



Spent Fuel Management: *Life Cycle Analysis Model*

Final Report

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Nuclear Decommissioning Authority

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Life Cycle Analysis Model*

Final Report

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The *Spent Fuel Management: Life Cycle Analysis Model* study has developed and employed a model which provides an economic analysis of potential future disposition options for the UK's significant stock of spent fuel. These stocks comprise uranium and plutonium fuels which have been irradiated in nuclear reactors, plus the components of irradiation experiments and tests. Most of the fuels are from historic and current power generation programmes, but the *Spent Fuel Study* also considers the fuels and components from the experiments and experimental reactors used to support the UK nuclear power development programme. All options involve a degree of technical and economic uncertainty, and the study assumes these uncertainties will be overcome. The fuels could be stored over the long term, sold, or reprocessed and the recovered materials converted to fuel to be re-used in nuclear power stations.

The *Spent Fuel 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. A range of current plans exist to manage the spent fuels. The *Spent Fuel Study* does not explicitly assess or comment on these plans or their delivery. Rather, it seeks to analyse the whole range of options available from declaring all the fuels to be wastes through to a case with reprocessing and maximum re-usage as fuel. It also investigates contingencies should any option not be realised.

The *Spent Fuel Study* has been carried out in conjunction with the *Uranium and Plutonium: Macro-Economic Study (Materials Study)* by the same contractors. Any nuclear materials produced by the reprocessing of spent fuel are linked to a relevant scenario in the *Materials Study* to enable their value/liability to be assessed. Neither *Study* makes any presumptions about where any recycled fuel would be used, but enables a variety of reactor assumptions to be examined. The *Materials Study* has already been published and should be read together with this report.

The *Spent Fuel Study* does not set out a preferred option or make any recommendations.

WHAT ARE THE SPENT FUELS AND HOW MUCH IS THERE?

Spent Fuel

Nuclear power reactors, and reactors used for testing nuclear fuel and its component parts, take in fuels or test materials generally containing the nuclear materials uranium, plutonium, or, more rarely, thorium. When these materials are removed from the reactor they are classed as 'used' or '*Spent Fuel*'.

Depending on how much they have been irradiated, these fuels can be so radioactive as to require significant concrete shielding to protect workers and the public from ionising radiation. Some fuels with low levels of radiation may be capable of being handled after only a few years. The radiation from spent fuel generally decreases with time, with the predominant short-term radiation coming from fission products with a half life¹ of a few, to a few tens, of years. Spent fuel from power reactors is generally so radioactive that considerable shielding is required for its storage or processing even after many tens of years.

When fuel is used in current power reactors only a small proportion of the nuclear materials in the original fuel are 'burned' in the reactor. Potential fuel materials are also generated during the fuel's residence in the reactor. For example, Plutonium (Pu) is produced from uranium²³⁸ while nuclear fuel is producing power in a reactor. This Plutonium itself then participates in nuclear reactions, generating more power.

UK Reactor Programmes and Spent Fuel

In the UK, the initial nuclear power reactors, commissioned between 1956 and 1970, were based upon Magnox technology which use natural² uranium metal fuel in a magnesium alloy can. This fuel relies upon prompt reprocessing in a plant situated at Sellafield in West Cumbria. The Magnox reprocessing programme is assumed to be completed around 2012. There will be approximately 6000te of future spent fuel arising from the Magnox programme, all of which is scheduled to be reprocessed. The materials produced from reprocessing are currently stockpiled at Sellafield and Capenhurst.

The UK's second programme of nuclear power stations, the Advanced Gas-cooled Reactors (AGRs) commissioned between 1983 and 1988, use slightly enriched ceramic uranium dioxide fuel in stainless steel cans. Some fuel is scheduled for reprocessing in the Thermal Oxide Reprocessing Plant (THORP), with the rest currently planned for long term wet storage at

¹ the "half life" is the time required for the radiation level to decay to half its original value

² i.e. "unenriched". Natural uranium contains approximately 0.7% of the fissile U²³⁵ isotope and 99.3% of the non-fissile U²³⁸ isotope.

Sellafield prior to its assumed immobilisation and disposal. At present, approximately 1,500tHM of this fuel is scheduled to be reprocessed in THORP, with a further 4,500tHM fuel arising to the end of the current reactor lifetimes programmed to be stored.

The most recent reactor in the UK, the Sizewell B Pressurised Water Reactor (PWR) was commissioned in 1995 and uses low enriched fuel in zirconium alloy cans. The power station was designed with enough storage capacity so that its lifetime fuel could be stored on site. This is expected to amount to some 1000tHM and is currently the responsibility of British Energy (BE).

The Magnox and AGR systems were uniquely British designs, and their development entailed the testing of fuel components and the building and use of a number of test reactors and major prototypes. Some of the irradiated material from these test reactors has been reprocessed and some, in the absence of facilities for disposing of High Level Waste (HLW) and spent fuel, was stored, together with the remains of tests, samples and partially refined materials. This fuel, of the order of 20,000 inventory items but containing less than 500tHM, forms the 'cluster' of the UK inventory with the unprocessed fuel from the three main reactor types forming the 'core'. Most of the 'cluster' fuels are currently planned to be stored pending decisions about their long term future.

WHAT CAN BE DONE WITH THESE SPENT FUELS?

