



# Uranium and Plutonium: *Macro-Economic Study*

Final Report

June 2007

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Nuclear Decommissioning Authority

**Uranium and Plutonium:  
*Macro-economic Study***

**Final Report**

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**The *Uranium and Plutonium: Macro-economic Study* provides an economic analysis of potential future disposition options for the UK's significant stock of nuclear materials. These materials (Uranium and Plutonium, in a variety of physical and chemical forms) have arisen principally from uranium enrichment, nuclear fuel manufacture and used nuclear fuel reprocessing. They could be immobilised and disposed of, stored over the long term, sold or converted to fuel to be re-used in nuclear power stations.**

**The *Study* has been conducted on behalf of the Nuclear Decommissioning Authority (NDA) by *Environmental Resources Management Limited (ERM)* and *Integrated Decision Management Limited (IDM)*. It lays out different potential futures and determines their financial, socio-economic and environmental impacts. The *Study* analyses a range of options from declaring all the materials to be wastes through to a case with maximum re-usage as fuel. The *Study* makes no presumptions about where any recycled fuel would be used, but enables a variety of reactor assumptions to be examined. The *Study* does not set out a preferred option or make any recommendations on options to the NDA or to the Government. The recommendation of options follow an integrated, transparent, decision-making process conducted by NDA, Government, Regulators and other stakeholders.**

#### **WHAT ARE THE NUCLEAR MATERIALS AND HOW MUCH IS THERE?**

Over the years the United Kingdom has built up a significant stock of nuclear materials. Two activities from the nuclear fuel cycle (see *Figure 1* for a schematic) are responsible for the 'core' of materials in the inventory:

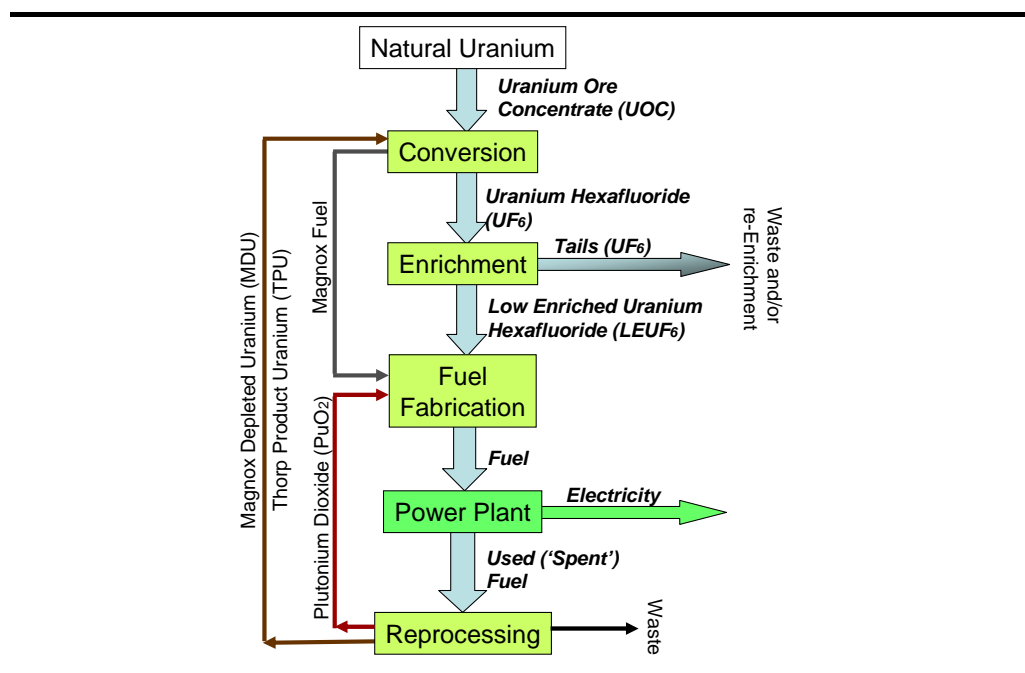
1. naturally-occurring ("natural") uranium contains approximately 0.71% of the fissile U235 isotope used to generate nuclear power in current reactors. The UK's first generation "Magnox" reactors use uranium with this concentration of U235. Other reactors (including AGR<sup>1</sup>, which is responsible for the majority of the UK's nuclear electricity generation) need uranium with higher U235 concentrations (in the range 3-5% U235). Thus natural **uranium must be "enriched"**, to produce the higher U235 concentrations needed for fuel manufacture. Since we have taken an "enriched" stream of uranium out of the enrichment plant, we are left with a "depleted" residue which has a lower U235 content (typically in the range 0.2-0.4%) than the natural uranium "feed". This residue is generally referred to as "Tails";
2. **reprocessing of used ("spent") fuel** recovers usable uranium and plutonium.

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<sup>1</sup>Advanced Gas-Cooled Reactor

These two activities generate the 'core' of the UK's nuclear materials inventory. This is made up of four major materials, with approximate quantities shown in *Table 1* below.

