fuel. There is an ongoing debate as to whether the so called “spent fuel standard” for plutonium disposition is something that is desirable from an ultimate disposability perspective and this needs to be considered further in the decision making phase of this study.

If the reuse option is to be progressed in detail then extensive supply chain engagement and ultimately a competition process is likely to take place. If a decision was made to reuse the material it would ultimately be made by the Government. In this respect the Government, with NDA, has a number of options on where it enters the value chain with respect to plutonium. It could, subject to international treaty obligations:

- Sell or lease the plutonium powders directly to a 3rd party country,
- Contract for MOX fabrication either in the UK or abroad and sell the resulting MOX fuel
- Fund MOX fabrication directly and sell the resulting fuel
- Fabricate MOX, utilise it in UK commercial new build reactors and develop a commercial arrangement to take a share of electricity sale revenues
- Fabricate MOX, utilise it in UK state owned reactors and sell the resulting electricity.

For the purposes of this study the NDA has examined the options of selling or leasing plutonium for use in either UK commercial New Build, European or Canadian reactor systems, or fabrication of MOX and selling or leasing the resulting MOX fuel for irradiation in either UK commercial New Build, European or Canadian reactors.

The option of reuse in the UK has been added to this updated analysis, compared to our earlier 2008 paper, as it is judged to be technically credible in the light of Government’s published consultations and Secretary of State decisions on new nuclear reactor build in the UK . The NDA is not considering alternative reactor systems such as high temperature reactors (HTR’s) and thorium fuelled reactors at this time, although this could be added if they became available commercially. For example, if the Russian developed Gas Turbine Modular Helium Reactor (GT-MHR) was successfully deployed for the Russian plutonium disposition programme, this may need to be considered, albeit many years in the future.

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Plutonium Credible Options Analysis (Gate A) 2010

5.4.2 Consideration of High Level Factors for Reuse

For reuse, a high level analysis of the factors given in section 5.2.2 is presented below.

Availability:

It is considered that reuse technology is available and mature now, although reuse as CANDU MOX has not been demonstrated at a commercial scale.

Coherent nuclear strategy:

Reuse of plutonium would align to the UK's 50 year old strategy to separate the plutonium from spent (immobilised) fuel. The material still has significant energy potential and reuse would release that energy while producing a viable wastefrom (spent fuel).

Cost effectiveness:

At this stage in our study, the cost effectiveness is difficult to judge due to the large variance in the economic outputs from this study. As currently modeled, there is a potential upside from increased revenue from fuel sales for reuse options.

Energy resource:

Reuse of plutonium would utilise plutonium as a future energy resource.

Engineering challenge:

Some options present more engineering and technical challenge than others; The engineering of any plutonium facility is very challenging, as can be demonstrated by the cost of a modern plutonium store and the operational difficulties experience in the Sellafield MOX Plant. Adding a large quantity of spent MOX fuel to the Geological Disposal Facility would increase the engineering and technical complexity of that facility.

Environmental:

Reuse options appear to be the most environmentally friendly, as they require fewer facilities and reduce the requirement to mine and mill very large quantities of fresh uranium. Radioactive discharges from all plutonium disposition options are considered to be very small as non-aqueous processes are almost exclusively used.

Future-proofing:

This will depend on the prevailing energy policy of future UK Governments and is difficult to judge in this study. Reuse does not foreclose future reuse options in fast reactors if required, although considerable expenditure would be required to recover the plutonium from the spent MOX fuel.

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Plutonium Credible Options Analysis (Gate A) 2010

International best practice:

All other countries with separated plutonium now appear to be planning to convert their excess plutonium into MOX fuel for reuse, although some countries are still maintaining a research programme to support immobilisation technologies should they be required.

International Conventions/Treaties:

All disposition options described in this study, correctly exercised, would be consistent with International Guidelines for the Management of Civil Plutonium as described on the DECC website¹⁹.

Practicability:

All reuse options are considered practical, however reuse as CANDU MOX has not yet been demonstrated at a commercial scale.

Proliferation resistance:

Generally speaking, as discussed later in this document, reuse technologies offer the highest level of proliferation resistance.

Proliferation:

This is a measure of the impacts of policy on the options and hence outside the scope of this NDA study. Proliferation resistance measures are being developed and applied against all the options to assist in the development of policy.

Public perception and acceptability:

For stakeholders that view plutonium as a material which should not have been separated in the first place a decision to reuse the material would not be popular, and there would be an expectation that firstly, it was not re-separated and that it was only done on the basis of demonstrated benefit. For those that see plutonium as an asset this option is likely to be acceptable, however there are those that would prefer to see reuse occur in fast reactors rather than the currently proposed fleet of thermal reactors as a more effective utilisation of the fuel.

Recycling of plutonium in thermal reactors has been carried out successfully in France, Germany and Switzerland, and a programme has recently commenced in Japan. No new safety issues have arisen associated with burning MOX fuel rather than standard UOX fuels in the LWRs, and this has helped to alleviate initial public concerns around the reactor sites.

¹⁹<http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/nuclear/issues/plutonium/file26403.doc>

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Reversibility:

The intent of this option is that it is a route for the disposal of plutonium and is not designed to be reversible. However should the next generation decide that the plutonium in the spent MOX fuel was important for domestic energy supply it is technically feasible to re-separate the material, albeit this would be an expensive process with a significant lead time. Closed cycle plutonium management is not being considered as credible at this time, and it is not anticipated that this decision would be reviewed for several decades.

Safety and hazard:

Generally speaking, all options must be implemented with due regard to safety and to reduce risk and preferably hazard. This is not a differentiating factor.

Security:

All options (except continued indefinite storage) offer more barriers to material diversion and hence enhanced security.

Social factors:

Reuse options require some of new construction and a high degree of specialist skills to be maintained over time. This should be some socio-economic advantage to local communities.

Technical maturity:

Of all the technologies, reuse as LWR MOX is the most mature and requires very little development to overcome technical and engineering challenges. CANDU MOX is not as mature as LWR MOX

Transport:

For the overseas reuse options, a considerable amount of transport will be required for reuse options. Additionally, reuse options, the transportation of large amounts of spent MOX towards the end of the century is likely to give considerable challenge.

5.5 Combined Options

5.5.1 Outline of the Option

A small percentage (around 0.2%) is thought to be waste on economic grounds, as it is stored as residue material, and up to a further 11 teHM may need to have at least some chemical cleaning to make it suitable for reuse. It is likely that disposal will play as least some part in the future strategy. Similarly none of the options can be implemented without at least interim storage and deferred storage is proposed as the contingent strategy. The likelihood is that the final strategy will be tailored to the individual properties of different plutonium sources and that could result in a number of solutions being implemented. The next phase of work will continue to address the

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Plutonium Credible Options Analysis (Gate A) 2010

suitability of different plutonium 'families' to the different potential implementation options.

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6 High-Level Analysis of Potential Implementation Routes

6.1 Outline of the Implementation Options Assessed

6.1.1 Store until 2120 and Dispose

In this option plutonium is stored until the Sellafield site approaches the end of life in 2100 and is then encapsulated over a period of 20 years which enables all the material to be transported to the GDF by the end of the Sellafield site life in 2120. No separate consideration has yet been made of the material which is currently held at Dounreay. For this strategy to be enacted as currently modelled the Dounreay material would need to be moved to Sellafield for immobilisation and product storage. Eventually the product will be sent to the Geological Disposal Facility for disposal. This is not in line with the current Scottish Radioactive Waste policy and this issue needs to be addressed in the next phase of work.

6.1.2 Dispose immobilised in cement or polymer

This option considers the disposal of plutonium in a cement matrix. Cementation is a widely used technology within the UK nuclear industry for the immobilisation of nuclear wastes, especially ILW. Some variations on process options are possible, especially on how and the extent to which the plutonium is dispersed in the cement, and the nature of the grout material used. However, the basic process involves in-drum paddle mixing of dry cementitious powder, water and plutonium waste. The product is a homogenous monolith of mixed encapsulant and waste in a 500 litre drum.

Using the current ILW disposal facility concept very low loadings of plutonium in package are assumed. The loading of plutonium in the waste form has a very large impact on cost estimates for cement disposal of plutonium: increasing the plutonium loading in the waste form reduces the number of waste form packages and therefore the overall disposal costs.

Due to the very low throughputs of plutonium within the facility, a total of 7 immobilisation plants are required. Each immobilisation facility is assumed to operate for 40 years and they are built one after another, every year, operating from 2020. The drums are then stored and emplaced in a suitable storage facility, which is considered to be an Encapsulated Product Store (EPS) design. In total 8 such new stores are required in [REDACTED]. Four more stores would be required if the transfer of the waste form packages from the stores to the disposal facility did not start from circa 2047 onwards depending on the availability of the disposal facility. Disposal is assumed to be complete by 2075. If higher incorporation rates were possible for this form of immobilisation, disposal in a high level waste facility may become necessary and therefore delay commencement of final disposal until 2075, although much fewer stores and immobilisation plants would also be required.

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Plutonium Credible Options Analysis (Gate A) 2010

6.1.3 Prompt Immobilisation and Disposal as Glass

This option considered the homogeneous vitrification of plutonium in glass at an incorporation rate of 10%. The vitrification plant has a lead time of 12 years and the encapsulation is completed in 21 years. The vitrified product is then stored in SPRS type stores until 2075 when it is transported to the high level waste disposal facility over a period of 20 years.

6.1.4 Dispose as ceramic using Hot Isostatic Press

This option considers the disposal of plutonium using Hot Isostatic Pressing (HIP) in a ceramic matrix. HIP is a technique that uses the simultaneous application of pressure and temperature to produce a waste form of high quality and durability.

In the UK, this technique is being developed by the National Nuclear Laboratory at Sellafield for the immobilisation of plutonium containing residues. The waste is immobilised as a ceramic puck in a steel can with a plutonium loading of 10% plutonium.

The immobilisation facility is assumed to operate for 26 years from 2025 to 2051. The resulting pucks are stored and then emplaced in a suitable storage facility and to an SPRS standard.

6.1.5 Prompt Immobilisation and Disposal as Low Specification MOX (two variants)

Two variants of this option are considered:

- Fabrication of low specification MOX pellets in a modified SMP, followed by canning in SPRS cans, and
- Fabrication of low specification MOX assemblies in a new MOX plant.

SMP is scheduled to operate until , although new contracts may alter that date. Assuming a 3 year refurbishment and post operational

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Plutonium Credible Options Analysis (Gate A) 2010

clean out, the plant would be operational for low spec MOX production in 2020²⁰. In the SMP variant as a result of the reduced throughput of SMP, it is considered that a new SPRS storage module is required in 2032 to ensure continued safe and secure storage of plutonium on the Sellafield site. The second variant is based on a new full MOX plant with the cost estimate reduced to reflect the lower QA standards that need to be employed for fuel of this specification. In this variant the fuel assemblies are stored prior to disposal.

6.1.6 Reuse as MOX Fuel (3 variants)

Three variants of this option have been considered, reuse in an overseas or a UK LWR reactor and reuse in a CANDU reactor. In each instance MOX would be fabricated in UK prior to UK transport or overseas shipment to the reactor in which it is to be utilised. For overseas use, this is assumed to be in Europe for the case of the LWR fuel and Canada for the case of CANDU fuel. Fuel manufacture commences in 2025 and is assumed to be complete by 2053 for LWR fuel and by 2057 for CANDU fuel. For the lease variants it is assumed that the fuel is returned to the UK and shipped to the disposal facility between 2075 and 2095. Incorporation rates for LWR fuel are around 7 wt% plutonium, and around 2 wt% plutonium for CANDU fuel.

6.1.7 Sale as Plutonium Powder

This option shows the plutonium powder being sold to a third party Country, for peaceful uses only, to be reused as fuel. The option assumes that shipment of the powder starts in 2030 and takes 30 years to complete. To support this option, a new fleet of ships and transport assets would be required. As this option starts late, due to the requirement to build storage and manufacturing facilities abroad, then at least one SPRS storage module will be required. For the lease variant it is assumed that spent fuel is returned to the UK for disposal between 2080 and 2100.

6.2 Technical Readiness

The diagram below shows the variation in technical readiness as measured using the NDA technical readiness levels. These are based on the DoE measure of technical maturity and further details of the process can be found in Appendix D.

The diagram is used to show indicatively the lead times that might be expected for different implementation routes once the technology is mature and the level of maturity the technologies are currently at.

²⁰ Based on Sellafield Limited LTP10 Data

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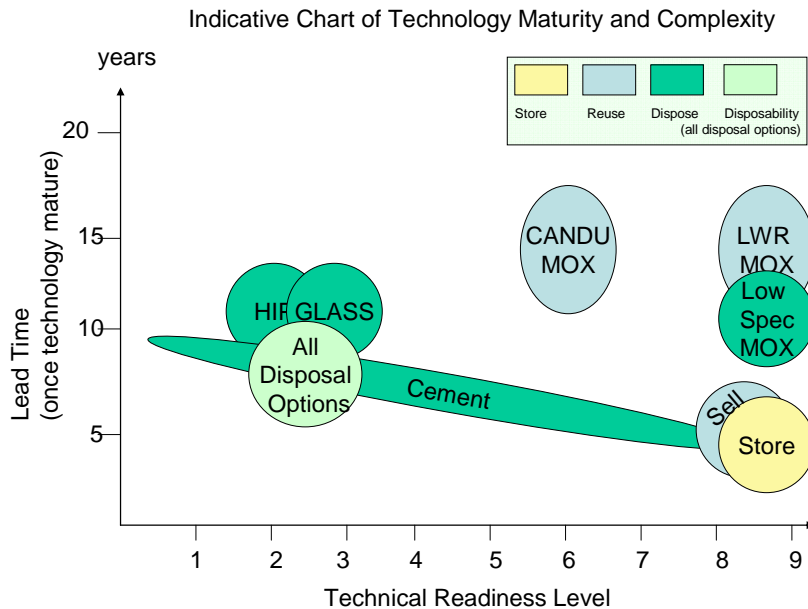


Figure 2: Technical Readiness Bubble Diagram

The implementation routes which are most preferable from the technology perspective are those in the right of the diagram, although there are other factors that need to be taken into consideration.

Further detail on the technical maturity of different technologies can be found in Appendix A.

The level of technical maturity of cement as an immobilisation route depends upon the incorporation rate assumed. Cement is widely used for plutonium contaminated waste at a low concentration and the technology in this application could be considered to be approaching maturity. At higher incorporation rates the technology is not proven, it is possible that new grout formulation would be required and the durability of the waste form would need to be proven. This explains the shape of the cement option on the bubble diagram.

The lead times for the reuse options are likely to be longer than the waste options due to the permitting regime that is likely to be applied. This is shown pictorially with the use of the elliptical bubbles for these options.

The disposability of all waste forms is relatively immature and this is reflected by the pale green bubble. This is currently the limiting factor for all options.

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6.3 Cost/Economic Analysis

The summarised financial data presented here has been prepared taking account of risk via Monte Carlo analysis. The effect of this is to show possible cost outcomes in the charts below that appear to fall outside the range of costs set out in the cost estimate tables set out in the appendices of this paper.

Furthermore, as the cost estimate ranges for each option are not generally equally centred around the 'best estimate' (more downside risks are taken into account than upsides for each variable) the sum of the costs at P50 shown below will not directly equal the sum of the best estimate costs included in the estimate tables.

6.3.1 Total Cost (Undiscounted)

For each of the plutonium disposition implementation routes considered, the cash flow was calculated on a yearly basis. Monte Carlo sampling of the uncertain parameters was used to compute 200 realisations for each strategy. The probability distributions for the total cost for each of the strategies are presented in the graph below. However, at this stage some of the strategies still have a low overall estimated feasibility.

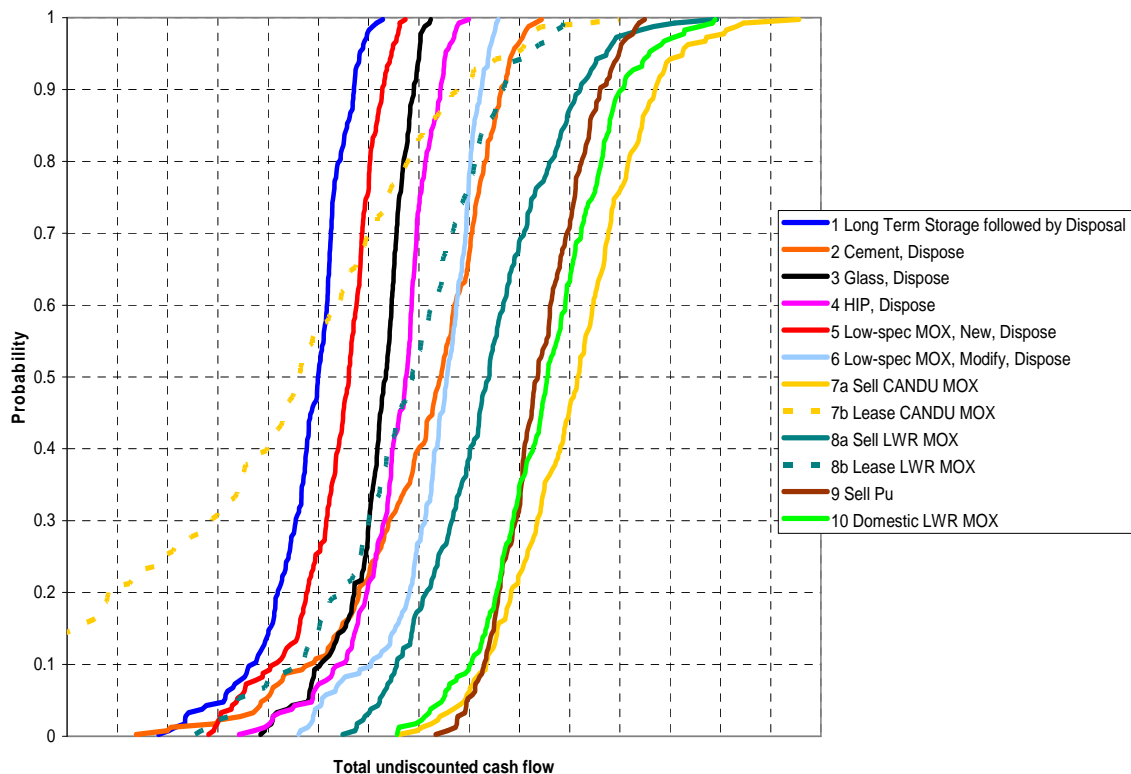


Figure 3: Goldsim Cashflow / Probability Chart for the 10 Options (Undiscounted)

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The above figure shows that the strategy with the greatest uncertainty at this stage is 7b (leasing CANDU MOX fuel). This is because of the combined uncertainties associated with manufacturing the fuel, revenue from leasing it and disposal of the spent fuel in a relatively large number of containers.

The disposal strategies generally carry less uncertainty than the reuse strategies, with the exception of option 2 (cement), which has large uncertainty in the number of packages that could be required.

Options 5 and 6 (low-spec MOX) look the best dispose strategies in terms of their uncertainty ranges. However until these ranges are narrowed it would be inappropriate to draw any formal conclusions. The key uncertainties are discussed further in Section 6.8.

The undiscounted cost of storage (option 1) is the highest as an allowance for the immobilisation and disposal of the plutonium up to the Sellafield site end date (2120) is included. As these costs are well into the future, the discounted cost of continued storage is very different, as demonstrated in section 6.3.2 below.

6.3.2 Discounted Costs (Best Estimate)

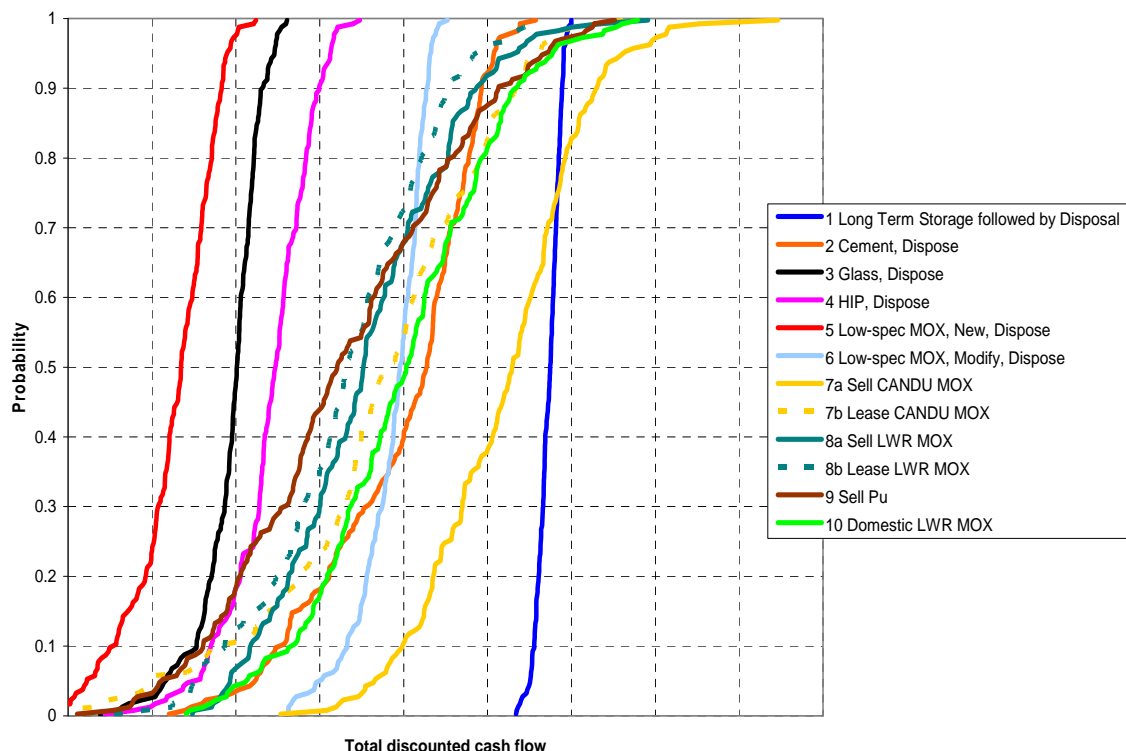


Figure 4: Goldsim Cashflow / Probability Chart for the 10 Options (Discounted)

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The phasing of the options should be regarded as indicative at the present time as phasing has yet to be optimised and no account has yet been taken of the affordability of any of these options, which could in itself result in significant changes.

Figure 4 shows that the strategy with the greatest uncertainty at this stage is 7b (leasing CANDU MOX fuel). This is because of the combined uncertainties associated with manufacturing the fuel, revenue from leasing it and disposal of the spent fuel in a relatively large number of containers. The CANDU MOX sale option (7a) looks attractive, and this is mainly due to the comparatively (against LWR MOX) low cost of the MOX fuel plant. However, as CANDU MOX is not yet commercially demonstrated, caution should be exercised when considering these figures.

Discounting the costs clearly has a significant impact on the cost of long term storage. This illustrates the sensitivity of the study to discount rates (UK Treasury Green Book rates were used in this study).

This section has been included for completeness; however the uncertainties shown in Figure 4 along with the non optimised time line means that little emphasis should be placed on the numbers at this time.

6.3.3 Revenue and Discounted Revenue

The revenues which are estimated to be received have been offset against the costs in Figures 3 and 4. The outcomes are highly uncertain and it is recommended that market engagement is embarked upon to underpin these estimates. The uncertainties are discussed in Section 6.8.3.

6.3.4 Key Factors driving costs base

The cost estimates are made up of five significant components. They are:

- The capital cost of new stores for plutonium (particularly important for option 1, long term storage)
- The capital cost of a new immobilisation plant and its subsequent decommissioning
- The capital cost of new stores required for immobilised waste product prior to availability of a disposal facility and their subsequent decommissioning
- For the overseas reuse options, the cost of transporting abroad and the investment costs in new transport assets²¹ (this does not apply to “reuse in the UK” option)

²¹ It may be possible to use the market to provide this service, but given the uncertainty of the market and the risk of non availability of transportation would pose, it has been assumed that

- Disposal cost

The analysis shows that on a purely economic basis early immobilisation, prior to the availability of a GDF for the disposition of material is not preferred as the costs of the encapsulated product stores far outweigh the costs of the plutonium stores due to the increased volume. Within a number of the options the encapsulated product store is assumed to be a high integrity modern store, such as the Sellafield Product and Residue Store. It is possible that costs could be reduced if a different security standard were to be approved for the immobilised wastes, given that the plutonium is encapsulated.

There is a high degree of variability in encapsulated plant cost, driven by a number of factors, the type of plant being designed, the throughput (driven largely by the incorporation rate), and technology maturity. This makes it difficult to draw any direct comparisons between the capital cost of the new plants at this time. An example of this is a cement plant, which at an incorporation rate of 7.5 kg/drum results in one plant that needs to operate for 13 Years. At the incorporation rate which is currently proposed, for one cement plant it would require operations for around 300 years. This has been modelled assuming multiple plants to reduce the number of years over which the plants are required to operate. The effect of incorporation rate on cost is shown in 6.7.1.

The disposal costs have been estimated by RWMD and are a significant component of the total cost. These costs have yet to be optimised and it is anticipated that significant reduction could be achieved. Furthermore no consideration has yet been made of the options which off-set disposal from other sources. This applies to the reuse options where the spent fuel generation through MOX burning, is offset to a degree the quantity of uranium oxide fuel that would otherwise have been disposed of. Where the fuel is to be burnt overseas this off-set should theoretically feed into higher revenues. If MOX was burnt in the UK the effect would be seen directly in terms of off-set to the UK GDF costs from uranium fuels.

6.4 Safety Analysis

The safety analysis has been conducted using an applied SED methodology²² to consider the relative hazard over time. The effect of moving material from the older stores to SPRS has not been modelled as it is considered to be common to all the options and therefore the analysis is not sensitive to this factor. The approach has been simplified to show the relative hazard of each of the strategies rather than an absolute value.

this service is provided through INS. An opportunity therefore exists to offset this cost through winning additional work to the transport fleet procured for this purpose.

²² Instruction for the calculation of the Radiological Hazard Potential – Appendix 4 – Rev2 13th June 06

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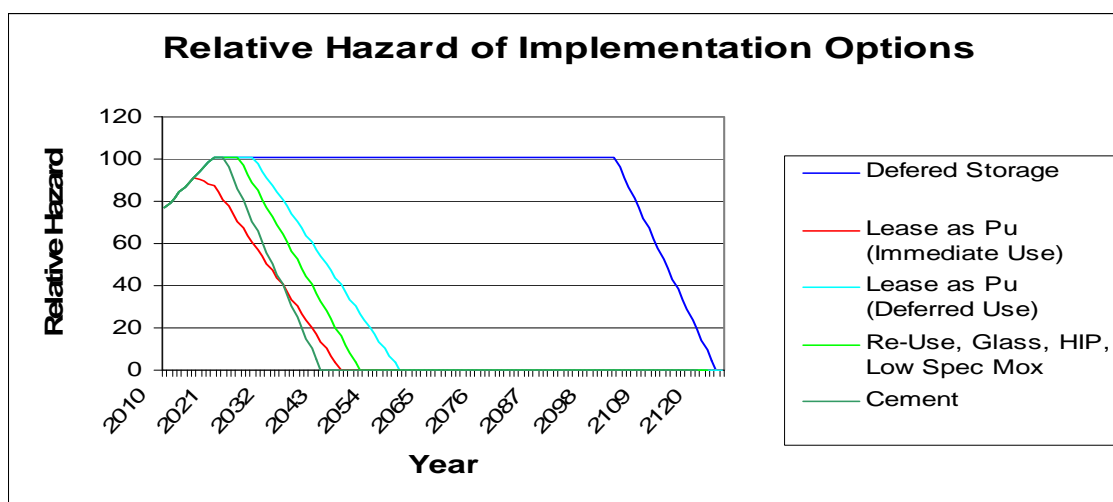


Figure 6: Relative Hazard of Different Implementation Routes

The graph shows that the key sensitivity in respect of safety is how quickly the material is immobilised. It can be seen that the differences between the various options are all driven by the timing. From a safety and environmental detriment perspective alone this would suggest that the most favourable option was the one with the lowest lead time and or the highest processing rate.

The analysis conducted to date is relatively simple and currently takes no account of the radiotoxic potential of the wastes. Applying this methodology would introduce an increased hazard from the options where the plutonium is irradiated. However, if the metric were to be strictly considered, and MOX fuel is substituted for uranium oxide fuel that would otherwise be produced, the methodology should consider the increase in hazard resulting from the plutonium component of the fuel minus the hazard off-set from the mining, milling and enrichment of the uranium which it displaces.

This degree of sophistication was considered too complex for the credible options stage of the work, which formally requires high level qualitative or semi-quantitative assessment, but needs to be developed, in conjunction with the regulators for the next phase of the project. It would also require an approach to be developed to the treatment of negative safety impact which occurs outside of the UK.

6.5 Environmental Analysis

The analysis undertaken to date is largely qualitative, although some of the more significant impacts have been quantified and are discussed below. The limited analysis that has been conducted to date shows that the environmental impact is sensitive to the incorporation rate that can be achieved. To enable meaningful comparison of the options this uncertainty needs to be narrowed.

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The most significant impact which has been estimated is the CO₂ impact which is avoided by reusing plutonium instead of mining, milling and enriching fresh uranium. The initial analysis, which needs to be confirmed in the next stage of the project, indicates that this is likely to result in a significant net benefit in terms of CO₂ equivalence.

6.5.1 Radiological Impact

The impact resulting from final disposal is in the final stages of assessment, and it is intended that RWMD will publish this report in early 2011.

All the implementation routes currently under consideration involve the dry processing of material. The International Atomic Energy Agency (IAEA) has previously looked at fuel cycle and reactor strategies including the use of reprocessed plutonium. Its key conclusions on the health & environmental implications²³ were:

- In normal operation, there are no significant differences in terms of human health and environmental safety impacts among the nuclear fuel cycle options considered;
- A remaining issue is the potential for major accidents which may have significant health and environmental consequences. The prevention of such accidents calls for a high level of vigilance and an ongoing improvement of safety;
- Long-term storage and disposal of spent fuel or radioactive waste do not raise any particular problems in terms of health. Individual exposure remains at extremely low levels as long as no intrusions into the disposal sites occur;
- Plutonium toxicity is not a major factor in the context of normal operational impacts. Certainly, however, there is much misconception about this issue, which has been often used as a strong argument against the fuel cycle, including reprocessing of nuclear fuel.

The discharges that would result from any of the options under consideration are likely to be low given that they would result from aerial discharge of ventilation gases which had been subjected to extensive filtration prior to discharge and radiological discharges are unlikely to be a discriminating factor between implementation routes.

The analysis to date has not considered any discharges which would result from the mining and milling of fresh uranium fuel overseas. This is believed to be a significant impact for fresh uranium oxide fuel which could be off-set through the use of MOX, but it has yet to be quantified.

²³ <http://www.iaea.org/Publications/Magazines/Bulletin/Bull401/article2.html#author>

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6.5.2 Carbon impact

The most significant environmental impact arising as a result of the plutonium strategic option analysis appears to be the CO₂ that results from the construction of new facilities and stores, operation of facilities and the ultimate disposal.

The analysis that has been conducted to date is largely qualitative, although some of the more significant impacts have been quantified.

Construction

All the options involve the construction of new processing facilities. In terms of complexity they range from cement plants, through Hot Isostatic Press and Low Specification MOX manufacture to full scale MOX manufacture and vitrification. The cementation plant is in principle simple and therefore is assumed to be less intensive in terms of materials of construction. However the very low levels of plutonium incorporation in the encapsulated product are currently assumed, due to the level of development of a disposal facility safety case. This means that a minimum of seven plants would actually be required, and more if the GDF does not open in 2040 for ILW. Any benefit gains from a simple plant is therefore likely to be negated by the number of plants required.

Operation

In terms of operating energy costs all the dispose options use cementation, vitrification or ceramic technology. Indicative CO₂ impacts have been calculated for each waste type. The cement option, assuming the high numbers of packages required by a low incorporation rate results in around 45Mte CO₂ equivalent, the use of a vitrification process assuming a 10% incorporation rate results in 11Mte CO₂ equivalent and fuel fabrication results in around between 44.7 Mte CO₂ equivalent (1500te) and 149.1Mte CO₂ equivalent (5000te). For the fuel in the disposal form this effect is a direct impact, if the fuel is to be reused that the manufacturing CO₂ impact is neutralised by the fuel that that would otherwise be manufactured in its place.

For the reuse option, where the material is to be utilised in reactors there is an off-set effect which results from the not having to mine, mill and enrich fresh uranium. This has been estimated at around 840Mte CO₂ equivalent. This off-set is likely to result in a significant CO₂ benefit from the reuse options.

Storage

There is an energy impact from the stores that have to be built to hold the encapsulated product, assuming that a disposal facility is not available on a timescale which enables direct disposal. For example the impact of an additional SPRS store to hold the products of the ceramic and vitrified waste forms is estimated at around 24 Mte CO₂ equivalent. The stores required for the cement product are of a lower specification, however the increase in volume of the cement compared to the other waste forms means that more stores are required and it is likely that a similar

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impact would result. Delaying encapsulation until a disposal facility was available would enable this impact to be avoided.

Disposal

The energy impact of disposal is directly related to the volume of waste and so the disposal impacts of the ceramic and vitrified waste forms are broadly similar due to the similar incorporation rates. The volume taken up by the cement is much larger and results in a significantly higher environmental impact.

6.6 Socioeconomic Analysis

The socio-economic analysis has been conducted using the same methodology as the macro-economic study. The cost/job figures have been escalated to convert from the 2007 money values used in the macro-economic study to the 2010 money values. Further details of the factors used can be found in Appendix D.

The statistics only reflect jobs created in the UK.

The histogram shows the total number of jobs (in man-years) generated from each implementation route and the split between direct and indirect employment.