A range of current plans exist to manage the spent fuels. The *Spent Fuel Study* does not explicitly assess or comment on these plans or their delivery. Rather, it seeks to analyse the whole range of options available from declaring all the fuels to be wastes through to a case with reprocessing and maximum re-usage as fuel. It also investigates contingencies should any option not be realised.

We have examined the following three methods of spent fuel management:

1. Disposal – after conversion into a suitable wasteform
2. Storage – for varying timescales;
3. Reprocessing – recovering nuclear material and disposing of waste.

Disposal

We have assumed that spent fuel may be processed into a form suitable for long-term storage, for example placing spent PWR fuel into a copper canister with a cast iron insert. The waste packages would then be placed into a deep geological repository.

Storage

Nuclear fuel once removed from the reactor is *stored*, either in wet or dry conditions. The vast majority of the UK's 'core' spent fuel is stored in wet

storage ponds. The length of time different fuel types can be stored is dependent upon the spent fuel's chemical and physical properties.

Reprocessing

The nuclear materials in spent fuels may be recovered by the process of *reprocessing*. This process separates the fuel into three parts: the remaining uranium, the plutonium which has been generated, and the fission products and other wastes. In the UK, reprocessing is currently carried out only at Sellafield, though smaller scale operations were previously carried out at Dounreay in Caithness, with experimental work at Harwell in Oxfordshire.

Reprocessing produces plutonium as plutonium dioxide (PuO₂) powder, uranium as uranium trioxide (UO₃) powder and the waste as a highly active liquid. In the main commercial reprocessing operations, notably in the UK and France, this liquid is being transformed into a stable glass – a process called vitrification.

Historically, the motivation for reprocessing has been to recover the plutonium generated, in particular for use as fuel in advanced reactors (for example 'Fast Reactors') which offer much greater utilisation of uranium. However, these reactors have not yet reached the stage of commercial deployment, and, world-wide, plutonium from reprocessing is either being stockpiled or is being used to make Mixed-Oxide (MOX) fuel for current LWRs.

The economics of reprocessing, together with its safety and environmental effects, has been probably the most controversial aspect of nuclear power over the last 50 years. It raises strong emotions in many groups of stakeholders, and reprocessing in the UK has been the subject of interest from neighbouring nations (for example Ireland and Norway) and international agreements (e.g. the Oslo-Paris Convention, OSPAR) in relation to marine discharges.

WHY ARE THESE SPENT FUELS IMPORTANT?

Spent fuels generally remain on reactor sites for a period of cooling before being transferred to Sellafield for storage, pending reprocessing³. External bodies regulate this storage against criteria including safety and security. The minimum spent fuel management programme is one which maintains safety and security, in line with these 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.

³ The major exception is British Energy's Sizewell B PWR plant, where the spent fuel is stored on site.

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. Most of the fuels 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 them as a waste, of storing it or of processing to bring the nuclear materials to market⁴. However a proportion of the spent fuels, particularly in the 'cluster' category, is likely to be considered as waste and will be destined for disposal when the UK's repository is available.

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 CoRWM⁵ process.

There are many possible scenarios for the UK spent fuels stocks, with some fuels declared as waste, some stored, and the materials from some re-used following reprocessing⁶. Consistent with the *Materials Study*, the *Spent Fuel Study* considered this multiplicity of scenarios to be bounded by three 'futures' for managing the fuels where all fuels are declared as waste, all are stored, or all are processed for re-use as new fuel. These are termed *Bounding Scenarios*, and called *Waste, Store, and Use*:

1. The *Waste Bounding Scenario* processes the spent fuel into forms suitable for deep geological disposal into the UK Radioactive Waste Repository as soon as this is available. Disposing of all spent fuel as waste assumes that they are not considered to have a value (consistent with a future of low uranium market prices and no long term UK nuclear power programme) and might reflect a UK Government view that non-financial downsides take precedence;
2. The *Store Bounding Scenario* places all the spent fuels 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

⁴ The properties of, and value which can be attributed to, the nuclear materials from reprocessing form the major part of the *Uranium and Plutonium: Macro-economic Study (Materials Study)* which is concerned with the identification and analysis of potential routes for their management.

⁵ 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>).

⁶ All nuclear materials contained within spent fuels 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 fuels are automatically classified as waste (and other options for their disposition thus excluded). Similarly, it has been assumed that no fuels are automatically classed as assets.

in the *Store Bounding Scenario* it is assumed that no use is found, and disposal takes place by 300 years from now⁷;

3. The *Use Bounding Scenario* assumes that the spent fuels are reprocessed and the separated uranium and plutonium is used to make new fuel. Uranium stocks would be re-used via conversion to UF₆, enrichment and fuel fabrication, producing fuel which is essentially identical in energy yield to that produced from natural uranium. The 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 UK⁸. 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 examined⁹. 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, which can involve combinations of use, storage and disposal, can be investigated and modelled.

By necessity a large number of assumptions have been made in the *Spent Fuel 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 development of the *Waste and Storage Bounding Scenarios* followed the process undertaken in the *Materials Study*. For the *Use* scenarios, the assumption is that reprocessing recovers nuclear materials from the spent fuel, which are then recycled into the nuclear fuel cycle. The *Use*

⁷ The 300 year period is in line with CoRWM (Committee for Radioactive Waste Management) recommendations, which are based on the assumption that societal control cannot be guaranteed for longer periods

⁸ 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.