**Figure 1** *The Nuclear Fuel Cycle*



**Table 1** *Inventory of Core UK Nuclear Materials*

Material	Source	Form	Storage Medium	Quantity (tonne HM <sup>1,2,3</sup> )
Tails Uranium Hexafluoride	Tails UF <sub>6</sub>	Residue from enrichment of natural uranium for manufacture of AGR fuel	Solid <sup>4</sup> Steel cylinders	25,000
Magnox Depleted Uranium	MDU	Sellafield reprocessing of used fuel from Magnox reactors	Powder Steel drums	30,000
Thorp Product Uranium	TPU	Sellafield reprocessing of used fuel from AGR reactors in Thermal Oxide Reprocessing Plant (Thorp)	Powder Steel drums	5,000
Plutonium Dioxide	PuO <sub>2</sub>	Sellafield reprocessing (Magnox and Thorp)	Powder Double stainless steel cans	100
<b>TOTAL</b>				<b>60,000</b>

<sup>1</sup> UK-owned materials only. A (significantly lower) quantity of foreign-owned materials is currently in the UK awaiting return to its owners (in some cases following further processing)  
<sup>2</sup> tonnes Heavy Metal equivalent (i.e. mass of uranium and/or plutonium within the materials)  
<sup>3</sup> Assuming contracted reprocessing quantities are reprocessed in Magnox reprocessing and Thorp facilities (planned end dates for both 2012). Does not include the potential materials which could result in reprocessing spent fuel beyond current contracts/planned end dates (Spent Fuel management is analysed in the NDA's *Spent Fuel Management: Life Cycle Analysis Model* study, undertaken by ERM and IDM on behalf of NDA and due to report in 2007)  
<sup>4</sup> Solid at room temperature and pressure, but becomes a gas at relatively low temperatures and is highly reactive, giving off hydrogen fluoride on reaction with water or water vapour

The NDA is the owner of around 50,000tHM of these materials. UKAEA (the UK Atomic Energy Authority) and MOD (Ministry of Defence) also have holdings, and British Energy owns significant amounts of TPU and Plutonium.

The *Study* has concentrated on these major stocks which make up the 'core' of the NDA's nuclear inventory. Decisions on how to treat this "core" inventory will in due course set the parameters for assessing all NDA nuclear materials.

In addition there are also various quantities of low and high enriched uranium as oxide powders, fluoride powders and uranium metal. These 'clusters' of nuclear materials contain approximately 2,000 tonnes HM and cover many individual items including mixtures of uranium, plutonium and thorium, accumulated during the development of nuclear power in the UK. The current holders of these materials have developed plans for recovery, storage or conversion to waste for these items. These plans will need to be re-examined in the light of whatever decisions are taken by the Government and the NDA about the treatment of 'core' materials.

#### **WHAT CAN BE DONE WITH THESE MATERIALS?**

All NDA nuclear materials are currently held in purpose-built stores on NDA sites. External bodies regulate these stores against criteria including their safety and security. The minimum materials management programme is one which maintains safety and security, in line with regulations, into the future: there is no viable 'do nothing' or 'cost nothing' option. There is also a degree of urgency, because while the UK currently retains the technology, infrastructure and expertise to undertake any of the options discussed in this paper, under some scenarios this may not continue to be the case. It is therefore important that decisions are taken on a timescale compatible with either providing the capability in the UK, or assuring provision of services from overseas.

Part of the NDA's strategic responsibility for the UK's nuclear legacy is that its choices should ensure the best value to the UK taxpayer. From a financial accounting point of view, the materials are currently classed as assets of zero value.

Most of this material could be considered as either a liability or an asset, depending on a variety of factors such as the uranium market price and the relative costs of treating it as a waste, of storing it or of processing to bring the materials to market. Specific costs of the UK continuing to meet its national and international security and non-proliferation commitments were not included within the scope of the *Study*, nor any assessment of how these commitments may change in the future. Similarly, the potential risks and costs of accidents or acts of terrorism were excluded. A specific assessment was conducted to establish that the disposition options assessed met the

environmental and legal principles for long term radioactive materials management established during the CoRWM<sup>2</sup> process.

Looking ahead a proportion of the materials is likely to be considered as waste and will be destined for disposal when the UK's repository is available. At the other end of the scale, some uranium stocks are immediately tradable, either in their current form or after blending with other uranium. Should the NDA's stocks be considered for trade, then their potential value is likely to be a key factor in decision making, and the re-use scenarios aim to assess potential market value.

All the materials mentioned above could be either declared as waste, stored, or processed for re-use<sup>3</sup>. There are many possible scenarios, with some materials declared as waste, some stored, and some re-used. The *Study* considered this multiplicity of scenarios to be bounded by three futures for managing the materials where all materials are declared as waste, all are stored, or all are processed for re-use as fuel. These were termed *Bounding Scenarios*, and called *Waste*, *Store*, and *Use*:

1. the *Waste Bounding Scenario* processes the nuclear materials into forms suitable for deep geological disposal into the UK Radioactive Waste Repository as soon as this is available. Disposing of all materials as waste assumes that they are not considered to have a value or might reflect a UK Government view that non-financial downsides take precedence. The *Waste Bounding scenario* is consistent with a future of low uranium market prices and no long term UK nuclear power programme;
2. The *Store Bounding Scenario* places all the materials into long term storage on the assumption that they may have a value in the future. An open-ended storage period would not be consistent with the life cycle analysis methodology employed in the *Study* (whereby all materials must eventually be disposed of, whatever route they take to this disposal). Thus in the *Store Bounding Scenario* it is assumed that no use is found, and disposal takes place by 300 years from now<sup>4</sup>;
3. The *Use Bounding Scenario* assumes that the materials have value now, and makes use of them as fuel. Uranium stocks would be re-used via conversion (to UF<sub>6</sub>, for all materials other than "Tails" which are already UF<sub>6</sub>), enrichment and fuel fabrication, producing fuel which is essentially identical in energy yield to that produced from natural uranium. The

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<sup>2</sup> The Committee for Radioactive Waste Management was set up in 2003 to provide independent advice to Government on the long-term management of the UK's solid higher activity radioactive waste (see <http://www.corwm.org.uk>).