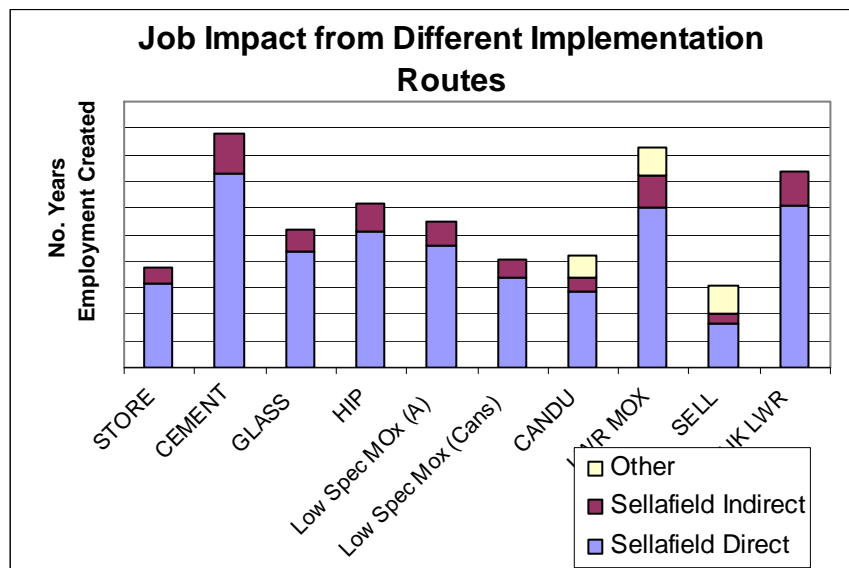


Figure 7: Socio-economic Impact of Different Implementation Routes

It should be noted that as employment generation is related to the spend associated with different activity types it is not surprising that largest number of jobs results from the cement options. The comments on incorporation rate, in section 6.8.1 and their impact of the total capital spend apply equally to the socio-economic impact.

The store and sell options can not be compared directly with the other routes. The store option only considered those jobs required to keep the material in a safe and

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secure condition until 2120 and does not include the employment created from either the reuse, immobilisation or disposal costs which are included in the other implementation options. The sell option assumes that the material is not returned to the UK and so no disposal is included. The CANDU MOX option creates the same order of jobs as the store option in the analysis, which is most likely due to the low capital and operational cost provided by AECL in their submission to this study. As the CANDU MOX route is of low technical maturity, these figures indicate the high risk that the estimates provided are overly optimistic.

Note, the store option (option 1) socio-economic analysis presented above does not include the immobilisation and disposal of the plutonium. Clearly, should that information be required, it can be considered as additive.

6.7 Security and Proliferation Resistance

Security and proliferation resistance were key criteria that stakeholders viewed as important. NDA agree and have started to include them as criteria in the decision making phase of the project, and are advising Government on potential methodologies. The various implementation options have received an early analysis against these criteria as the framework is in the latter stages of development for such an assessment. Work is ongoing with NNL to establish this framework, and an analysis of other internationally based methods has been completed.

Fissile nuclear materials could conceivably be diverted or stolen for use in a fission weapon. Alternatively, fissile and non-fissile nuclear materials could be stolen by a sub-national group (e.g. a terrorist organisation) for use in a radioactive dispersal device. Protection against such proliferation scenarios is provided by the physical and institutional security measures as well as safeguard measures which designed to detect and deter diversion. Protection is also provided by the inherent nuclear, physical and chemical characteristics of the nuclear materials and these will become more important once nuclear materials are emplaced in a GDF (Geological Disposal Facility) where eventually the level of institutional control will decline and eventually cease.

Justification of the preferred options for plutonium management will therefore require a strategy to demonstrate that the preferred option has been assessed against the appropriate proliferation resistance criteria. It may be acceptable for this purpose just to present a qualitative assessment of the different options. However, this would involve subjectivity and it would be far more powerful to use an objective comparative assessment method.

Proliferation resistance guidelines and assessment tools have been developed over the past ten years in response to international initiatives such as TOPS, INPRO and GIF. These methods are now becoming more mature and though there is still no single internationally accepted approach, many of the underpinning technical requirements have now been agreed.

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NNL have recently developed a “U-A” methodology²⁴ for proliferation resistance assessment, which incorporates the Gen IV PRPP (Proliferation Resistance and Physical Protection) metrics. In work sponsored by NDA, it is now considered that this U-A methodology could be used to assess UK plutonium management options. It is anticipated that the process will highlight the strengths and weaknesses of the different options and will highlight the key questions that would need to be addressed in justifying the preferred options.

Where possible, an early qualitative assessment against each of the options using the NNL U-A methodology has been given below. The methodology has been applied to a stage by stage breakdown on the ten plutonium options, using the Gen IV categorisations. At the moment, only state-sponsored proliferation has been considered, and plutonium theft/diversion will be evaluated shortly. It would be expected that a similar picture will apply, albeit with differences of detail. For every option the utility function $U(x)$ has been plotted versus the Access function $A(x)$ and the graphs show a clear progression at each stage. Figure 8 below is the plot for Option 10, which shows a clear progression from stage to stage (though not every stage brings an improvement) and there are no retrograde steps. For the calculation in Figure 8, only Magnox grade plutonium has been evaluated. Low numbers on both axis indicates better proliferation resistance.

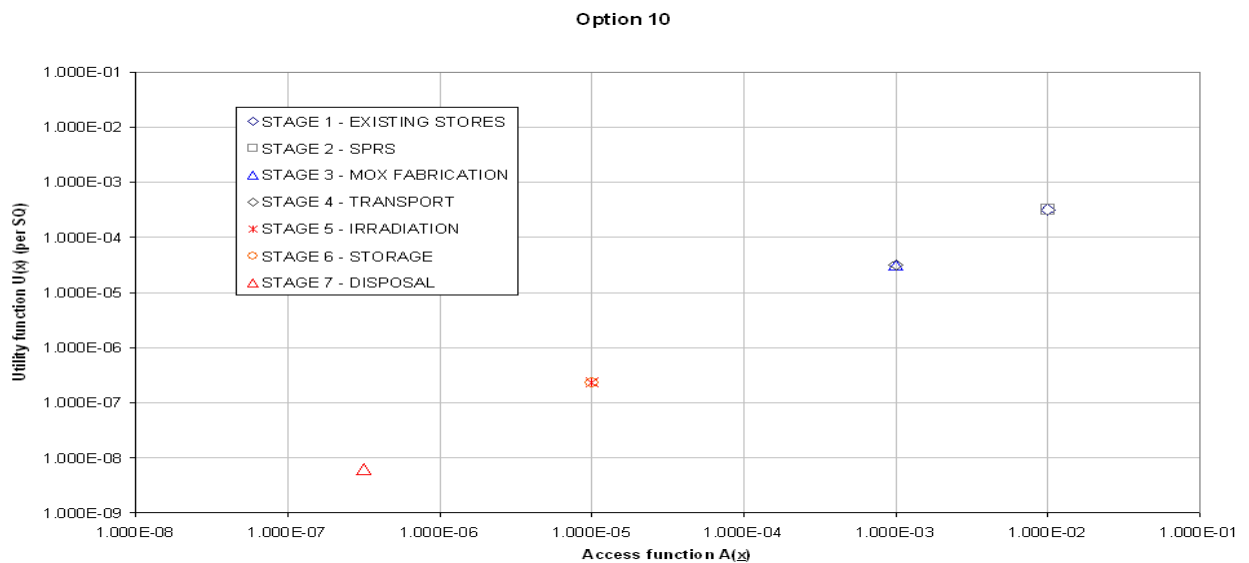


Figure 8: Stage by Stage Analysis of Proliferation Resistance for Option 10.

The plot below in Figure 9 below summarises the overall results for all 10 options. There are four clear groupings. The first one combines Options 1 (store) and 9 (sell) and shows no improvement. Option 9 has been calculated on the basis that the UK

²⁴ In the U-A methodology, the U represents a “utility” function (i.e. how easy is it to use) and the A represents an “access” function (i.e. how easy is it to acquire).

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would have no material control over the plutonium once sold. The other three groupings show progressive improvements in proliferation resistance, with options 7, 8 and 10 (i.e. reuse) indicating clear advantages.

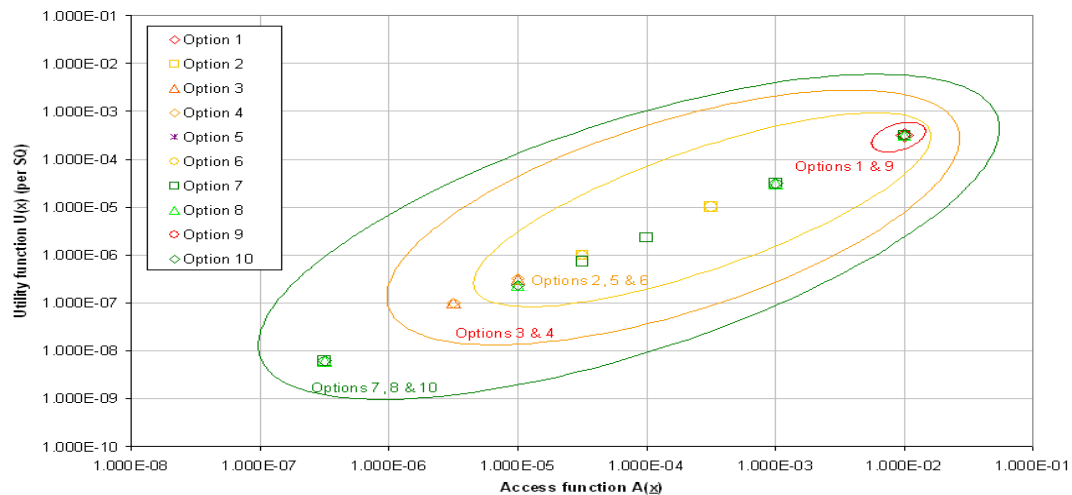


Figure 9: Proliferation Resistance: Comparison of Options

Referring to the analysis illustrated in Figure 9, should the UK adopt option 9 with assured conditions of sale, such that the material is converted to MOX fuel, irradiated and the UK allowed to verify the end state of the fuel, then option 9 would have the same improvement as options 7,8 and 10.

6.8 Key Areas of Uncertainty

6.8.1 Incorporation rate

Incorporation rate is a key factor in driving costs, it affects the number of years operation and in some of the options it also affects the capital spent on both encapsulation plants, product stores and their subsequent decommissioning costs.

The graph below shows the variation in cost with plutonium incorporation rate for cement. The incorporation rates, on which the low spec MOX, vitrification and HIP options are based, have yet to be underpinned in terms of their acceptability in a GDF. Until confidence is gained that the rates (or higher ones) are acceptable this will remain a key area of uncertainty. It most dramatically affects the cement option because of the low incorporation rates which are currently being prescribed by RWMD.

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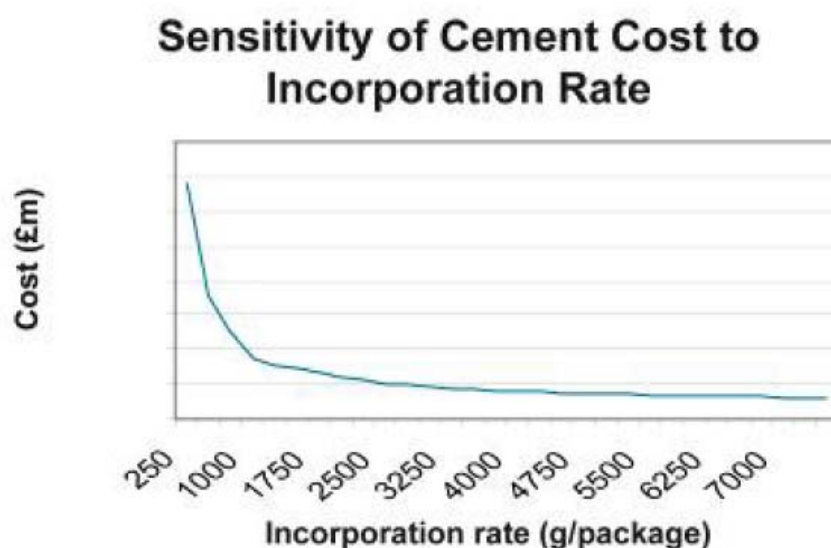


Figure 10: Sensitivity to incorporation rate for the cement waste form option

6.8.2 Timing

Product Storage

The biggest area of timing which affects uncertainty is the point at which an immobilisation plant is built with respect to the availability of a disposal facility. The options generally assume immobilisation at the earliest opportunity, bearing in mind the technical constraints, but not any affordability considerations. This results in the volume of waste being increased as a factor of the incorporation rate and storage of the immobilised product being required until a GDF is available in 2075.

The effect of not having to build immobilisation plants and product stores varies widely depending on the option being considered and the level of confidence in the estimate.

Treatment to Remove Americium

For the fuel to be optimal for use by third parties, without additional treatment costs being incurred, then the average americium levels are generally assumed to be needed to be below 4%. Fulfilling this requirement means that early action is required for the plutonium derived from Oxide reprocessing, in terms of blending or pre-treatment, although early exploratory work with Areva indicates that the americium in the UK inventory of plutonium can be managed by appropriate blending of material prior to reuse. CANDU MOX fuel, due to its low incorporation of plutonium, is considered less susceptible to americium management issues than LWR fuel.

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6.8.3 Revenue

The uncertainty bounds in the projected total cash flow for some of the strategies are extremely large. With more information on the factors affecting the costs of the strategies it will be possible to reduce these uncertainty bounds. It is not possible to determine whether the commercial use of plutonium is credible until the uncertainty bounds have been narrowed.

6.8.4 Characterisation

The characterisation of impurity levels associated with some of the older material is poor and so it is not possible at this time to assess definitively its suitability to be treated through some of the immobilisation routes. Likewise the amount of pre-treatment necessary to enable either reuse or disposal is not clear. Work in the next phase needs to take place to enable this uncertainty to be bounded.

6.8.5 Off-set costs

Offset costs could potentially result from two sources:

- Options which allow co-encapsulation with other waste streams such that the disposal cost of one are off-set against the other
- Options which reuse MOX and off-set the disposal costs of a proportion of uranium oxide fuel against the MOX disposal costs.

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7 High Level Advantages and Disadvantages of Each Option

As can be seen in Appendix A, there is a lot of technical and logistical information and cost data for each option. This section attempts to summarise the relative advantages and disadvantages of the options, and it should be noted that no inference of preference is intended with each summary.

7.1 Option 1: Store

Advantages

There are three main advantages to this option, which are the discounted financial cost of implementing the solution, the environmental impact and the technical readiness.

- The financial advantage is because most of the required financial expenditure occurs post 2120, where discounted costs of facilities become comparatively very small. However, if fiscal management is your only driver, then this is an option to consider.
- The environmental impact while continuing to store is low clearly because there is comparatively little activity, transport and construction during the period of storage.
- The technical readiness is an advantage as there are a minimal number of processing facilities required, all of which have a high level of technical maturity

Disadvantages

The most significant disadvantages to this option are safety/hazard, proliferation resistance and socio-economics.

- From a safety perspective there is prolonged and increasing worker dose without any real benefit, which will only get worse with time, and because the plutonium is not immobilised, the safety and environmental detriment is significantly worse for this option.
- Proliferation resistance is poor - as there are no additional chemical barriers to the material - and it will remain in a mobile state where the plutonium isotopes have not been denatured.
- Socio-economically there are disadvantages as new construction and operations are kept to a minimum in this option.

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7.2 Option 2: Cement Immobilisation


Advantages

The main advantages to this option are technical maturity and socio-economics.

- Technically this option is relatively mature, as the cementation of radioactive wastes is a well-established technology.
- Due to the large number of cement plants, stores and product drums being required, this option is labour intensive and hence an advantage socio-economically.

Disadvantages

There are many disadvantages to this option, some so much so that the option was considered as potentially non-credible during this latest update. However, if the plutonium loadings in the wasteform were to increase significantly, this option may offer some merits and hence it was not considered reasonable to rule out as incredible at this stage. This decision will be reviewed in the future.

- The plutonium isotopes have not been denatured and are potentially extractable from the encapsulated medium.
- The large number of facilities and significant volume of cement required to make this wasteform results in significant environmental impact.
- Proliferation Resistance is better than continued storage, but not as good as other options. This is to be expected as there is a relatively non-robust chemical barrier added to the material, it would be in a non-mobile state but the plutonium isotopes have not been denatured.
- Logistically this is the most demanding option as 7 cementation plants and between 7 and 11 storage units need to be co-ordinated with around  drums of waste, each weighing over half a tonne.

7.3 Option 3: Vitrification Immobilisation

While comparing this option to the other nine, it is also worth doing a direct comparison with HIP immobilisation as both offer a similar product with similar properties albeit via a different route.

Advantages

- Vitrification immobilisation does considerably reduce the state-sponsored proliferation risk from the material, albeit not as much as the reuse options. This is to be expected as there is a relatively robust chemical barrier (glass) added to the material, it is now in a non-mobile state but the plutonium isotopes have not been denatured.

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Plutonium Credible Options Analysis (Gate A) 2010

- There are no other stand out advantages to this option, although it does offer some improvements in socio-economics and safety.

Disadvantages

- This option is technically immature and requires the most development of any of the options.
- Economically this option is not as favourable as the HIP immobilisation option.

7.4 Option 4: HIP Immobilisation

While comparing this option to the other nine, it is also worth doing a direct comparison with vitrification immobilisation as both offer a similar product with similar properties albeit via a different route.

Advantages

- HIP immobilisation does considerably reduce the risk of state-sponsored proliferation from the material, albeit not as much as the reuse options. This is to be expected as there is a relatively robust chemical barrier (ceramic) added to the material, it is now in a non-mobile state but the plutonium isotopes have not been denatured.
- There are no other stand out advantages to this option, although it does offer some improvements in socio-economics and safety.

Disadvantages

- This option is technically immature for large scale bulk plutonium, although it requires less development than the vitrification immobilisation option.
- Economically this option is more favourable than the vitrification immobilisation option.

7.5 Option 5: Low Specification MOX Immobilisation (New Facility)

This option should be compared directly to option 6, which does not need a new MOX facility. However, due to historic performance issues, the reliability of option 6 is seen to be high risk, and so both option 5 and 6 need to be considered in parallel.

Advantages

- This option is technically mature.
- Socio-economically construction and operation of a new production facility and several large stores is required.

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Plutonium Credible Options Analysis (Gate A) 2010

Disadvantages

- Financially this is a relatively expensive option compared to the associated options 3, 4 and 6.
- Low specification MOX immobilisation does essentially reduce the state-sponsored proliferation risk from the material, albeit not as much as some of the other options. This is to be expected as there is a relatively non-robust chemical barrier (dissolvable ceramic) added to the material, it is now in a non-mobile state but the plutonium isotopes have not been denatured.
- Environmentally this option needs the construction of several new facilities (production and stores) and so is at a disadvantage to most of the other options.

7.6 Option 6: Low Specification MOX Immobilisation (Existing Facility)

This option should be compared directly to option 6, which does not need a new MOX facility. However, due to historic performance issues, the reliability of option 6 is seen to be high risk, and so both option 5 and 6 need to be considered in parallel.

Advantages

- This option is technically mature.
- Financially this is a relatively inexpensive option compared to the associated options 3, 4 and 6, as no new (expensive) production facility is required.
- Socio-economically construction and operation of several large stores is required.

Disadvantages

- Low specification MOX immobilisation does essentially reduce the state-sponsored proliferation risk from the material, albeit not as much as some of the other options. This is to be expected as there is a relatively non-robust chemical barrier (dissolvable ceramic) added to the material, it is now in a non-mobile state but the plutonium isotopes have not been denatured.
- Environmentally this option needs the construction of several new facilities (many product stores) and so is at a disadvantage to some of the other options.
- This option relies on the continuing good performance of the Sellafield MOX Plant (SMP) at considerably higher throughput than currently demonstrated. Therefore this option is considered to be the highest risk of all the options.

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7.7 Option 7: CANDU MOX Reuse

This option should be compared directly to the other reuse options, i.e. 8 and 10.

Advantages

- As with all reuse options, CANDU MOX reuse offers good proliferation resistance when in the final spent fuel form. There is a potential of achieving significant economic and energy value from the plutonium.

Disadvantages

- There are a large amount of international shipments of MOX fuel that will be required. It is still uncertain as to the public acceptability of this impact
- .Socio-economically this option does not produce as many jobs as the other options.
- The technical and commercial feasibility of this option is considered to be low.

7.8 Option 8: Overseas LWR MOX Reuse

This option should be compared directly to the other reuse options, i.e. 7 and 10.

Advantages

- As with all reuse options, LWR MOX overseas reuse offers good proliferation resistance when in the final spent fuel form. There is a potential of achieving significant economic and energy value from the plutonium. The cost data in the model has a reasonable degree of certainty due to the commercial maturity of this option.

Disadvantages

- There would be a large amount of international shipments of MOX fuel that will be required (not as many as CANDU MOX), and it is still uncertain as to the public acceptability of this impact.
- Socio-economically this option does not produce as many jobs as the other options.
- There is a high degree of financial uncertainty surrounding this option as it has not yet been commercialized.

7.9 Option 9: Sell

Advantages

- The main advantages of this option are the discounted financial cost of implementing the solution, the environmental impact and the technical

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readiness. The financial evaluation indicates that this option could be considered.

- The technical readiness is an advantage as there are a minimal number of processing facilities required, all of which has a high level of technical maturity

Disadvantages

- The most significant disadvantages to this option are proliferation resistance, international stakeholder relations and socio-economics.
- If the UK sells the plutonium without condition, then proliferation resistance is poor as there are no additional chemical barriers to the material, it is still in a mobile state and the plutonium isotopes have not been denatured while under UK management. However should the UK be assured that the plutonium has been converted into MOX fuel, irradiated and disposed, then the proliferation resistance would be high and this would turn option a disadvantage into an advantage.
- It is considered that sale of the plutonium stockpile would receive a large amount of negative stakeholder reaction, especially as it appears to be contrary to international best practice at this time. A very large number of regular international shipments of plutonium over several decades would most likely be required which would give rise to international security concerns.
- Socio-economically there are disadvantages as new construction and operations are kept to a minimum in this option.

7.10 Option 10: UK LWR MOX Reuse

This option should be compared directly to the other reuse options, i.e. 7 and 8.

Advantages

- As with all reuse options, LWR MOX in the UK reuse offers good proliferation resistance when in the final spent fuel form. There is a potential of achieving significant economic and energy value from the plutonium. The cost data in the model has a reasonable degree of certainty due to the commercial maturity of this option.

Disadvantages

- There are very few disadvantages with this option.

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8 Work to be undertaken in the next Phase

The NDA's Strategy Management System (SMS) has been developed over the last two years, and will continue to improve as more studies are carried out in the various strategic areas. Plutonium was the first credible options paper to be developed within the new SMS system and this update has benefitted from developments in the SMS since the study was first published.

This section briefly outlines the work to be undertaken in the next phase that will address key uncertainties in the programme.

8.1 Narrowing of Uncertainty Bounds

There are five main areas where work needs to focus to allow the uncertainty associated with the strategic options to be narrowed:

8.1.1 Characterisation

The plutonium separation programme commenced in the 1950's and was focussed at that time on generation of plutonium for defence purposes. Quality assurance was a term that had yet to emerge from the manufacturing industry and hence the assurance regime, including characterisation and record keeping is not to the standard that would be expected today. This leaves a number of question marks over the suitability of part of the inventory for onward processing either for disposal or reuse. In order to increase understanding, a characterisation programme is necessary, and needs to be developed with the Site Licensees to ensure that all pertinent data is analysed and that a sampling programme, if required, is implemented in a manner that ensures dose to operators is kept as low as reasonably practicable.

8.1.2 Geological Disposal Facility

Work within the GDF programme since 2008 has focussed on several key areas to support the plutonium programme.

- A better understanding has been established of the safety case criteria for the disposal concept, which is key to establishing whether the (i) durability of the waste forms proposed is acceptable and (ii) in establishing the optimum incorporation rates of plutonium within the waste form. This work includes a consideration of the criticality safety aspects from the fissile materials. A disposal system safety case (DSSC) is currently in preparation, and this includes stocks of separated plutonium. The risks post-closure are calculated to be very low because it is highly retarded by sorption in the geosphere and, hence, almost all of the plutonium-239 and plutonium-240 in its inventory would decay before reaching the biosphere.
- Opportunities have been identified for the co-disposal of some of the plutonium with other waste forms. If this was acceptable then there is

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potential to reduce the volume of waste which needs to be disposed of and hence reduce costs. This concept is currently under evaluation.

- Public acceptability of the ultimate disposal of plutonium in a disposal facility is something that needs to be addressed by NDA as part of the GDF programme

8.1.3 Technical Development

The different implementation routes are at differing stages of technical maturity and in some cases were originally developed for different purposes. Incorporation rate of plutonium is a key sensitivity to the disposal cost. A better understanding of the incorporation rates that could be achieved for different waste forms is important. This needs to be considered along side the safety case for the disposal facility so that incorporation rates can be optimised.

8.1.4 Commercial Benefits

There are a very large number of variants that could be assessed for the reuse options, all of which have different potential commercial benefits. This is outlined in section 5.4.1. In order to narrow the range of benefit that could be achieved the market appetite for any of the options outlined needs to be established, the work needs to take place with Government to understand their preferences in terms of a commercial model.

8.1.5 Long Term Storage

Much of the knowledge base on long term storage is based on US research and development which is predicated on the plutonium isotopics of the US military fuel. There are significant differences between the US and UK plutonium isotopics. To understand the long term behaviour of this material in storage a research and development plan is currently underway.

8.2 Timing optimisation

In determining the timing of individual implementation routes it has been assumed that they proceed as fast as the technology allows, and that disposal happens as soon as a disposal facility is available. This is assumed to be in 2040 for an ILW disposal facility and 2075 for a HLW disposal facility for consistency with the current site plans. This approach takes no account of any other wastes which have to be moved to a disposal facility on the same timescales, the optimisation of storage arrangements to avoid the need for additional stores or phasing advice for sites which is currently being produced by NDA.

The next phase of work needs to more carefully examine the timing of the options and look to optimise the timescales based on disposal facility availability windows and safety considerations. More work should also be undertaken to determine the likely conditions of acceptance for any reactor that may be used in a reuse option to better understand the limitations of the americium content of the inventory.

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8.3 Policy Development

It is NDA's understanding that a change to policy is required to implement any of the strategy options. In some cases a formal government led consultation may be required prior to execution of the chosen option.

There are also a number of policy areas which impact on the decision made where the policy framework as it applies to plutonium, requires further clarification. These include areas such as:

- Energy policy including security of supply
- Climate change
- Security (non-proliferation) frameworks considerations including whether spent fuel standard is considered as important

NDA are continuing to work with Government in these areas.

8.4 Stakeholder Engagement

Draft stakeholder engagement plans are in the process of being drafted with a view to supporting Government in any Consultation they may carry out on plutonium policy options in the near future. Stakeholder engagement needs to continue through the decision making phase of the project and NDA will propose mechanisms for sharing information and opportunities to influence the direction of the project.

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9 Conclusion

It is clear that a final decision on UK plutonium management policy needs to be taken by UK Government, preferably in the short term.

Further work should be undertaken to narrow the uncertainty bounds and be informed by Government(s) guidance on policy application. It is clear however that the work over the previous two years (since the publication of the first version of this study) has significantly added to the body of knowledge which should better enable decision making in the future.

NDA should continue to work with Government to gain an understanding of the policy frameworks with respect to energy, climate change and security of nuclear material, in which future decisions should be taken.

Deferred disposal, with storage until 2120 (or the end date of the Sellafield site) should be implemented as an active contingency while the ultimate plutonium management strategy is developed.

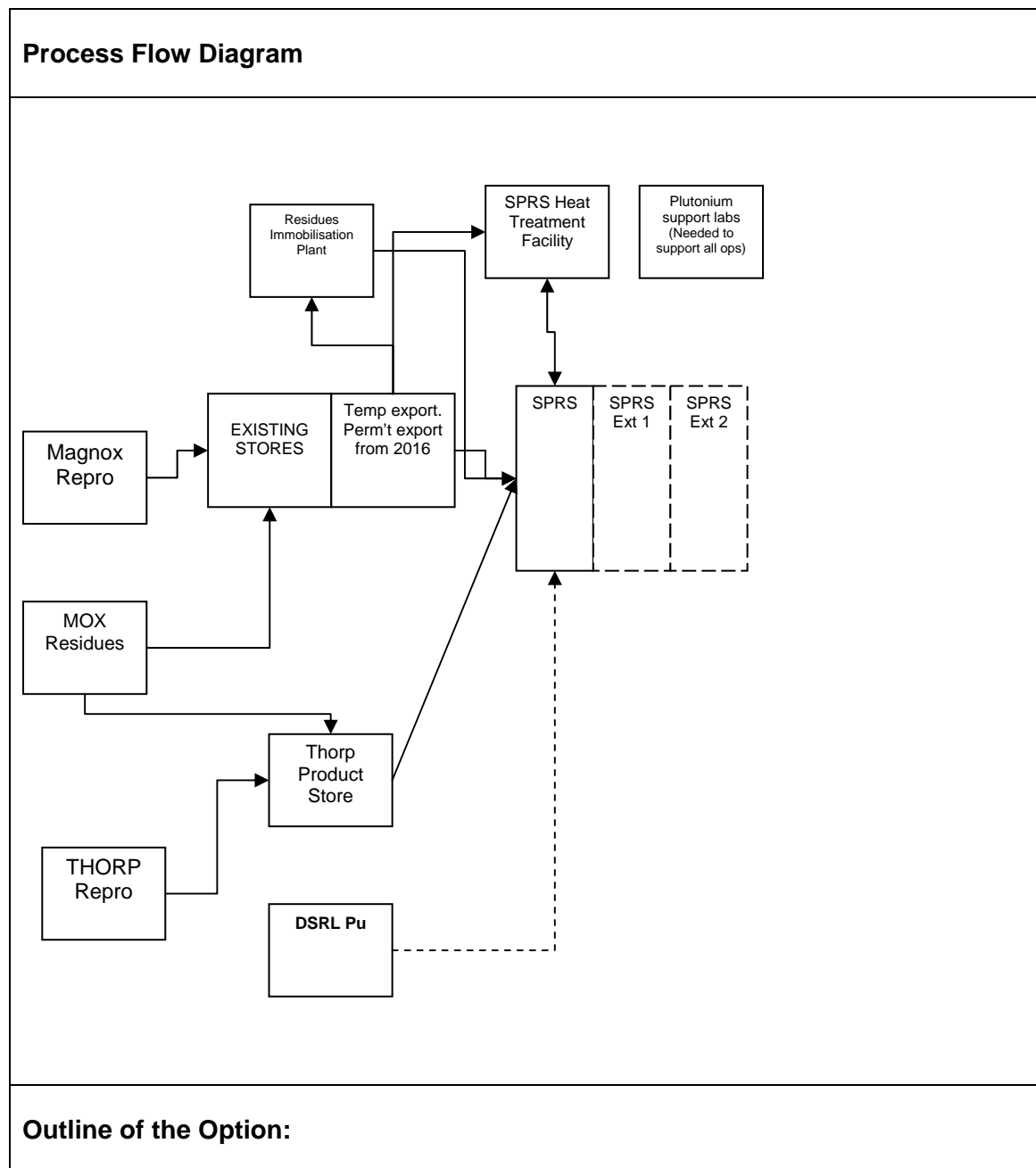
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Appendix A: Datasheets for Implementation Options

CREDIBLE OPTION DATASHEET 1

POLICY OPTION: STORAGE

Implementation Strategy Option 1: Store until 2120



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For this option, where data is available it is drawn from the current Sellafield Lifetime Plan and this is fed forward into estimates. However there are a number of key areas which are not currently addressed in the LTP and estimates have been drawn from industry data and analogous plant to provide these estimates.

For consistency with the current Sellafield baseline a storage period up until 2120 is assumed. However if the material is to leave the Sellafield site by that date then decisions need to be made much earlier to allow new facilities and/or transport assets to be procured. This is discussed further in the section timescales and time constraints.

This option stores the material indefinitely, and therefore would not attract a cost at the end for immobilisation and disposal. In reality this option would need to provide a final disposal solution for the material if it had not been used prior to the end of the Sellafield site. Hence in order to make a fair modelling comparison, the data shown in section 6.3 has included a HIP immobilisation and disposal option to storage from 2075.

For modeling purposes it is assumed that plutonium stored at Dounreay will be transported to Sellafield for storage in SPRS (or similar appropriate store). However, most of the plutonium stored at Dounreay is mixed with HEU (High Enriched Uranium) and storage of HEU is contrary to existing planning permissions and safety cases for SPRS, so some work is assumed to have been completed to enable this material to be stored at Sellafield. A separation process is likely to be required to recover the plutonium from the HEU.

This option only includes material which is currently in UK safeguards, that is the civil material. If additional UK owned material were to enter safeguards and be added to the inventory then the sizes for the planned stores would need to be reviewed.

The Option in Summary

- i) storage in existing stores until SPRS is available
- ii) construction of new SPRS extensions for availability in 2032 and 2043
- iii) Provision of new plutonium support laboratories in 2019 and 2060
- iv) SPRS Heat Treatment Facility and a second facility for reconditioning the material after extended storage in 2060, which would be incorporated into SPRS extension 2.
- v) Decommissioning of SPRS, extension modules, older stores, packaging and heat treatment facilities, and new plutonium support laboratories. Decommissioning is phased to take place at the end of the operating period of the plants.
- vi) A HIP immobilisation plant for plutonium residues is required.

Assumptions

- The requirement for chemical analysis is not yet known. Operating costs of laboratory facilities are included and the cost of the analysis is assumed to be covered in the uncertainty range of the Heat Treatment Facility.

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- New facilities will be required for characterisation, packaging and treatment (the SPRS Heat Treatment Facility).
- Material may be withdrawn from existing stores or new stores for characterisation
- Approximately 40 teHM of the material requires sampling and heat treatment for long term storage.