⁹ 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).

stage of the *Spent Fuel Study* must therefore feed into one of the *Materials Study* scenarios.

HOW MUCH ELECTRICITY COULD BE GENERATED FROM FUELS PRODUCED FROM THE SPENT FUELS?

An alternative way to assess the quantity of spent fuel is by reference to the amount of electricity which could be generated from the fuel that could be manufactured from the materials contained in the spent fuel. 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 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 to breed plutonium (which is extracted and used in MOX fuel). U238 is much more abundant than U235 in the spent fuel stocks.

The expected AGR and PWR spent fuel stocks could, if reprocessed, yield enough nuclear materials to produce 1550-1850tHM¹⁰ of PWR fuel, sufficient to fuel a modern PWR reactor for a sixty-year life, or the equivalent of 1.5 years of current UK electricity generation.

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, and the materials from the AGR and PWR fuel stocks would increase this by about 100 years.

¹⁰ at uranium prices of \$10-150/lb U₃O₈

HOW WAS THE STUDY CONDUCTED?

Concept

The concept used for both the *Materials Study* and this *Spent Fuel Study* was:

1. to identify the possible stages (“*Blocks*”) which materials and spent fuels 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. to assemble these parameterised *Blocks* 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 life cycle 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 and spent fuels 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/liability cost on the nuclear materials derived by the reprocessing of spent fuel 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 equal¹¹ to the most common alternative (i.e. fuel produced from a natural uranium starting point).

The value of fuel derived from nuclear materials contained in the UK's stocks of spent fuel 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 \$120/lbU₃O₈, and in the last 25 years the dollar exchange rate has varied between less than \$1.1=£1 to greater than \$2.0=£1.

¹¹ 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, three other scenarios were modelled, giving a spread of possibilities of different futures for specific materials.

PWR fuel is the responsibility of British Energy: PWR fuel scenarios are included solely to enable the totality of UK spent fuel options to be examined.

For AGR fuel, there are two options which lead to the choice of 'Use' or reprocessing. One, as in the *Use Bounding Scenario*, is to utilise a resource. The other uses reprocessing in THORP as the only currently available management route for AGR fuel, given that its long term wet storage over many decades is not proven. The resulting uranium and plutonium can then either be used, stored or declared as waste. The *Table* below shows the six scenarios modelled.

Table 1 *Scenarios Considered*

Scenario	AGR	PWR
Waste Bounding Scenario	Waste	Waste
SFS1	Use	Waste
SFS2	Waste	Store
Store Bounding Scenario	Store	Store
SFS3	Use	Store
Use Bounding Scenario	Use	Use

The scenarios which include 'Use' of spent fuel separate out uranium and plutonium from the fuel. These materials must then be managed, and are assumed to join one of the scenarios already modelled in the *Uranium and Plutonium: Macro-economic Study*. In *SFS1*, AGR fuel is reprocessed, and the separated plutonium joins the existing stocks and is assumed to be used as MOX fuel in a single or twin PWR station, and the resulting spent fuel is disposed of. The separated uranium is declared a waste and disposed of. In *SFS3*, AGR fuel is reprocessed, and the separated plutonium and uranium joins the existing stocks and is stored as a strategic resource. The relevant scenarios are shown in the *Table* below.

Table 2 *Combination of Materials and Spent Fuel Scenarios*

Materials Scenario	Tails	MDU	TPU	Pu	AGR	PWR	Spent Fuel Scenario
Waste Bounding Scenario	waste	waste	waste	waste	waste	waste	Waste Bounding Scenario
MS1	waste	store	store	waste			
MS2	use	use	use	waste			
MS3	waste	store	store	store	waste	store	SFS2
MS3	waste	store	store	store	use	store	SFS3
Store Bounding Scenario	store	store	store	store	store	store	Store Bounding Scenario
MS4	store	use	use	store			
MS5	waste	waste	waste	use	use	waste	SFS1
MS6	waste	waste	use	use			
MS7	waste	use	use	use			
MS8	store	store	store	use			
Use Bounding Scenario	use	use	use	use	use	use	Use Bounding Scenario

All the scenarios were modelled with and without discounting at Treasury ‘Green Book’ rates, and ‘Use’ scenarios were modelled across a range of uranium prices, 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). The dependence on existing infrastructure is an important driver for the timescale of decision making.

The *Study* performed specific case studies on a range of ‘cluster’ fuels which in some cases effectively ruled out one or more options. In particular, the viability of ‘Use’ scenarios was totally dependent on the availability of existing reprocessing plant. Many of the ‘cluster’ fuels have little residual materials value and reprocessing in new plant would be prohibitively expensive.

WHAT ARE THE FINDINGS OF THE STUDY?

Financial and Non-Financial Criteria

Spent fuel management options should be developed and assessed using a wide range of criteria, both financial and non-financial in nature. The *Spent Fuel Study* now reported provides an explicit analysis of financial, socio-economic and environmental criteria; the model developed also provides for a “multi-attribute analysis (MAA)” to be undertaken. This MAA allows different scenarios and sensitivities to be compared across criteria covering public safety, worker safety, security, life-cycle impacts, socio-economics, amenity, transport and cost. The relative weighting of criteria is stakeholder-dependent.