<sup>3</sup> All materials can technically be re-used, if necessary after suitable recovery. Whether such re-use is economically feasible depends on a range of factors, including the price of uranium on the market. The *Study* has assumed that no materials are automatically classified as waste (and other options for their disposition thus excluded). Similarly, it has been assumed that no materials are automatically classed as assets.

<sup>4</sup> The 300 year period is in line with CoRWM recommendations, which are based on the assumption that societal control cannot be guaranteed for longer periods

plutonium stocks would be used as inputs to Mixed Oxide Fuel (MOX) fabrication. Processing to fuel and subsequent use could take place anywhere, but the most accessible economic case assumes that all operations would be carried out in the UK<sup>5</sup>. For the purposes of the *Study*, the *Bounding Scenario* therefore assumes that the resulting fuel is used in an ongoing UK nuclear electricity generation programme of new, modern reactors with 60 year lifetimes. The capacity of this programme has been arbitrarily set at 12 GW, roughly equivalent to 20% of current UK capacity (in line with nuclear's share over the past 20 years). A 12 GW programme may, or may not, give some guide to nuclear's share going forward. This new generation of reactors is assumed only for the purposes of this *Study*. It is also assumed for the purposes of the study that these reactors will be followed by a 12 GW programme of advanced ("Fast") reactors which would enable the 'maximum re-use' of the current stocks of nuclear materials to be examined<sup>6</sup>. In order to complete the journey of the materials to disposal, it is assumed that disposal of all fuel-related materials takes place by 300 years from now.

These *Bounding Scenarios* represent the boundaries of possibilities within which more detailed and realistic scenarios can be investigated and modelled.

By necessity a large number of assumptions have been made in the *Study*, which must be taken into account when interpreting the findings as changes to the assumptions can give rise to significant variance in predicted economic returns. The formulation of the *Waste* and *Storage* options are relatively straightforward but the *Use* option introduces yet more assumptions and uncertainties. There are also 'pinch points': dates by which decisions have to be made or options will be made considerably more expensive or even closed off.

### ***HOW MUCH ELECTRICITY COULD BE GENERATED FROM FUELS PRODUCED FROM THE MATERIALS?***

An alternative way to assess the quantity of materials present is by reference to the amount of electricity which could be generated from the fuel that could be manufactured from the materials (following suitable treatment and processing). This calculation does not take account of whether re-use of materials would be the most cost-effective, or in any other way the best or

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<sup>5</sup> All stages leading to the production of fuel and its subsequent use in reactors could take place partially or fully outside the UK. Whether all services could be supplied as and when required, and what the commercial conditions would be, are uncertain. Thus the *Use Bounding Scenario* assumes all stages leading to fuel production and its subsequent use in reactors occur in the UK.

<sup>6</sup> For the purposes of the model, whether the Fast Reactor programme is included or whether the reactor programme is limited to a "once through" PWR programme has only a marginal impact on costs as modelled. Because Fast Reactor costs are uncertain, it has been assumed in the modelling that Fast Reactors are cost neutral (i.e. revenue from electricity sales matches costs). Thus including or excluding them from the analysis as modelled has only a minor impact on costs (due to differences in the quantity of uranium to be disposed of).

worst, disposition option – it serves merely to illustrate the potential scale of the stocks.

There is a limited potential to use such fuel within the UK’s current nuclear reactors, and unless there were to be new nuclear reactors constructed in the UK major re-use could only occur either in existing or new reactors abroad.

- in the medium-term, the *Use Bounding Scenario* has assumed that any new UK reactor would be a PWR (Pressurised Water Reactor), fuelled by enriched uranium and/or Mixed Oxide (MOX) fuel;
- in the longer term (from 2040 at the earliest), it may be possible to commercially construct advanced reactors such as Gas Cooled Fast Reactors (French and Japanese energy policy assumes such deployment on these timescales). These reactors can use the non-fissile U238 fraction of uranium as fuel – there is approximately 100 times as much of this in the materials stock as the fissile U235 fraction needed for currently available reactors.

The *Table* below shows that 1½ -3 PWR reactors could be fuelled over their 60 year lifetime by the stock of UK materials. Roughly equal quantities of fuel could be produced from the UK’s Plutonium and Uranium stocks.

**Table 2** *Potential Fuel and Electricity Production from UK Materials stock*

Material	Potential PWR Fuel Production (tHM)	Potential PWR Electricity Generation (TWh)	Number of PWR Reactors Fuelled***
Plutonium	1,500	550	1.1
Uranium*,**	500-2,500	200-900	0.4-1.9
<b>Total</b>	<b>2,000-4,000</b>	<b>750-1,450</b>	<b>1.5-3.0</b>

\*Tails, MDU and TPU combined

\*\*Calculations for Uranium depend on assumptions regarding the future price of uranium on the international market

\*\*\*Assuming 1000 MWe reactor with 60 year lifetime

For the *Use Bounding Scenario*, the number of Fast Reactors which could be fuelled is significantly higher, and depends on how Plutonium is managed in a future reactor programme. A 12GWe programme of Fast Reactors could be fuelled by the existing stocks of uranium materials for around 700 years.