Exclusions

- Non safeguarded materials
- Overseas materials which is assumed to be returned to customers.
- Activities for immobilising and disposing of the material – these would be required to meet the hazard profile shown in the safety section. However, in order to make a fair financial comparison, this option has been modelled in section 6.3 by adding a HIP immobilisation route to the store option from 2075. This has the effect of significantly increasing the undiscounted cost, but has little effect on the discounted cost due to the time taken to implement the immobilisation.

Treatment of Chloride contaminated material

Is it assumed that treatment of chloride contaminated material needs to take place prior to movement into new stores to meet SPRS conditions of acceptance. It is assumed that the SPRS heat treatment facility will be able to decontaminate this material, and so chloride contaminated material does not need a purpose built treatment facility, as assumed in the previous version of this report.

Cost Data and Uncertainty

The capital cost of SPRS is assumed to be sunk at this time and is excluded from the estimate

The majority of the cost data is drawn from the Sellafield Lifetime Plan for this option. When process blocks are missing from LTP, estimates have either been drawn from industry or the SLC. For facilities not included in LTP, operating costs have been assumed to be 10% of the capital cost and decommissioning costs are based on a parametric of 40% of capital cost as advised by the SLC. This is considered pessimistic for stores.

Costs estimates are provided in Table 1 for the on-going storage of plutonium based on storage until 2120. Decommissioning of the facilities would then take place.

1. Store – PuO₂ powder

Prior to export to any disposition plant the material will have to be safely and securely stored. Estimates for this have been taken from the Sellafield LTP and include extensions to the SPRS facility.[2]

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2. SPRS Heat Treatment Facility

The purpose of this facility is to sample, characterise and, if necessary, pre- treat the plutonium prior to long term storage. Data for this block is derived from existing projects being carried out at Sellafield.

3. Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and troubleshooting in support of operations are assumed. [7]

4. Disposal Costs

All immobilisation and disposal costs are excluded from the tables of data above. However for the financial analysis, it is necessary to ascertain the total lifecycle cost to make fair comparisons. Hence the cost estimate for deferred storage includes immobilisation, packaging and disposal costs from one of the disposal options. This extra cost is included in the undiscounted and discounted cost charts in the main body of the report, although the fact that immobilisation occurs in many decades time means that the discounted cost of such plants is comparatively very small.

Cost sensitivity and uncertainty

Cost uncertainty is dictated by final timescale over which the plutonium is stored and the potential requirement for further treatments to ensure that it continues to be stored in a safe and secure condition. See Knowledge Gaps and R&D needs.

Technical Maturity

Interim Storage: TRL = 9

Long Term Storage: TRL = 7

Interim storage of plutonium oxide powder is well understood and is implemented on an industrial scale and so is considered to have a technical maturity of 9. Estimates vary as to the time period for which is technical maturity is consider valid and engineering judgement suggests that this level of technical maturity is valid for around 30 years.

This reference case assumes storage for another 100 years which goes beyond any international experience for storage of this type of material. This is compounded by the fact that much of the international research is based on the isotopics of US material not UK material and R&D work is required to investigate the applicability of this data and if necessary to generate data which is specific to the UK material. In using the TRL guidance to assess readiness of the long term storage there is no directly applicable category. A TRL of 3 applies where analytical and experimental critical function and/or characteristic proof of concept is required and TRL of 9 applies

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for a total system used successfully in operations. In reality the long term storage system is part TRL3 and part TRL9. A TRL 7 is applied in situations where sub-system demonstration in an operational environment is available and it is considered that this provides the most representative TRL as the storage systems themselves are well proven, but the behaviour of the material (as sub system of the store) requires further R&D to demonstrate long term behaviour.

The physical properties of UK plutonium oxide powder are different to US plutonium oxide powder, in that UK powders have a much higher surface area and hence are more susceptible to water absorption. This has the potential to affect long term storage but more work is required on UK derived plutonium.

Lead Time

This option is the reference strategy and so discussion on lead time is not directly applicable. The section on time constraints discusses the lead time associated with other options. This provides the drivers for making decisions either in support of an end date for storage of 2120, or to avoid capital spend associated with this option.

The detailed lead time for the new facilities are as discussed below:

SPRS Extension 1: The lead time for this facility is not directly relevant to the phasing. The facility is required for 2032 and the design and build programme is phased over 5 years.

SPRS Extension 2: The lead time for this facility is not directly relevant to the phasing. The facility is required for 2043 and the design and build programme is phased over 5 years

SPRS Heat Treatment Facility : A new heat treatment facility is consistent with Sellafield LTP10. This plant is costed on a footprint basis with key equipment inside. The current design includes can opening equipment, furnaces and a repackaging area. There would be sampling points in the process and characterisation costs are not included in the estimate for the plant. It is possible for the facility to incorporate a plutonium powder blender within the design cost estimate. A decision will need to be taken on how to package the heat treated products – Magnox or Thorp cans – although any disposition path will be required to deal with both types of cans.

Environmental Impact

There will be some environmental impact, albeit likely low, if pre-treatment of contaminated plutonium is required prior to emplacement in modern storage facilities. There may be additional plant complications and discharges due to the removal of non-radiological Impurities (e.g. chlorides).

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**Plutonium
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There will be an environmental impact from the building of new plant and stores.

There is no disposal included directly as part of storage, therefore the environmental impact for final disposal will be considered within another option. The impact will be approximately the same for each option and therefore has not been calculated further.

Socio Economic Impact

Socio-economic Impacts are calculated using the figures derived in the ERM report and applied to the costs for each option, given in man-years of jobs required:

Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			
Other Construction			
Other operations			

Safety – Change in relative hazard over time

The assumptions in this section are consistent with the Sellafield life time plan in terms of timescales. However in order to make a fair modelling comparison, the data shown in section 6.3 has included a HIP immobilisation and disposal option to be added to storage from 2075.

It is assumed that a HLW GDF is available in 2075 and that exports proceed linearly from 2075 until 2120 when all the material is assumed to have been moved to a disposal facility, which allows for a 30 year operational period and a 15 year disposal period.

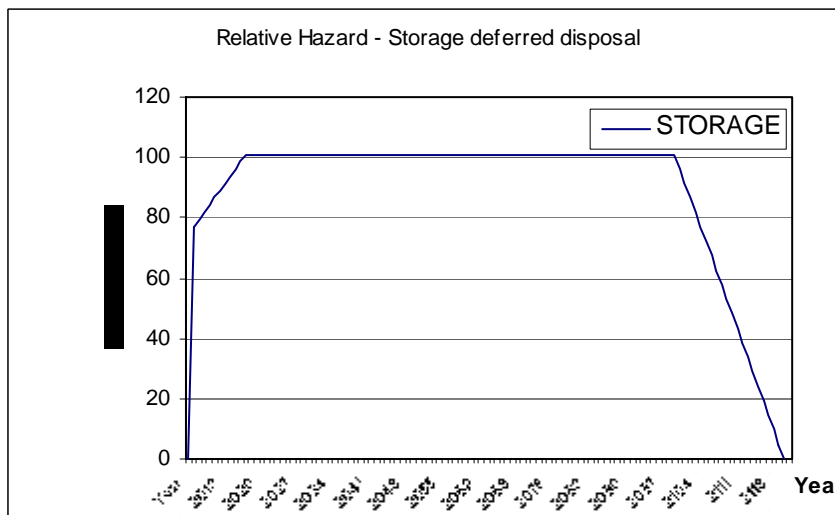
For this to be enacted an immobilisation plant needs to have been designed and operations commenced by 2075. Assuming a lead time of 20 years, which is consistent with many of the disposal options this means that at the latest a decision on disposal route, along with the R&D to support disposal, needs to have been made by 2055.

Safety case analysis would suggest the form factor decreasing for the hazard by a

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factor of 100,000 for immobilised product compared to loose powder.

Using a simple inventory form factor analysis to examine the hazard then this would change over time as indicated by the graph below.



Proliferation Resistance

From the discussion and charts in section 6.7, long term storage does not essentially reduce the state-sponsored proliferation risk from the material, despite moving it to new stores. This is to be expected as there are no additional chemical barriers to the material, it is still in a mobile state and the plutonium isotopes have not been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion “proliferation risk”.

Disposability

There are no disposability issues associated with the store option; disposability needs to take place using one of the other strategy options.

RWMD¹⁵ were asked to examine the possibility of direct disposal of plutonium powder in the context of identifying showstoppers around potential waste form. They concluded that disposal as plutonium powder would constitute as a show stopper and it has not been included in the any of the Optioneering.

Hence, for the financial analysis in this study, one of the immobilisation technologies in this report is assumed applied to the plutonium so that final disposal can take place before the end of the Sellafield site is reached.

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Knowledge gaps and R&D needs

The knowledge base around the interim storage of plutonium powder is well understood, however little work has been done to support storage in the very long term. For that reason R&D work has been commissioned by the NDA to look at:

- Properties of UK stored plutonium
- Radiolysis or surface reactions in plutonium oxide powder

In addition the chemical form of the chloride contamination in the plutonium is not well understood. This report assumes that heat treatment will be sufficient to remove the chlorine and some work has been carried out since 2008 that indicates the chloride levels in chloride contaminated plutonium can be adequately managed by heating the material before use. This process does not appear to remove all the chloride, but it does reduce the chloride levels to a manageable (and blendable) level.

Risks and Opportunities

Risks

The risks to the storage option are that costs in addition to those included in this estimate are incurred, for example, that the regulators require conversion of the current plutonium oxide powder into an alternative passive form more suitable for long term storage.

Opportunities

If a decision is taken on an alternative strategy for plutonium then there could be opportunity to avoid spend on some of the currently planned storage facilities.

Time constraints and timescale decision drivers

This section considers that timescale on which decisions are required if capital spend associated with this option is to be avoided.

Decision Point 1: 2017

The capital spend for the 1st module of the SPRS extension is required by 2032 and therefore needs to commence in 2027. To avoid the need for this store a route out for some of the material either via disposal or reuse would be required. Assuming a worst case 15 year design, authorise and construct lead time for a plant to pursue an alternative strategy the design and construction programme would need to start around 2017. (Note that this assumption is different to the earlier version of this report which gave an estimated 20 year lead time for such activities). This is likely to be

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worst case, as, with suitable improvements, the existing stores could be made to last a few years more than the currently perceived lifetimes.

In the event of some of the reuse options being chosen a protracted planning process could be involved and it would be conservative to assume that a decision would have to be made in the immediate future (i.e. around 2011/12) to avoid the need for SPRS extension 1.

Decision Point 2: 2028

It is possible that a decision will be made on a timescale that would avoid the need for the first module of the SPRS extension, however the next opportunity for costs avoidance is for the second extension. This facility is required to commence operations by 2043 with construction starting in 2038 to achieve this. Following the same logic as above a decision is required about 2028 to avoid this spend.

Expenditure on a heat treatment facility is unlikely to be avoided if a decision were taken in this timeframe as most scenarios require such a facility.

Stakeholder views

A number of stakeholders have previously¹⁴ expressed the view that a strategic decision on the future usage of the plutonium stockpile should be pursued. The regulators have also expressed a view that a contingency plan should be put in place and it is proposed the storage with deferred disposal provides this contingency.

Policy Impacts

There are no impacts against the current policy for this default option.

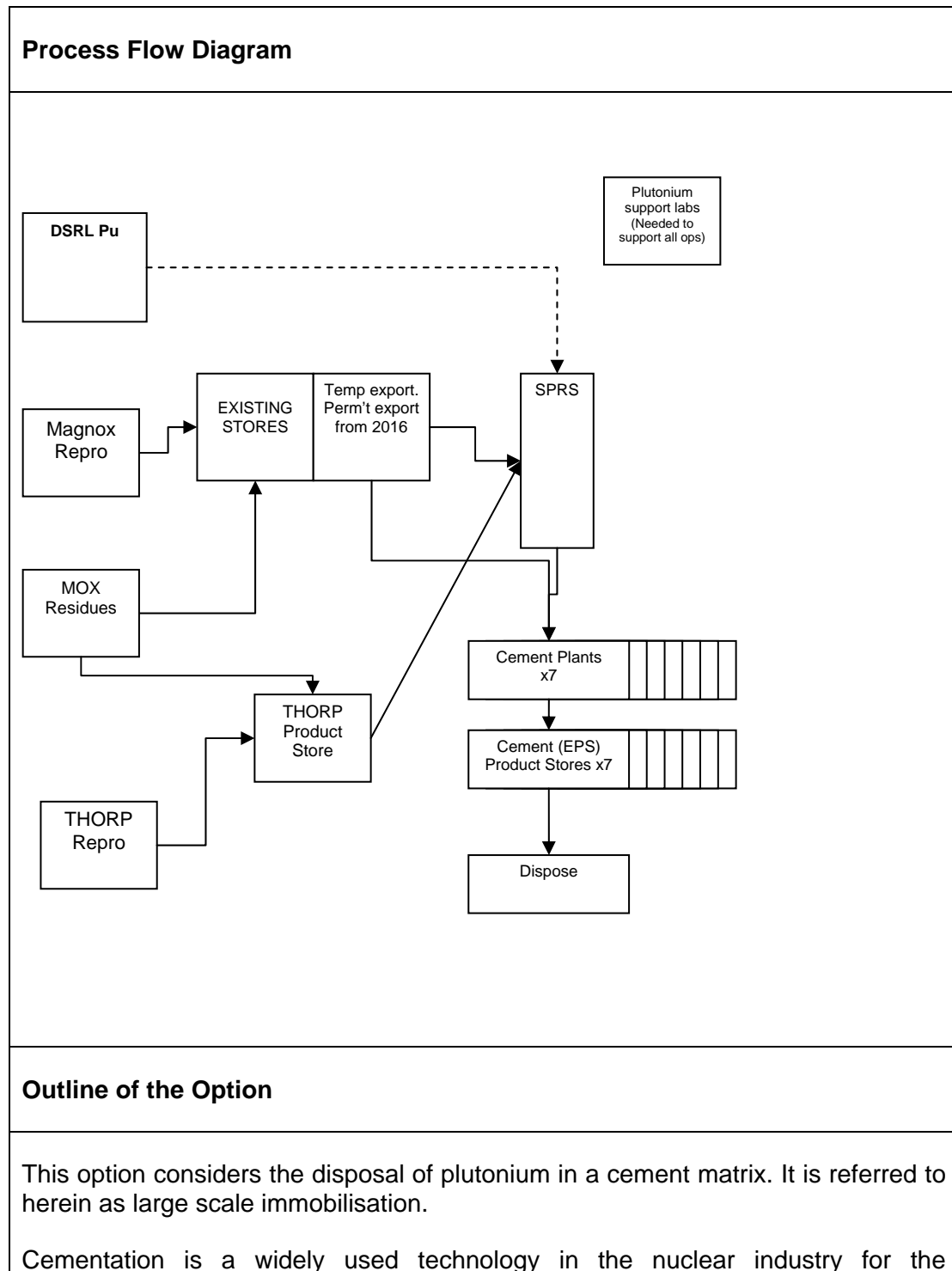
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Plutonium Credible Options Analysis (Gate A) 2010

CREDIBLE OPTIONS DATA

POLICY OPTION: DISPOSAL

Implementation Strategy 2: Cement



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immobilisation of nuclear wastes, especially ILW.

Although ruled out by the BNFL stakeholder dialogue in 2004, cementation is a well understood technology and has therefore been reconsidered.

For modeling purposes it is assumed that plutonium stored at Dounreay will be transported to Sellafield for interim storage in SPRS (or similar appropriate store). However, most of the plutonium stored at Dounreay is mixed with HEU (High Enriched Uranium) and storage of HEU is contrary to existing planning permissions and safety cases for SPRS, so some work is assumed to have been completed to enable this material to be stored at Sellafield. The immobilisation process is likely to be required to include the HEU as well as the plutonium.

Some variations on process options are possible, especially on how and the extent to which the plutonium is dispersed in the cement, and the nature of the grout material used. However, the basic process involves in-drum paddle mixing of dry cementitious powder, water and plutonium. A grout cap is added and the waste package is set aside to cure. The principle is to produce a homogenous monolith of mixed encapsulant and waste.

A process flow diagram is provided. The key steps are:

- (i) Storage in existing stores, SPRS, without any extensions to SPRS. However, in the high case, one new SPRS module in 2032 might be required if the construction of the cementation plant is significantly delayed. Hence this is included as a risk rather than a base assumption.
- (ii) Process development and proving, possibly using infrastructure already in LTPs e.g. Dounreay and Sellafield facilities
- (iii) Cementation of plutonium powders and wastes starting from 2020, in 7 plants, each starting one year after the previous (i.e. a ramped throughput).
- (iv) Storage of cemented product in 7 EPS type stores for circa [redacted] drums. If disposal was not available from 2045, then up to 11 stores would be required
- (v) Transport to GDF for disposal

There are two alternative variants to the large scale cement immobilisation described herein. The first is small scale where waste in sacrificial containers is immobilised. The second is dispersion in a polymeric matrix which then may also be encapsulated in grout. Neither has been assessed in detail at the current time.

Key Assumptions

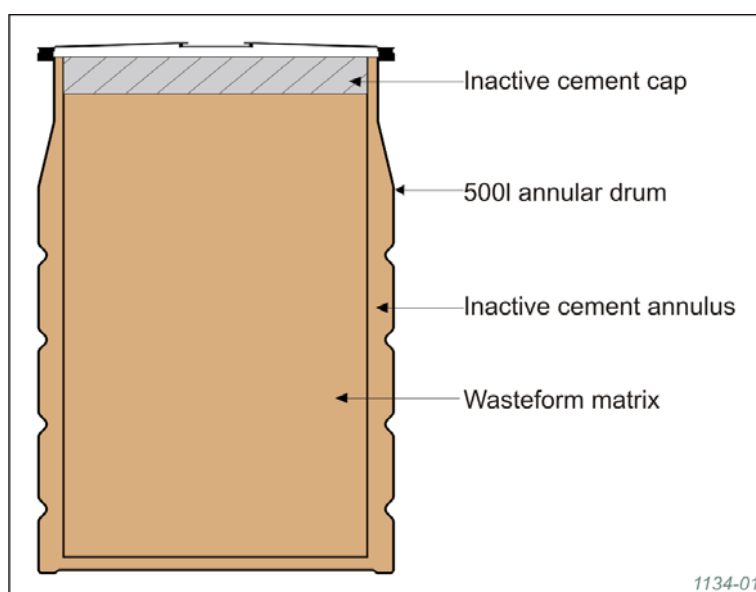
An assessment of the plutonium-loading in the waste form package has been performed which has considered mass & volume, total activity, fissile mass content, decay power output and dose rate¹⁷. From this study, if the waste is treated as ILW then the fissile content of the package is the limiting factor. A criticality safety assessment (CSA) has been developed for disposal of separated plutonium in the geological disposal facility for ILW. This considers criticality safety during transport, operations and post-closure (over a range of timescales).

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Plutonium Credible Options Analysis (Gate A) 2010

The number of plutonium cement waste packages produced is very sensitive to the specified loading of plutonium in the waste form. For the reference estimate described herein a plutonium-loading of 370g per 500 litre drum was adopted. It should be noted that a uranium oxide based cement product (DUCrete) has received a lot of research attention historically, and so incorporation of plutonium oxide in cement is considered to be a similar technical challenge that already has significant levels of technical underpinning.

A further study has recently been completed by RWMD on Packaging Options for Disposal of Plutonium Stocks. In this study the cement option is based on mixing a small quantity of PuO_2 powder with cement grout in an annular design 500-litre drum (see below).



There would be some uncertainty about the distribution of the PuO_2 powder in the grout, and it is possible that it will accumulate nearer the base of the package due to its high density. A sub-option is to mix the PuO_2 powder at a higher concentration in small containers to be encapsulated with further cement grout within the 500-litre drum, forming a thicker annulus. A potential advantage of this sub-option would be to isolate the PuO_2 powder more centrally in the package, providing greater certainty about its location in the package.

The maximum mass of plutonium as oxide per package suggested by the submission to RWMD was 7.5kgHM, the quantity currently held in AGR derived PuO_2 storage cans. This quantity of PuO_2 powder was not considered appropriate by RWMD, due to its high radiogenic heat output. In the RWMD analysis, based on a limiting factor of 3W radiogenic heat output, the maximum mass of plutonium oxide per 500L drum of waste was given as 0.37kg,

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The RWMD assessment also considered criticality safety during transport and operations. It concluded that operational criticality safety may be less restrictive than the transport criticality safety. Overall, criticality safety limits are likely to be unattractively restrictive features for the cement grout encapsulation due to the high number of drums required. On the positive side, due to greater packing densities, this option was shown to significantly reduce (-12.4%) the footprint of the GDF against the Design System Safety Case (DSSC) with a comparable reduced cost of [REDACTED]. Hence, depending on plutonium loadings for this wasteform, the package still has some merits for future consideration.

As the plutonium incorporation rate is very low and highly dispersed, sampling and analysis of packages prior to encapsulation was not considered to be required. The key steps being receipt and weighing of the can, opening and loading of the material into the disposal container.

Similarly, due to the low incorporation rates high levels of impurities are assumed to be tolerable e.g. chloride contaminated plutonium does not require a pre-treatment. The plutonium residues immobilisation facility is judged not to be required for this option, as the materials should be suitable for encapsulation in cement and therefore would be treated with the bulk plutonium.

It should be noted that, if plutonium can be incorporated into a cement wasteform, then the residue HIP treatment facility would not be required and that the plutonium residues would be treated by the cement plant.

Cost Data and Uncertainty

Cost Data for the Process Blocks

Detailed cost data are provided in Table 2 for a plutonium-loading in the waste form of 370g per 500 litre drum. Derived estimates for plutonium-loadings of 500 and 1000g are also provided that illustrate the sensitivity of the disposal cost to the plutonium-loading parameter; this sensitivity arises primarily due to the number of packages required.

1. Store – PuO₂ powder prior to encapsulation

Prior to operation of the plutonium cement encapsulation plant the material will have to be safely and securely stored. Estimates for this have been taken from the Sellafield LTP. Based on throughput assumptions detailed in Table 2, it is thought likely that SPRS extensions would not be required should this option be implemented commencing in 2012. However, there is only a small margin of available space available and so the high end estimate for this option will include the cost of an extension in 2032. Hence this is included as a risk rather than a base assumption.

2. Cement plant (CEM1)

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Costs for immobilisation of plutonium in cement matrix were derived from UKAEA estimates. Plant construction costs have been derived from proposed ILW plants to be constructed at Harwell and Dounreay Sites. [UKAEA estimates are based on 115 teHM plutonium]. However, most recent packaging assessment from RWMD assumes that a loading of 370g per package is feasible, and so throughput requirements for this plant are based on this incorporation rate. Assuming a 40 year operating life for such a plant, then 7 such cementation plants would be required to support this option.

3. Encapsulated Product Store

Following encapsulation the plutonium-bearing cemented product is surface stored until ILW disposal facility (i.e. GDF) is ready. Storage costs for cemented product were based on Sellafield Encapsulated Product Store. Lifecycle costs (Capital, Operation, Decommissioning) for storage of 12,500 m³ of ILW are taken from the Sellafield LTP10. Based on a [redacted] package capacity, this option would require up to 7 stores of an EPS design, assuming that transport to a GDF commences in 2047, other wise up to 11 stores would be required.

4. Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and troubleshooting in support of operations are assumed.

5. Transport and Disposal of waste form packages in a ILW GDF

For the reference cost estimate transport costs for transfer of the waste form package to the disposal facility were given as £625 per drum¹⁸. Disposal costs for each drum of £4500 were assumed.

Cost Sensitivity & Uncertainty

The loading of plutonium in the waste form has a very large impact on cost estimates for cement disposal of plutonium. The sensitivity of plutonium encapsulation costs to this parameter is shown below for 250, 500 and 1000g per waste form package. Increasing the plutonium loading in the waste form reduces the number of waste form packages and therefore the overall disposal costs.

A upper/mid-range plutonium-loading of 370g was used in the reference cost estimate. Given the sensitivity of the cost estimates to the plutonium-loading further development work to optimise plutonium-loading through consideration of both the waste form and disposal facility concept is likely to be beneficial.

Technical Maturity

The use of cement grouts for the disposal of ILW wastes is a well-proven technology that is mature and widely available, with good UK experience. The

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technology readiness level is judged to be 7 to 8 i.e. “system prototype demonstration in relevant environment”.

Due to the sensitivity of cost estimates to plutonium loadings further development work to optimise plutonium-loading through consideration of both the waste form and disposal facility concept may lead to marked reductions in estimates for disposal as this waste form. Emplacement of the waste form in a facility based on the HLW/SF disposal facility may allow increased plutonium loadings, however, further constraints may apply that offset some of the cost benefit gained, for example, a requirement to prove long-term durability of the waste form through addition of engineered barriers.

Lead Time

Estimates of for the design and build of the infrastructure to encapsulate plutonium as cement are included in Table 2.

Environmental Impact

The environmental discharges from the relatively simple processing should be minimal from a new plant and zero from storage activities. The longer term environmental impact will be dominated by the assessment of the durability of the waste form with the GDF.

The energy and resource use for a cement plant is relatively heavy but the environmental impacts are well known.

Assuming [redacted] waste form, design of concrete 2,371 kg/cu.m and CO₂ to air rate of 120 te per kilo-tonne of concrete => 40Mte CO₂. (cementindustry.co.uk).

A higher incorporation rate would dramatically reduce this impact. The environmental sensitivity to incorporation rate would follow approximately the same curve as the cost impact to incorporation rate, which is discussed under sensitivities in the main body of the report.

The cement option would require up to 7 Engineered Product Stores for storage of the encapsulated product. This impact has not yet been calculated due to the uncertainty around the number of stores that would be required but is thought in the extreme worst case to be broadly similar to the impact of an SPRS type store.

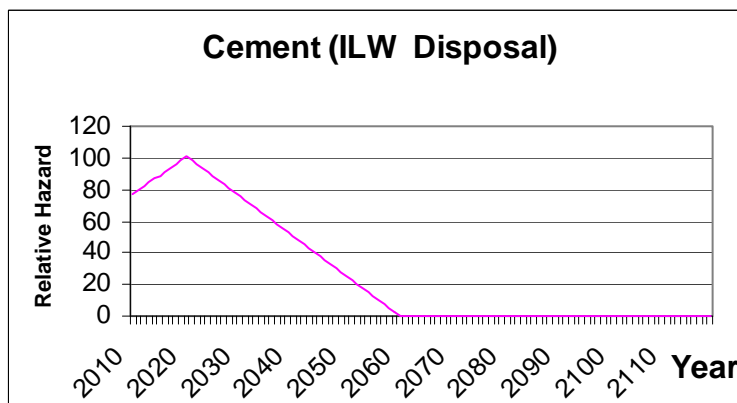
Socioeconomic Impact (in man-years)

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**Plutonium
Credible Options Analysis (Gate A)
2010**

Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			
Other Construction			
Other operations			

Safety – Relative Hazard Over Time



Assumes that conditioning plant is available in 2020, that cementation plants operates for 40 years, ILW disposal commences in 2040 and completed in 2106 in line with Sellafield assumptions.

Proliferation Resistance

From the discussion and charts in section 6.7, cement immobilisation does essentially reduce the state-sponsored proliferation risk from the material, albeit not a much as some other options. This is to be expected as there is a relatively non-robust chemical barrier added to the material, it is now in a non-mobile state but the plutonium isotopes have not been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion “proliferation risk”.

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<p>Disposability</p>
<p>An assessment of the plutonium-loading in the waste form package has been performed which has considered mass & volume, total activity, fissile mass content, decay power output and dose rate. [17] From this study, if the waste is treated as ILW then the fissile content of the package is the limiting factor. A criticality safety assessment (CSA) has been developed for disposal of separated plutonium in the geological disposal facility for ILW [15]. This considers criticality safety during transport, operations and post-closure (over a range of timescales).</p>
<p>Knowledge gaps and R&D needs</p>
<p>As described above the use of cement grouts for the disposal of ILW wastes is a well-proven technology. Due to the sensitivity of cost estimates to plutonium loadings further development work to optimise plutonium-loading through consideration of both the waste form and disposal facility concept may lead to marked reductions in estimates for disposal as this waste form.</p> <p>Further work to improve the durability of the waste form requires further investigation and research.</p> <p>The disposability of the plutonium cement waste form and its accommodation with the disposal facility are key areas for further R&D. NDA has work being undertaken by UKAEA and NNL examining options for this under its generic research framework programme, known as DRP.</p>
<p>Risks and Opportunities</p>
<p>Risks</p> <p>Durability of waste form not suitable for higher incorporation rates. The QA requirements for the waste packages may be onerous, as required by Regulators and GDF acceptance criteria, and hence add to the cost of this options</p> <p>The proliferation resistance afforded by the waste form may prove unacceptable, particularly at higher plutonium incorporation rates.</p> <p>Opportunities</p> <p>There may be potential to look at cementitious encapsulation as part of a co-disposal programme with other ILW waste forms, particularly for low volume plutonium families. This is unlikely to provide a bulk solution for plutonium immobilisation but may be suitable as part of a number of solutions to the total</p>

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inventory.
Time constraints and timescale decision drivers
<p>The design and build of the necessary infrastructure to encapsulate plutonium in cemented form is relatively straightforward due to the maturity of the technology. The major impact on timescales and decisions are driven by the plutonium loading of the waste form/package for two reasons.</p> <p>Firstly, if a low plutonium loading of 250g per drum is adopted then the delivery of a massive engineering project would engage considerable UK resources.</p> <p>Secondly, as the cost estimate is sensitive to plutonium loading a programme of work is required to optimise this. This would require significant research and development to define, prove and agree plutonium-loading in the waste form and its predicted behaviour and acceptability in a disposal facility. There is currently no concept for a plutonium disposal facility.</p> <p>The design and build of a plutonium cement facility without a specified waste form agreed between NDA, RWMD and Regulators would be at considerable risk.</p>
Stakeholder views
<p>Stakeholder views with respect to cement were not specifically sought, although a number of views were expressed. Some thought that this technology was not yet sufficiently underpinned by scientific or technical work. There was some concern raised that at the lower proven incorporation rates it could result in a very large number of packages and high waste and interim storage costs. One response was received highlighting some of the technical work which has been done to date on this subject.</p>
Policy Impacts
<p>There are no specific policy impacts surrounding plutonium as a waste disposal form. The environmental impacts, resulting from a low incorporation rate would make this option less attractive from a BPEO perspective. If it is to be considered further as a bulk solution then incorporation rates would need to be increased.</p>

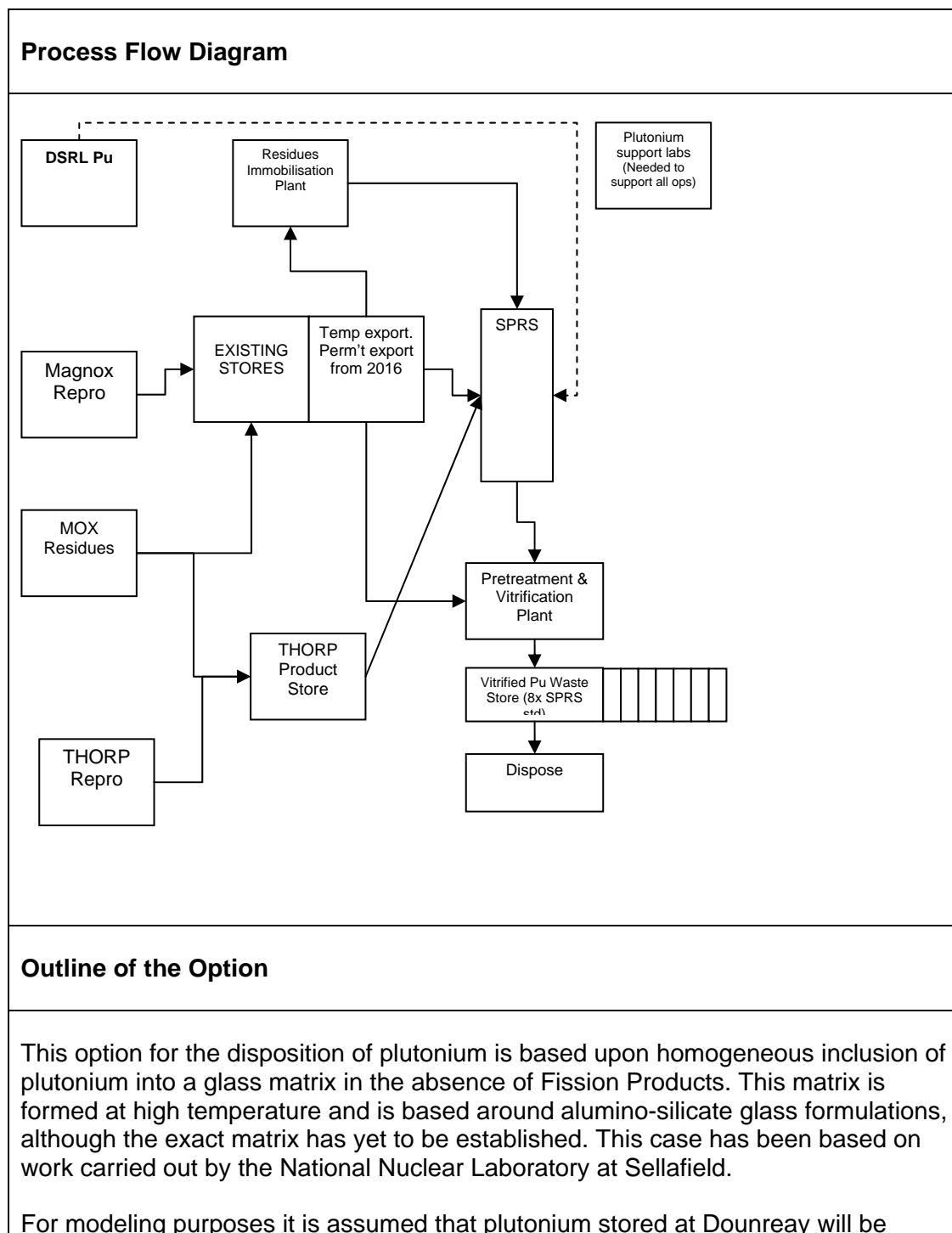
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Plutonium Credible Options Analysis (Gate A) 2010

CREDIBLE OPTIONS DATA

POLICY OPTION: DISPOSAL

Implementation Strategy 3: Vitrification



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transported to Sellafield for interim storage in SPRS (or similar appropriate store). However, most of the plutonium stored at Dounreay is mixed with HEU (High Enriched Uranium) and storage of HEU is contrary to existing planning permissions and safety cases for SPRS, so some work is assumed to have been completed to enable this material to be stored at Sellafield. The immobilisation process is likely to be required to include the HEU as well as the plutonium.