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 for financial costs, 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.

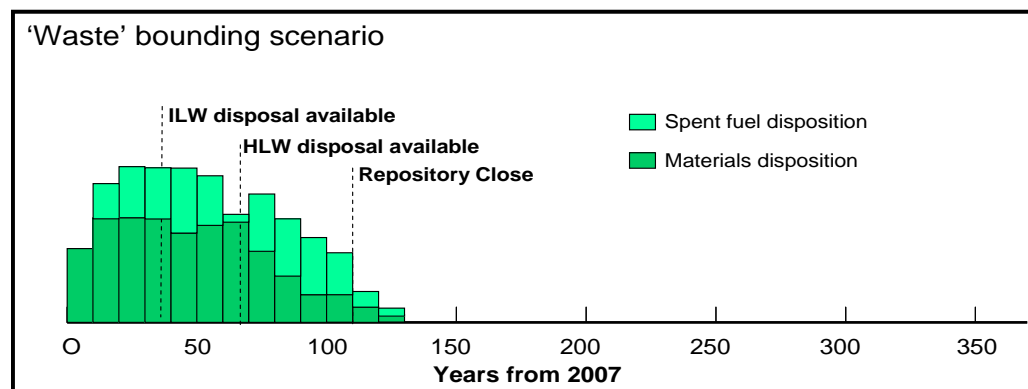
Waste: Operational Activity and Financial Cost Estimates

The waste scenarios condition the fuels into forms suitable for geological disposal. In the case of ‘core’ fuels, disposal would be to a High Level Waste (HLW)/Spent Fuel repository, whereas some ‘cluster’ fuels may be able to be disposed of as Intermediate Level Waste (ILW). It is assumed that these activities are carried out on a timescale so that the resulting wasteforms become part of the disposal programme for the UK’s radioactive waste, with ILW disposal to repository available from 2040, and HLW/spent fuel disposal to repository from 2075. Key assumptions are:

- all Magnox fuel is reprocessed through existing facilities.
- all AGR fuel is disposed of after drying, cask storage and packaging.
- all Sizewell B PWR fuel is removed from the station pond, dry stored in casks, packaged and disposed.
- suitable spent fuel wasteforms can be identified and approved on the timescale of repository availability.

This programme gives considerable operational activity in the short and medium term, but all operations cease when disposal is complete, assumed to be by 2125 at the latest. The schematic in *Figure 1* shows the level of activity and therefore of spend required for the *Waste Bounding Scenario*.

Figure 1 **Waste Scenario: Operational Activity Schematic**



Additional, undiscounted, central-estimated costs for the *Waste Bounding Scenario* for spent fuel are modelled at £3 billion. 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 the present value to around £0.6 billion.

Store: Operational Activity and Financial Cost Estimates

The store scenarios place the fuels into long term storage as a strategic resource. This is predicated on the assumption that the materials contained in the fuels could be used in the future (e.g. if prices of natural uranium on the international market rise). If fuels have not been used, they are disposed of by 300 years from now (using the same wasteforms 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.

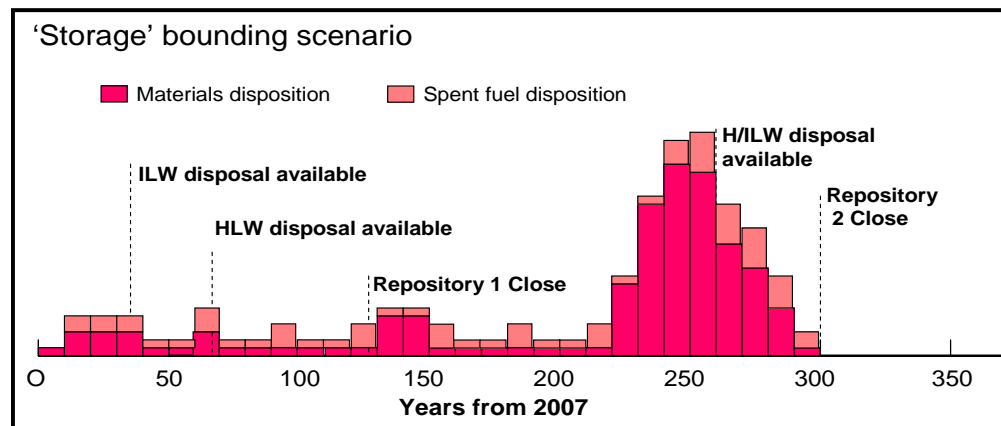
The *Store Bounding Scenario* converts the stored fuels into wasteforms in the period from around 250 years' time. The scenario requires waste disposal about 260 years from now and a new repository is assumed to be constructed (the repository for current UK waste is assumed to close in around 2125). Key assumptions are:

- all Magnox fuel is reprocessed through existing facilities.
- in most cases it is assumed that the fuels can be stored in their current forms, but some, for example some 'cluster' fuels, if not declared as waste in the short term must be converted to a more stable form for long term storage.
- it is assumed that AGR fuels are moved to dry storage and can be stored indefinitely in this condition. PWR fuels are also dry stored, together with any 'cluster' fuels.
- storage is presumed to be in casks, which are refurbished on a 25 year cycle and replaced after 150 years¹².
- an additional repository will not be required – incremental disposal to the repository required for disposal of nuclear materials will be possible.
- *Waste Bounding Scenario* assumptions apply to packaging and final disposal.