## HOW WAS THE STUDY CONDUCTED?

### *Concept*

The concept used for the *Uranium and Plutonium: Macro-economic Study* was:

1. to identify the possible stages (“*Blocks*”) which materials pass through in the likely range of futures;
2. to characterise the financial and other parameters of each *Block*, based on its operational elements and the plant requirements (materials, staffing, scheduling, etc.). This characterisation allows the *Blocks* to be modelled;
3. these parameterised *Blocks* were then assembled into time-scaled *Scenarios*, modelled and subjected to sensitivity analysis.

### *Data: Sources and Uncertainty*

The data included in the *Blocks* are assumptions drawn from the technical and engineering knowledge and judgement of the current NDA Site Licensee Companies (SLCs), Nexia Solutions and the *ERM and IDM* Project Team. As far as possible, current designs and construction methods have been assumed as have current technologies and chemical processes. It is also recognised that there will be particular uncertainties associated with the *Use* option as it assumes the viability of a Fast Reactor programme.

The data is subject to significant uncertainty which may be reduced by targeted activities going forward. Whilst the data is considered sufficient for the macro-economic model, significant further work, including front end engineering studies and underpinning research and development, would be required to inform any investment decision making based upon the preliminary findings of this *Study*.

### *The Model: Inputs, Operation and Outputs*

Economic inputs into the model include ranges of market values of Uranium and of discount rates. Socio-economic analysis has been undertaken by deriving a set of factors which allow employment (direct and indirect) by type and by site to be estimated based upon the capital and operational costs of each scenario/sensitivity modelled. The resultant figures are then analysed with reference to the local economies surrounding each site.

A specific Life Cycle Assessment of environmental impacts per scenario has been undertaken, examining the carbon footprint and radiotoxic releases to air of each scenario. In addition, a policy-based analysis against environmental and legal principles and the recommendations of CoRWM has been undertaken to assess whether the scenarios are supportable within the range of interpretation currently applied to these principles.

The model itself is a bespoke model produced for the project by *ERM and IDM*. It works by simulating the transport of materials between the various plants and stores, by processing these materials into new materials within *Blocks* and by disposing of final wastes into Repositories. The model ensures that all material is accounted for at all times; any residues from plant or storage inefficiencies are accounted for and managed (generally as waste). Thus the stock of uranium and plutonium is constant unless new stocks are added or power is generated in reactors. The model produces annual outputs covering a range of factors, including disaggregated costs (undiscounted and discounted), environmental and socio-economic impacts.

### *Key Economic Parameters*

The financial discount rate used is a powerful driver of discounted costs, particularly as some of the scenarios to be modelled extend 300 years from now. For example, applying a 3% discount rate to an expenditure of £1 billion in year 300 would indicate a requirement to set aside only £140,000 today. Thus the viability and acceptability of any scenario will be significantly affected by the discount rate at which it is judged. For long term schemes, the Treasury “Green Book” recommends a 3.5% discount rate for short-term appraisal, with declining discount rates for longer-term analysis (post 30 years). These rates have been used as the ‘base case’ in the model, with other rates modelled as sensitivities.

For scenarios which include the *Use* of materials, the model seeks to place a value or liability cost on the nuclear materials for any given set of assumptions. The appropriate point to derive value is the earliest point in the production chain at which the product is interchangeable with product from other sources. Within the *Study*, finished PWR fuel has been chosen as the common point for value derivation. This choice allows uranium oxide (produced from either enriched reprocessed or natural uranium) and MOX fuels to be valued at the same point in the production chain. The value of the PWR fuel produced from nuclear materials is then set equal<sup>7</sup> to the most common alternative (i.e. fuel produced from a natural uranium starting point).

The value of fuel from UK’s stocks of nuclear material will therefore be set very largely by the value of mined natural uranium, which is priced in US dollars per pound of uranium ore concentrate (\$/lb UOC). In the last seven years the spot price of uranium has varied from less than \$10 to over \$110/lb UOC, and in the last 25 years the dollar exchange rate has varied between less than \$1.1=£1 to greater than \$2.0=£1.

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<sup>7</sup> Sensitivities where the value of fuel produced is lower than the natural uranium alternative have also been considered.

## WHAT SCENARIOS WERE CONSIDERED?

As discussed above, three *Bounding Scenarios* were modelled to define the range of possibilities. In addition, eight other scenarios were modelled, giving a spread of possibilities of different futures for specific materials. *Table 3* shows the scenarios modelled.

**Table 3** *Scenarios Considered*

Scenario	Tails UF <sub>6</sub>	MDU	TPU	Pu
Waste Bounding Scenario	Waste	waste	waste	waste
1	Waste	store	store	waste
2	Use	use	use	waste
3	Waste	store	store	store
Store Bounding Scenario	Store	store	store	store
4	Store	use	use	store
5	Waste	waste	waste	use
6	Waste	waste	use	use
7	Waste	use	use	use
8	Store	store	store	Use
Use Bounding Scenario	Use	use	use	Use

In recognition of the uncertainties associated with the *Use* scenario and the viability of a fast reactor programme, scenarios were modelled where materials are recycled into a single generation (“once through”) 12 GWe PWR programme, with disposal of spent fuel at the end of the 60-year reactor lives.

All the scenarios were modelled across a range of uranium prices, discount rates and US dollar exchange rates. Additionally, a range of key sensitivities was applied to each scenario, notably informed by the ‘pinch points’ (dates by which decisions have to be made or options will be made considerably more expensive or even closed off).

