

# A low carbon nuclear future: Economic assessment of nuclear materials and spent nuclear fuel management in the UK

Smith School of Enterprise and the Environment  
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Principal Investigator	Professor Sir David King FRS
Authors	Professor Gregg Butler Grace McGlynn Michael Evans
Contributors	Dame Sue Ion Owen Owens

Smith School of Enterprise and the Environment  
University of Oxford  
Hayes House  
75 George Street  
Oxford  
OX1 2BQ  
[www.smithschool.ox.ac.uk](http://www.smithschool.ox.ac.uk)

## Foreword



During my time as Chief Scientific Adviser to HM Government, I commissioned a review of the UK's energy outlook. My concerns at the time were based on the fact that the UK was then ill prepared to deal with the challenges around security of supply and defossilising its energy sources and that we needed another generation of nuclear power stations. While this view was not initially shared by the then Government in the 2003 White Paper it soon became apparent that in order to meet our 60%, then 80% reduction in emissions by 2050 nuclear energy would have a vital role to play.

Over the coming decade as a country we face a number of challenges which require significant and strategic investment and planning if we are to meet our core objectives of ensuring the supply of reliable, low carbon and affordable electricity. And of particular importance is the need to replace a quarter of our existing power stations by 2020, which are ageing and unlikely to meet current let alone future environmental regulations.

A low carbon economy is integral to the UK's ongoing development, both economically and in order to meet our environmental commitments.

From that commitment there must be a plan for how the UK delivers a defossilised future that removes issues around security of supply. As much of our current energy infrastructure comes to the end of its lifetime over the coming decade, we now need to make clear and strategic decisions around future energy sources and also protect ourselves from being a net importer of energy and from potential price volatilities.

The UK's nuclear mission at the turn of the decade, when nuclear power was not considered to be economically viable, was focused on the challenge of dealing with the legacy of facilities, used nuclear fuel and radioactive waste from the early days of nuclear development and the operation of previous generations of reactors and their associated fuel cycle. As the UK now moves closer to the building of new nuclear reactors, this mission must be reframed in the context of the Government's policy to decarbonise energy production.

We now need to consider how we optimise our existing nuclear assets and expertise, ensuring that we maximise the opportunities and benefits to the UK associated with an ongoing nuclear programme. This study is an economic assessment of nuclear materials and spent nuclear fuel management which examines four possible Scenarios\* involving the use of existing and new facilities at Sellafield, and assesses them according to their likely cost, risk and potential return for the UK taxpayer in the context of new nuclear build in the UK.

\* The term Scenario is used in the context of this study as an account or synopsis of a projected course of action, events or situation.



Professor Sir David King, Director, Smith School of Enterprise and the Environment



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# Smith School of Enterprise and the Environment



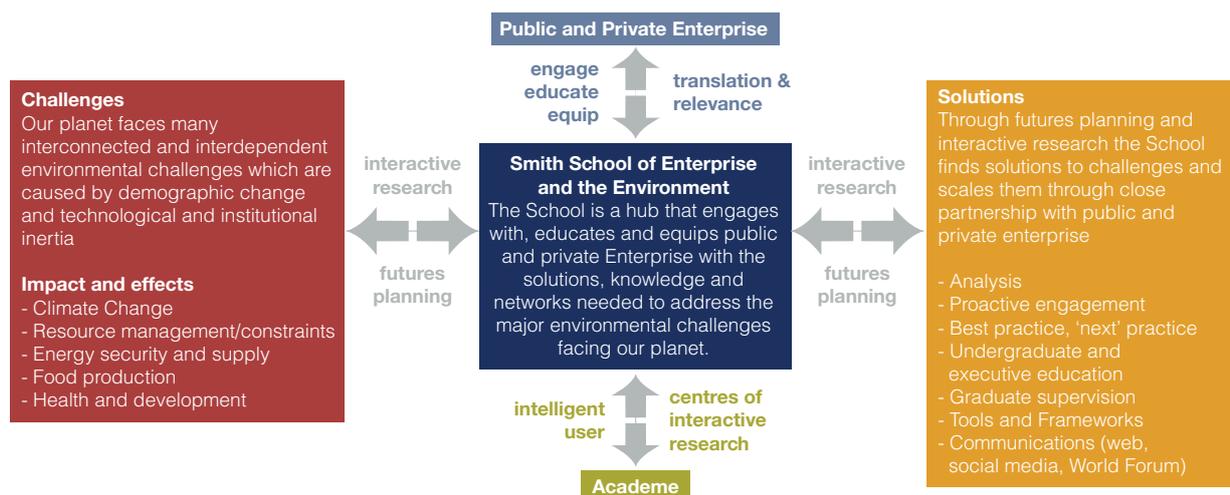
The Smith School is an interactive hub within Oxford University that engages with, educates and equips public and private enterprise with the solutions, knowledge and networks needed to address the major environmental challenges facing our planet.