Again the schematic in *Figure 2* below shows the range of activities and therefore spend associated with this scenario.

¹² It is not known whether initial Casks could be used throughout the full 300-year period. Even if their 'engineering' integrity were assured, initial designs may not meet future regulatory requirements. In the absence of better information, an assumption of one replacement for the 300-year period has been made.

Figure 2 Store Scenario: Operational Activity Schematic



The additional, undiscounted, central-estimated cost of this spent fuel scenario has been modelled as around £3.6 billion. This is slightly more expensive than the *Waste Bounding Scenario* – it includes the same waste processing and disposal activities but adds additional storage. Discounting at the Treasury ‘Green Book’ rates reduces the present value to around £0.5 billion (i.e. slightly lower than that for the *Waste Bounding Scenario*).

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.

Use: Operational Activity and Financial Cost Estimates

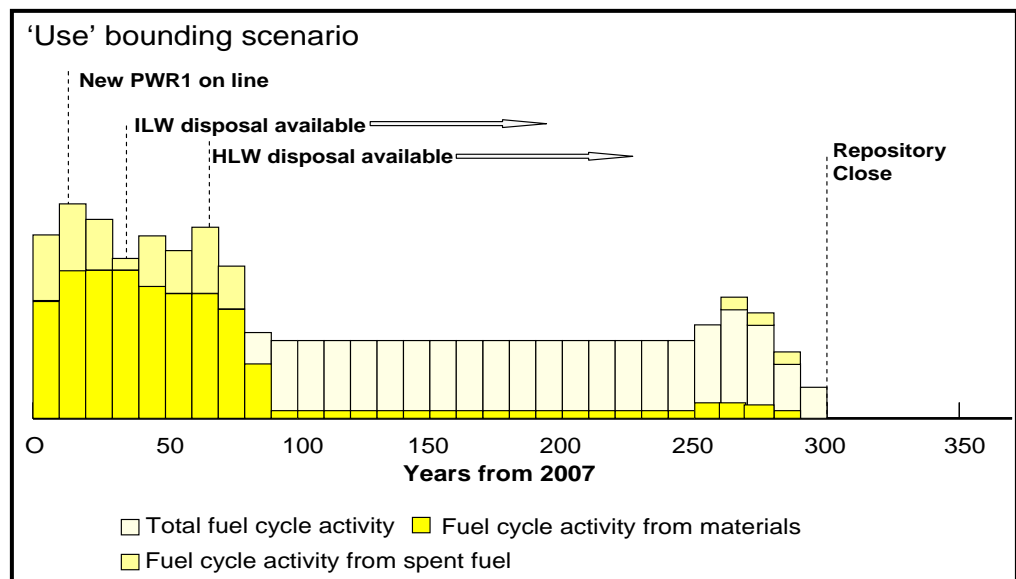
The *Use Bounding Scenario* converts all the practically available material from reprocessing into fuel for a 12 GWe programme of UK PWR reactors (there is enough material to fuel about 1 reactor of 1000 MWe capacity over its 60 year lifetime). For the purposes of the *Study*, the spent fuel from this programme of UK PWR reactors is subsequently reprocessed and the materials recycled into fast reactors, allowing very much greater utilisation of the uranium¹³.

The schematic in *Figure 3* shows this activity, together with a representation of the Fast Reactor fuel cycle activities (very 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). Note that as the reactor programme is the same as that used for the *Materials Study*, the addition of materials derived from spent fuel does not change the scale of the fuel cycle activity. There will be more residual uranium stock to be disposed of in the 250-300 year period, but this is not significant enough to show on this schematic.

¹³ 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).

Figure 3

Use: Operational Activity Schematic



The schematic indicates activity – but the cost of this activity will be reduced by the worth which can be obtained from the materials derived from the spent fuels. The value of these materials is assessed by the price which can be obtained for fuel manufactured from them, which is related to the price of fuel made from newly-mined uranium. The price 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:

- this scenario is concurrent with the Nuclear Materials *Use Bounding Scenario*, and the reprocessed materials provide additional throughput through the subsequent processing plants.
- all Magnox fuel is reprocessed through existing facilities.
- all AGR fuel and Sizewell B PWR fuel is reprocessed.
- THORP can be refurbished as necessary to perform the reprocessing operations with a capital investment of £1 billion.
- Regulation and policy would allow THORP to operate for as long as required (an extension of around 20 years from 2012 would be needed).
- the Sellafield MOX Plant can be successfully refurbished to produce high specification MOX fuel from all plutonium derived from the spent fuels.
- 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.
- the exchange rate is £1=\$1.8 throughout the period.
- the uranium price on the international market varies from \$10 to \$150 per pound.