Inclusion of Fission Products (FPs) into the matrix was considered but was not pursued in detail at this time on the grounds that to deliver that option would require a slowing down of the hazard reduction work associated with Highly Active Liquor and, further, that glass formulations capable of retaining FPs in the matrix generally have a poor solubility in relation to plutonium, thus limiting plutonium loading and consequently giving rise to a very large number of containers for disposal.

Other heterogeneous alternatives such as low specification MOX in cans disposed in an HLW glass matrix and packaged were also not pursued at this time for the same reasons.

It is assumed that the current WVP does not carry out this option primarily due to the facts that the current technology is not compatible with that required for vitrification of plutonium, the limited lifetime of the facility and the “beta- gamma” status of the current plant. A new alpha facility is therefore proposed.

This option includes all civil material which is currently in UK safeguards. If additional UK owned material were to enter safeguards and be added to the inventory then the estimates of cost for the plan would need to be reviewed.

The option in summary

- i) Storage of plutonium in existing stores and SPRS until withdrawn for treatment
- ii) Pre- Treatment and Packaging including characterisation in the Heat Treatment Facility
- iii) Provision of new plutonium support laboratories
- iv) HIP of plutonium residues as required
- v) Provision of vitrification immobilisation facility
- vi) Manufacture of immobilised plutonium vitrified waste form
- vii) Storage in purpose built stores pending availability of disposal facility (similar to SPRS)
- viii) Consolidation of SPRS cans into vitrification canisters in new facility
- ix) Transport of waste to disposal site once GDF available
- x) Disposal of waste in UK GDF
- xi) Decommissioning of SPRS, extension modules, characterisation, heat treatment and packaging facilities, immobilisation plant, transport assets.

A preliminary cost estimate has been provided by NNL for the design, build and operation of a vitrification facility to treat approximately 100 teHM plutonium and immobilise as a vitrified waste form. These costs were in part extracted from those for SMP and Sellafield Product and Residue Store (SPRS). Key assumptions used

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in this assessment are described below.

Additionally, the wasteforms will need to be produced and appropriately verified against agreed Regulatory specifications, which could potentially involve significant extra costs. These potential costs are not included in this assessment.

Assumptions

- Project commences 2015
- Material may be withdrawn from existing stores or new stores for characterisation
 - Approximately 40 teHM of the material requires sampling
- New plutonium support laboratories will be required for sampling and treatment
- Pre-treatment to remove/reduce Chloride required – carried out in SPRS Heat Treatment Facility
- Empty plutonium cans disposed of at Sellafield as PCM
- Plutonium residues incompatible with vitrification route (no R&D done to date on impurity acceptance) so new residue HIP facility required as well.
- "waste" cans will be produced in a new UK facility on or adjacent to Sellafield site over 21 years (assumes 10% plutonium incorporation) and placed in SPRS type stores.
- In addition to the existing SPRS, an additional 7 SPRS modules / extensions
- [REDACTED]
- [REDACTED]
- [REDACTED]
- Prior to disposal, cans will be placed in WVP containers in new overpack facility
- Total disposal canisters is [REDACTED]
- UK GDF available for receipt of higher activity waste from 2075
- Transport of waste to GDF will be achieved via a fleet of new flasks over a 20 year period
- Disposal in GDF is assumed to be in canisters at a cost of [REDACTED] per canister

Exclusions

Non safeguarded materials

Overseas materials which is assumed to be returned to customers

Cost Data and Uncertainty

Cost data for the process blocks

Cost estimates are provided for a plutonium-loading in vitrified product of approximately 10% by weight. Order of magnitude cost estimate for an

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immobilisation facility have been made and given in Table 3. The estimated total lifetime cost of the facility is the sum of individual costs for R&D, Capital, operation and maintenance, POCO and Decommissioning. These costs were used with transport and disposal costs to construct a lifecycle cost estimate for plutonium immobilisation.

1. Store – PuO₂ powder prior to encapsulation

Prior to operation of the plutonium vitrification plant the material will have to be safely and securely stored. Estimates for this have been taken from the Sellafield LTP. This does not include extensions to the SPRS facility, although in the high estimate an assumption is made that one may be needed in case the deployment of the disposition technology is delayed². Hence this is included as a risk rather than a base assumption

2. HIP Plant and Disposal for Plutonium Residues

Capex for this plant is [REDACTED] with an assumed operating cost of [REDACTED] per year. Throughput is [REDACTED] cans per year so the plant runs for approximately 6 years. Commences around 2022.

3. SPRS Heat Treatment Facility

The purpose of this facility is to sample, characterise and, if necessary, pre-treat the plutonium prior to long term storage. Data for this block is derived from Sellafield LTP10.

4. Vitrification plant

This cost estimate is based on data provided in reference 2. Technology development costs have been estimated and included, [REDACTED] The order of cost estimate for the plant was developed from NNL's process block diagram with each stage assigned a glovebox or room. Costs for design, build, operation and decommissioning of the immobilisation plant and ancillary infrastructure are given. Data for this block is derived from National Nuclear Laboratory estimates [1].

5. Immobilised Product Store

Following immobilisation the plutonium-bearing cans are stored in SPRS-type modules. In addition to the existing SPRS, an additional 7 SPRS modules will be required, [REDACTED] [1]

The cost basis for the SPRS modules is given in the Sellafield LTP10. It is assumed that there is enough space for these modules.

6. Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and

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troubleshooting in support of operations are assumed [7].

7. Transport and Disposal of waste form packages in a HLW/SF-type disposal facility

Prior to emplacement the vitrified waste form, in SPRS cans, will be loaded in Waste Vitrification Plant (WVP) canisters. Two WVP canisters are included within one disposal canister. Costs for overpacking are given.

A best estimate for this facility and transport costs has been taken from NNL work.

Disposal costs have been calculated assuming [redacted] disposal cost per disposal canister.

Cost sensitivity and uncertainty

Cost uncertainty is dictated by a number of technical risks which require areas of further development to underpin, see Knowledge Gaps and R&D needs.

As with other options, a major determining factor in the overall cost estimate for this option is the incorporation rate of PuO₂ within each waste package. Even small improvements to the incorporation rate results in considerable savings at every stage beyond the vitrification process, due to the lower number of packages that require interim storage, transport, overpack and GDF emplacement. The incorporation rate for plutonium in glass needs to be underpinned.

Technical Maturity

Interim Storage: TRL = 9

Interim storage of plutonium oxide powder is well understood and is implemented on an industrial scale and so is considered to have a technical maturity of 9. Estimates vary as to the time period for which is technical maturity is considered valid but an assumption has been made that it is valid for around 30 years.

plutonium can emptying: TRL = 9

Routine activity , although may be challenging with older cans

Heat Treatment and packaging: TRL =3

The contaminants, their ease of removal and thus scope of the treatment and chloride removal process is not well understood

Immobilisation plant : TRL = 3

Still in early R&D phase

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Plutonium Credible Options Analysis (Gate A) 2010

Immobilised Product storage TRL = 3

Still in early R&D phase

Disposal : TRL = 2-3

No fully developed systems for disposal

Lead Time

The detail lead time for the new facilities are as discussed below:

SPRS Type Product Stores: The lead time for these facilities is 5 years and, as they are required in [REDACTED] the first project will need to start in 2020.

SPRS Heat Treatment/packaging plant: A new repack facility is assumed to have a lead time of 3 years giving an earliest start to repackaging operations of 2024. No major R&D lead time considered, although the scope of the treatment plant is not clear. Significant permissioning and licensing activities expected

Vitrification plant

The plant has a lead time of 7-10 years and construct¹

Waste transports

No lead time is required for this but it is assumed that waste is transported to the GDF from 2075 onwards over a 20 year period.

Environmental Impact

The environmental discharges from the processing similar to that for HLW vitrification should be minimal from a new plant and zero from storage activities. The longer term environmental impact will be dominated by the assessment of the durability of the waste form with the GDF.

The energy use for a vitrification plant is relatively heavy but is known.

Assuming 104 teHM of plutonium at 10% incorporation rate gives circa 900 te of glass to be melted. Dependent on the type of induction heater the energy usage can range between 5 – 20 kWh/ kg glass. This gives a total energy demand of 18,000 MWh which equates to 11,000 te CO₂ based on Savannah River Plant

The environmental impact of a SPRS type store, which is assumed to be required

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**Plutonium
Credible Options Analysis (Gate A)
2010**

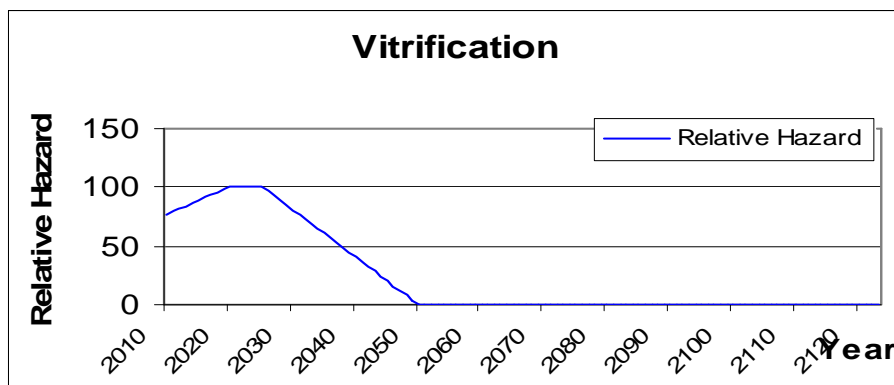
for the storage of encapsulated product, is around 24,700 te CO₂ eq.

Socioeconomic Impact

Socio-economic Impacts are calculated using the figures derived in the ERM report and applied to the costs for each option.

Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			
Other Construction			
Other operations			

Safety – SED scores over time



The shape of the graph reflects the separated stock building up until conversion of the material into vitrified product, which reduces the relative hazard in line with the production profile.

Proliferation Resistance

From the discussion and charts in section 6.7, vitrification immobilisation does

NOT PROTECTIVELY MARKED - REDACTED

considerably reduce the state-sponsored proliferation risk from the material, albeit not as much as the reuse options. This is to be expected as there is a relatively robust chemical barrier (glass) added to the material, it is now in a non-mobile state but the plutonium isotopes have not been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion “proliferation risk”.

Disposability

A full disposability assessment has not been made. It has been assumed the waste form will be emplaced in a HLW/SF type disposal facility. However, there are potentially significant uncertainties on the cost of disposal including but not limited to:

- Ability to demonstrate a criticality safety case with the assumed plutonium loading
- GDF Implementation scope and schedule
- Ability to dispose in a single rock type including potential spatial limitations
- Ability to dispose of the baseline inventory in a single facility

Additionally, the wasteforms will need to be produced and appropriately verified against agreed Regulatory specifications, which could potentially involve significant extra costs. These potential costs are not included in this assessment.

Knowledge gaps and R&D needs

A preliminary list of knowledge gaps and R&D needs is shown below.

- Development of a waste form specification for storage and disposal;
- Detailed assessment of plutonium vitrified product as a waste form, including GDF package and operating envelope;
- Qualification of waste form for disposal;
- Underpinning of plutonium incorporation rate and process;
- Process development and establishment of process envelope;
- Detailed assessment of Immobilisation facility design and costing, including OR Modelling to confirm throughput;
- Determine impact of storing plutonium vitrified product in SPRS, including assessment of passive cooling regime and ability to meet export and import requirements;
- Review Sellafield Site Layout and confirm SPRS can be extended and second/third SPRS facility can be built to provide storage for [REDACTED] packages, storage;
- Confirm SPRS is the most appropriate storage facility type;
- Establish GDF design concept.

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Risks and Opportunities

Given the low TRL assessment and, consequently, the large number of knowledge gaps and R&D needs there are a number of significant risks to address. These include but are not limited to:

- Inability to qualify plutonium vitrified product as disposable waste form;
- plutonium incorporation rate is not underpinned;
- Proof of process is not achieved;
- Underpinning R&D programme reveals problems which will increase costs;
- Self-heating aspects of the package impact adversely on product quality;
- Product quality is affected by radiation damage particularly over long timescales;
- A safety case for a High Temperature process does not gain regulator sanction on a production scale;
- Costings to date represent new plant concepts which have not been accurately estimated;
- A much greater programme is required to qualify the waste form than is merited purely on technical grounds

Opportunities exist to avoid the significant cost of product storage by only producing the product when the GDF is available and directly disposing to the GDF.

Time constraints and timescale decision drivers

The cost estimate is sensitive to the plutonium loading of the waste form package. A significant development programme will be required to:

- Prove the technology (i.e. develop the wasteform)
- Prove the waste form and compatibility with disposal facility concept

The design and build of a facility without proving the technology at pilot scale and without a specified waste form agreed between NDA, RWMD and Regulators would be at considerable risk.

The impact of americium in-growth is not considered crucial for this option although costs would increase to provide shielding for aged product in the various facilities

Stakeholder views

Stakeholder views with respect to vitrified waste in the absence of Fission Products were not specifically sought, although a number of views were expressed. Some thought that this technology was not yet sufficiently underpinned by scientific or

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Plutonium Credible Options Analysis (Gate A) 2010

technical work. There was some concern raised that the option would have high waste and interim storage costs.

Policy Impacts

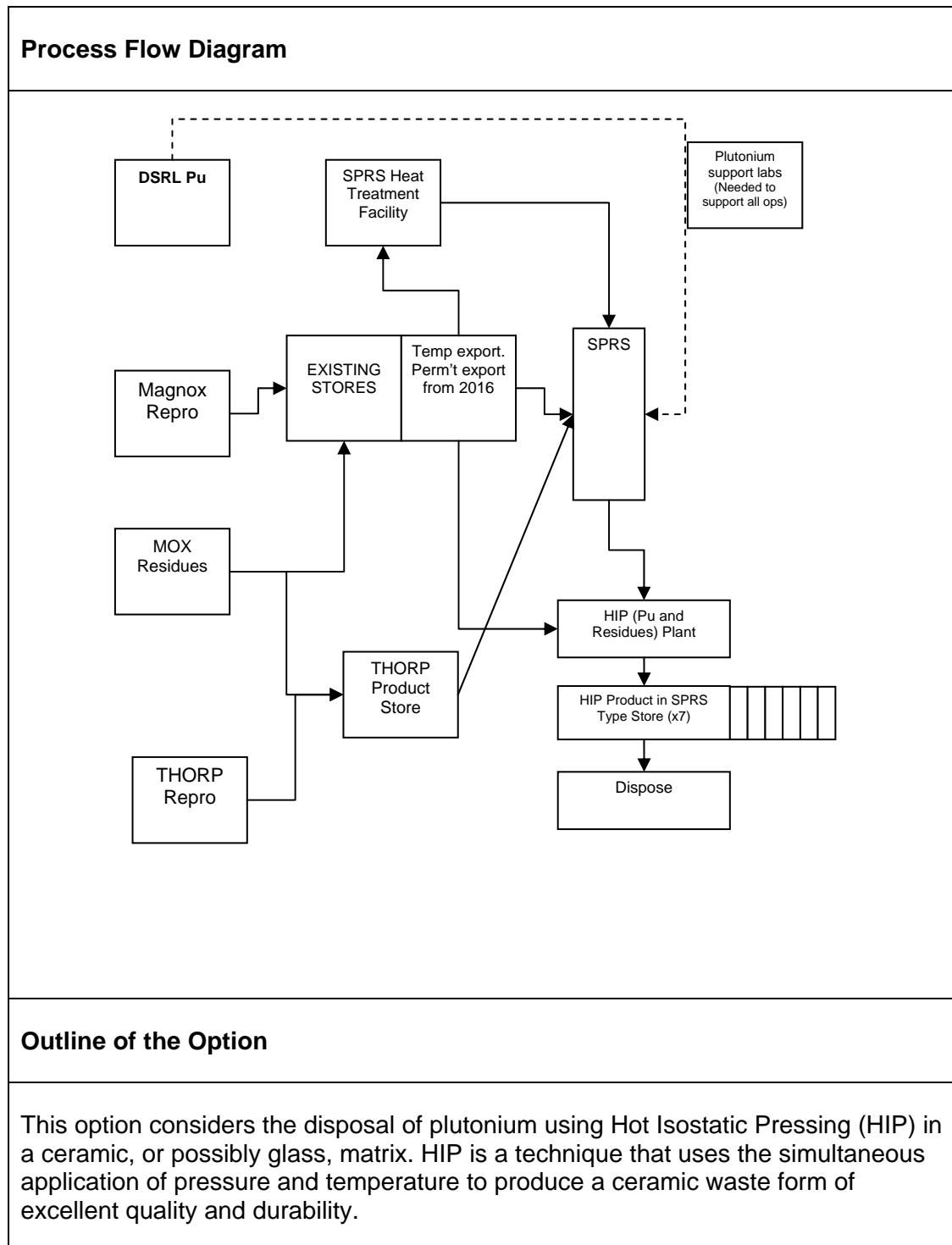
There are no specific policy impacts surrounding plutonium as a waste disposal form, although the impact on the GDF project may be significant

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CREDIBLE OPTIONS DATA

POLICY OPTION: DISPOSAL

Implementation Strategy 4: Hot Isostatic Press



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There is worldwide interest in the immobilisation of plutonium in both vitrified and ceramic waste forms. The US DoE has examined ceramics in particular as part of a programme on disposition for US surplus weapons grade plutonium. In this case the DoE work expressed a preference for a ceramic-based waste form over glass as:

- Ceramic form is more robust to theft, diversion or reuse as extraction of plutonium is more complicated;
- Ceramic form is expected to be more durable in a GDF environment;
- Ceramic form offers potential costs savings over glass;
- Technology is more flexible.

In the UK, this technique is being developed by the National Nuclear Laboratory at Sellafield for the immobilisation of plutonium containing residues in a ceramic waste form. The technology has been developed in collaboration with the Australian Nuclear Science and Technology Organisation (ANSTO).

For modeling purposes it is assumed that plutonium stored at Dounreay will be transported to Sellafield for interim storage in SPRS (or similar appropriate store). However, most of the plutonium stored at Dounreay is mixed with HEU (High Enriched Uranium) and storage of HEU is contrary to existing planning permissions and safety cases for SPRS, so some work is assumed to have been completed to enable this material to be stored at Sellafield. The immobilisation process is likely to be required to include the HEU as well as the plutonium.

Numerous and extensive studies have been undertaken on suitable ceramic hosts for plutonium. Based on work undertaken the preferred candidate waste forms are titania pyrochlore and zirconolite. However, due to the expense and difficulties associated with alpha active work these studies have overwhelmingly been undertaken using surrogate materials for plutonium e.g. cerium and uranium.

A process flow diagram for the HIP process is provided. The key steps are:

- i. Storage in existing stores, SPRS, no SPRS new modules required,
- ii. HIP of plutonium powders and wastes
- iii. Storage of ceramic products
- iv. Transport to GDF for disposal

Heat treatment in the SPRS facility (see previous options) of plutonium powders may not be necessary as the HIP process has a large amount of pre-processing in order to make the powder a suitable feedstock for the HIP process. However, due to the large amount of chloride in the chloride contaminated plutonium, and the low level of technical maturity for this process, the Heat Treatment Facility associated with SPRS is included in this scenario as shown in the diagram.

A preliminary cost estimate has been provided by NNL for the design, build and operation of a HIP facility to treat approximately 104 te plutonium and immobilise as a zirconia based ceramic.[1] These costs were in part extracted from those for SMP and Sellafield Product and Residue Store (SPRS). Key assumptions used in this

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assessment are given in references [1] and [15] and described below.

Key Assumptions

The waste that is to be immobilised is a free flowing plutonium oxide powder. The Heat Treatment Facility is required for a characterisation or pre-treatment, even though there is some degree of feed preparation required for the HIP process. The waste is immobilised as a ceramic puck with a plutonium loading of 10%wt plutonium. It has been assumed that emplacement will occur in a HLW/SF type disposal facility and cannot start until 2075.

The waste is emplaced as ceramic pucks in Sellafield Product Residue Store (SPRS) cans with approximately [redacted] plutonium per SPRS can. [redacted] SPRS cans are loaded in one Waste Vitrification Plant (WVP) canister, resulting in [redacted] plutonium per WVP canister, and two WVP canisters are included within one disposal canister.

For disposal in HIP wasteform, the limiting factor for the quantity of plutonium for incorporation from the latest RWMD study appears to be radiogenic heat of the packages, and not criticality.

This results in around [redacted] disposal canisters (total of [redacted] plutonium per disposal canister). The canisters are emplaced in deposition holes with one canister per hole. The distance between deposition holes is [redacted].

The waste is stored prior to disposal and these costs are based on SPRS plus module extensions.

The HIP immobilisation plant will operate for 26 years at ~ 4t p.a. and includes 2 yr commissioning.

A significant R&D programme will be required prior to design and build.

Decommissioning costs will be 40% of capital and operating costs at 10% of capital p.a.

Cost Data and Uncertainty

Cost data for the process blocks

Cost estimates are provided in Table 4 for a plutonium-loading in ceramic of approximately 10% by weight. Order of magnitude cost estimate for a ceramic immobilisation facility have been made and given in reference [1]. The estimated total lifetime cost of the facility is the sum of individual costs for R&D, Capital, operation and maintenance, POCO and Decommissioning. These costs were used with transport and disposal costs to construct a lifecycle cost estimate for plutonium immobilisation using a HIP process.

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1. Store – PuO₂ powder prior to encapsulation

Prior to operation of the plutonium ceramic encapsulation plant the material will have to be safely and securely stored. Estimates for this have been taken from the Sellafield LTP and this does not include extensions to the SPRS facility. Due to the throughputs and technical maturity of this option (compared to vitrification), the assumption is that an extension to SPRS is considered unnecessary and is not included in a high risk cost provision².

2. SPRS Heat Treatment Facility

The purpose of this facility is to sample, characterise and, if necessary, pre-treat the plutonium prior to long term storage. Data for this block is derived from Sellafield LTP10.

3. HIP Plant (HIP1)

This cost estimate is based on data provided in reference [1]. Technology development costs have been estimated and included, ~£41M. The order of cost estimate for the ceramic immobilisation plant was developed from>NNL's process block diagram with each stage assigned a glovebox or room. In order to provide best estimates and to assign capital costs the process was split into the following regions

- Feed Region
- HIP suite
- Canning Room
- Buffer Store
- Import/Export
- Off-gas system

Costs for design, build, operation and decommissioning of the ceramic immobilisation plant and ancillary infrastructure are given in Table 4.

4. Immobilised Product Store

Following immobilisation the plutonium-bearing ceramic pucks are stored in SPRS-type modules. The original SPRS and new modules are used to store the waste form packages until transfer and emplacement in an appropriate disposal facility.

The cost basis for SPRS modules is the same as the original SPRS. Based on the number of packages, [REDACTED]

[REDACTED].[2]

5. Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and

NOT PROTECTIVELY MARKED - REDACTED

troubleshooting in support of operations are assumed.[7]

6. Transport and Disposal of waste form packages in a HLW/SF-type disposal facility

Prior to emplacement the ceramic pucks in SPRS cans will be loaded in Waste Vitrification Plant (WVP) canisters. Two WVP canisters are included within one disposal canister.

A best estimate for transport costs has been taken from reference [1].

Disposal costs have been calculated assuming [redacted] disposal cost per disposal canister, reference [15].

Cost sensitivity and uncertainty

Cost uncertainty is dictated by a number of technical risks which require areas of further development to underpin, see Knowledge Gaps and R&D needs.

As with other options, a major determining factor in the overall cost estimate for this option is the incorporation rate of PuO₂ within each waste package. Even small improvements to the incorporation rate results in considerable savings at every stage beyond the HIP process, due to the lower number of packages that require interim storage, transport, overpack and GDF emplacement. The incorporation rate for plutonium in ceramic needs to be underpinned.

Technical Maturity

There is no active industrial experience, no active pilot scale experience and therefore the HIP process is accorded a low TRL level, of 2 – 3. However, no major showstoppers have been identified with use of the technology.

Development work to optimise plutonium-loading may lead to marked reductions in estimates for disposal.

Lead Time

Significant lead times to develop HIP technology are expected due to the need to accommodate a significant R&D programme. An active plant start date of 2025 has been used in the cost estimates.

The SPRS type storage modules are required to start 5 years before operations are required, for example the first module will commence development in 2020.

NOT PROTECTIVELY MARKED - REDACTED

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2010**

Environmental Impact

HIP requires significant quantities of energy as it requires extremely high pressures (~ 20,000 psi) and high temperatures (~1,000°C). The process has the potential for generating contamination due to the grinding and dry mixing of wastes and carrier matrix, although this should be contained through the design of the containment and ventilation system.

The safety and operational complexities mean that the process plant and abatement system is more complicated and therefore more expensive to build, operate and maintain. No qualitative assessment of this impact has yet been done. This will be progressed as the technology becomes sufficiently mature for reasonable assessment to be undertaken.

There may be additional plant complications and discharges due to the removal of non-radiological impurities (e.g. chlorides).

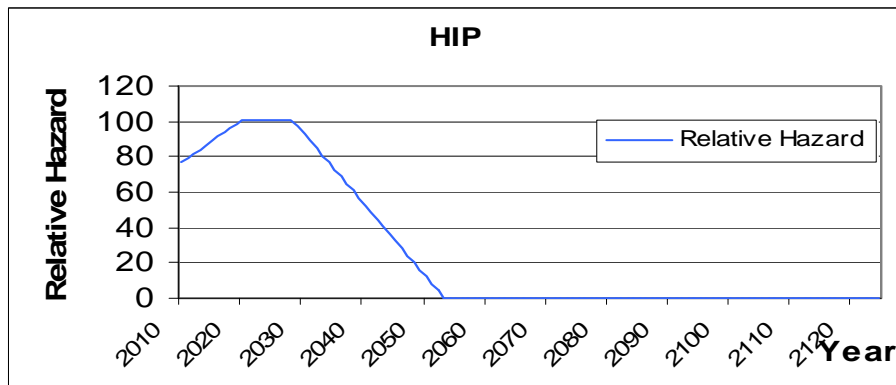
The environmental impact of a SPRS type store, which is assumed to be required for the storage of encapsulated product, is around 24,700 te CO₂ eq.

Socioeconomic Impact

Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			
Other Construction			
Other operations			

Safety – SED scores over time

NOT PROTECTIVELY MARKED - REDACTED



Proliferation Resistance

From the discussion and charts in section 6.7, HIP ceramic immobilisation does considerably reduce the state-sponsored proliferation risk from the material, albeit not as much as the reuse options. This is to be expected as there is a relatively robust chemical barrier (inert ceramic) added to the material, it is now in a non-mobile state but the plutonium isotopes have not been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion “proliferation risk”.

Disposability

A full disposability assessment has not been made. It has been assumed the waste form will be emplaced in a HLW/SF type disposal facility. Disposal costs have been calculated assuming [redacted] disposal cost per disposal canister, reference [15]. However, there are potentially significant uncertainties on the cost of disposal including but not limited to:

- Ability to demonstrate a criticality safety case with the assumed plutonium loading
- GDF Implementation scope and schedule
- Ability to dispose in a single rock type including potential spatial limitations
- Ability to dispose of the baseline inventory in a single facility

Additionally, the wasteforms will need to be produced and appropriately verified against agreed Regulatory specifications, which could potentially involve significant extra costs. These potential costs are not included in this assessment.

Knowledge gaps and R&D needs

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A preliminary list of knowledge gaps and R&D needs is shown below.

- Development of a waste form specification for storage and disposal;
- Detailed assessment of plutonium Ceramic as a waste form, including GDF package and operating envelope;
- Qualification of waste form for disposal;
- Underpinning of plutonium incorporation rate and process;
- Process development and establishment of process envelope;
- Detailed assessment of Ceramic Immobilisation facility design and costing, including OR Modelling to confirm throughput;
- Determine impact of storing plutonium Ceramic in SPRS, including assessment of passive cooling regime and ability to meet export and import requirements;
- Review Sellafield Site Layout and confirm SPRS can be extended and second SPRS facility can be built to provide storage for 7 storage units;
- Confirm SPRS is the most appropriate storage facility;
- Establish GDF design concept.

Risks and Opportunities

Given the low TRL assessment and, consequently, the large number of knowledge gaps and R&D needs there are a number of significant risks to address. These include but are not limited to:

- Inability to qualify plutonium Ceramic as disposable waste form;
- plutonium incorporation rate is not underpinned;
- Proof of process is not achieved;
- Underpinning R&D programme reveals problems which will increase costs;
- Self-heating aspects of the package impact adversely on product quality;
- Product quality is affected by radiation damage particularly over long timescales;
- A safety case for a potentially high temperature, high pressure process does not gain regulator sanction on a production scale;
- Costings to date represent new plant concepts which have not been accurately estimated;
- A much greater programme is required to qualify the waste form than is merited purely on technical grounds

Time constraints and timescale decision drivers

The cost estimate is sensitive to the plutonium loading of the waste form package. A significant development programme will be required to:

- Prove the technology

NOT PROTECTIVELY MARKED - REDACTED



Plutonium Credible Options Analysis (Gate A) 2010

- Prove the waste form and compatibility with disposal facility concept

The design and build of a facility without proving the technology at pilot scale and without a specified waste form agreed between NDA, RWMD and Regulators would be at considerable risk.

Stakeholder views

Stakeholder views with respect to HIP ceramic were not specifically sought, although a number of views were expressed. Most acknowledged that the technology to deliver this solution was still relatively immature

Policy Impacts

There are no specific policy impacts surrounding plutonium as a waste disposal form.

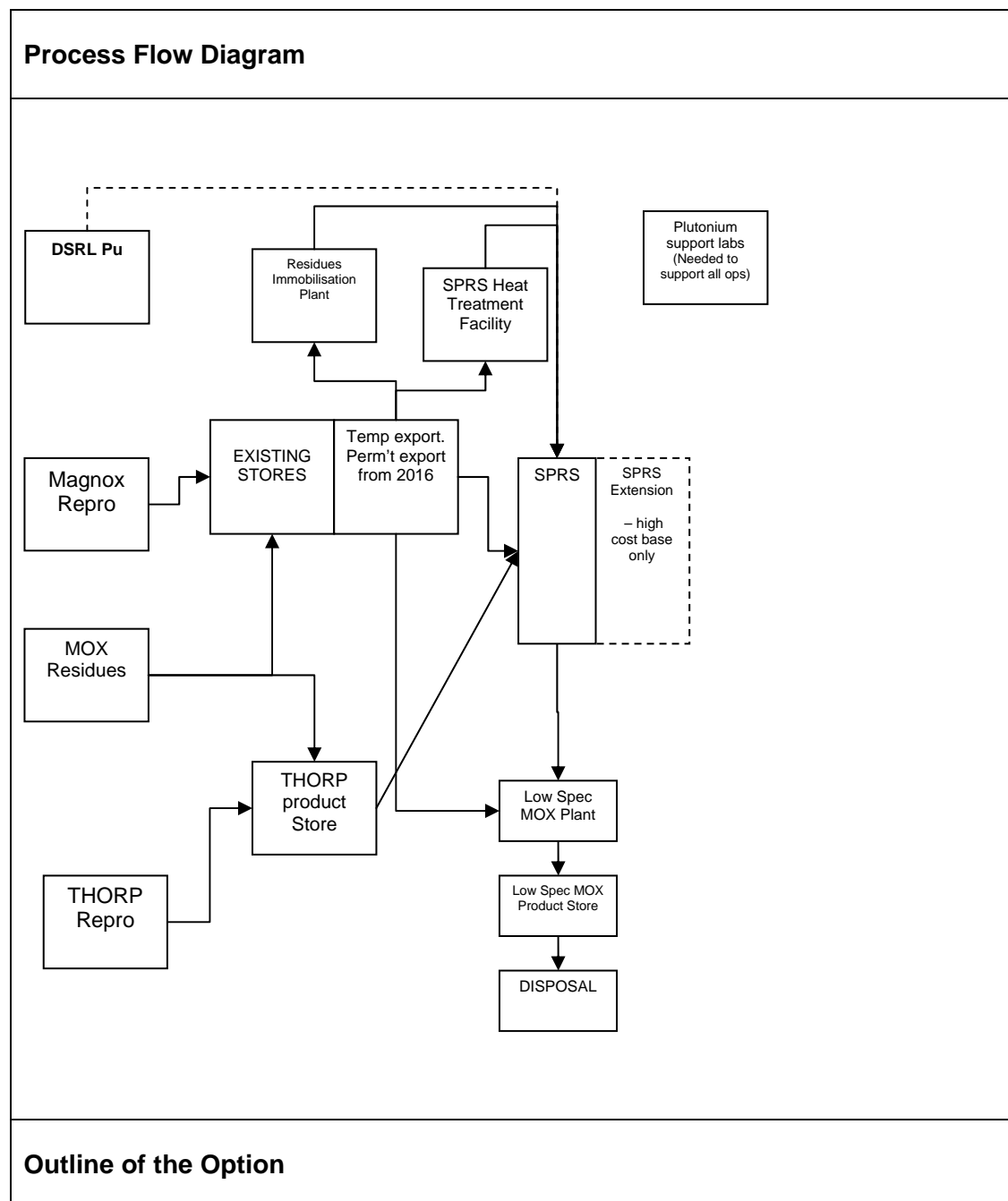
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Plutonium Credible Options Analysis (Gate A) 2010

CREDIBLE OPTIONS DATA

POLICY OPTION: DISPOSAL

Implementation Strategy 5: Low Specification MOX – New Production facility, disposal variant 2 (Assemblies)



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This option considers production of low spec MOX in the form of assemblies. Data is mainly drawn from the AREVA response to the NDA industrial underpinning exercise as well as published information associated with the US MOX plant, MFFF [22]. However there are a small number of areas where NDA consider that data is omitted or understated and, for these, estimates have been drawn from available industry and analogous plant data including National Nuclear Laboratory reports.