## WHAT ARE THE FINDINGS OF THE STUDY?

The results now presented are based on the assumptions that:

- central cost estimates apply to all plants;
- all plants commissioned will be built to schedule and cost;
- plants will run to full capacity (or at any level up to this as required) at all times; and,
- all inputs and products from plants and stores move freely, allowing an optimised operation of the integrated whole.

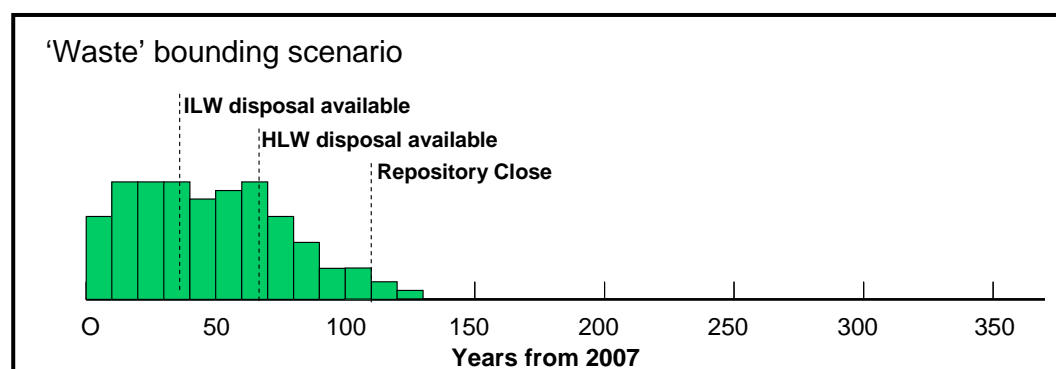
These assumptions are very significant, in that real long-term programmes will be subject to uncertainties in all these areas. Modelling results should always be viewed in the light of these uncertainties.

## Waste

The waste scenarios convert the materials to forms suitable for geological disposal. This can be as simple as putting uranium powders into sealed containers, or as complex as converting plutonium into a low-specification MOX fuel, or some other ceramic wasteform. It is assumed that these activities are carried out on a timescale so that these wasteforms become part of the disposal programme for the UK's radioactive waste, with Intermediate Level Waste (ILW) disposal to repository available from 2040, and High Level Waste (HLW) disposal to repository from 2075.

This programme gives considerable activity in the short and medium term, but all activities cease when disposal is complete, assumed to be by 2125 at the latest. The schematic in *Figure 2* shows the level of activity and therefore of spend required for the *Waste Bounding Scenario*.

*Figure 2* Waste Scenario: Activity Schematic



Assuming that:

- only NDA-owned materials are included;
- uranium can be disposed of as  $UO_3$  or  $U_3O_8$  (rather than the more costly  $UO_2$ );
- the Sellafield MOX plant can be converted to produce 40 tonnes of low specification MOX per year from 2022/23;
- low specification MOX is an acceptable Plutonium waste form to regulators;

undiscounted costs for the *Waste Bounding Scenario* have been estimated to lie in the range £2-3 billion. Costs could certainly lie outside the range – the principal uncertainties relate to the acceptability and cost of the plutonium and uranium waste forms and the availability of the repository to accept wastes promptly (delays in either repository construction or any queue for emplacement would add costs, potentially significantly).

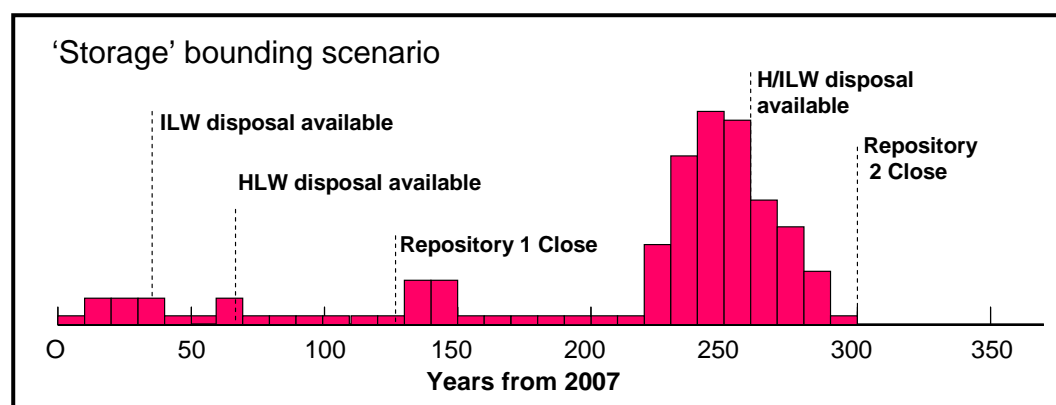
The cost of this scenario does not depend on the price of uranium, or on the US dollar exchange rate. Discounting at Treasury "Green Book" rates reduces present costs to around £1 billion.

## Store

The store scenarios place the materials into long term storage as a strategic resource. This is predicated on the assumption that the materials could be used in the future (e.g. if prices of natural uranium on the international market rise). If materials have not been used, they are disposed of by 300 years from now (using the same wastefoms and plants as the waste scenarios, but later in time) – noting that such a scenario would have incurred the cost of storage with no benefit in undiscounted terms. In most cases it is assumed that the materials can be stored in their current forms, but some, for example Tails UF<sub>6</sub>, must be converted to a more stable form for long term storage.