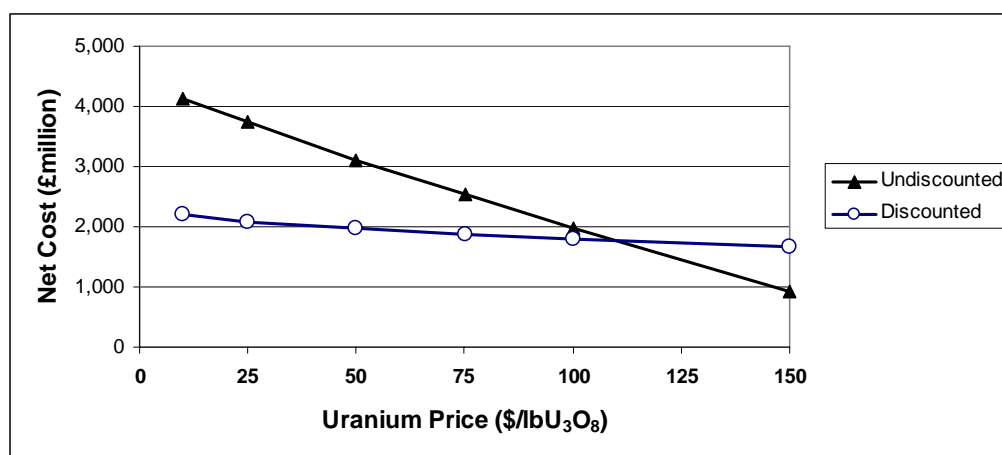
Additional, undiscounted, central-estimated costs for spent fuel *Use Bounding Scenario* are estimated to lie in the range £4.1 billion to £0.9 billion, while

discounting at Treasury 'Green Book' rates reduces the present value range to £2.2 billion to £1.7 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 modelled¹⁴.

Net costs decrease by approximately £500 million for each \$25 per pound increase in the price of uranium on the international market (see *Figure 4* below). These estimates are subject to considerable uncertainty and much of the uncertainty would increase net costs. Principal amongst these uncertainties are:

- whether fuels produced can be sold at equivalent prices to those starting from natural uranium;
- the ability of the Sellafield MOX plant to produce high throughputs of quality fuel;
- whether a refurbished THORP would operate as planned;
- what the throughput of THORP will be;
- whether the MOP (Magnox Operating Plan) can be delivered in full using existing facilities: the *Study* analysed five potential contingencies (using combinations of increasing the period of use of existing facilities, storing dry fuel and conditioning) to the MOP and found incremental undiscounted costs could range from £0.5-1.75 billion.

Figure 4 Net Costs from Use Bounding Scenario as a function of Uranium Price



Cluster Fuels: Operational Activity and Financial Cost Estimates

The *Study* has examined several of the more significant cluster fuels. For some of these the recovery of relatively small amounts of nuclear material would be very expensive and treatment as Waste would appear the most appropriate option. However, some cluster fuels are potentially viable for recovery and

¹⁴ 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.

therefore worthy of further examination, but such routes depend upon the availability and timescales of existing reprocessing routes.

Environmental and Socio-Economic Impacts

This *Study* and the companion *Materials Study* have derived, often for the first time, a set of block-specific environmental and socio-economic factors. These allow impacts to be quantified for all scenarios and sensitivities modelled. Three non-financial criteria have been explicitly quantified and analysed:

1. socio-economic impacts;
2. emissions of carbon dioxide (CO₂);
3. impacts from radiotoxic emissions.

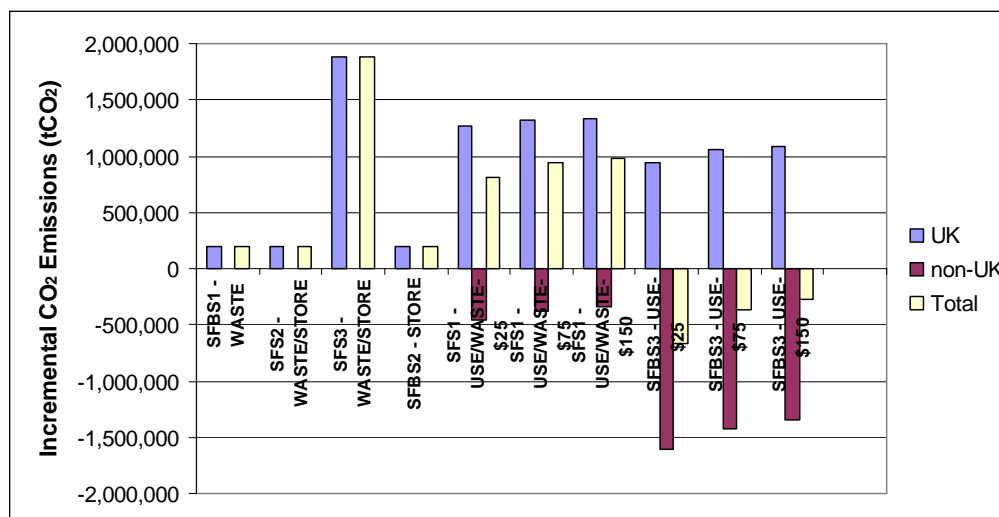
Socio-economic impacts are relatively minor. The *Study* projects that the scenarios would create 35-60,000 FTEs (full time employment years) over the 300-year period, with approximately three-quarters of these at Sellafield. Higher numbers of FTEs are indicated in the *Waste* and *Store* scenarios, although any use of Fast Reactors incremental to the *Materials Study* may create more reprocessing and fuel manufacturing jobs at Sellafield. The range of 35-60,000 FTEs would do little more than soften slightly the major losses in employment expected at existing sites. Socio-economic impacts are not sufficient to distinguish between scenarios: rather, these impacts on local economies should be optimised for whichever scenario is taken forward.