It should be highlighted that the capital cost of a new facility is based upon the estimate provided by AREVA for a high – spec MOX facility but operating costs are reduced to around 80% of that required for standard LWR MOx production.

Facilities which may be needed and are not included in the AREVA response include pre-treatment, that may be required as a result of the formation of radiolysis products in storage or contaminants, characterisation that is required for reuse and provision of plutonium analytical services beyond the life time of the current Sellafield plutonium support laboratories.

Due to the waste form requiring a different storage configuration for this option it is considered likely that a reduction of the current Sellafield capital baseline in regard to plutonium storage can be made.

It is assumed that the current SMP does not carry out this option due to the limited lifetime of the facility and the limited demonstrated capacity.

For modeling purposes it is assumed that plutonium stored at Dounreay will be transported to Sellafield for interim storage in SPRS (or similar appropriate store). However, most of the plutonium stored at Dounreay is mixed with HEU (High Enriched Uranium) and storage of HEU is contrary to existing planning permissions and safety cases for SPRS, so some work is assumed to have been completed to enable this material to be stored at Sellafield. The immobilisation process is likely to be required to include the HEU as well as the plutonium.

For the Low Specification MOX pellets in cans SMP was assumed to be used. However, the performance to date of SMP has not met expectations and as such it is assumed that the current SMP does not carry out this option. A new plant is assumed necessary due to the significant shortfall in rod production capacity. However it may be possible to enhance rod production in the existing SMP which means that the actual cost of delivering a Low Specification MOX option might lie between option 5 and option 6.

This option includes all UK civil material which is currently in UK safeguards. If additional UK owned material were to enter safeguards and be added to the inventory then the estimates of cost for the plan would need to be reviewed.

The option in summary

- i) plutonium storage in existing stores and SPRS until withdrawn for use
- ii) Construction of a new storage modules in SPRS from 2015
- iii) Pre-treatment and Packaging including characterisation in a new Heat

NOT PROTECTIVELY MARKED - REDACTED

Treatment Facility

- iv) Provision of new plutonium support laboratories
- v) Provision of low spec MOX fabrication plant (~50 teHM pa)
- vi) Manufacture of around [redacted] of Low Spec MOX fuel (based on 11% plutonium incorporation)
- vii) Storage of low spec assemblies in purpose built stores pending availability of disposal facility
- viii) Transport of Low Spec MOX fuel to disposal site once GDF available
- ix) Disposal of Low Spec MOX assemblies in UK GDF
- x) Decommissioning of SPRS, extension modules, characterisation, treatment and packaging facilities, MOX plant, transport assets.

Assumptions

- Project commences 2015
- Material may be withdrawn from existing stores or new stores for characterisation
 - Approximately 40 teHM of the material requires sampling
- New facilities will be required for sampling and treatment
- Pre-treatment to remove chloride required – other families may require treatment depending on timing (initial assumption that none required)
- Empty plutonium cans disposed of at Sellafield as PCM
- MOx fuel will be produced in a new UK facility on or adjacent to Sellafield site using depleted Uranium carrier, provided by NDA at nil cost
- Low spec MOX fuel stored in custom built store pending disposal route availability (3 off modules)
- Offsite transport of waste will be achieved over a 20 year period
- UK repository available for receipt of Low Spec MOX fuel 2075
- Disposal in GDF is assumed to be in standard canister containing a total of [redacted] – This could be mixed with other LWR spent fuels.

AREVA did not declare uncertainty on their estimates so -20% to +100% was used. Operating costs for the facility were reduced to 80% of the high specification MOX facility. For other facilities, annual operating costs, unless specifically included in LTPs, were estimated to 10% of capital costs, with an uncertainty of -10 to +20%. Similarly, recent parametric estimates for decommissioning of alpha plants indicate that appropriate provisions are 40% of capital costs. This is considered pessimistic for stores.

Cost data for the process blocks

Cost estimates are provided in Table 5 for a plutonium fabrication into low specification MOX of approximately 11% by weight. Order of magnitude cost estimate for a new MOX fabrication facility have been made and given in reference [11]. The estimated total lifetime cost of the facility is the sum of individual costs for R&D, Capital, operation and maintenance, POCO and Decommissioning. These costs were used with transport and disposal costs to construct a lifecycle cost estimate for plutonium immobilisation.

NOT PROTECTIVELY MARKED - REDACTED

1. Store – PuO₂ powder prior to immobilisation (SPRS)

Prior to operation of the Low spec MOX plant the material will have to be safely and securely stored. Estimates for this have been taken from the Sellafield LTP and do not require an extension to the SPRS facility due to the high throughput of the plant[2]. In case of plant deployment delays, a SPRS extension is assumed for the high cost base only.

2. SPRS Heat Treatment Facility

The purpose of this facility is to sample, characterise and, if necessary, pre-treat the plutonium prior to fabrication of Low specification MOX assemblies. Data for this block is derived from existing projects being carried out at Sellafield. If extensive pre-treatment is required, such as aqueous polishing then the cost is significantly greater.

3. Low Specification MOX plant

This cost estimate is based on data provided in reference [22]. No technology development costs have been included. The order of cost estimate for the plant was developed from AREVAs estimates for a commercial specification MOX plant. Operating costs are assumed to be 80% of that required for producing high specification MOX. Costs for design, build, operation and decommissioning of the plant and ancillary infrastructure are given [22].

4. Assembly Stores

Following immobilisation the assemblies are stored in assembly storage modules, not dissimilar to the current Vitrified Product Store, until transfer and emplacement in an appropriate disposal facility.

The capital cost basis for these modules (3 off) is taken from the AREVA response with other costs generated from application of operational and decommissioning norms.[22] [2]

5. Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and troubleshooting in support of operations are assumed [2].

6. Transport and Disposal of waste form packages in a HLW/SF-type disposal facility

Prior to emplacement the assembly waste form will be loaded into an overpack.

A best estimate for this facility and transport costs has been taken from reference [2].

Disposal costs have been calculated assuming [redacted] disposal cost per disposal

NOT PROTECTIVELY MARKED - REDACTED

canister, reference [3].

Cost sensitivity and uncertainty

Cost uncertainty is dictated by a number of technical risks which require areas of further development to underpin, see Knowledge Gaps and R&D needs.

As with other waste options, a major determining factor in the overall cost estimate for this option is the incorporation rate of PuO₂ within each waste package. Even small improvements to the incorporation rate results in considerable savings at every stage beyond the MOX process, due to the lower number of packages that require interim storage, transport, overpack and GDF emplacement. The incorporation rate for plutonium needs to be underpinned.

Additionally, for a new build Low Specification MOX facility it may not be necessary to provide as much functionality as that assumed for a fuel fabrication facility and as such the cost of this option is considered an upper bound. The Low Specification MOX option assuming pellets in cans produced in the existing SMP, is judged to be the lowest cost, Low specification MOX option.

Technical Maturity

Interim Storage: TRL = 9

Interim storage of plutonium oxide powder is well understood and is implemented on an industrial scale and so is considered to have a technical maturity of 9. Estimates vary as to the time period for which is technical maturity is considered valid but an assumption has been made that it is valid for around 30 years.

Plutonium can emptying: TRL = 9

Routine activity, although may be challenging with older cans.

Heat Treatment and packaging: TRL =3

The contaminants, their ease of removal and thus scope of the treatment and chloride removal process is not well understood.

Low Specification MOX fabrication: TRL = 9

Routine large scale manufacturing of LWR in e.g. MELOX. No reason why Low Spec MOX should be more challenging.

Assembly storage TRL = 9

Short term interim storage of assemblies is well understood and is implemented on an industrial scale and so is considered to have a technical maturity of 9.

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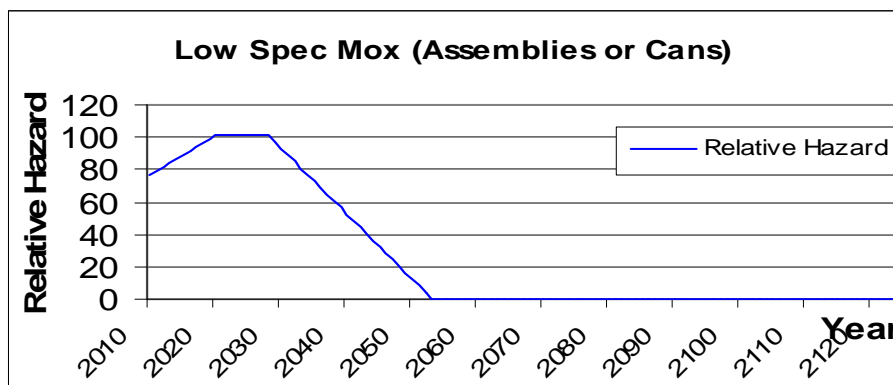
<p>Disposal : TRL = 2</p> <p>No developed systems for disposal</p>
<p>Lead Time</p> <p>The detail lead time for the new facilities are as discussed below:</p> <p>SPRS Heat Treatment Facility: A new facility is assumed to have a lead time of 3 years giving an earliest start to heat treatment operations of 2024. No major R&D lead time considered, although the scope of the treatment plant is not clear. Significant permissioning and licensing activities expected.</p> <p>Low specification MOX plant</p> <p>The plant has a lead time of 10 years including 5 year construction as per [22]</p> <p>Assembly store: The lead time for this facility is not directly relevant to the phasing and would be built as demanded by the Low Spec MOX plant.</p> <p>Waste transports</p> <p>No lead time is required for this but it is assumed that waste is transported to the GDF from 2075 onwards over a 20 year period.</p>
<p>Environmental Impact</p> <p>The environmental discharges from the processing similar to that for SMP should be minimal from a new plant and zero from storage activities. The longer term environmental impact will be dominated by the assessment of the durability of the waste form with the GDF.</p> <p>The environmental impact from production in this option using 41 kg CO₂ eq / kg is ~ 41,000 te CO₂ eq.</p> <p>The environmental impact of a SPRS type store, which is assumed to be required for the storage of encapsulated product, is around 24,700 te CO₂ eq. An assembly store is expected to be similar in terms of impact.</p>
<p>Socioeconomic Impact</p> <p>Socio-economic Impacts are calculated using the figures derived in the ERM report and applied to the costs for each option.</p>

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**Plutonium
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2010**

Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			
Other Construction			
Other operations			

Safety – SED scores over time



The shape of the graph reflects the separated stock building up until conversion of the material into Low Specification MOX assemblies, which reduces the relative hazard in line with the production profile.

Proliferation Resistance

From the discussion and charts in section 6.7, low specification MOX immobilisation does essentially reduce the state-sponsored proliferation risk from the material, albeit not as much as some of the other options. This is to be expected as there is a relatively non-robust chemical barrier (dissolvable ceramic) added to the material, it is now in a non-mobile state but the plutonium isotopes have not been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion “proliferation risk”.

NOT PROTECTIVELY MARKED - REDACTED

Disposability

A full disposability assessment has not been made. It has been assumed the waste form will be emplaced in a HLW/SF type disposal facility. However, there are potentially significant uncertainties on the cost of disposal including but not limited to:

- Ability to demonstrate a criticality safety case with the assumed plutonium loading
- GDF Implementation scope and schedule
- Ability to dispose in a single rock type including potential spatial limitations
- Ability to dispose of the baseline inventory in a single facility

A key opportunity exists to co-dispose of the Low Spec MOX with other UK LWR spent fuel e.g. Sizewell B to create a more proliferation resistant package. This may also give some significant economic benefits, although the concept has not been considered in detail.

Knowledge gaps and R&D needs

A preliminary list of knowledge gaps and R&D needs is shown below.

- Development of a waste form specification for storage and disposal;
- Detailed assessment of Low Spec MOX product as a waste form, including GDF package and operating envelope;
- Qualification of waste form for disposal;
- Underpinning of plutonium incorporation rate and process;
- Process development and establishment of process envelope;
- Detailed assessment of facility design and costing, including OR Modelling to confirm throughput;
- Determine impact of storing plutonium product in assembly store, including assessment of passive cooling regime and ability to meet export and import requirements;
- Review Sellafield site layout and confirm stores could be located;
- Establish GDF design concept.

Risks and Opportunities

Given the low TRL assessment for disposal and, consequently, the large number of knowledge gaps and R&D needs there are a number of significant risks to address. These include but are not limited to:

- Inability to qualify plutonium waste product as disposable waste form;
- Plutonium incorporation rate is not optimised for this scenario, could be

NOT PROTECTIVELY MARKED - REDACTED

<p>much higher than current assumption;</p> <ul style="list-style-type: none"> • Underpinning R&D programme reveals problems which will increase costs; • Self-heating aspects of the package impact adversely on product quality; • Product quality is affected by radiation damage particularly over long timescales; • A much greater programme is required to qualify the waste form than is merited purely on technical grounds <p>The re-use of SMP itself is a potential opportunity. Other opportunities exist to avoid the significant cost of product storage by only producing the product when the GDF is available and directly disposing to the GDF.</p>
<p>Time constraints and timescale decision drivers</p>
<p>The cost estimate is sensitive to the plutonium loading of the waste form package. A significant development programme will be required to:</p> <ul style="list-style-type: none"> • Prove the technology • Prove the waste form and compatibility with disposal facility concept <p>The impact of americium in-growth is considered crucial for this option given that the costs are based on an existing LWR fabrication facility with a 4% Am limit – processing of aged product would increase this cost to provide shielding for the various facilities. However, recent studies have indicated that americium could be dealt with by appropriate blending of plutonium powders prior to use.</p>
<p>Stakeholder views</p>
<p>Stakeholder views with respect to Low specification MOX were not specifically sought</p>
<p>Policy Impacts</p>
<p>There are no specific policy impacts surrounding plutonium as a waste disposal form, although the impact on the GDF project may be significant, and this disposition route is out of step with other International initiatives.</p>

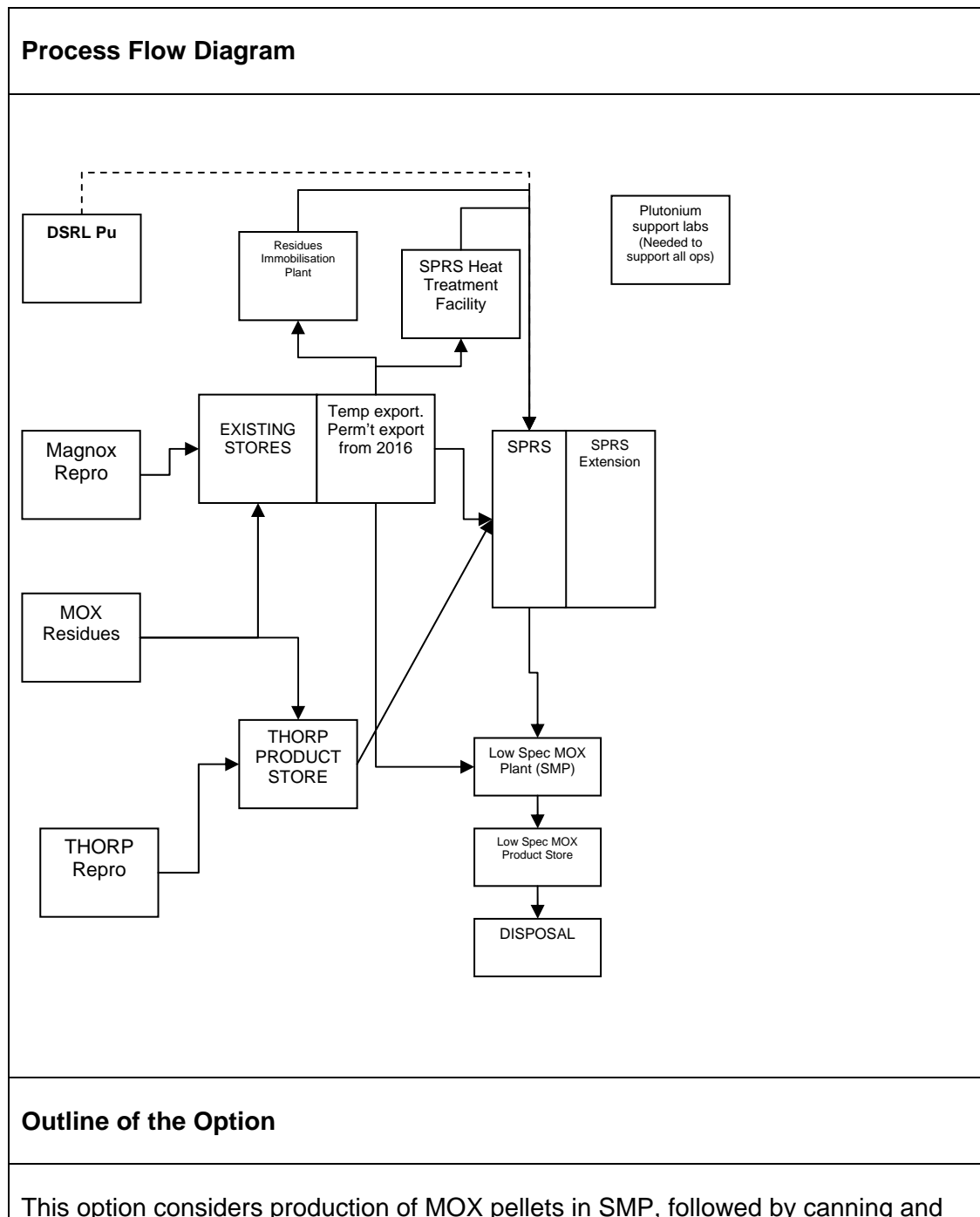
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Plutonium Credible Options Analysis (Gate A) 2010

CREDIBLE OPTIONS DATA

POLICY OPTION: DISPOSAL

Implementation Strategy 6: Low Specification MOX – Existing Production facility, Disposal variant



NOT PROTECTIVELY MARKED - REDACTED

subsequent disposal into the GDF. The primary source of data is from National Nuclear Laboratory who carried out a study which utilised SLC data in regard to SMP operating costs.

Due to the lead time for this option and the anticipated throughput of the facility, it is considered likely that one extension to SPRS is still required.

Facilities which may be required and are not included in the National Nuclear Laboratory paper include pre-treatment, that may be required as a result of the formation of radiolysis products in storage or contaminants, characterisation that is required for reuse and provision of plutonium analytical services beyond the life time of the current Sellafield plutonium support laboratories.

Whilst throughput has been disappointing in SMP, it is considered that the pelleting area could deliver this solution with relatively minor modifications. As such it is assumed that the current SMP carries out this option, but modified and with improved throughput. It may be possible to enhance local production in this area which means that the actual cost of delivering a Low Specification MOX option might lie between option 5 and option 6.

For modeling purposes it is assumed that plutonium stored at Dounreay will be transported to Sellafield for interim storage in SPRS (or similar appropriate store). However, most of the plutonium stored at Dounreay is mixed with HEU (High Enriched Uranium) and storage of HEU is contrary to existing planning permissions and safety cases for SPRS, so some work is assumed to have been completed to enable this material to be stored at Sellafield. The immobilisation process is likely to be required to include the HEU as well as the plutonium.

This option includes all UK civil material which is currently in UK safeguards. If additional UK owned material were to enter safeguards and be added to the inventory then the estimates of cost for the plan would need to be reviewed.

The Option in Summary

- i) Storage in existing stores and SPRS until withdrawn for use
- ii) Construction of new storage modules in SPRS from 2015
- iii) Pre- Treatment and Packaging including characterisation in a new Heat Treatment Facility
- iv) Utilisation of a modified SMP to produce 40 teHM pellets pa
- v) Manufacture of around [REDACTED] MOX pellets at 11% plutonium incorporation ([REDACTED] packages)
- vi) Storage of plutonium in SPRS type cans pending availability of GDF
- vii) Overpack of cans into vitrification canisters
- viii) Transport of cans to GDF once available
- ix) Disposal of canisters in GDF
- x) Decommissioning of SPRS, extension modules, chloride removal, treatment and packaging facilities, MOX plant, transport assets.

Assumptions

NOT PROTECTIVELY MARKED - REDACTED

- Project commences 2019 with SMP modified from 2021
- Material may be withdrawn from existing stores or new stores for characterisation
 - Approximately 40 teHM of the material requires sampling and treatment
- New facilities will be required for sampling and treatment
- Empty plutonium cans disposed of at Sellafield as PCM
- Circa 1000 teHM of MOX pellets will be produced in a modified SMP (assumes 11% plutonium and remainder using depleted uranium carrier, provided by NDA at nil cost)
- Low spec MOX pellets stored in SPRS type stores pending disposal route availability
- Cans will be placed in WVP containers in new overpack facility
- Total disposal canisters is [REDACTED]
- Offsite transport for waste will be achieved over a 20 year period
- UK GDF available for receipt of overpacked Low spec MOX pellets from 2075
- Disposal in GDF is assumed to be in canisters at a cost of [REDACTED] per canister

Exclusions

Non safeguarded materials

Overseas materials which is assumed to be returned to customers

Cost Data and Uncertainty

Uncertainty estimates are generally assumed to be -20% to +100%. For other facilities, annual operating costs, unless specifically included in LTPs, were estimated to 10% of capital costs, with an uncertainty of -10 to +20%. Similarly, recent parametric estimates for decommissioning of alpha plants indicate that appropriate provisions are 40% of capital costs. This is considered pessimistic for stores.

Cost data for the process blocks

Cost estimates are provided for a plutonium-loading in MOX pellet product of approximately 11% by weight. Order of magnitude cost estimate for an immobilisation facility have been made and given in reference [2]. The estimated total lifetime cost of the facility is the sum of individual costs for R&D, Capital, operation and maintenance, POCO and Decommissioning. These costs were used with transport and disposal costs to construct a lifecycle cost estimate for plutonium immobilisation.

1. Store – PuO₂ powder prior to encapsulation (SPRS Extension 1)

NOT PROTECTIVELY MARKED - REDACTED

Prior to operation of the modified SMP the material will have to be safely and securely stored. Estimates for this have been taken from the Sellafield LTP and include an extension to the SPRS facility due to the lower throughputs for the plant (c.f. option 5). The Sellafield LTP assumes that MOX production in SMP continues until 2019. Following this period of fuel production, the plant would need to be cleaned out and modifications made to enable "low spec MOX" to be manufactured from around 2021.

2. Heat Treatment and Packaging Plant

The purpose of this facility is to sample, characterise and, if necessary, pre-treat the plutonium prior to fabrication of low specification MOX pellets. Data for this block is derived from existing projects being carried out at Sellafield. If extensive pre-treatment is required, such as aqueous polishing, then the cost is significantly greater.

3. SMP

This cost estimate for modifications is based on data provided in reference 2. Costs for design, build, operation and decommissioning of the modified SMP and ancillary infrastructure are given.

4. Immobilised Product Stores

Following immobilisation the plutonium-bearing cans are stored in SPRS-type modules. The capital cost basis for these storage modules (3 off) is taken from the AREVA response (see option 5) with other costs generated from application of operational and decommissioning norms.[22] [2]

5. Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and troubleshooting in support of operations are assumed.

6. Transport and Disposal of waste form packages in a HLW/SF-type disposal facility

Prior to emplacement the waste form, in SPRS cans, will be loaded in Waste Vitrification Plant (WVP) canisters. Two WVP canisters are included within one disposal canister. Costs for overpacking are given.

A best estimate for this facility and transport costs has been taken from reference [2].

Disposal costs have been calculated assuming [redacted] disposal cost per disposal canister, reference.

Cost sensitivity and uncertainty

NOT PROTECTIVELY MARKED - REDACTED

Cost uncertainty is dictated by a number of technical risks which require areas of further development to underpin, see Knowledge Gaps and R&D needs.

As with other options, a major determining factor in the overall cost estimate for this option is the incorporation rate of PuO₂ within each waste package. Even small improvements to the incorporation rate results in considerable savings at every stage beyond the fabrication process, due to the lower number of packages that require interim storage, transport, overpack and GDF emplacement. The incorporation rate for plutonium in the MOX needs to be underpinned.

Technical Maturity

Interim Storage: TRL = 9

Interim storage of plutonium oxide powder is well understood and is implemented on an industrial scale and so is considered to have a technical maturity of 9. Estimates vary as to the time period for which is technical maturity is considered valid but an assumption has been made that it is valid for around 30 years.

plutonium can emptying: TRL = 9

Routine activity although may be challenging with older cans.

Treatment and packaging: TRL =3

The contaminants, their ease of removal and thus scope of the treatment and chloride removal process is not well understood.

Low Specification MOX fabrication: TRL = 9

Routine large scale manufacturing of LWR in e.g. MELOX. No reason why Low Specification MOX pellets should be more challenging.

Pellet storage TRL = 9

Short term interim storage of pellets is well understood and is implemented on an industrial scale. Long term storage is not yet understood but should be more favourable than that of PuO₂ powder storage so is considered to have a technical maturity of 9.

Disposal : TRL = 2/3

No developed systems for disposal.

Lead Time

NOT PROTECTIVELY MARKED - REDACTED

The detail lead time for the new facilities are as discussed below:

SPRS extension 1: The lead time for this facility is not directly relevant to the phasing. In the worst case, the facility is required for 2032 and the design and build programme is phased over 5 years.

SPRS Heat Treatment Facility/: A new heat treatment / repack facility within the main SPRS module is assumed to have a lead time of 3 years giving an earliest start to repackaging operations of 2024, and costs are taken from Sellafield LTP10. No major R&D lead time considered. Significant permissioning and licensing activities expected.

Modifications to SMP

Depending on the future operation of SMP to deliver its primary mission of manufacturing MOX for overseas customers the modifications are conservatively estimated to takes 3 years, although permissioning and re-justification may be the limiting timescales. The current date of SMP completing its current scope is early 2019 so unless the operations are curtailed a credible start date is not until after that time. If this primary mission is retained and SMP performance did not improve as anticipated then the date of 2019 could be delayed to e.g. 2030. This would challenge the ability of SMP to deliver this mission due to age of the facility.

Waste transports

No lead time is required for this but it is assumed that waste is transported to the GDF from 2075 onwards over a 20 year period.

Environmental Impact

The environmental discharges from the processing similar to that for SMP should be minimal and zero from storage activities. The longer term environmental impact will be dominated by the assessment of the durability of the waste form with the GDF.

The environmental impact from production in this option using 41 kg CO₂ eq/kg is ~ 41,000 te CO₂ eq.

The environmental impact of a SPRS type store, which is assumed to be required for the storage of encapsulated product, is around 24,700 te CO₂ eq.

Socioeconomic Impact

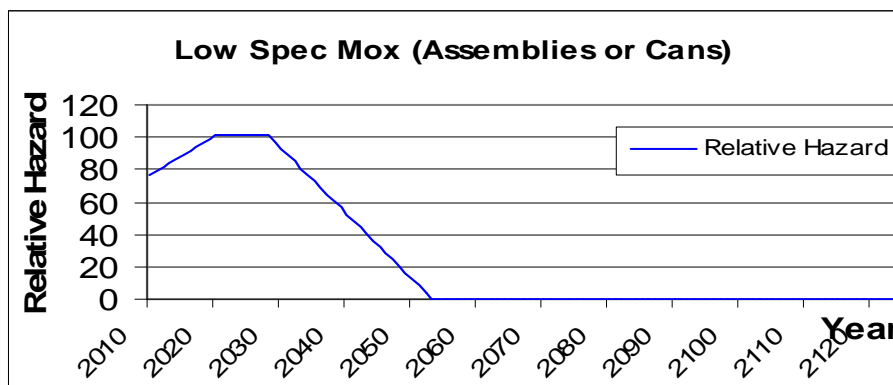
Socio-economic Impacts are calculated using the figures derived in the ERM report and applied to the costs for each option.

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			
Other Construction			
Other operations			

Safety – SED scores over time



The shape of the graph reflects the separated stock building up until conversion of the material into Low Specification MOX, which reduces the relative hazard in line with the production profile.

Proliferation Resistance

From the discussion and charts in section 6.7, low specification MOX immobilisation does essentially reduce the state-sponsored proliferation risk from the material, albeit not as much as some of the other options. This is to be expected as there is a relatively non-robust chemical barrier (dissolvable ceramic) added to the material, it is now in a non-mobile state but the plutonium isotopes have not been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion “proliferation risk”.

NOT PROTECTIVELY MARKED - REDACTED

Disposability

A full disposability assessment has not been made. It has been assumed the waste form will be emplaced in a HLW/SF type disposal facility. However, there are potentially significant uncertainties on the cost of disposal including but not limited to:

- Ability to demonstrate a criticality safety case with the assumed plutonium loading
- GDF Implementation scope and schedule
- Ability to dispose in a single rock type including potential spatial limitations
- Ability to dispose of the baseline inventory in a single facility

A key opportunity exists to co-dispose of the low spec MOX pellets with other UK HLW to create a more proliferation resistant package. This may also give some significant economic benefits, although the concept has not been considered in detail.

Knowledge gaps and R&D needs

A preliminary list of knowledge gaps and R&D needs is shown below.

- Development of a waste form specification for storage and disposal;
- Detailed assessment of Low spec MOX product as a waste form, including GDF package and operating envelope;
- Qualification of waste form for disposal;
- Underpinning of plutonium incorporation rate and process;
- Process development and establishment of process envelope;
- Detailed assessment of facility design and costing, including OR Modelling to confirm throughput;
- Determine impact of storing plutonium product in SPRS store, including assessment of passive cooling regime and ability to meet export and import requirements;
- Review Sellafield Site Layout and confirm stores could be located;
- Confirm SPRS type store is the most appropriate storage facility type;
- Establish GDF design concept.

Risks and Opportunities

Given the low TRL assessment for disposal and, consequently, the large number of knowledge gaps and R&D needs there are a number of significant risks to address. These include but are not limited to:

- Inability to qualify waste product as a disposable waste form;

NOT PROTECTIVELY MARKED - REDACTED

Plutonium Credible Options Analysis (Gate A) 2010

- plutonium incorporation rate is not underpinned;
- Underpinning R&D programme reveals problems which will increase costs;
- Self-heating aspects of the package impact adversely on product quality;
- Product quality is affected by radiation damage particularly over long timescales;
- A much greater programme is required to qualify the waste form than is merited purely on technical grounds

The re-use of SMP itself is the opportunity or conversely risk. Other opportunities exist to avoid the significant cost of product storage by only producing the product when the GDF is available and directly disposing to the GDF.

Time constraints and timescale decision drivers

The cost estimate is sensitive to the plutonium loading of the waste form package. A significant development programme will be required to:

- Prove the technology
- Prove the waste form and compatibility with disposal facility concept

The impact of americium in-growth is considered crucial for this option given that the costs are based on an existing SMP fabrication facility.

Stakeholder views

Stakeholder views with respect to Low specification MOX were not specifically sought, although a number of views were expressed.

Policy Impacts

There are no specific policy impacts surrounding plutonium as a waste disposal form, although the impact on the GDF project may be significant, and this disposition route is out of step with other International initiatives.

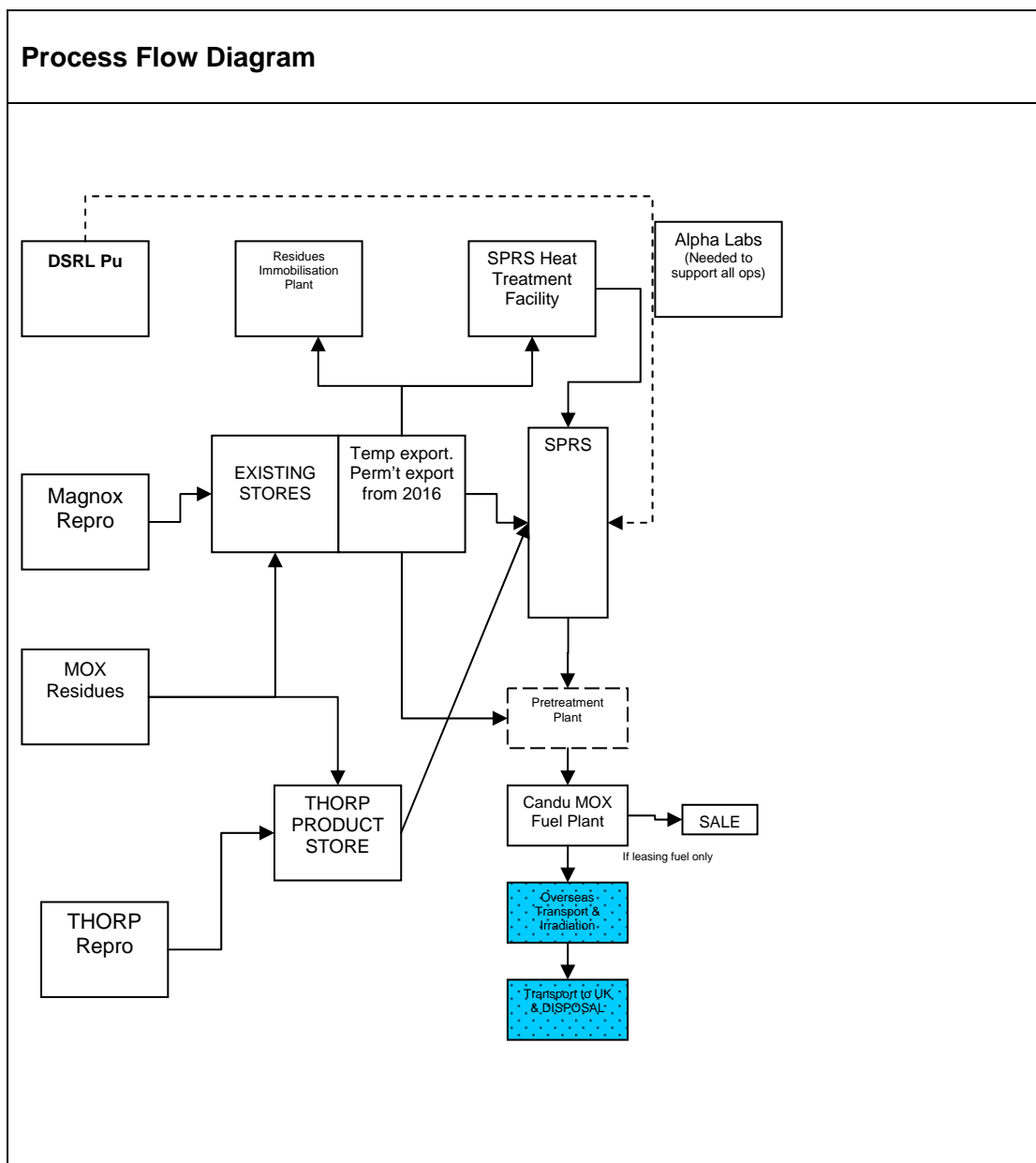
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Plutonium Credible Options Analysis (Gate A) 2010

CREDIBLE OPTIONS DATA

POLICY OPTION: RE-USE

Implementation Strategy 7: Use of MOX CANDU Variant



Outline of the Option

This option considers the conversion of the UK plutonium stockpile into CANDU MOX fuel which is subsequently irradiated in overseas (nominally Canadian) reactors. Data is mainly drawn from the VT/AECL response to NDA industrial

NOT PROTECTIVELY MARKED - REDACTED

underpinning exercise [11]. However there are a small number of areas where NDA consider that data is omitted or understated and for these, estimates have been drawn from available industry and analogous plant data [2].