The *Store Bounding Scenario* converts all the materials into wastefoms in the period from around 250 years' time. The scenario requires waste disposal about 260 years from now and a new repository is assumed to be constructed (the repository for current UK waste is assumed to close in around 2125). Again the schematic below shows the range of activities and therefore spend associated with this scenario.

Figure 3 *Store Scenario: Activity Schematic*



Assuming that:

- only NDA-owned materials are included;
- Plutonium can be stored as PuO<sub>2</sub> oxide powder in currently defined secure facilities;
- Uranium and Plutonium stores can be refurbished at 10% of initial costs after 50 and 100 years, then need to be replaced after 150 years;
- UF<sub>4</sub> is an acceptable long term form for UF<sub>6</sub> storage;

the undiscounted cost of this scenario has been modelled are estimated to lie in the range £3.5-7 billion. This is more expensive than the *Waste Bounding Scenario* – it includes the same waste processing and disposal activities but adds additional storage and, importantly, needs an extra new Repository (whose undiscounted cost is estimated to range from £1.25-3.75 billion)<sup>8</sup>. A

<sup>8</sup> Based on an examination of existing literature and studies, this *Study* has concluded that a base case capital cost estimate for a UK Repository for ILW and HLW is £1.7 billion. A 'low' estimate is assumed to be 20% below this figure. The 'high' estimate of £3.75 billion is taken from a NIREX study.

further important sensitivity concerns the acceptability of PuO<sub>2</sub> powder as a form for long term storage and the costs of this storage.

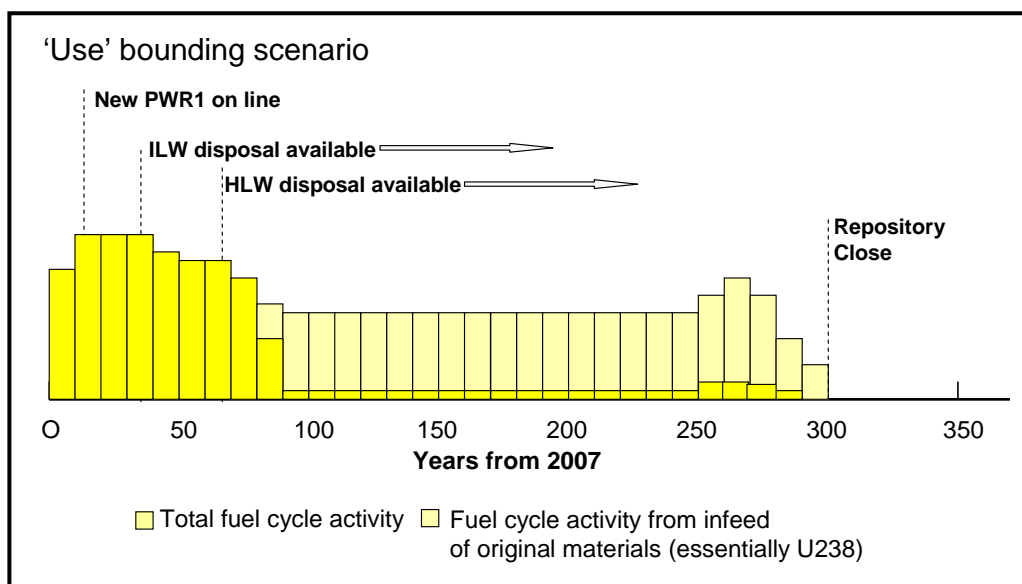
The cost of this scenario does not depend on the price of uranium, or on the US dollar exchange rate, but as the bulk of the activity is undertaken a long time in the future, the effect of discounting is very marked. Discounting at the Treasury “Green Book” rates reduces present costs to around £0.3 billion (i.e. significantly lower than that for the *Waste Bounding Scenario*).

### Use

The *Use Bounding Scenario* converts all the practically available material into fuel for a 12GWe programme of UK PWR reactors (there is enough material to fuel 1½ to 3 reactors of 1000 MWe capacity over their 60 year lifetime, see Table 2). For the purposes of the *Study*, the spent fuel from this programme of UK PWR reactors is subsequently reprocessed and the materials recycled into fast reactors, allowing very much greater utilisation of the uranium (current stocks of uranium could maintain 20% of current UK electricity generation for of the order of 700 years)<sup>9</sup>.

The schematic in Figure 4 shows this activity, together with a representation of the Fast Reactor fuel cycle activities (light yellow) and the much lower level of activity concerned with the storage and preparation of currently stored materials (dark yellow, from 75 years onwards).

Figure 4 Use Scenario: Activity Schematic



by the worth which can be obtained from the materials. The value of the materials is assessed by the price which can be obtained for the fuel, which is related to the price of fuel made from newly-mined uranium. The price

<sup>9</sup> For the purposes of the model, whether the Fast Reactor programme is included or whether the reactor programme is limited to a “once through” PWR programme has only a marginal impact on costs as modelled. Because Fast Reactor costs are uncertain, it has been assumed in the modelling that Fast Reactors are cost neutral (i.e. revenue from electricity sales matches costs). Thus including or excluding them from the analysis as modelled has only a minor impact on costs (due to differences in the quantity of uranium to be disposed of).

obtained for the fuel increases with uranium price and is also dependent on the US dollar exchange rate, so the cost of the scenario reduces as the uranium price rises and the dollar weakens.