The School strongly believes that the only way to address the environmental challenges we face is by convening and partnering with both public and private Enterprise

The Smith School helps Public Enterprise with Policies that create opportunities for Private Enterprise to develop Solutions to address the major environmental Challenges facing our planet.

It does this by playing three roles:

- A translator and integrator
- An intelligent user of research
- An inter-disciplinary hub



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# Executive Summary



## The UK's nuclear energy landscape

The scientific evidence supporting the existence of climate change, while incomplete, is still compelling enough to have caused successive United Kingdom (UK) Governments to accelerate the move towards a low-carbon energy supply.

As part of this shift, an emphasis has emerged in recent years upon replacing the UK's existing nuclear infrastructure with a network of advanced Generation III reactors, and utility companies have announced plans which would be capable of delivering 16 gigawatts (GW) by the middle of the next decade.

According to this report from the Smith School of Enterprise and the Environment, this has created a window of opportunity to influence the UK's strategic approach to how its stockpiles of separated plutonium, uranium and un-reprocessed spent fuel might be managed within the context of this new-build programme.

The report also considers the policy levers enabling the safe management of our nuclear legacy and the development of a long-term strategy for the storage, reprocessing or disposal of the UK's current and future nuclear fuel and waste stockpiles.

## Nuclear power as part of the energy mix

The first wave of the UK's historic nuclear programme came on line between 1956 and 1971, with the construction of twenty six Magnox reactors (on eleven sites). Between 1976 and 1989 a further fourteen Advanced Gas-cooled Reactors (AGRs) came on line (on seven sites) to eventually replace the Magnox fleet, and in 1995 the country's single Pressurised Water Reactor (PWR) started to produce power at Sizewell B in Suffolk. Today only two of the Magnox stations are still operating,

leaving a total of 19 reactors at ten nuclear power stations sites to provide around 18% of the electricity generated in the UK.

The Energy White Paper of 2003 did not include nuclear power as a viable future option, but a succession of consultations and policy developments from 2006 led to the publication of the 'Meeting the Energy Challenge' White Paper in 2007, which expressed the Government's view that 'nuclear' should be part of the future energy mix. With the current commitments to reduce 'greenhouse gas' emissions in the UK, including a reduction of 34% by 2020, it is now considered that nuclear power is vital to achieving our emission targets, reducing the fossil fuel contribution to our electricity generation, and ensuring security of supply.

## Options for the study

Past nuclear programmes have led to the UK possessing stocks of separated plutonium, reprocessed uranium and spent fuel. These nuclear materials, spent AGR fuel, and spent fuel which will be generated by future new-build reactors, can all be either treated as a resource for recycling into new fuel or as waste for disposal. Both approaches would require the development and management of major plants at significant cost – there is no cheap 'do nothing' option.

### *Disposal*

Uranium disposal, while relatively straightforward would require the development of an approved waste-form, a method of producing that waste-form, and a disposal route. Plutonium is much more challenging, requiring not only a waste-form suitable for disposal but also a plant or plants to create it, in a process that would come under great pressure for the earliest possible delivery due to security and safety concerns.

AGR spent fuel is the product of a uniquely British reactor system, and presents novel problems for both storage and disposal, which will also require new facilities and operations.

### **Recycle**

The possibilities of recycling each of these materials would require the construction and operation of new plants and potentially the refurbishment of existing facilities. Examples of these would be a new Mixed Oxide fuel (MOX) plant - in the case of plutonium recycle; and refurbishment of the existing Thermal Oxide Reprocessing Plant (THORP) at Sellafield if the spent AGR fuel is to be reprocessed and the products recycled.

There are significant costs involved with all these operations. Recycling costs would, to a greater or lesser extent be offset by the value of the fuels produced, while the costs of waste production and disposal would almost inevitably fall to the Government and thence to the taxpayer.

### **The scope of the study**

The nuclear materials and AGR spent fuel referred to above mainly arise, and are stored at, Sellafield in West Cumbria. This report has chosen to examine four possible Scenarios involving the use of existing and new facilities at Sellafield and assesses them according to their likely cost, risk and potential return. The findings are based on a spreadsheet model assuming capital and operational costs for the Sellafield facilities. The model and the assumptions made are described in Appendix 1.