Facilities which may be required and are not currently in the VT/AECL response includes pre-treatment, that may be required as a result of the formation of radiolysis products in storage, characterisation, that is required for reuse and provision of plutonium analytical services beyond the life time of the current Sellafield plutonium support laboratories.

Due to the lead time for this option it is considered likely that much of the current Sellafield capital baseline in regard to plutonium storage is still required. However if the material is to leave the Sellafield site by the proposed date then decisions need to be made much earlier to allow new facilities and/or transport assets to be procured.

It is assumed that the current SMP does not deliver this option due to the limited lifetime of the facility, the different fuel fabrication process and the limited demonstrated capacity.

This option includes all UK civil material which is currently in UK safeguards. If additional UK owned material were to enter safeguards and be added to the inventory then the estimates of both cost and potential revenue for the plan would need to be reviewed.

For modeling purposes it is assumed that plutonium stored at Dounreay will be transported to Sellafield for interim storage in SPRS (or similar appropriate store). However, most of the plutonium stored at Dounreay is mixed with HEU (High Enriched Uranium) and storage of HEU is contrary to existing planning permissions and safety cases for SPRS, so some work is assumed to have been completed to enable this material to be stored at Sellafield. This reuse process is likely to be required to separate the HEU from the plutonium prior to utilisation.

Revenue delivered and cost incurred by NDA (i.e. the net cost of the disposition) is clearly very dependent on the commercial model and location of any potential CANDU reactors to utilise the MOX.

At this time it is considered that an overseas reactor utility is the customer for the MOX, since any UK new build reactors are not anticipated to be of CANDU design.

The option in summary

- i) Plutonium storage in existing stores and SPRS until withdrawn for use
- ii) Pre-treatment and packaging including characterisation in a new Heat Treatment Facility
- iii) Provision of a plutonium chemical clean up plant for 11.7 teHM of plutonium, operational for 5 years.
- iv) Provision of new plutonium support laboratories
- v) Provision of CANDU MOX fabrication plant (~160 teHM per year)
- vi) Manufacture of around [REDACTED] CANDU MOX fuel on just in time

NOT PROTECTIVELY MARKED - REDACTED

- basis for 4 off CANDU reactors
- vii) Transport of CANDU MOX fuel to overseas reactor
 - viii) Irradiation in overseas CANDU reactor
 - ix) Transport of irradiated CANDU MOX fuel from overseas reactor back to the UK once GDF available
 - x) Disposal of irradiated CANDU MOX in UK GDF, with disposal costs paid for by utility
 - xi) Decommissioning of SPRS, extension modules, heat treatment facility, plutonium support laboratories, MOX plant, transport assets.

Assumptions

- Project commences 2015
- Material may be withdrawn from existing stores or new stores for characterisation
 - Approximately 40 teHM of the material required characterisation (all but the repacked material)
- New facilities will be required for sampling and packaging facility(including plutonium support laboratories) and heat treatment
- Any impurity/Am issues are avoided via blending in the Heat Treatment Facility, due to CANDU fuel low incorporation levels and tolerance of reactor systems. Chemical clean up to remove non-americiium impurities still required for 11.7 teHM of plutonium.
- Empty plutonium cans treated at Sellafield as PCM
- CANDU MOX fuel will be produced in a new UK facility on or adjacent to Sellafield site (assumes 2% PuO₂ and 98% depleted Uranium carrier, provided by NDA at nil cost to utility)
- Production facility refurbished once during operational life
- CANDU MOX will be irradiated in an overseas CANDU reactor, nominally in Canada, over a 30 year period
- Spent MOX fuel stored at nil cost to NDA at reactor pending disposal route availability
- Transport for unirradiated fuel to Canada will be achieved via a fleet of new flasks and two ships over the 30 year period ([REDACTED] per flask and just [REDACTED] shipments per year)
- UK GDF available for receipt of spent CANDU MOX fuel 2075
- Transport of irradiated fuel to the UK will be achieved via a fleet of reconditioned flasks and one ship over a 20 year period (4 teHM per flask at around 2 shipments per year)
- Disposal in GDF is assumed to be in containers at equivalent cost per teHM as LWR MOX i.e. 0.53tHM per canister, noting that it is expected that this cost will be borne by the utility

Exclusions

Non safeguarded materials

Overseas materials which is assumed to be returned to customers

NOT PROTECTIVELY MARKED - REDACTED

Cost Data and Uncertainty

VT/AECL declared that uncertainty on their estimates was -20% to +100%. For other facilities, annual operating costs, unless specifically included in LTPs, were estimated to 10% of capital costs, with an uncertainty of -10 to +20%. Similarly, recent parametric estimates for decommissioning of alpha plants indicate that appropriate provisions are 40% of capital costs. This is considered pessimistic for stores.

Cost data for the process blocks

Cost estimates are provided in Table 7 for a plutonium fabrication into MOX of approximately 2% by weight. Order of magnitude cost estimate for a new MOX fabrication facility have been made and given in reference [11]. The estimated total lifetime cost of the facility is the sum of individual costs for R&D, capital, operation and maintenance, POCO and decommissioning. These costs were used with transport and disposal costs to construct a lifecycle cost estimate for plutonium management.

1. Store – PuO₂ powder prior to disposition (SPRS)

Prior to operation of the MOX plant the material will have to be safely and securely stored. No extra module to SPRS is required as the existing stores should be able to cope with storage once the MOX plant commences operations.

2. SPRS Heat Treatment Facility

The purpose of this facility is to sample, characterise and, if necessary, pre- treat the plutonium prior to fabrication of MOX assemblies. Data for this block is derived from existing projects being carried out at Sellafield.

3. Plutonium Chemical Clean Up Plant

This facility will be required to remove chemical impurities such as iron from an estimated 11.7 teHM of the plutonium inventory, to make it reusable. Costs for this plant have been obtained from a newly commissioned piece of work by the National Nuclear Laboratory⁽³²⁾.

4. MOX plant

This cost estimate is based on data provided in reference 11. No technology development costs have been included. The order of cost estimate for the plant was developed from AECL/VTs estimates for a commercial specification MOX plant although for the main facility NDA increased the upper bound to reflect a more complex fabrication plant. Costs for design, build, operation and decommissioning of the plant and ancillary infrastructure are given in the Table 7.

NOT PROTECTIVELY MARKED - REDACTED

5. Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and troubleshooting in support of operations are assumed.

6. Transport and Disposal of waste form packages in a HLW/SF-type disposal facility

The fuel is exported for use in the reactor and details of the costing are given in [10]. After storage at the reactor the spent fuel is returned to the UK once a GDF is available and sent for direct disposal into canisters.

Disposal costs have been calculated assuming [redacted] disposal cost per disposal canister.

Technical Maturity

Interim Storage: TRL = 9

Interim storage of plutonium oxide powder is well understood and is implemented on an industrial scale and so is considered to have a technical maturity of 9. Estimates vary as to the time period for which is technical maturity is considered valid but an assumption has been made that it is valid for around 30 years.

Plutonium can emptying: TRL = 9

Routine activity, although may be challenging with older cans.

Heat Treatment and packaging: TRL = 3

The contaminants, their ease of removal and thus scope of the treatment and chloride removal process is not well understood.

Plutonium Chemical Treatment Plant. TRL = 9

A well understood process in both plutonium purification in existing facilities such as THORP and also in specific plutonium polishing facilities in France.

MOX fabrication: TRL = 6

Only small scale CANDU MOX fabrication has taken place although large scale manufacturing of LWR MOX takes place in e.g. MELOX.

MOX irradiation: TRL = 7

Demonstrated small scale irradiation of MOX to similar levels as those proposed.

NOT PROTECTIVELY MARKED - REDACTED

International MOX and SF transport: TRL = 9

Routine activity to Japan, although very politically sensitive, and carried out under strict security arrangements. Transport of CANDU MOX fuel has never been undertaken at this scale of transport.

Disposal : TRL = 2/3

No developed concept, or actual experience, for disposal of CANDU MOX but, in theory, should be compatible with currently proposed UK GDF concept.

Lead Time

The detail lead time for the new facilities are as discussed below:

SPRS Heat Treatment/packing plant: A new Heat Treatment Facility is assumed to have a lead time of 3 years giving an earliest start to repackaging operations of 2024. No major R&D lead time considered, although the scope of the treatment plant is not clear. Significant permissioning and licensing activities expected

Plutonium Chemical Cleaning Plant

This plant has a lead time of 10 years. No major R&D lead time required, as the technical maturity is considered to be high.

MOX plant

The MOX plant has a lead time of 7-10 years and is constructed as per the AECL/VT report

MOX and SF transports

No lead time is required for this but it is assumed that unirradiated MOX is transported from 2025 onwards for a period of 30 years, with spent fuel being returned to the UK from 2075 onwards over a 20 year period. Also intergovernmental agreements are needed to allow overseas irradiation and return of spent fuel.

Environmental Impact

There will be some environmental impact, albeit likely low, if pre-treatment is required. There may be additional plant complications and discharges due to the removal of non-radiological Impurities (e.g. chlorides).

The environmental discharges from the processing similar to that for SMP should be minimal from a new plant and zero from storage activities. The longer term

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

environmental impact will be dominated by the assessment of the durability of the waste form with the GDF.


There will be an environmental impact from the building of new plant.

The energy use for a SMP plant is known. The environmental impact from production in this option using 41 kg CO₂ eq / kg is ~ 205,000 te for CANDU type fuel. However the avoided burden from the replacing of 11 million tonnes of Australian uranium ore is 840 Mte CO₂ eq.

There will be an environmental impact from the building of 2 ships (~ 14,000 te CO₂) and the transportation of material.

The main operational environmental impact will be from transportation, mainly sea container ship and will be dominated by the number of transports rather than the total cargo weight.

Socioeconomic Impact

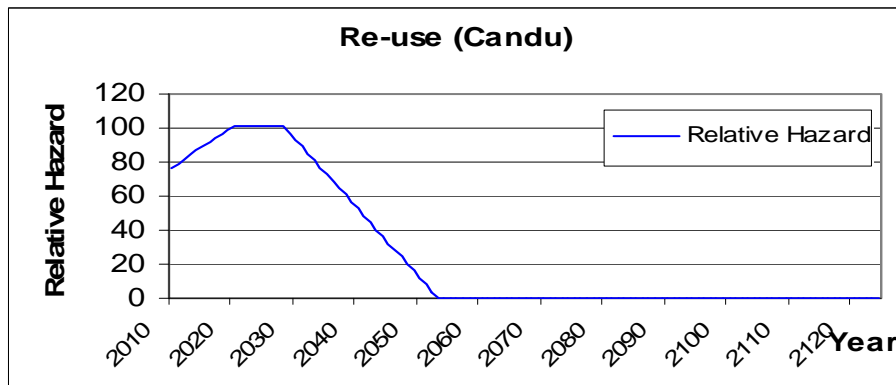
Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			
Other Construction			
Other operations			

Socio-economic Impacts are calculated using the figures derived in the ERM report and applied to the costs for each option.

Safety – SED scores over time

NOT PROTECTIVELY MARKED - REDACTED

Plutonium Credible Options Analysis (Gate A) 2010



The shape of the graph reflects the separated stock building up until conversion of the material into MOX, which reduces the relative hazard in line with the production profile.

Proliferation Resistance

From the discussion and charts in section 6.7, CANDU MOX reuse does significantly reduce the state-sponsored proliferation risk from the material, to a greater extent than the other non-reuse options. This is to be expected as there is an additional highly radioactive barrier introduced, there is a relatively non-robust chemical barrier (dissolvable ceramic) added to the material, it is now in a non-mobile state and the plutonium isotopes have been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion "proliferation risk".

Disposability

In this option the fuel would be disposed of as spent MOX. The RWMD assessment has not identified any show stoppers associated with disposal in this form. A full disposability assessment has not been made. It has been assumed the waste form will be emplaced in a HLW/SF type disposal facility. However, there are potentially significant uncertainties on the cost of disposal including but not limited to:

- Ability to demonstrate a criticality safety case with the assumed plutonium loading
- GDF Implementation scope and schedule
- Ability to dispose in a single rock type including potential spatial limitations
- Ability to dispose of the baseline inventory in a single facility

NOT PROTECTIVELY MARKED - REDACTED

Knowledge gaps and R&D needs

Whilst a small number of MOX elements of this form have been fabricated and irradiated, the experience in terms of CANDU MOX is significantly less than that of standard LWR. R&D would also be required to establish the disposability case for CANDU MOX in the GDF

A preliminary list of knowledge gaps and R&D needs is shown below.

- Development of a waste form specification for disposal;
- Detailed assessment of Spent MOX as a waste form, including GDF package and operating envelope;
- Qualification of waste form for disposal;
- Process development and establishment of process envelope;
- Detailed assessment of facility design and costing, including OR Modelling to confirm throughput;
- Review Sellafield Site Layout and confirm plant could be located;
- Establish GDF design concept.

Risks and Opportunities

This option is dependent on the acceptability of the bulk transport of unirradiated plutonium fuels and spent fuels to/from overseas, unless a UK CANDU reactor was to be built. This overseas transport is theoretically possible under the current regulatory and security regimes, however any changes in the future regulation or policy could render this option unachievable. If a UK CANDU reactor fleet was built then this would avoid the expense of overseas transport of unirradiated and spent fuel.

It have been assumed that new ships are required to execute this option, however there may be opportunities to use some of the existing PNTL fleet.

The option assumes that all the inventory is suitable for reuse. This would need to be confirmed through sampling and appropriate characterisation to ensure that the material fabricated would meet the conditions for acceptance fro subsequent irradiation.

The commercial revenues may vary either positively or negatively from that assumed, depending on market conditions and customer negotiations.

Depending on the timescales for implementation of this option it may be required to either blend or clean the plutonium to remove Am or other species/contaminants, although CANDU fuel is considered relatively robust to incorporating impurities.

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Time constraints and timescale decision drivers

For the fuel to be optimal for use by third parties, without additional treatment costs being incurred, then the average americium levels are generally assumed to be needed to be below 4%. Fulfilling this requirement means that early action is required for the plutonium derived from oxide fuel reprocessing, in terms of blending or pre-treatment. Even acting on the timescales of this option may not preclude the need for processing prior to use in reactors, although CANDU MOX fuel, due to its low incorporation of plutonium, is considered less susceptible to this than LWR fuel.

Stakeholder views

For stakeholders that view plutonium as a material which should not have been separated in the first place, a decision to reuse the material would not be popular and there would be an expectation that firstly, it was not re-separated and that it was only done on the basis of demonstrated benefit. For those that see plutonium as an asset this option is likely to be acceptable, however there are those that would prefer to see reuse in fast reactors as a more effective utilisation of the fuel.

Internationally the CANDU reactors are not viewed favourably by those seeking a low proliferation fuel cycle.

Policy Impacts

If this option is to be pursued then assurance would need to be sought that the transportation of this material would be regarded as acceptable from a policy and security perspective. In addition, irradiation of UK material in reactors overseas would need to be underwritten by the respective governments.

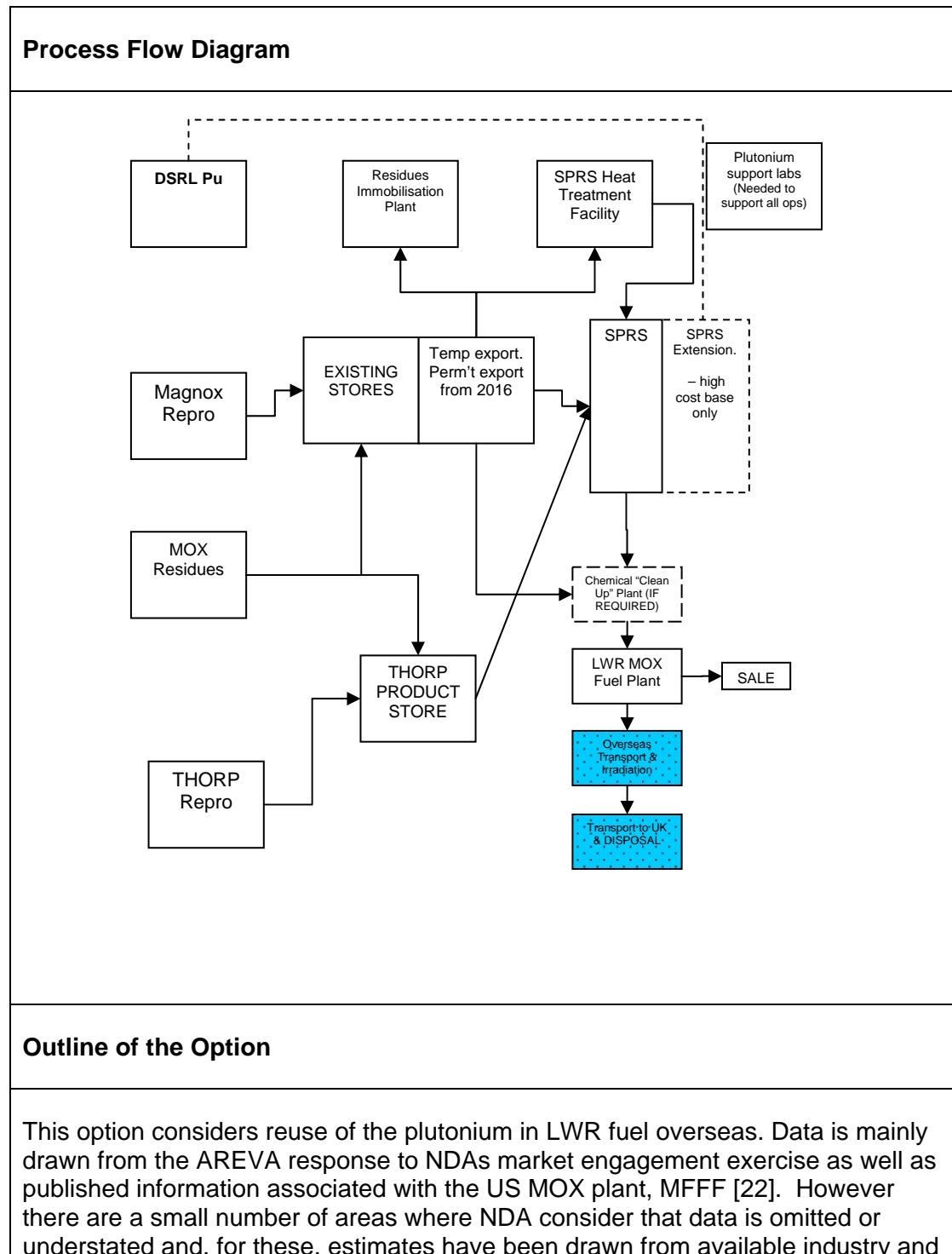
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Plutonium Credible Options Analysis (Gate A) 2010

CREDIBLE OPTIONS

POLICY OPTION: RE-USE

Implementation Strategy 8: Use of MOX Overseas – LWR Variant



NOT PROTECTIVELY MARKED - REDACTED

analogous plant data.

Facilities which may be required and are not included in the AREVA response include pre-treatment, that may be required as a result of the formation of radiolysis products in storage or contaminants, characterisation that is required for reuse and provision of plutonium analytical services beyond the life time of the current Sellafield plutonium support laboratories

Due to the lead time for this option it is considered likely that much of the current Sellafield capital baseline in regard to plutonium storage is still required. However if the material is to leave the Sellafield site by the proposed date then decisions need to be made much earlier to allow new facilities and/or transport assets to be procured.

It is assumed that the current SMP does not deliver this option due to the limited lifetime of the facility and the limited demonstrated capacity.

This option includes all UK civil material which is currently in UK safeguards. If additional UK owned material were to enter safeguards and be added to the inventory then the estimates of both cost and potential revenue for the plan would need to be reviewed.

For modeling purposes it is assumed that plutonium stored at Dounreay will be transported to Sellafield for interim storage in SPRS (or similar appropriate store). However, most of the plutonium stored at Dounreay is mixed with HEU (High Enriched Uranium) and storage of HEU is contrary to existing planning permissions and safety cases for SPRS, so some work is assumed to have been completed to enable this material to be stored at Sellafield. This reuse process is likely to be required to separate the HEU from the plutonium prior to utilisation.

Revenue delivered and cost incurred by NDA (i.e. the net cost of the disposition) is clearly very dependent on the commercial model and location/ownership of any potential reactors to utilise the MOX.

For this option it is considered that an overseas reactor utility is the customer for the MOX.

The option in summary

- i) Storage in existing stores and SPRS until withdrawn for use
- ii) Pre- Treatment and Packaging including characterisation in a new Heat Treatment Facility
- iii) Provision of new plutonium support laboratories
- iv) Provision of LWR MOX fabrication plant (~60 teHM pa)
- v) Manufacture of around 1500HM of LWR MOX fuel on just in time basis for LWR reactors
- vi) Transport of MOX fuel to overseas reactor
- vii) Transport of irradiated MOX fuel from reactor back to UK once GDF available
- viii) Disposal of irradiated MOX in UK GDF with disposal costs paid for by

NOT PROTECTIVELY MARKED - REDACTED

- utility
- ix) Decommissioning of SPRS, extension modules, chloride removal facility, treatment and packaging facilities including plutonium support laboratories, MOX plant, and transport assets.

Assumptions

- Project commences 2015
- Material may be withdrawn from existing stores or new stores for characterisation
 - Approximately 40 teHM of the material requires sampling and treatment
- Scope of characterisation is conservatively assumed to be analysis of isotopic and chemical impurities, physical powder properties and water content for all the inventory in a new facility
- Based on Areva's experience, it is likely that the americium issue can be managed by blending but risks remain that the MOX plant design will need to be approved by the UK Regulators and the fuel to be approved by reactor operators. Clean up may therefore still be necessary and is given as an upper bound cost to the Heat Treatment Facility (i.e. a risk to the baseline)
- Empty plutonium cans treated at Sellafield as PCM
- MOX fuel will be produced in a new UK facility on or adjacent to Sellafield site (assumes 6.75-7.6% PuO₂ and remainder depleted Uranium carrier, provided by NDA at nil cost to utility)
- Production facility refurbished once during operational life
- MOX will be irradiated in European reactors nominally over a 30 year period
- Spent MOX fuel stored at nil cost at reactor pending disposal route availability
- Offsite transport for unirradiated fuel will be achieved via a fleet of new flasks and two new ships over the 30 year period
- UK GDF available for receipt of MOX fuel from 2075
- Transport of irradiated fuel will be achieved via a fleet of new flasks over a 20 year period
- Disposal in GDF is assumed to be in standard cost per disposal canister with each canister holding [REDACTED] spent MOX

Exclusions

Non safeguarded materials

Overseas materials which is assumed to be returned to customers

Cost Data and Uncertainty

AREVA did not declare uncertainty on their estimates so -20% to +100% was used. For other facilities, annual operating costs, unless specifically included in LTPs, were estimated to 10% of capital costs, with an uncertainty of -10 to

NOT PROTECTIVELY MARKED - REDACTED

+20%. Similarly, recent parametric estimates for decommissioning of alpha plants indicate that appropriate provisions are 40% of capital costs. This is considered pessimistic for stores.

Cost data for the process blocks

Cost estimates are provided in Table 8 for plutonium fabrication into MOX of approximately 7% by weight. Order of magnitude cost estimate for a new MOX fabrication facility have been made and given in reference [22]. The estimated total lifetime cost of the facility is the sum of individual costs for R&D, capital, operation and maintenance, POCO and decommissioning. These costs were used with transport and disposal costs to construct a lifecycle cost estimate for plutonium management.

1. Store – PuO₂ powder prior to encapsulation

Prior to operation of the MOX plant the material will have to be safely and securely stored. No extra module to SPRS is required as the existing stores should be able to cope with storage once the MOX plant commences operations, although the risk that an extra module is incorporated into the financial data as an upper bound cost..

2. SPRS Heat Treatment Facility

The purpose of this facility is to sample, characterise and, if necessary, pre- treat the plutonium prior to fabrication of MOX assemblies. Data for this block is derived from existing projects being carried out at Sellafield. If extensive pre-treatment is required, such as aqueous polishing then the cost is significantly greater and an upper bound is based on the US MFFF facility.

3. Plutonium Chemical Clean Up Plant

This facility will be required to remove chemical impurities such as iron from an estimated 11.7 teHM of the plutonium inventory, to make it reusable. Costs for this plant have been obtained from a newly commissioned piece of work by the National Nuclear Laboratory⁽³²⁾.

4. MOX plant

This cost estimate is based on data provided in reference 22. No technology development costs have been included. The order of cost estimate for the plant was developed from AREVAs estimates for a commercial specification MOX plant. Costs for design, build, operation and decommissioning of the plant and ancillary infrastructure are given.

5. Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and

NOT PROTECTIVELY MARKED - REDACTED

troubleshooting in support of operations are assumed.

6. Transport and Disposal of waste form packages in a HLW/SF-type disposal facility

The fuel is exported for use in the reactor and details of the costing are given. After storage at the reactor the spent fuel is returned to the UK in purpose built transport containers (using purpose built ships) once a GDF is available and sent for direct disposal into spent fuel canisters.

Disposal costs have been calculated assuming [REDACTED] disposal cost per disposal canister, reference.

Commercial Value

A range of possible commercial benefits may be accrued depending upon the commercial model.

If it is assumed that a revenue of [REDACTED] is generated then the total benefit would be [REDACTED] assumed to be spread over the operating period of the plant.

There is also a potential value in providing transport solutions for customers of this MOX fuel, which is not included in this assessment.

Disposal costs paid for by utility.

Technical Maturity

Interim Storage: TRL = 9

Interim storage of plutonium oxide powder is well understood and is implemented on an industrial scale and so is considered to have a technical maturity of 9. Estimates vary as to the time period for which is technical maturity is considered valid but an assumption has been made that it is valid for around 30 years.

Plutonium can emptying: TRL = 9

Routine activity , although may be challenging with older cans

Heat Treatment Facility: TRL =3

The contaminants, their ease of removal and thus scope of the treatment and chemical clean up process is not well understood.

NOT PROTECTIVELY MARKED - REDACTED

Plutonium Chemical Treatment Plant. TRL = 9

A well understood process in both plutonium purification in existing facilities such as THORP and also in specific plutonium polishing facilities in France.

MOX fabrication: TRL = 9

Routine large scale manufacturing of LWR MOX in e.g. MELOX.

MOX irradiation: TRL = 9

Demonstrated large scale irradiation of MOX to similar levels as those proposed.

International MOX and SF transport: TRL = 9

Routine activity to Japan, although very politically sensitive, and carried out under strict security arrangements. Transport of CANDU MOX fuel has never been undertaken at this scale of transport.

Disposal : TRL = 2/3

No developed concept, or actual experience, for disposal of MOX but should be compatible with proposed UK concept.

Lead Time

The section on time constraints discusses the lead time associated with other options that provide the drivers for making decisions.

The detail lead time for the new facilities are as discussed below:

SPRS Heat Treatment Facility: A new repack facility is assumed to have a lead time of 3 years and has an earliest start time of 2024. No major R&D lead time considered, although the scope of the treatment plant is not clear. Significant permissioning and licensing activities expected

Plutonium Chemical Cleaning Plant

This plant has a lead time of 10 years. No major R&D lead time required, as the technical maturity is considered to be high.

MOX plant

The MOX plant has a lead time of 7-10 years and construction as per the AREVA report

MOX and SF transports

NOT PROTECTIVELY MARKED - REDACTED

Plutonium Credible Options Analysis (Gate A) 2010

A 5-10 year lead time to procure MOX and Spent Fuel assets is required for this, and it is assumed that unirradiated MOX is transported from 2024 onwards for a period of 30 years, with spent fuel being returned to the UK from 2080 onwards over a 20 year period. Also intergovernmental agreements are needed to allow overseas irradiation and return of spent fuel.

Environmental Impact

There will be some environmental impact, albeit low, if pre-treatment is required. There may be additional plant complications and discharges due to the removal of non-radiological Impurities (e.g. chlorides).

The environmental discharges from the processing similar to that for SMP should be minimal from a new plant and zero from storage activities. The longer term environmental impact will be dominated by the assessment of the durability of the waste form with the GDF.

There will be an environmental impact from the building of new plant.

The energy use for a SMP plant is known. The environmental impact from production in this option using 41 kg CO₂ eq / kg is ~ 61,000 te CO₂ eq for LWR fuel. However the avoided burden from the replacing of 11 million tonnes of Australian uranium ore is 840 Mte CO₂ eq.

There will be an environmental impact from the building of 2 ships (~ 14,000 te CO₂) and the transportation of material.

The main operational environmental impact will be from transportation, mainly sea container ship and will be dominated by the number of transports rather than the total cargo weight.

Socioeconomic Impact

Socio-economic Impacts are calculated using the figures derived in the ERM report and applied to the costs for each option.

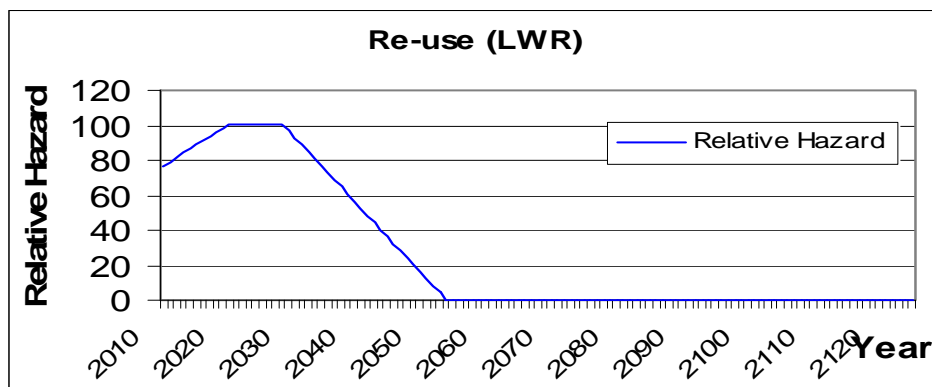
Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			

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Other Construction	
Other operations	

Safety – SED scores over time



The shape of the graph reflects the separated stock building up until conversion of the material into MOX, which reduces the relative hazard in line with the production profile.

Proliferation Resistance

From the discussion and charts in section 6.7, overseas LWR MOX reuse does significantly reduce the state-sponsored proliferation risk from the material, to a greater extent than the other non-reuse options. This is to be expected as there is an additional highly radioactive barrier introduced, there is a relatively non-robust chemical barrier (dissolvable ceramic) added to the material, it is now in a non-mobile state and the plutonium isotopes have been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion “proliferation risk”.

Disposability

In this option the fuel would be disposed of as spent MOX. The RWMD assessment has not identified any show stoppers associated with disposal in this form. A full disposability assessment has not been made. It has been assumed the waste form will be emplaced in a HLW/SF type disposal facility. However, there are potentially significant uncertainties on the cost of disposal including but not limited

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to:

- Ability to demonstrate a criticality safety case with the assumed plutonium loading
- GDF Implementation scope and schedule
- Ability to dispose in a single rock type including potential spatial limitations
- Ability to dispose of the baseline inventory in a single facility

Knowledge gaps and R&D needs

A large number of MOX elements of this form have been fabricated and irradiated, so no significant R&D would be required. R&D would be required to establish the disposability case for MOX in the GDF.

A preliminary list of knowledge gaps and R&D needs is shown below.

- Development of a Spent Fuel waste form specification for disposal;
- Detailed assessment of Spent MOX as a waste form, including GDF package and operating envelope;
- Qualification of waste form for disposal;
- Process development and establishment of process envelope;
- Detailed assessment of facility design and costing, including OR Modelling to confirm throughput;
- Review Sellafield Site Layout and confirm plant could be located;
- Establish GDF design concept.

Risks and Opportunities

This option is dependent on the acceptability of the bulk transport of unirradiated plutonium fuels and spent fuels to/from overseas. This transport is possible under the current regulatory and security regimes, however any changes in the future could render this option unachievable. If a UK LWR MOX burning reactor fleet was built then this would avoid the expense of overseas transport of unirradiated and spent fuel.

It has been assumed that new ships are required to execute this option, however there may be opportunities to use some of the existing PNTL fleet.

The option assumes that all the inventory is suitable for reuse. This would need to be confirmed through sampling and appropriate characterisation to ensure that the material fabricated would meet the conditions for acceptance for subsequent irradiation.

The commercial revenues may vary either positively or negatively from that assumed, depending on market conditions and customer negotiations.