In common with the *Materials Study*, *carbon dioxide emissions* are low/negligible relative to emissions from other sources. *Figure 5* summarises results for the six scenarios modelled, with those for *SFS1* and *SFBS3* (the *Use Bounding Scenario*) shown for uranium prices of \$25, \$75 and \$150/lbU₃O₈ respectively. Main points are:

- maximum net emissions are below 2 MtCO₂ for the entire 300-year period. A 1 GW coal-fired power station emits approximately 5 MtCO₂ annually;
- without use or reprocessing, emissions are an order of magnitude lower than this maximum (of the order of 0.2 MtCO₂ over the 300-year period);
- if fuels made from recycled materials are used, avoided carbon emissions from mining/milling and enrichment are of a similar order of magnitude to those emitted (predominantly from reprocessing operations).

Carbon dioxide emissions are not considered to offer any reason to select between scenarios.

Figure 5 Incremental CO₂ Emissions by Scenario (over 300 years, undiscounted)



Impacts from radiotoxic emissions could, depending on assumptions made, be more significant. Reprocessing operations are acknowledged to be the key source of radiotoxic emissions from the UK’s nuclear operations¹⁵; if reprocessed materials are used to make fuel, the emissions are counter-acted by decreased emissions from avoided mining and milling of new uranium.

It is assumed that the MOP (Magnox Operating Plan) is met in all scenarios using existing facilities, and thus this does not distinguish between the scenarios modelled. Thus the key reprocessing differentiator between scenarios is the use of THORP, particularly its possible extension for operation beyond 2012 (a much larger quantity of spent fuel could be reprocessed post-2012 than before).

The assessment of the impacts from radiotoxic emissions seeks to model their distribution and predict the radiation dose to people over varying geographical areas (local, UK, Europe, World) and timescales (up to 100,000 years). This dose then results in impacts to human health which can be valued. The majority of the impact comes from summing very small individual doses to a very large population over a very long time period (rather than from large individual doses to a small number of people over a short time period). It is possible to arrive at very different results depending on the time period and geographical area considered, the use of discounting, the level of individual risk increase considered to be material and the economic value attributed to morbidity/mortality effects.

¹⁵ Emissions from storage are negligible. While emissions from the conditioning phase need not be negligible, these are considered to be low relative to reprocessing on the grounds that they are presumed to be performed under regulatory control which ensures that any discharges will be ALARP. Other processes with significant impacts are outside the scope of this Study (e.g. High uranium liquors from HLW processes discharged to sea via EARP and SETP). Accidental releases and accidents in general are not considered in the Study.

The *Study* has conducted an analysis based on currently available data, literature and methodologies, in particular that use in the ExternE Study¹⁶. Impacts from scenarios which do not include reprocessing (i.e. *Waste, Store* and their combination) are negligible. For *Use* scenarios, the following conclusions have been drawn:

- based on UK-specific studies using prudent assumptions¹⁷, increased radiotoxic emissions from the UK are more than counter-acted by decreased impacts from lowered uranium mining and milling operations outside the UK. Applying standard valuations of health impacts to these indicates world-wide health benefits up to the order of £0.5 billion (undiscounted);
- certain other reprocessing data sources and studies give different ranges of impacts. Precise reasons are not easy to establish¹⁸, but are likely to be due to the factors noted above (time period, discounting, material risk level, economic health valuation) and/or the different quantities and make-up of reprocessing chemistry and the substances emitted;
- applying economic valuations to the 'worst case' reprocessing figures and studies available from the literature can lead to positive net radiotoxic emissions. Applying standard valuations of health impacts to these indicates maximum world-wide impacts on health of the order of £0.5 billion.

The figures and conclusions presented above must be treated with considerable caution. The tentative conclusion drawn is that impacts from radiotoxic emissions could, depending on assumptions made, be significant. The scale of economic costs appears to be lower than the differences in financial costs between the *Use* scenario and other scenarios at most uranium price projections considered.

IS THERE A BEST WAY FORWARD?

This *Study* has examined the additional or incremental costs of dealing with UK spent fuel over and above the costs of future disposition options for the UK's stock of nuclear materials.

It is outside the scope of the *Study* to make recommendations. The *Study* does not explicitly assess or comment on the range of current spent fuel management plans or their delivery. Rather, it seeks to analyse the whole range of options available from declaring all the fuels to be wastes through to a case with reprocessing and maximum re-usage as fuel. It also investigates

¹⁶ Dreicer MV, Tort P and Manen (1995). ExternE, Externalities of Energy, Vol. 5: Nuclear. Centre d'etude sur l'Evaluation de la Protection dans le domaine Nucleaire (CEPN). Report for European Commission DGXII, Luxembourg.

¹⁷ No lower limit on individual risk, impacts assessed to world population (assumed to be 10 billion people) for 100,000 years.

¹⁸ LCA studies in the nuclear sector are at a relatively early stage.

contingencies should any option not be realised: one of the NDA's key activities going forward is to ensure that its plans are robust with regard to contingencies against unexpected events. Such unexpected events would lead to downside costs which could be highly significant but which could be minimised by contingency planning conducted as early as is possible.