Assuming that:

- only NDA-owned materials are included;
- the Sellafield MOX Plant can be successfully refurbished to produce high specification MOX fuel from all Plutonium stocks from 2022/23 (even those that are presently contaminated or mixed);
- MOX produced has an equivalent value to fuel produced from natural uranium;
- reprocessed uranium can be converted and enriched at the same cost as natural uranium;
- 'base case' capital expenditure estimates are used;
- the exchange rate is £1=\$1.8 throughout the period;
- the uranium price on the international market varies from \$10 to \$150 per pound;

undiscounted costs are estimated to lie in the range £-3.5 billion (i.e. a net benefit) to £+2.5 billion. Whether The Fast Reactor programme is included or power generation ceases after a single "once through" programme of PWR Reactors has a marginal impact on costs as modelled<sup>10</sup>.

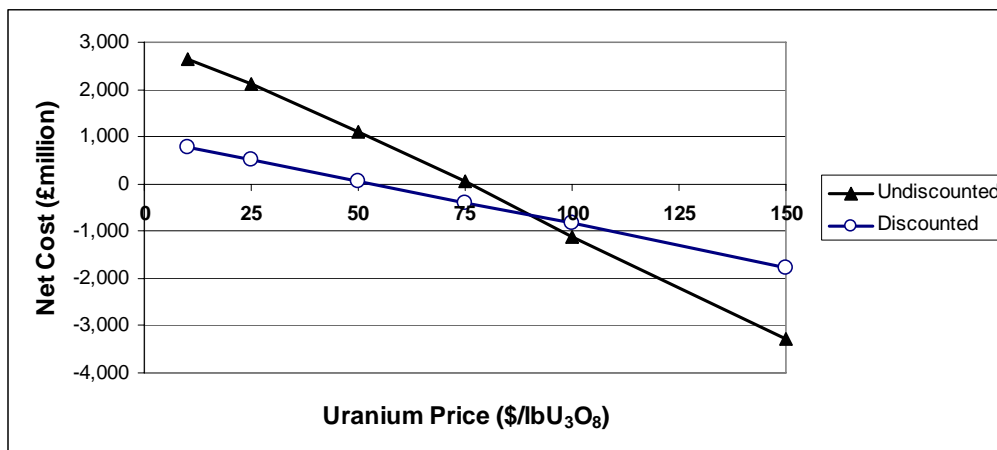
Net costs decrease by approximately £1 billion for each \$25 per pound increase in the price of uranium on the international market (see *Figure 5*). These estimates are subject to considerable uncertainty and much of the uncertainty would increase net costs. Principal amongst these are whether fuels produced can be sold at equivalent prices to those starting from natural uranium and whether the Sellafield MOX plant can produce high throughputs of quality fuel.

Discounting at Treasury "Green Book" rates reduces the cost range to £-2 billion to £1 billion.

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<sup>10</sup> Because Fast Reactor costs are uncertain, it has been assumed in the modelling that they are cost neutral (i.e. revenue from electricity sales matches costs). Thus excluding them from the analysis has only a minor impact on costs (due to the materials that would have been used to produce fuel for the Fast Reactors now needing to be disposed of). If the Fast Reactor programme is not included, net costs increase by approximately £200 million at all uranium prices.

Figure 5 Net Costs from Use Bounding Scenario as a function of Uranium Price



### Environmental and Socio-Economic Impacts

The *Study* has derived, often for the first time, a set of block-specific environmental and socio-economic factors. Results show that variations between *Scenarios* concerning environmental and socio-economic impacts are minor:

- without a Fast Reactor programme, incremental employment from the 11 scenarios modelled ranges from 30,000-60,000 FTEs (full time employment years), i.e. an average of 100-200/year over the 300-year period modelled;
- radiotoxicity impacts are minor except where there is *Use* of materials, where there is a benefit from reductions in the mining and milling of natural uranium. Clearly these benefits accrue outside the UK;
- average carbon dioxide savings across the 300-year period (see *Figure 6*) range from approximately 8,000tCO<sub>2</sub>/year to negative savings (i.e. increased emissions) of around 2,000tCO<sub>2</sub>/year. This is a negligible amount when compared to, for example, the CO<sub>2</sub> emission savings which could result from using the NDA's materials for nuclear power generation<sup>11</sup>.

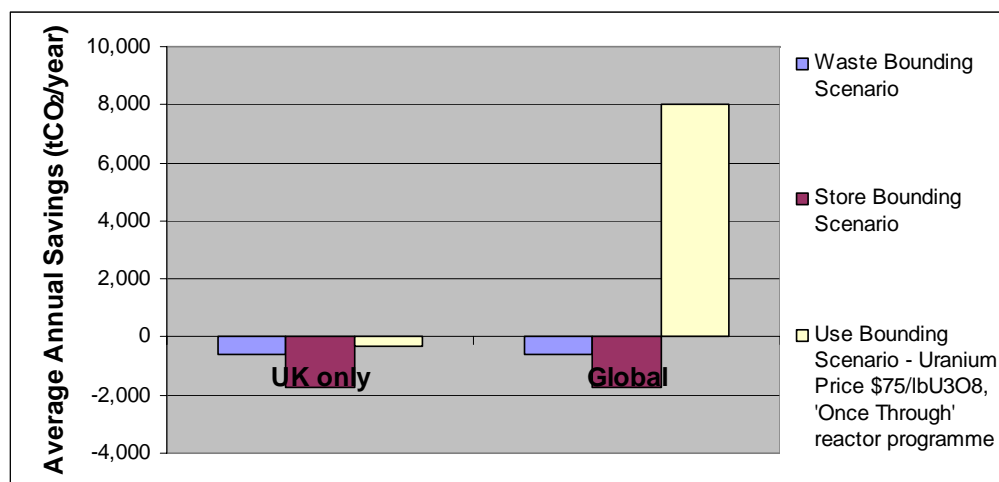
Given the minor differences in environmental and socio-economic impacts, it is financial costs which are the key distinguishing attribute between *Scenarios*.