Depending on the timescales for implementation of this option it may be required to

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<p>either blend or clean the plutonium to remove Am or other contaminants.</p> <p>If GDF implementation is delayed, the Reactor Utilities may not be able to store the spent MOX fuel for longer times than contractually agreed, which could lead to significant compensation payments (not included in this assessment).</p>
<p>Time constraints and timescale decision drivers</p>
<p>For the fuel to be optimal for use by 3rd parties, without additional treatment costs being incurred, then the average americium levels are generally assumed to be needed to be below 4%. Fulfilling this requirement means that early action is required for the plutonium derived from Oxide reprocessing, in terms of blending or pre-treatment. Even acting on the timescales of this option may not preclude the need for processing prior to use in reactors.</p>
<p>Stakeholder views</p>
<p>For stakeholders that view plutonium as a material which should not have been separated in the first place a decision to reuse the material would not be popular and there would be an expectation that firstly, it was not re-separated and that it was only done on the basis of demonstrated benefit. For those that see plutonium as an asset this option is likely to be acceptable, however there are those that would prefer to see reuse in fast reactors as a more effective utilisation of the fuel</p>
<p>Policy Impacts</p>
<p>If this option is to be pursued then assurance would need to be sought that the transportation of this material would be regarded as acceptable from a policy and security perspective. In addition, irradiation of UK material in reactors overseas would need to be underwritten by the respective governments.</p>

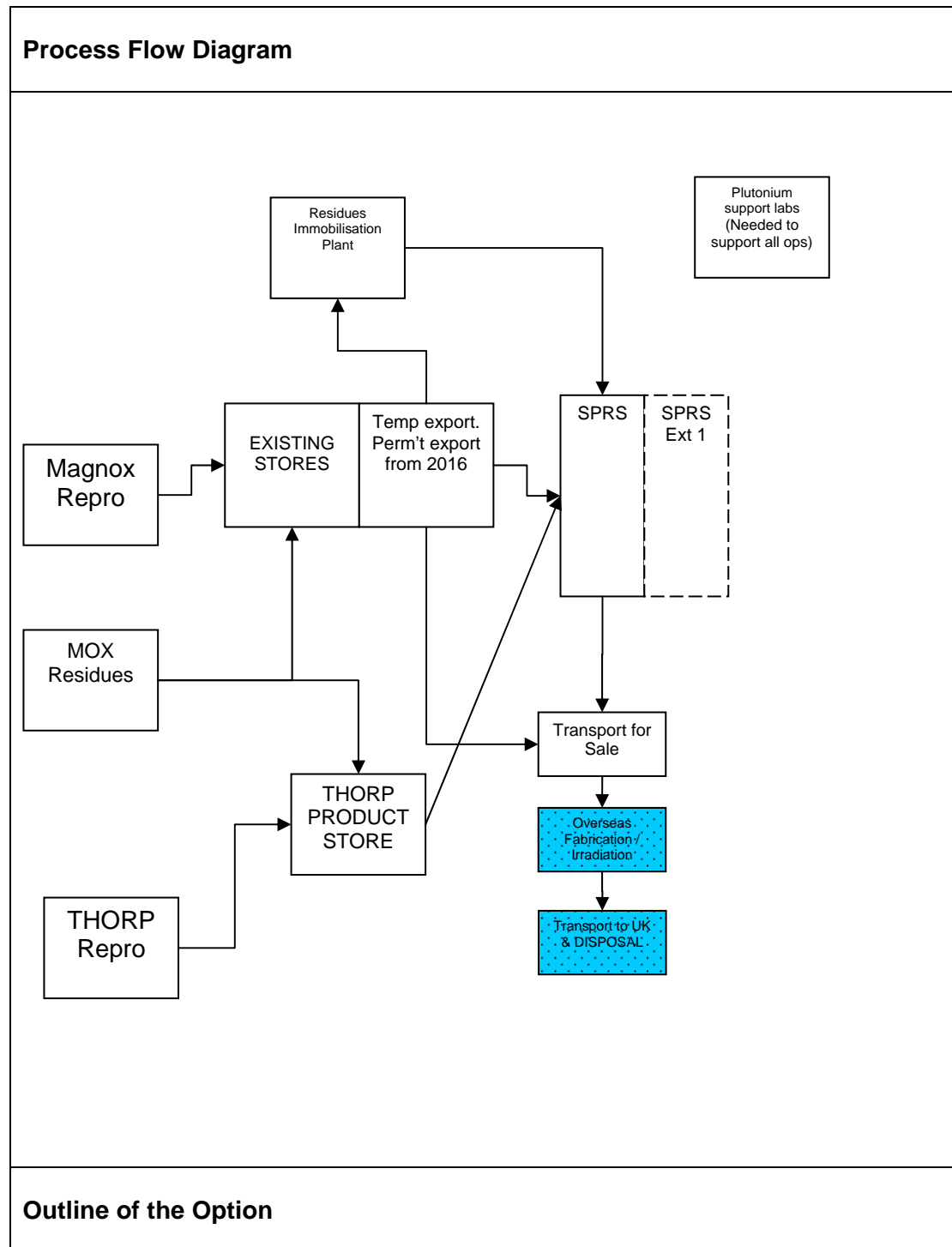
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CREDIBLE OPTIONS DATA

POLICY OPTION: RE-USE

Implementation Strategy 9: Sell or Lease as plutonium oxide



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It should be noted that, since the first version of this paper was published, this option is becoming less credible both politically and logistically, but a decision has been taken to continue with it in the study for completeness.

This option assumed that the material can be sold and transported to another country, in compliance with international security and treaty requirements.

In this option the material would be retrieved from storage, packaged for transport and exported in a series of shipments over time.

It is assumed that plutonium stored at Dounreay will not be transported to Sellafield for interim storage in SPRS (or similar appropriate store), as the material would be exported to the purchaser directly from Dounreay, rather than going to Sellafield first. Costs for the treatment and export of Dounreay plutonium are included in the DSRL LTP and will not change from option to option. Therefore these costs are not included in any option.

It is assumed that a total of 240 shipments would be required over a period of 30 years and that could commence in 2030. This is based on the current transport licensing regime. This is unlikely to be credible, and would most likely require a change in Regulations and transport and security infrastructure to enable this option to be realised.

It is assumed that new transport assets would be required; the number is partially dependent on the transport strategy and the country to which it is to be shipped. To provide a conservative estimate of the upper bound of transport costs and assets required it is assumed that the transport would be intercontinental and that two ships would be required. The lower bound is based on the assumption of transport to Europe for conversion to MOX fuel and subsequent use in an LWR MOX burning reactor.

It is assumed that a new package would also need to be developed and manufactured.

In this option the Thorp and Magnox material would be retrieved and a Thorp export facility would be required.

It is assumed that pre-treatment is necessary for use and to make a transport safety case, accordingly the costs are included.

The option assumed that 11.7 teHM of material which is not immediately marketable in its current specification are excluded from the inventory. This option therefore only considers around 90 teHM of the material. The sensitivities around this assumption are discussed in the body of the report. In the event that this option was executed as a plutonium lease the spent MOX could be transported back to this UK and disposed of alongside the existing spent fuels. It is assumed that this would take place between 2080 and 2100.

Assuming a decision were to be made in 2013 storage would be required until

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2043 which means there is an opportunity to avoid the costs associated with the construction and decommissioning of the second SPRS extension module, although the first module is likely to be needed due to the extended duration of the movements and the commencement time. The receiving nation is also likely to have to construct a new store to accommodate the extra plutonium, as it is unlikely that they will have sized their current facilities for a 100 teHM excess.

On this basis approximately 40 teHM requires processing through a treatment and packaging facility which will take about 8 years.

New plutonium support laboratories, operational in 2019 are included in the option.

Assumptions

New package license required

60 packages manufactured to execute spent fuel transport and, based on current designs, 18 packages for plutonium transport. As stated earlier, the number of shipments required means this option is unlikely to be credible, and hence new packages for plutonium transport will need to be designed and procured. Additionally, new ships designed and built to the highest security standards will be required.

Exclusions

A chlorine removal plant has not been included in this option as it is assumed that the chlorine contaminated material can not be sold.

~11 tonnes of material which it is assumed is not marketable without further treatment. This material would require immobilisation and disposal.

Non-safeguarded material

Overseas material which is returned to customers

Cost Data and Uncertainty

The capital cost of SPRS is assumed to be sunk at this time and is excluded from the estimate

The majority of the cost data is drawn from the Sellafield Lifetime plant for this option. When process blocks are missing from LTP, estimates have either been drawn from industry or the SLC. For facilities not included in LTP, operating costs have been assumed to be 10% of the capital cost and decommissioning costs are based on a parametric of 40% of capital cost as advised by the SLC. This is considered pessimistic for stores.

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Costs estimates are provided in Table 9 of the on-going storage of plutonium based on storage until 2120. Decommissioning of the facilities would then take place.

1. Store – PuO₂ powder prior to sales (SPRS)

Prior to selling the material will have to be safely and securely stored. Estimates for this have been taken from the Sellafield LTP and include an extension to the SPRS facility.[19] It is assumed that the current import facility to SPRS and SPRS Extension 1 could be reversed to make it capable of exporting material. This however is a significant assumption that could be very expensive [redacted] if this assumption is incorrect.

2. SPRS Heat Treatment Facility

The purpose of this facility is to sample, characterise and, if necessary, pre- treat the plutonium prior to transfer to SPRS. Data for this block is derived from existing projects being carried out at Sellafield. If extensive pre-treatment is required, such as aqueous polishing then the cost is significantly greater and an upper bound is based on the US MFFF facility [6]

3 Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and troubleshooting in support of operations are assumed. [7]

4 Transport Costs

Transport costs have been based on INS estimates of the fixed and variable costs for fuel shipments. It has been assumed that new assets would be procured for both the outward bound leg of any transport and the return some decades later. This assumes that spent fuel is stored by the reactor utility until it is returned for disposal in the lease variant of this option.

5 Disposal Costs

Disposal costs are based on those derived for the Spent Fuel in Tables 7 and 8 for LWR and CANDU type fuels.

Commercial Value

An elicitation process has been conducted to estimate the revenue that may be achieved from the sale of plutonium powder. This value is highly uncertain and would be heavily influenced by the degree of competition of the material. This represents the entry point to the supply chain and therefore attracted value of any of the reuse options, and has been estimated at around [redacted]

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<p>of plutonium.</p>
<p>Technical Maturity</p>
<p>TRL = 8</p> <p>Transport is a well developed concept and in principle could begin immediately using existing assets. Given the longer term implementation of this options relies in new ships and packages which have yet to be licensed it is assigned a TRL of 8.</p>
<p>Lead Time</p> <p>The current package design is only licensed for Magnox type material and typical package design and construction lead times are around 5 years (based on recent experience by INS). A concept design has already been produced and is it anticipated that this lead time could be reduced if required.</p> <p>It is assumed that a new package would be required.</p> <p>Similarly the design and construction time for new ships is around 5 years assuming a design which is similar to those which are already in use.</p> <p>The lead time assumes that transport could begin using existing transport assets.</p> <p>It is assumed that the shipping programme would start with material that does not require sampling or repackaging. A new repack facility is assumed to have a lead time of 3 years giving an earliest start to repackaging operations of 2024.</p>
<p>Environmental Impact</p> <p>There will be some environmental impact, albeit likely low, if pre-treatment is required for the sell option.</p> <p>There will be an environmental impact from the building of 2 ships (~ 14,000 te CO₂).</p> <p>The main operational environmental impact will be from transportation, mainly sea container ship and will be dominated by the number of transports rather than the total cargo weight. Using a CO₂ emission factor of 13 grams per te of cargo per km and a packages material mass of 200 te (50% plutonium mass) transported in 240 shipments:</p> <p>From UK to USA (~ 6000 km): 3,500 te CO₂.</p>

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From UK to France (~800 km [Liverpool – Le Havre]): 475 te CO₂.

There will also be an impact from the transport of material to the port, dependent on the route to which port and by what mode of transport.

The avoided burden from the replacing of 11 million tonnes of Australian uranium ore is 840 Mte CO₂ eq
(Container Shipping Information Service).

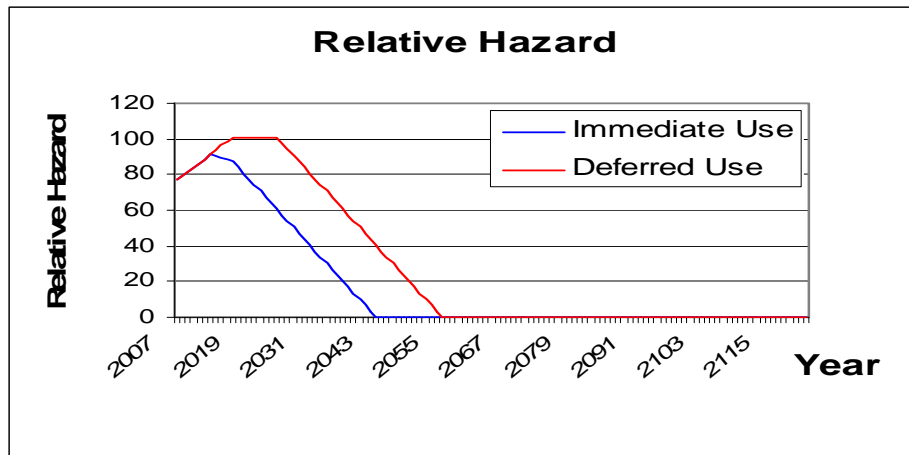
Socioeconomic Impact

Socio-economic impact has been calculated in terms of years of employment using the methodology used in the macro-economic report and as detailed in Appendix D.

Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			
Other Construction			
Other operations			

Safety – SED scores over time

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The graph shows the variation in the relative hazard resulting from material being shipped to a third party for immediate use or deferred use which assumed a new plant abroad would have to be built.

It used a form factor of E5 to account for the reducing hazard resulting from the encapsulation into fuel. Note as this option involves transport to a third party overseas much of the hazard will impact outside of the UK.

Proliferation Resistance

From the discussion and charts in section 6.7, sale does not essentially reduce the state-sponsored proliferation risk from the material from a UK perspective, despite moving overseas. This is to be expected as there are no additional chemical barriers to the material while under UK control, it is still in a mobile state and the plutonium isotopes have not been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion “proliferation risk”.

Disposability

In the event that the material is sold disposability would not be an issue for the UK.

In the event that material is leased the fuel would be disposed of a spent MOX. The RWMD assessment has not identified any show stoppers associated with disposal in this form. Further work would be required to confirm the acceptability of disposal in this form.

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<p>Knowledge gaps and R&D needs</p>
<p>New packages for plutonium shipment and INF3 ship designs would be required but concepts already exist. This is not considered to be a significant gap.</p> <p>In the event that material is returned as spent MOX further work would need to be done to underpin this suitability of this material for disposal. More detail is included in the reuse options.</p>
<p>Risks and Opportunities</p>
<p>This option is completely dependent on the acceptability of transportation of plutonium powders. This is possible under the current regulatory and security regimes, however any changes in the future could render this option unachievable and the only route to sale of the material in these circumstances would be in a different form.</p> <p>It have been assumed that new ships are required to execute this options however there may be opportunities to use some of the existing PNTL fleet.</p> <p>The option assumes that around 90% of the inventory is suitable for reuse. This would need to be confirmed through sampling to ensure that the material shipped met the conditions for acceptance for the receiving facility.</p>
<p>Time constraints and timescale decision drivers</p>
<p>For the fuel to be optimal for use by 3rd parties, without additional treatment costs being incurred, then the average americium levels are generally assumed to be needed to be below 4%. Fulfilling this requirement means that early action is required for the plutonium derived from Oxide reprocessing, in terms of blending or pre-treatment. Even acting on the timescales of this option may not preclude the need for processing prior to use in reactors.</p>
<p>Stakeholder views</p>
<p>Stakeholder views were split as to whether this option should be considered. Of the people that said this was an option that was credible and to be included in this stage a significant number expressed concern about the security of the transportation of this quantity of plutonium.</p>

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Policy Impacts

If this option is to be pursued assurance would need to be sought that the bulk and sustained transportation of this material would be regarded as acceptable from a policy and security perspective, to the degree that future issues can be foreseen.

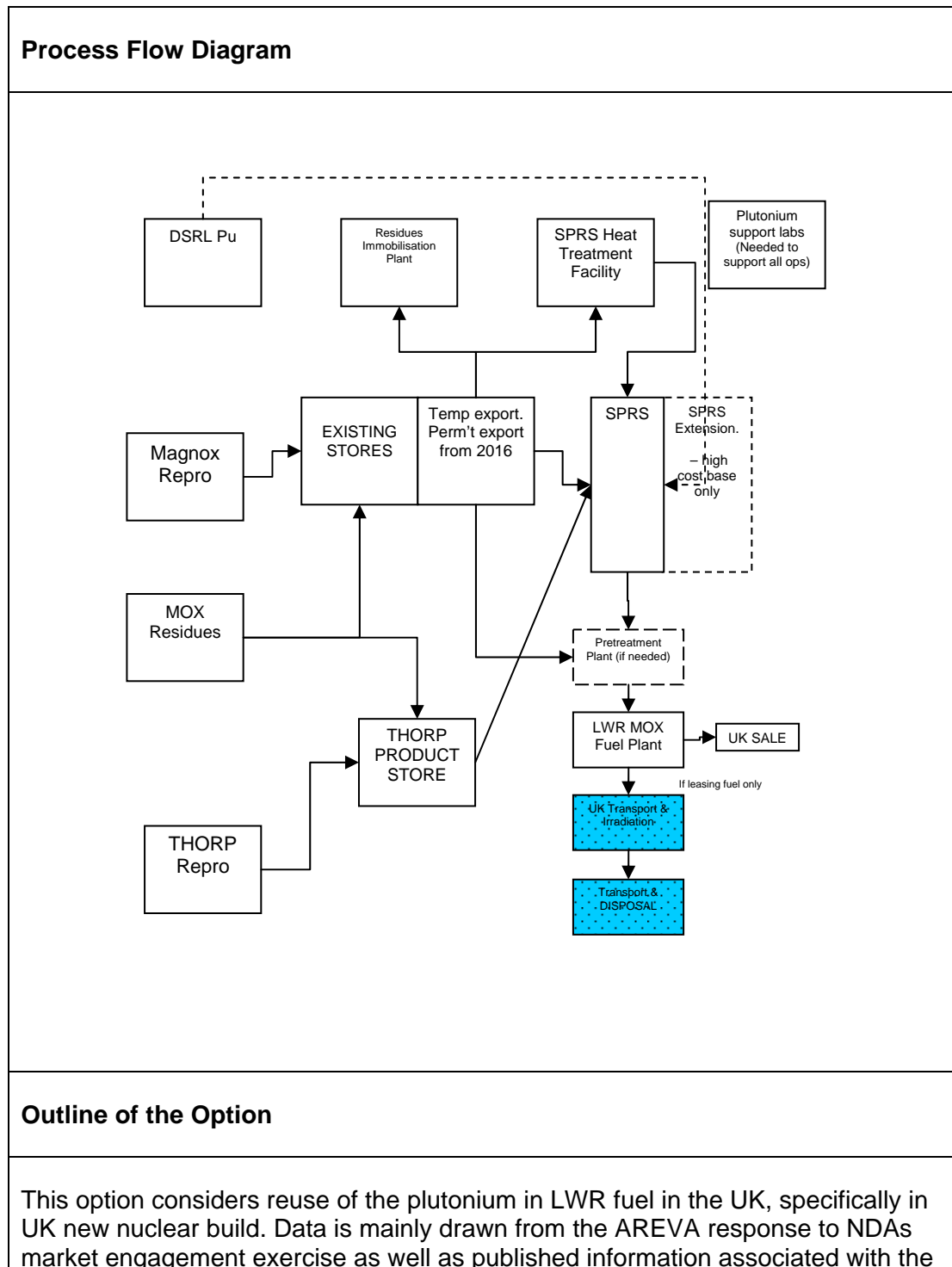
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Plutonium Credible Options Analysis (Gate A) 2010

CREDIBLE OPTIONS DATA

POLICY OPTION: RE-USE

Implementation Strategy 10: Use of MOX – in UK New Build LWR Variant



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US MOX plant, MFFF [22]. However there are a small number of areas where NDA consider that data is omitted or understated and, for these, estimates have been drawn from available industry and analogous plant data.

Facilities which may be required and are not included in the AREVA response include pre-treatment, that may be required as a result of the formation of radiolysis products in storage or contaminants, characterisation that is required for reuse and provision of plutonium analytical services beyond the life time of the current Sellafield plutonium support laboratories. This pre-treatment would only be required for some material (estimated to be 11 teHM at worst) and may potentially be avoided by blending out of specification material with better quality material.

Due to the lead time for this option it is considered likely that much of the current Sellafield capital baseline in regard to plutonium storage is still required. However if the material is to leave the Sellafield site by the proposed date then decisions need to be made much earlier to allow new facilities and/or transport assets to be procured.

It is assumed that the current SMP does not deliver this option due to the limited lifetime of the facility and the limited demonstrated capacity.

This option includes all UK civil material which is currently in UK safeguards. If additional UK owned material were to enter safeguards and be added to the inventory then the estimates of both cost and potential revenue for the plan would need to be reviewed.

For modeling purposes it is assumed that plutonium stored at Dounreay will be transported to Sellafield for interim storage in SPRS (or similar appropriate store). However, most of the plutonium stored at Dounreay is mixed with HEU (High Enriched Uranium) and storage of HEU is contrary to existing planning permissions and safety cases for SPRS, so some work is assumed to have been completed to enable this material to be stored at Sellafield. This reuse process is likely to be required to separate the HEU from the plutonium prior to utilisation.

Revenue delivered and cost incurred by NDA (i.e. the net cost of the disposition) is clearly very dependent on the commercial model and location/ownership of any potential reactors to utilise the MOX.

The option in summary

- i) Storage in existing stores and SPRS until withdrawn for use
- ii) Heat Treatment and Packaging including characterisation in a new plant
- iii) Provision of new plutonium support laboratories
- iv) Potential Pre-treatment facility for a small percentage of the plutonium.
- v) Provision of LWR MOX fabrication plant (~60 teHM pa)
- vi) Manufacture of around 1500 teHM of LWR MOX fuel on just in time basis for LWR reactors
- vii) Transport of MOX fuel to UK reactor
- viii) Transport of irradiated MOX fuel from reactor once GDF available

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- ix) Disposal of irradiated MOX in UK GDF with disposal costs paid for by utility
- x) Decommissioning of SPRS, extension modules, chloride removal facility, treatment and packaging facilities including plutonium support laboratories, MOX plant, and transport assets.

Assumptions

- Project commences 2015
- Material may be withdrawn from existing stores or new stores for characterisation
 - Approximately 40 teHM of the material requires sampling and treatment
- Scope of characterisation is conservatively assumed to be analysis of isotopic and chemical impurities, physical powder properties and water content for all the inventory in a new facility
- Pre-treatment required depending on initial assumption that might be required for part of the inventory
- Empty plutonium cans treated at Sellafield as PCM
- MOX fuel will be produced in a new UK facility on or adjacent to Sellafield site (assumes 6.75-7.6% PuO₂ and remainder depleted Uranium carrier, provided by NDA at nil cost to utility)
- Production facility refurbished once during operational life
- MOX will be irradiated in UK reactors nominally over a 30 year period
- Spent MOX fuel stored at nil cost at reactor pending disposal route availability
- Offsite transport for unirradiated fuel will be achieved via a fleet of new flasks over the 30 year period
- UK GDF available for receipt of MOX fuel 2075
- Transport of irradiated fuel will be achieved via a fleet of new flasks over a 20 year period
- Disposal in GDF is assumed to be in standard cost per disposal canister with each canister holding 0.53 teHM spent MOX

Exclusions

Non safeguarded materials

Overseas plutonium is assumed to be returned to customers

Cost Data and Uncertainty

AREVA did not declare uncertainty on their estimates so -20% to +100% was used. For other facilities, annual operating costs, unless specifically included in LTPs, were estimated to 10% of capital costs, with an uncertainty of -10 to +20%. Similarly, recent parametric estimates for decommissioning of alpha plants indicate that appropriate provisions are 40% of capital costs.

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This is considered pessimistic for stores.

Cost data for the process blocks

Cost estimates are provided in Table 8 for a plutonium fabrication into MOX of approximately 7% by weight. Order of magnitude cost estimate for a new MOX fabrication facility have been made and given in reference [22]. The estimated total lifetime cost of the facility is the sum of individual costs for R&D, capital, operation and maintenance, POCO and decommissioning. These costs were used with transport and disposal costs to construct a lifecycle cost estimate for plutonium management.

1. Store – PuO₂ powder prior to encapsulation

Prior to operation of the MOX plant the material will have to be safely and securely stored. Estimates for this have been taken from the Sellafield LTP and no extra module to SPRS is required as the existing stores should be able to cope with storage once the MOX plant commences operations.

2. SPRS Heat Treatment Facility

The purpose of this facility is to sample, characterise and, if necessary, pre-treat the plutonium prior to fabrication of MOX assemblies. Data for this block is derived from existing projects being carried out at Sellafield. If extensive pre-treatment is required, such as aqueous polishing then the cost is significantly greater and an upper bound is based on the US MFFF facility.

Based on Areva's experience, it is likely that the americium issue can be managed by blending within the Heat Treatment Facility but risks remain that the MOX plant design will need to be approved by the UK Regulators and the fuel to be approved by reactor operators. Clean up may therefore still be necessary and is therefore included as an upper bound cost of £1B for the facility.

3. Plutonium Chemical Clean Up Plant

This facility will be required to remove chemical impurities such as iron from an estimated 11.7 teHM of the plutonium inventory, to make it reusable. Costs for this plant have been obtained from a newly commissioned piece of work by the National Nuclear Laboratory⁽³²⁾.

4. MOX plant

This cost estimate is based on data provided in reference 11. No technology development costs have been included. The order of cost estimate for the plant was developed from AREVAs estimates for a commercial specification MOX plant. Costs for design, build, operation and decommissioning of the plant and ancillary infrastructure are given. Transport packages and security vehicles for land transport in the UK (plutonium and fresh MOX fuel) will additionally be required.

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5. Plutonium Support Laboratories

To support plutonium disposition activities, laboratories to undertake analysis to support waste processing and verification, technical improvement and troubleshooting in support of operations are assumed.

6. Transport and Disposal of waste form packages in a HLW/SF-type disposal facility

The fuel is exported for use in the reactor and details of the costing are given. After storage at the reactor the spent fuel is sent to the GDF when available and direct disposed into canisters.

Disposal costs have been calculated assuming £398k disposal cost per disposal canister, reference.

Commercial Value

A range of possible commercial benefits may be accrued depending upon the commercial model.

If it is assumed that a revenue of [REDACTED] is generated then the total benefit would be [REDACTED] assumed to be spread over the operating period of the plant

Disposal costs paid for by utility.

Technical Maturity

Interim Storage: TRL = 9

Interim storage of plutonium oxide powder is well understood and is implemented on an industrial scale and so is considered to have a technical maturity of 9. Estimates vary as to the time period for which is technical maturity is considered valid but an assumption has been made that it is valid for around 30 years.

Plutonium can emptying: TRL = 9

Routine activity , although may be challenging with older cans

Heat Treatment and packaging: TRL =3

The contaminants, their ease of removal and thus scope of the treatment and chloride removal process is not well understood.

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Plutonium Chemical Treatment Plant. TRL = 9

A well understood process in both plutonium purification in existing facilities such as THORP and also in specific plutonium polishing facilities in France.

MOX fabrication: TRL = 9

Routine large scale manufacturing of LWR MOX in e.g. MELOX.

MOX irradiation: TRL = 9

Demonstrated large scale irradiation of MOX to similar levels as those proposed.

UK MOX and SF transport: TRL = 9

Routine activity, although politically sensitive.

Disposal : TRL = 2/3

No developed concept, or actual experience, for disposal of MOX but should be compatible with proposed UK concept.

Lead Time

The section on time constraints discusses the lead time associated with other options that provide the drivers for making decisions.

The detail lead time for the new facilities are as discussed below:

SPRS Heat Treatment/packing plant: A new repack facility is assumed to have a lead time of 3 years giving an earliest start to repackaging operations of 2024. No major R&D lead time considered, although the scope of the treatment plant is not clear. Significant permissioning and licensing activities expected

Plutonium Chemical Cleaning Plant

This plant has a lead time of 10 years. No major R&D lead time required, as the technical maturity is considered to be high.

MOX plant

The MOX plant has a lead time of 7-10 years and construction as per the AREVA report

MOX and SF transports

No lead time is required for this but it is assumed that unirradiated MOX is transported within the UK from 2024 onwards for a period of 30 years, with spent

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fuel being sent from UK reactors to the Conditioning Facility / GDF from 2080 onwards over a 20 year period.

Environmental Impact

There will be some environmental impact, albeit likely low, if pre-treatment is required. There may be additional plant complications and discharges due to the removal of non-radiological Impurities (e.g. chlorides).

The environmental discharges from the processing similar to that for SMP should be minimal from a new plant and zero from storage activities. The longer term environmental impact will be dominated by the assessment of the durability of the waste form with the GDF.

There will be an environmental impact from the building of new plant.

The energy use for a SMP plant is known. The environmental impact from production in this option using 41 kg CO₂ eq / kg is ~ 61,000 te CO₂ eq for LWR fuel. However the avoided burden from the replacing of 11 million tonnes of Australian uranium ore is 840 Mte CO₂ eq.

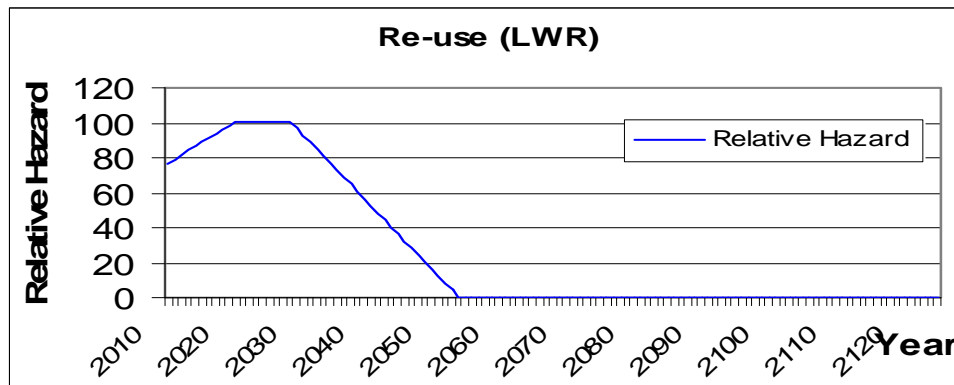
Socioeconomic Impact

Socio-economic Impacts are calculated using the figures derived in the ERM report and applied to the costs for each option.

Type/Location	Direct	Indirect	Total
Sellafield Construction Jobs			
Sellafield Ops Jobs			
Other Construction			
Other operations			

Safety – SED scores over time

NOT PROTECTIVELY MARKED - REDACTED



The shape of the graph reflects the separated stock building up until conversion of the material into MOX, which reduces the relative hazard in line with the production profile.

Proliferation Resistance

From the discussion and charts in section 6.7, UK LWR MOX reuse does significantly reduce the state-sponsored proliferation risk from the material, to a greater extent than the other non-reuse options. This is to be expected as there is an additional highly radioactive barrier introduced, there is a relatively non-robust chemical barrier (dissolvable ceramic) added to the material, it is now in a non-mobile state and the plutonium isotopes have been denatured (i.e. changed from reactor grade to deep burn grade plutonium, which offers greater proliferation resistance). Further work expected to be complete in early 2011 will also consider plutonium theft/diversion “proliferation risk”.

Disposability

In this option the fuel would be disposed of as spent MOX. The RWMD assessment has not identified any show stoppers associated with disposal in this form. A full disposability assessment has not been made. It has been assumed the waste form will be emplaced in a HLW/SF type disposal facility. However, there are potentially significant uncertainties on the cost of disposal including but not limited to:

- Ability to demonstrate a criticality safety case with the assumed plutonium loading
- GDF Implementation scope and schedule
- Ability to dispose in a single rock type including potential spatial limitations
- Ability to dispose of the baseline inventory in a single facility

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Knowledge gaps and R&D needs

A large number of MOX elements of this form have been fabricated and irradiated, so no significant R&D would be required. R&D would be required to establish the disposability case for MOX in the GDF.

A preliminary list of knowledge gaps and R&D needs is shown below.

- Development of a waste form specification for disposal;
- Detailed assessment of Spent MOX as a waste form, including GDF package and operating envelope;
- Qualification of waste form for disposal;
- Process development and establishment of process envelope;
- Detailed assessment of facility design and costing, including OR Modelling to confirm throughput;
- Review Sellafield Site Layout and confirm plant could be located;
- Establish GDF design concept.

Risks and Opportunities

This option is dependent on the acceptability of the bulk transport of unirradiated MOX fuels and spent fuels to/from a UK LWR reactor. This transport is possible under the current regulatory and security regimes, however any changes in the future could render this option unachievable.

The option assumes that all the inventory is suitable for reuse, except for 0.2 teHM of residues and given that some material (up to 11 teHM) may require some form of chemical clean-up. This would need to be confirmed through sampling and appropriate characterisation to ensure that the material fabricated would meet the conditions for acceptance for subsequent irradiation.

The commercial revenues may vary either positively or negatively from that assumed, depending on market conditions and customer negotiations.

Depending on the timescales for implementation of this option it may be required to either blend or clean the plutonium to remove americium or other contaminants.

Time constraints and timescale decision drivers

For the fuel to be optimal for use by 3rd parties, without additional treatment costs being incurred, then the average americium levels are generally assumed to be needed to be below 4%. Fulfilling this requirement means that early action is required for the plutonium derived from Oxide reprocessing, in terms of blending or pre-treatment. Even acting on the timescales of this option may not preclude the

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need for processing prior to use in reactors.