The *Study* sets out the advantages and disadvantages of each of the three *Bounding Scenarios*. For *Waste*, *Store* and *Use* these are broadly:

- *Waste* is perceived as a 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 reprocessed from spent fuels (particularly if the uranium price is high) but is subject to downside risks.

The situation is complicated by the option to mix strategies (e.g. to store one spent fuel and use another). There could also be the option of selling some of the reprocessed 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 *Study* has highlighted the very large uncertainties in all options, which emphasises that the results are a basis for further study and optioneering rather than a vehicle for drawing firm conclusion. The additional undiscounted cost of around £3 billion for the '*Waste*' *Bounding Scenarios* will vary according to changes in the wasteform regulatory approvals, repository concept, cost and timing. The role of discounting is also crucial, accounting for a present value change from £3-4 billion to around £500 million for the '*Store*' and '*Waste*' *Bounding Scenarios*, and a change of about four times for '*Use*'. The value of discounting considered will therefore fundamentally affect the view of options.

The six scenarios modelled are presented again in *Table 3*. Below this *Table*, *Figure 6* and *Figure 7* illustrate the complexity of financial cost results for the single case where the uranium price is \$75/lbU₃O₈, 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. Other observations are:

- SFS3, which reprocesses ('Use') AGR fuel as the only current management process, but stores the resulting nuclear materials, gives the highest indicated costs – a £2 billion increase from the 'Store' Bounding Scenario;
- Bounding Scenario 3 ('Use') can appear the least costly option at high uranium values when costs are undiscounted;
- 'Store' scenarios keep options open and delay costs, though both AGR and PWR storage scenarios involve moving to dry storage in the relatively short term.

The inclusion of non-financial criteria may affect which scenarios are perceived as the best options. The *Study* has concluded that socio-economic impacts and carbon dioxide emissions do not differ sufficiently between scenarios to alter choices which would be made on financial costs alone, but that impacts from radiotoxic emissions could, depending on assumptions made, be considered significant. Note that the figures and conclusions presented must be treated with considerable caution. The tentative conclusion drawn is that impacts from radiotoxic emissions could, depending on assumptions made, be significant. The scale of economic costs appears to be lower than the differences in financial costs between the *Use* scenario and other scenarios at most uranium price projections considered.

The *Study* has provided the NDA with a wide-ranging analysis of the possible futures for the UK's stocks of spent fuel. It has also pointed out the crucial roles which discounting and (for reprocessing options) uranium price play in the economic evaluation of different scenarios. 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 3 *Scenarios Considered*

Materials Scenario	Tails	MDU	TPU	Pu	AGR	PWR	Spent Fuel Scenario
Waste Bounding Scenario	waste	waste	waste	waste	waste	Waste	Waste Bounding Scenario
MS1	waste	store	store	waste			
MS2	use	use	use	waste			
MS3	waste	store	store	store	waste	Store	SFS2
MS3	waste	store	store	store	use	Store	SFS3
Store Bounding Scenario	store	store	store	store	store	Store	Store Bounding Scenario
MS4	store	use	use	store			
MS5	waste	waste	waste	use	use	Waste	SFS1
MS6	waste	waste	use	use			
MS7	waste	use	use	use			
MS8	store	store	store	use			
Use Bounding Scenario	use	use	use	use	use	Use	Use Bounding Scenario

Figure 6 Net Costs by Scenario, Uranium Price \$75/lbU₃O₈, Undiscounted

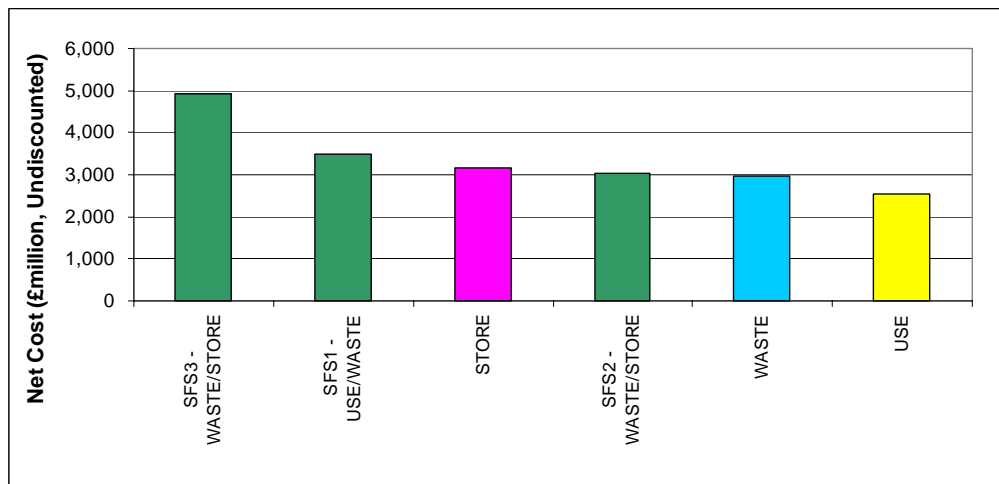


Figure 7 Net Costs by Scenario, Uranium Price \$50/lbU₃O₈, Discounted