<sup>11</sup> *Table 2* indicated that UK materials could fuel 1½-3 reactors, generating 12-25 TWh electricity per year. Defra recommends using a grid average of 0.43kgCO<sub>2</sub>/kWh at present: using this figure would give savings of the order of 5-10 million tCO<sub>2</sub>/year)



Figure 6

Average Carbon Dioxide Emissions over 300-year period modelled



### IS THERE A BEST WAY FORWARD?

It is outside the scope of the *Study* to make recommendations: recommending options should follow an integrated, transparent, decision-making process conducted by NDA, Government, Regulators and other stakeholders. Instead the *Study* sets out the advantages and disadvantages of each of the scenarios. For the three *Bounding Scenarios* (*Waste, Store, Use*), these are broadly:

- *Waste* is low risk and, if the uranium price is low, it is either the lowest undiscounted cost option or close to it;
- *Store* keeps options open and delays costs for significant periods (significantly reducing the present value of costs when discounted);
- *Use* may release significant value from the materials (particularly if the uranium price is high) but is subject to significant downside risks.

The situation is complicated by the option to mix strategies (e.g. to store one material and use another). There could also be the option of selling some of the plutonium and uranium materials on the market without first turning it into fuel (noting that the sale of plutonium in particular would need to be subjected to stringent security and political safeguards, with a limited set of potential customers).

The relative merits of the various options will also be affected by the outcome of the public consultation on the future of the nuclear industry in the UK and on how future UK policy deals with a range of issues including safety, security, environmental and socio-economic impacts, misappropriation risk and non-proliferation.

The eleven scenarios modelled are presented again in *Table 4*. Below this *Table*, *Figure 7* and *Figure 8* illustrate the complexity of results for the single case where the uranium price is \$50/lbU<sub>3</sub>O<sub>8</sub>, the exchange rate of £1=\$1.8 and 'base' capital expenditure estimates. It is notable how the position of scenarios changes with discounting and how mixing strategies can change costs.

The *Study* has provided the NDA with a wide-ranging analysis of the possible futures for the UK's stocks of uranium and plutonium materials. It has also pointed out the crucial roles which uranium price and discounting play in the economic evaluation of different scenarios, and the assumptions adopted by the NDA in these areas will be highly significant. The NDA will want to take these findings into account in its discussion with Government on the options for the future.

**Table 4** *Scenarios Considered*

Scenario	Tails UF <sub>6</sub>	MDU	TPU	Pu
Waste Bounding Scenario	Waste	waste	Waste	waste
1	Waste	store	store	waste
2	Use	use	use	waste
3	Waste	store	store	store
Store Bounding Scenario	Store	store	store	store
4	Store	use	use	store
5	Waste	waste	waste	use
6	Waste	waste	use	use
7	Waste	use	use	use
8	Store	store	store	use
Use Bounding Scenario	Use	use	use	use

**Figure 7** *Net Costs by Scenario, Uranium Price \$50/lbU<sub>3</sub>O<sub>8</sub>, Undiscounted*

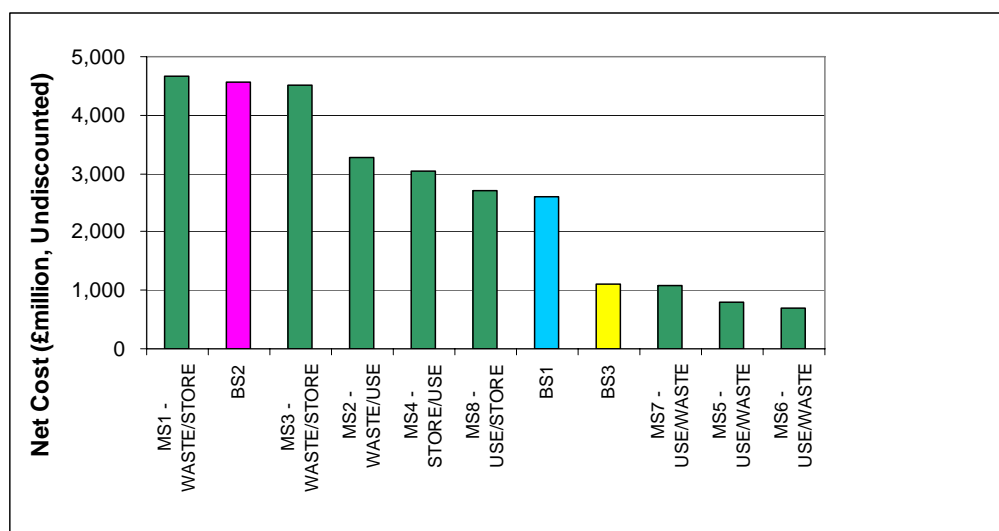


Figure 8

Net Costs by Scenario, Uranium Price \$50/lbU<sub>3</sub>O<sub>8</sub>, Discounted