Stakeholder views

For stakeholders that view plutonium as a material which should not have been separated in the first place a decision to reuse the material would not be popular and there would be an expectation that firstly, it was not re-separated and that it was only done on the basis of demonstrated benefit. For those that see plutonium as an asset this option is likely to be acceptable, however there are those that would prefer to see reuse in fast reactors as a more effective utilisation of the fuel.

For this UK reactor burn option, experience should be gained from the Japanese programme to burn MOX fuel in domestic reactors. There was a lot of information required by local groups and authorities prior to acceptance of MOX fuel to be accepted in individual reactors.

Policy Impacts

If this option is to be pursued then assurance would need to be sought that the transportation of this material would be regarded as acceptable from a policy and security perspective.

Since UK reactors are considered then a justification exercise would have to be carried out.

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Plutonium Credible Options Analysis (Gate A) 2010

Table 1 – Storage Costs

Capital Costs

Facility	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
SPRS Extension 1 (in 2032)			
SPRS Extension 2 (in 2043)			
SPRS Heat Treatment Facility / Repack			
Residue HIP Plant			
2 New plutonium support laboratories (in 2019 and 2060)			

Operating

Facility	Average annual operating costs			Nominal Years Operation	Total operating costs (£m)		
	Low	Mid	High		Low	Mid	High
Stores (old magnox stores)							
2010-2030							
2030-2060							
Stores (Thorp Product)				35			

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**Plutonium
Credible Options Analysis (Gate A)
2010**

SPRS + extensions		15	
2010-2025		95	
2025-2120			
Residue HIP Plant		5	
New plutonium support laboratories		108	
SPRS Heat Treatment Facility		85	
Security		108	

Decommissioning

Facility	Decommissioning Costs (£m)		
	Lower Bound	Best Estimate	Upper Bound
SPRS			
2 SPRS Extension Modules			
SPRS Heat Treatment Facility			
Residue HIP Plant			

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**Plutonium
Credible Options Analysis (Gate A)
2010**

Old Stores (Magnox and Thorp) New plutonium support laboratories	
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Note on Table:



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Plutonium Credible Options Analysis (Gate A) 2010

Table 2 Cost estimates for disposal of plutonium as cement waste form

Capital Costs

Facility	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
SPRS extension modules			
New plutonium support laboratories			
Cementation Plant			
Cement Product Store			

Operating

Facility	Average annual operating costs		Years of Operation	Total operating costs		
	Low High	Mid		Low	Mid	High
Stores (old magnox stores)			20 ⁽¹⁰⁾			
2010-2030						
2030-2060			30			
Stores (Thorp Product)			35			
SPRS + extensions			15			
2010-2025						

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**Plutonium
Credible Options Analysis (Gate A)
2010**

2025-2060		35	
New plutonium support laboratories		35	
Security Costs		50	
Total Cementation Plant		40	
Total Cement product Store		100	

Decommissioning

Facility	Decommissioning Costs (£m)		
	Lower Bound	Best Estimate	Upper Bound
SPRS	[Redacted]		
SPRS Extension			
Old Stores (Magnox and Thorp)			
New plutonium support laboratories			
Cementation Plant			
Cement Product Store			

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**Plutonium
Credible Options Analysis (Gate A)
2010**

Disposal: (Transport for disposal is included within the disposal costs).

	(Lower Bound) £m	Best Estimate £m	Upper Bound £m
Transport & Disposal			

Notes on the Tables:



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**Plutonium
Credible Options Analysis (Gate A)
2010**



NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

Table 3 – Vitrified Waste Form

Capital

Facility	Lower Bound £m	Best Estimate £m	Upper Bound £m
SPRS Extension 1			
Residue HIP Plant			
SPRS Heat Treatment Facility			
New plutonium support laboratories			
Vitrification plant			
Product Storage			
Overpack Facility			

Operating

Facility	Average annual operating costs (£m)	Years of operation	Total operations cost (£m)
Stores (old magnox stores)			
2010-2030			
2030-2050			
Stores (Thorp Product)		35	

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

SPRS (+ extension)		15	
2010-2025		70	
2025-2095			
Residue HIP Plant		5	
SPRS Heat Treatment Facility		20	
New plutonium support laboratories		25	
Vitrification plant		25	
Vitrified Pu Product Stores		70	
Consolidation – Overpack Facility		20	
Security		40	

Decommissioning

Facility	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
SPRS Extension 1			
SPRS main facility			
Old Stores (Magnox)			

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

and Thorp)			
Residue HIP Plant			
SPRS Heat Treatment Facility			
New plutonium support laboratories			
Vitrification plant			
Product stores			
Overpack facility			

Disposal: (Transport for disposal is included within the disposal costs).

	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
Glass			
PCM			

Notes on the table:



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**Plutonium
Credible Options Analysis (Gate A)
2010**



NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

Table 4 Cost estimates for disposal of plutonium as HIP Ceramic waste form

Capital Costs

Facility	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
SPRS Heat Treatment Facility			
Ceramic Product Stores (SPRS standard)			
New plutonium support laboratories			
Ceramic Plant			

Operating

Facility	Average annual operating costs	Years of Operation	Total operating costs	
Stores (old magnox stores)				
2010-2030				20 ⁽¹⁰⁾
2030-2050				20
Stores (Thorp Product)				35
SPRS				
2010-2025				15
2025-2095	70			

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

New plutonium support laboratories		35	
SPRS Heat Treatment Facility		20	
Security Costs		40	
Ceramic Plant		25	
Ceramic Product Stores		70	

Decommissioning

Facility	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
SPRS Heat Treatment/ Repack Facility			
SPRS			
Ceramic Product Stores			
Old Stores (Magnox and Thorp)			
New plutonium support			

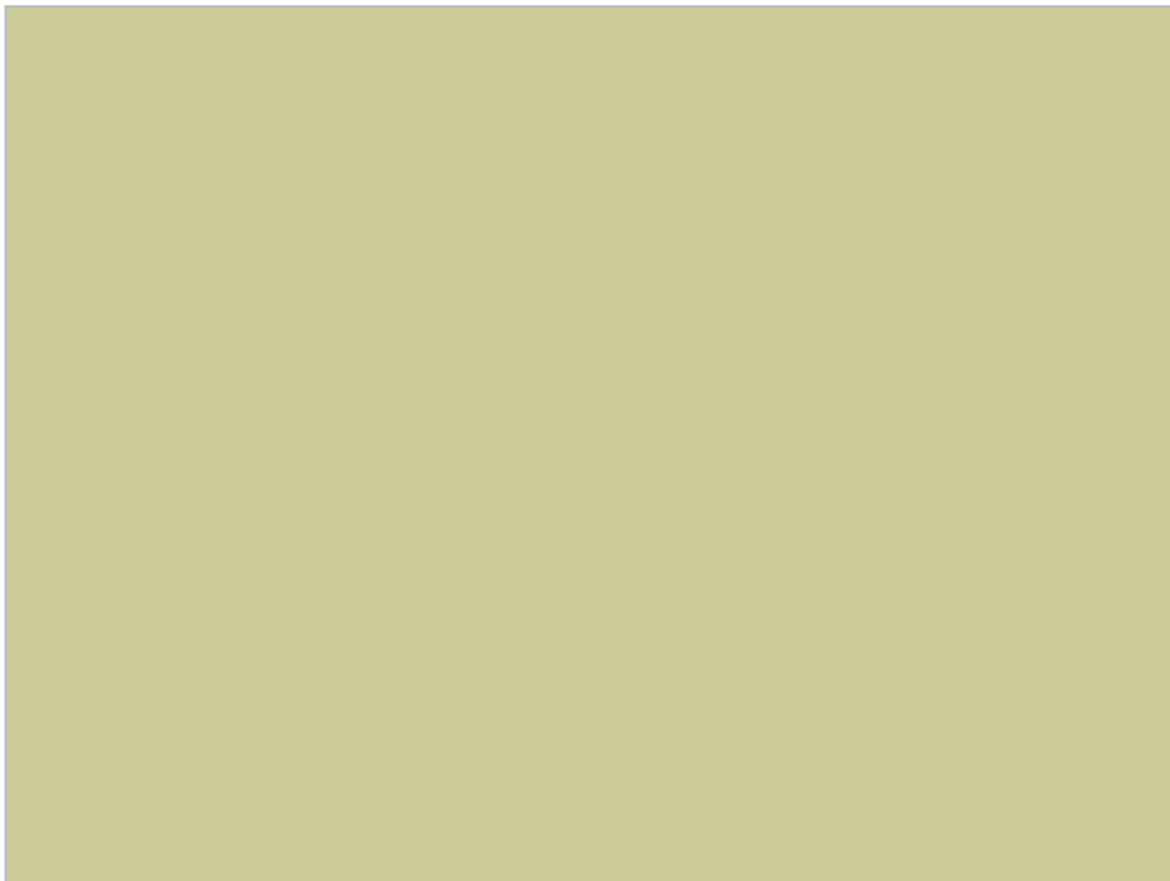
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**Plutonium
Credible Options Analysis (Gate A)
2010**

laboratories			
Ceramic Plant			

Disposal: (Packaging for disposal is included within the disposal costs).

	(Lower Bound) £m	Best Estimate £m	Upper Bound £m
Transport & Disposal			



NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

Table 5 – Low Specification MOX in new facility

Capital

Facility	Lower Bound £m	Best Estimate £m	Upper Bound £m
SPRS Extension 1			
Residue HIP Plant			
SPRS Heat Treatment Facility			
New plutonium support laboratories			
New MOX plant			
Product Storage			
Overpacking Facility			

Operating

Facility	Average annual operating costs (£m)	Years of operation	Total operations cost (£m)
Stores (old magnox stores)			
2010-2030		20 ⁽¹⁰⁾	
2030-2045		15	

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

Stores (Thorp Product)		35	
SPRS			
2010-2025		15	
2025-2045		20	
Residue HIP Plant		5	
SPRS Heat Treatment facility		20	
New plutonium support laboratories		35	
MOX plant		20	
Product Storage		60	
Overpacking Facility		10	
Security		35	

Decommissioning

Facility	Lower Bound	Best Estimate	Upper Bound
SPRS Extension 1			
SPRS main facility			
Old Stores (Magnox)			

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**Plutonium
Credible Options Analysis (Gate A)
2010**

and Thorp)			
Residue HIP Plant			
SPRS Heat Treatment Facility			
New plutonium support laboratories			
MOX plant			
Product stores			
Overpack facility			

Disposal

	Lower Bound	Best Estimate	Upper Bound
Glass			
PCM			

Notes on Table:



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**Plutonium
Credible Options Analysis (Gate A)
2010**



NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

Table 6 – Low Specification MOX pellets in cans in SMP

Capital

Facility	Lower Bound (£m)	Best Estimate £m	Upper Bound £m
SPRS Extension 1			
Residue HIP Plant			
SPRS Heat Treatment Facility			
New plutonium support laboratories			
Modify SMP plant			
Product Storage			
Overpacking			

Operating

Facility	Average annual operating costs (£m)	Years of operation	Total operations cost (£m)	
Stores (old magnox stores)				
2010-2030				20 ⁽¹⁰⁾
2030-2045				15
Stores (Thorp Product)		35		

NOT PROTECTIVELY MARKED - REDACTED

Plutonium Credible Options Analysis (Gate A) 2010

SPRS			
2010-2025		15	
2025-2045		20	
Residue HIP Plant		5	
SPRS Heat Treatment facility		20	
New plutonium support laboratories		35	
SMP plant		25	
Product Storage		60	
Overpacking		20	
Security		40	

Decommissioning

Facility	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
SPRS Extension 1			
SPRS main facility			
Old Stores (Magnox and Thorp)			
Residue HIP Plant			

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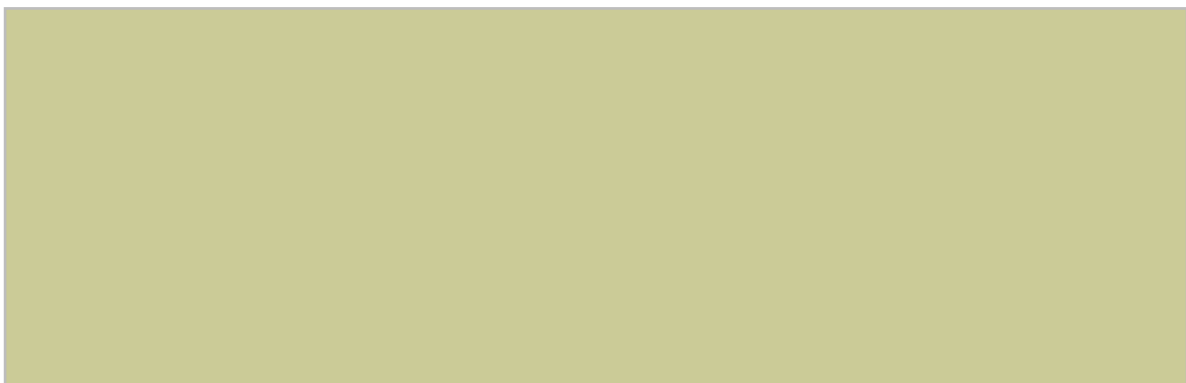
**Plutonium
Credible Options Analysis (Gate A)
2010**

SPRS Heat Treatment /packaging Facility	
New plutonium support laboratories	
SMP MOX plant (potentially sunk cost but included here)	
Product stores	
Overpack facility	

Disposal

	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
Low Spec MOX			
PCM			

Notes on the Table:



NOT PROTECTIVELY MARKED - REDACTED

Plutonium Credible Options Analysis (Gate A) 2010

Table 7 – CANDU re-cycle

Capital

Facility	(Lower Bound) £m	Best Estimate £m	Upper Bound £m
SPRS Heat Treatment Facility			
Pu Chemical Clean Plant			
Residue HIP Plant			
New plutonium support laboratories			
MOX plant			
Ships			
Transport flasks			

Operating

Facility	Average annual operating costs (£M)	Years of operation	Total operations cost		
Stores (old magnox stores)					
2010-2030				20 ⁽¹⁰⁾	
2030-2055				25	
Stores (Thorp Product)		35			

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**Plutonium
Credible Options Analysis (Gate A)
2010**

SPRS			
2010-2025		15	
2025-2055		30	
Pu Chemical Clean Plant		5	
Residue HIP Plant		5	
SPRS Heat Treatment facility		20	
New plutonium support laboratories		35	
MOX plant		30	
Flask transport (unirrad)		30	
Flask Maintenance (unirrad)		30	
Flask transport (irrad)		20	
Flask Maintenance (irrad)		20	
Security		45 ⁽¹⁵⁾	

Decommissioning

Facility	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
SPRS			

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

Pu Chemical Clean Plant	
Residue HIP Plant	
Old Stores (Magnox and Thorp)	
SPRS Heat Treatment facility	
New plutonium support laboratories	
MOX plant	
Flasks (unirrad)	
Flasks (irrad)	

Commercial Costs

	Cost £M	Years
Misc Commercial Costs		2015-2050

Disposal

	Lower Bound	Best Estimate	Upper Bound
MOX fuel			
PCM			

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**Plutonium
Credible Options Analysis (Gate A)
2010**

Notes on Table:



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**Plutonium
Credible Options Analysis (Gate A)
2010**

Table 8 – LWR re-cycle Overseas

Capital

Facility	Lower Bound £m	Best Estimate £m	Upper Bound £m
SPRS Extension 1			
SPRS Heat Treatment Facility			
Residue HIP Plant			
Pu Chemical Clean Plant			
New plutonium support laboratories			
MOX plant			
Ships			
Transport flasks			

Operating

Facility	Average annual operating costs	Years of operation	Total operations cost (£m)
Stores (old magnox stores)			
2010-2030			
2030-2055			

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

Stores (Thorp Product)		35	
SPRS			
2010-2025		15	
2025-2050		25	
Residue HIP Plant		5	
SPRS Heat Treatment facility		20	
Pu Chemical Clean Plant		5	
New plutonium support laboratories		35	
MOX plant		30	
Flask transport (unirrad)		30	
Flask Maintenance (unirrad)		30	
Flask transport(irrad)		20	
Flask Maintenance(irrad)		20	
Security		45	

Decommissioning

Facility	Lower Bound	Best Estimate	Upper Bound
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NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

SPRS Module 1	
SPRS main facility	
Old Stores (Magnox and Thorp)	
Residue HIP Plant	
SPRS Heat Treatment Facility	
Pu Chemical Clean Plant	
New plutonium support laboratories	
MOX plant	
Flasks (unirrad)	
Flasks (irrad)	

Commercial Costs

	Cost £M	Years
Misc Commercial Costs		2015-2050

Disposal

	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

MOX fuel	
PCM	

Notes on Table:



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**Plutonium
Credible Options Analysis (Gate A)
2010**

Table 9 – Sell Costs

(NB the costs codes blue are only required for the lease variant of this option).

Capital Costs

Facility	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
SPRS Heat Treatment facility			
SPRS extension 1			
Residue HIP Plant			
New plutonium support laboratories			
Ships transport out (assume 1 upper band, 2 lower band)			
Packages transport out (60 flasks at -10% +20% uncertainty)			
Ships transport return (assume 1 upper band, 2 lower band)			
Packages transport return (60 flasks at -10% +20% uncertainty)			

Operating

Facility	Average annual operating costs			Years of Operation	Total operating costs (£m)		
Stores (old magnox stores)							

NOT PROTECTIVELY MARKED - REDACTED

Plutonium Credible Options Analysis (Gate A) 2010

2010-2030	20 ⁽¹⁰⁾
2030-2060	30
Stores (old Thorp)	35
SPRS	
2010-2025	15
2025-2050	25
New plutonium support laboratories	35
Residue HIP Plant	5
SPRS Heat Treatment facility	20
Security Costs	35
Transport (out) Based on 240 shipments	30
Ship management (Out)	30
Flask Maintenance Based on maintaining 18 MOX Packages for 30 years	30
Flask Maintenance Based on maintaining 60 spent fuel flasks for	20

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**Plutonium
Credible Options Analysis (Gate A)
2010**

20 years							
Transport (return)				20			
Ship management (Return))				20			

Decommissioning


Facility	Decommissioning Costs (£m)
SPRS Heat Treatment facility	
Transport Assets	
SPRS	
SPRS Extension	
Residue HIP Plant	
Old Stores (Magnox and Thorp)	
Flasks	
New plutonium support laboratories	

Disposal: (Packaging for disposal is included within the disposal costs).

	(Lower Bound) £m	Best Estimate £m	Upper Bound £m
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**Plutonium
Credible Options Analysis (Gate A)
2010**

Fuel	
PCM	

Notes on the Table:



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Plutonium Credible Options Analysis (Gate A) 2010

Table 10 – LWR UK re-cycle

Capital

Facility	Lower Bound £m	Best Estimate £m	Upper Bound £m
SPRS Extension 1			
Residue HIP Plant			
SPRS Heat Treatment/packaging Facility			
Pu Chemical Clean Plant			
Plutonium support laboratories			
MOX plant			

Operating

Facility	Average annual operating costs	Years of operation	Total operations cost (£m)		
Stores (old magnox stores)					
2010-2030				20 ⁽¹⁰⁾	
2030-2055				25	
Stores (old Thorp)	35				
SPRS					

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**Plutonium
Credible Options Analysis (Gate A)
2010**

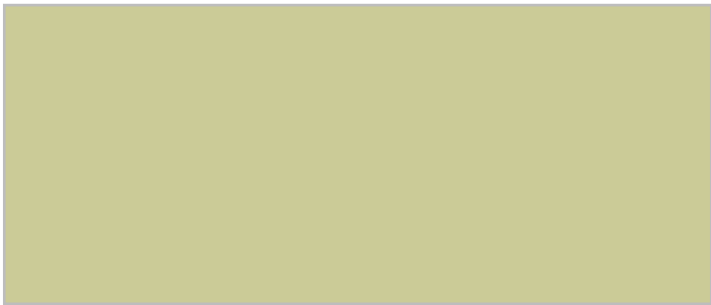
2010-2025		15	
2025-2050		25	
Residue HIP Plant		5	
SPRS Heat Treatment/ Packaging facility		20	
Pu Chemical Clean Plant		5	
Plutonium support laboratories		35	
MOX plant		30	
Security		45	

Decommissioning


Facility	Lower Bound	Best Estimate	Upper Bound
SPRS Extension 1			
SPRS main facility			
Old Stores (Magnox and Thorp)			
Residue HIP Plant			
SPRS Heat Treatment/packaging Facility			

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**Plutonium
Credible Options Analysis (Gate A)
2010**

Pu Chemical Clean Plant	
Plutonium support laboratories	
MOX plant	

Commercial Costs

	Cost £M	Years
Misc Commercial Costs		2015-2050

Disposal (note: only applicable to understand lifecycle costs – charged to reactor operator)

	Lower Bound (£m)	Best Estimate (£m)	Upper Bound (£m)
MOX fuel			
PCM			

Notes on Table:

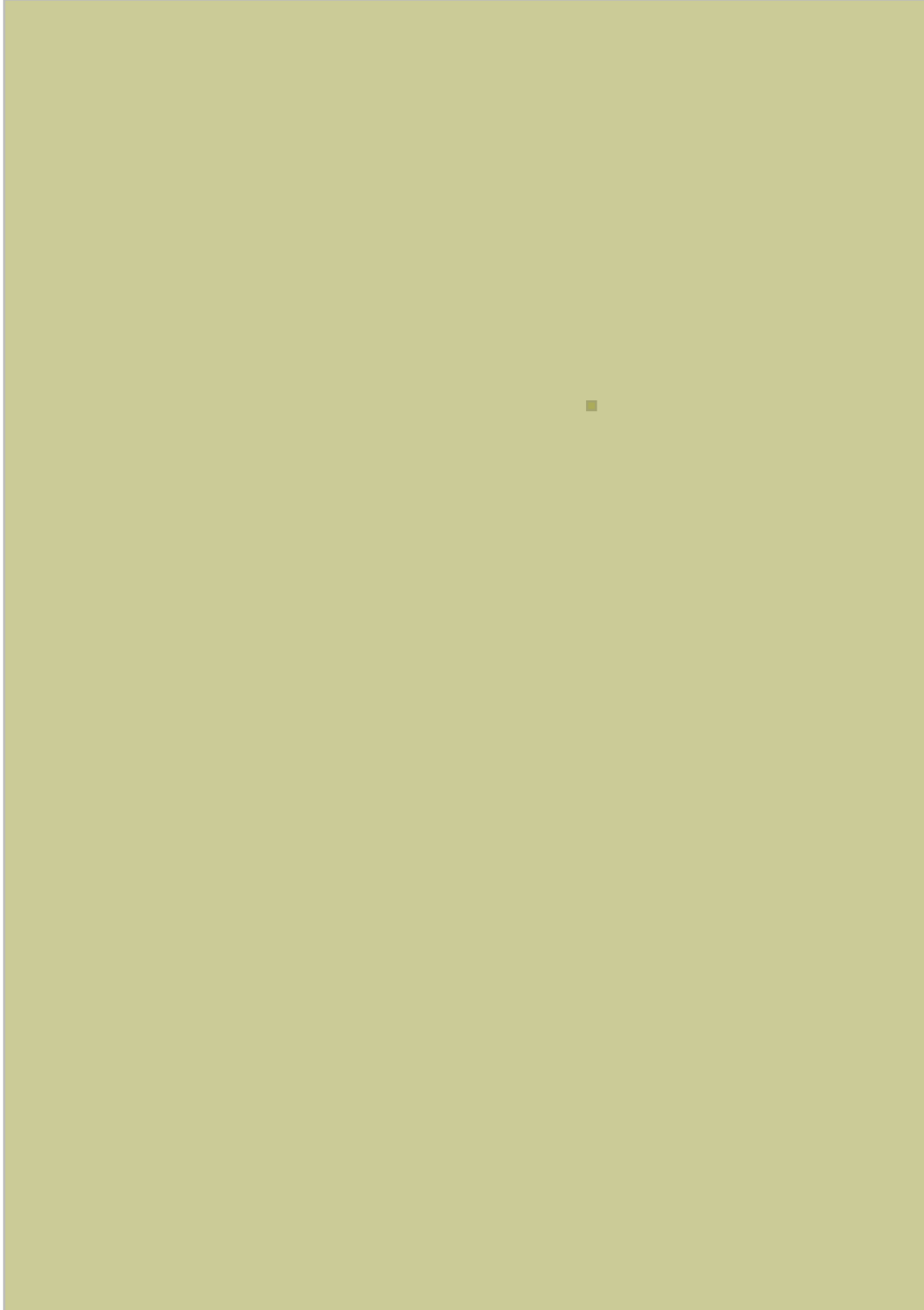


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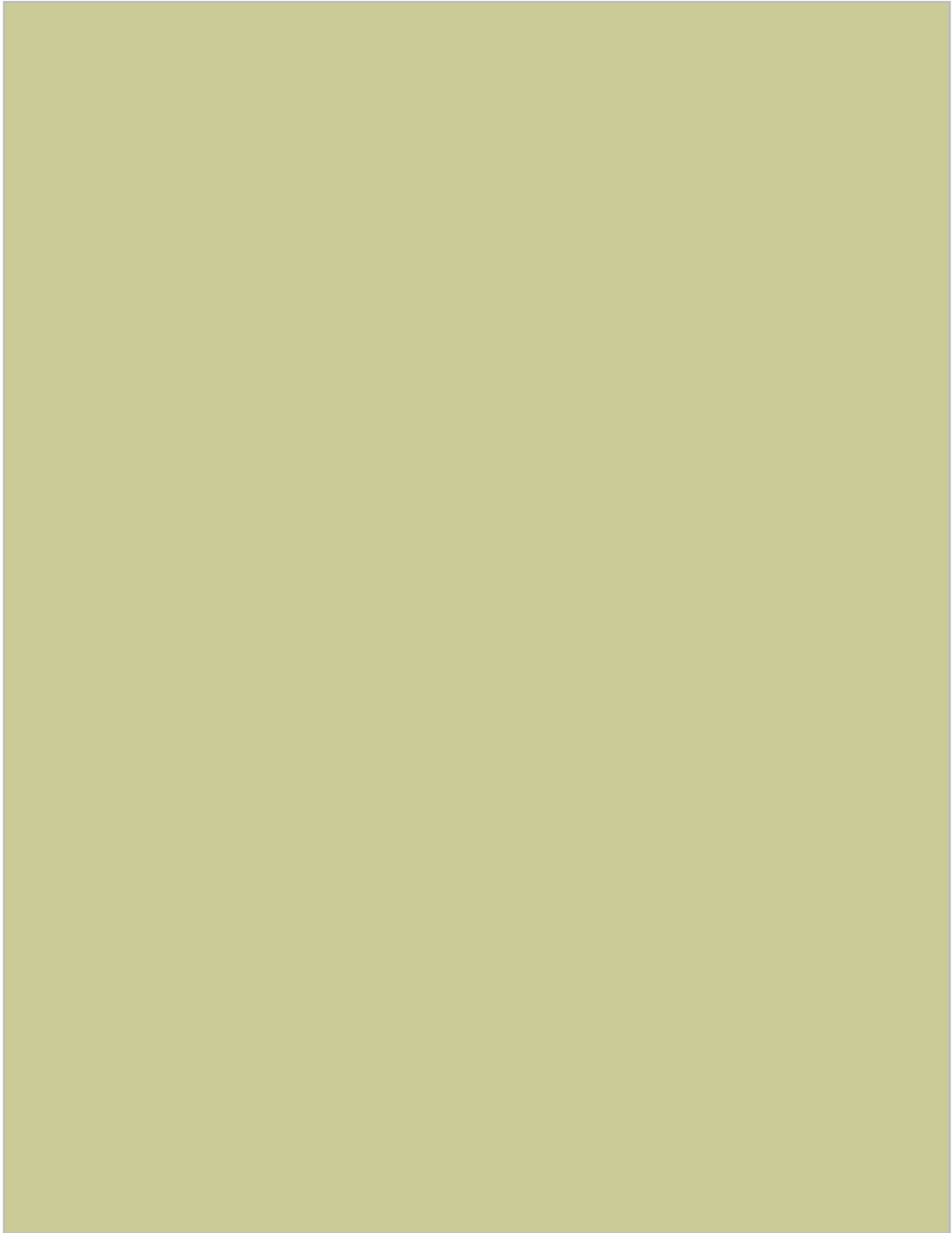


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References to Appendix A




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Appendix B: Economic External Review

	<p>Review of the NDA's Plutonium Credible Options Paper (2010)</p>
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Review of the NDA's Plutonium Credible Options Paper (2010)

Background

The NDA is updating the analysis of its credible options for plutonium disposition. This builds on a similar exercise undertaken in 2008.

The plutonium credible options paper reviews 10 options in some detail. The options are further underpinned by a probabilistic based cost and revenue model (GoldSim).

My Remit and the Assurance Process

I was asked by the NDA to provide an independent review of the plutonium credible options paper, with particular regard to:

- A general sense check
- Logic of the process flows within in each option
- Consistency and comparability between options

The review was an iterative process with the NDA lead author, which included clarifications and challenges which have been fed back and, where appropriate, incorporated in the final paper.

My qualification to conduct this assignment is based on a range of due diligence and assurance work I have done for the NDA over several years, and specifically work on previous plutonium disposition reviews in 2007 and 2008.

Conclusions

The conclusions from the assurance process are described below, and can be summarised as

- A broad range of options are covered
- Each option is described in some detail
- The level of uncertainties are represented in a fair manner
- Apart from some relatively minor queries that we are discussing with the NDA, the process flow and cost elements are represented in a fair manner and are consistent between options

Breadth of Options

The paper covers a broad range of plutonium disposition option (1 more than during the last review in 2008)

- Store
- Dispose: Cement
- Dispose: Vitrification
- Dispose: HIP (ceramic)

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Plutonium Credible Options Analysis (Gate A) 2010

- Reuse: Low Spec MOX (new plant)
- Reuse: Low Spec MOX (SMP)
- Reuse: CANDU MOX
- Reuse: Overseas MOX
- Reuse: Sell / Lease Pu
- Reuse: LWR UK

Depth of Coverage

Each option is covered in some detail, with references to support documentation where appropriate:

- Process flow
- Option description
- Key assumptions
- Cost data and uncertainties
- Technical maturity
- Lead times
- Environmental impact
- Socio-economic impact
- Safety
- Disposability
- Knowledge gaps and R&D needs
- Risks and opportunities
- Time constraints and timescale decision drivers
- Stakeholder views
- Policy impacts

Uncertainties

All options have differing but generally high levels of technical, timing and cost uncertainty. These uncertainties are fairly reflected in the cost modelling through the use of upper and lower ranges for key cost inputs and through the use of a probabilistic modelling tool (GoldSim) to produce the probability adjusted option costs.

The paper also sensibly highlights the need to narrow some of the key uncertainties as part of 'next steps' in order to provide a firmer foundation for decision making.

Process Flow Logic for each Option and Consistency between Options

Table 1 shows the grid we used to test the process flow logic and the consistency of process steps and costs between options.

Overall, the broad process steps for each option appear appropriate, and by and large the key parameters within each process step appear correctly represented. We did have a number of mostly minor queries about some of the key parameters, which are highlighted in 'red' in the table. At the time of preparing this assurance paper we are in the process of clarifying the queries with the lead author.

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Plutonium Credible Options Analysis (Gate A) 2010

Table 1: Credible Options Comparison of Process Steps and Key Parameters

	Process Step	Key Parameters	Store	Cement	Glass	HIP-Ceramic	LS MOX new	LS MOX SMP	CANDU MOX	O/seas MOX	Sell/Lease Pu	LWR UK

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Appendix C: Technical Readiness Level Definitions

Basic Technology Research	Level 1	Basic principles observed and reported
Research to Prove Feasibility	Level 2	Technology concept and/or application formulated
Technology Development	Level 3	Analytical and experimental critical functions and/or characteristic proof of concept
Technology Demonstration	Level 4	Component and/or bench validation in laboratory environment
System/Subsystem Development	Level 5	Component and/or bench validation in relevant environment
System Test & Operation	Level 6	System/subsystem model or prototype demonstration in relevant environment
	Level 7	System prototype demonstration in an operational environment
	Level 8	Actual system completed and qualified through test and demonstration
	Level 9	Actual system proven through successful operations e.g. through reliability and maintainability demonstration in service

NOT PROTECTIVELY MARKED - REDACTED

Appendix D: Approach for the calculation of socio-economic impact

D.1 Approach

The same approach as to that taken in the macro-economic study has been used in this report that is to utilise a cost per job for construction and operational activities. The original numbers were derived from the appropriate lifetime plans and these numbers have been escalated to reflect the change from the 2008 money values used in the 2008 version of this report.

Construction jobs have a much higher cost factor associated with them to reflect the considerable material costs associated with these activities.

Employment resulting from decommissioning and transportation activities is calculated using the operational job cost factors, and employment resulting from disposal activities have not been included in this version of the report due to the high degree of uncertainty, high cost, commonality between options and unreasonably high impact.

No consideration has yet been given to whether new plants will be required at Dounreay. This will be included as part of the scope of the next phase of work but the socio-economic impact for the Caithness areas has not yet been calculated. The much lower inventory at Dounreay means that the likely future impact is much smaller than that at Sellafield.

D.2 Escalation

Construction activities have been escalated at [REDACTED] from the values in the 2008 report which is in line with the construction indices during the period.

Operational costs at Sellafield have been escalated at [REDACTED] to reflect the pay rises received since 2008. This metric has also been applied to decommissioning activities.

Multipliers derived from lifetime plans have been used to calculate the indirect employment resulting from direct plutonium strategy activities. The factor used was 1.2.

NOT PROTECTIVELY MARKED - REDACTED

**Plutonium
Credible Options Analysis (Gate A)
2010**

Location	Type	Cost/Job/year 2008 (£)	Escalation Rate (%)	Revised Cost/Job/Year (£)
Sellafield	Construction	[Redacted Data]		
Sellafield	Operations			
All other locations	Construction			
Dounreay	Operations			
All Other locations	Operations			

Table D1: Job cost factors

NOT PROTECTIVELY MARKED - REDACTED