The Scenarios are as follow:

#### **1. Initial storage, designation as waste, and disposal of plutonium and spent AGR fuels.**

The Scenario postulates a modified and simplified Sellafield MOX plant to generate the low-specification MOX waste-form, and represents a minimum cost option. It also postulates retrieving AGR fuel from storage ponds where it is currently held, drying it, and dry-storing the fuel prior to conditioning for eventual disposal in the planned Geological Disposal Facility (GDF) after 2075. Uranium is considered to be sold/disposed of at zero cost.

**Main finding:** Scenario 1 minimises commercial risk but introduces the certainty of the UK Government paying for

the discharge of a liability. This Scenario probably gives the greatest risk of escalating costs due to technical uncertainty. This is the only option that does not generate any sales income, merely representing a method for discharging a UK liability.

#### **2. Conversion of plutonium into MOX fuel for new-build reactors, treating the spent AGR fuel as waste for disposal.**

The Scenario assumes the building of a new MOX plant in or near Sellafield, with a capacity of 100 tonnes of Heavy Metal (teHM) per annum. This would fabricate all the legacy MOX by around 2035, an earlier time than that required for loading the fuel into new-build reactors. It assumes that the Nuclear Decommissioning Authority (NDA) will derive an income from the sale of the fuel based upon the price of the natural uranium fuel displaced. AGR fuel stocks are assumed to be dismantled, and the fuel pins dried and stored prior to conditioning and disposal in the GDF (as for Scenario 1). Uranium is considered to be sold/disposed of at zero cost.

**Main finding:** Scenario 2 introduces an initial plant cost, but turns the UK plutonium liability into an energy asset and offers the prospect of reduced cost compared to Scenario 1. It is generally significantly less costly than Scenario 1.

#### **3. Conversion of plutonium into MOX, reprocessing of spent AGR fuel in a refurbished THORP, and using separated uranium and plutonium as fuel for new-build reactors.**

The Scenario avoids the need to provide long-term storage of spent AGR fuel and the associated development and operation of a suitable conditioning and disposal route. It also assumes that the Nuclear Decommissioning Authority (NDA) will derive an income from the sale of the fuel based upon the price of the natural uranium fuel displaced.

**Main finding:** Scenario 3 optimises the energy asset of the main NDA-owned spent fuel inventory, whilst removing the requirement for new processes and a new waste-form to accommodate spent AGR fuel. It represents a commercial risk from the setting of fuel prices, but reduces technical and regulatory risk. With the economic assumptions spent it is generally more costly than Scenario 2.

#### **4. As 3 above, but with continued reprocessing of UK or overseas fuel in the refurbished THORP and recycling the separated plutonium and uranium as fuel.**

The Scenario proposes that excess capacity in the refurbished THORP is used to reprocess spent fuel until 2040, and the expense of treating spent AGR fuel as a waste is avoided.

**Main finding:** *Scenario 4 can, in the right circumstances, provide the minimum cumulative net cost, but has the greatest dependence on commercial arrangements and therefore the highest commercial risk. It also relies on there being a strategic rationale for overseas and/or UK new-build utilities to contract for reprocessing services.*

#### **Scenario attributes and stakeholder engagement**

The study has considered parameters other than economics, as many of the aspects of the different Scenarios are of interest to a wide range of stakeholders. In the course of the production of this report, advantage was taken of the wealth of experience and expertise currently available within the nuclear sector, its independent regulators, the communities around key nuclear facilities, and the views expressed during stakeholder engagement and the many stages of policy consultation over the last decade.

The report is intended to be a contribution to ongoing stakeholder engagement, and the Smith School of Enterprise and the Environment would welcome any feedback on the report or on any other areas which should be addressed.

#### **Policy implications**

Over recent years, policy development in the UK has focused increasingly on new-build, including its radioactive waste and spent fuel management. However, there has not been similar attention paid to nuclear materials management, especially plutonium management. This has resulted in parts of the UK nuclear sector being set up for the '2003 nuclear end game' mission rather than the '2011 renaissance'.

#### **Conclusions**

This study has examined and derived example costs for a range of Scenarios addressing the UK stocks of nuclear materials and spent nuclear fuel. The study has also identified issues and sensitivities which would need to be evaluated alongside the cost profiles. The main conclusion is that the structure of the UK nuclear industry, having been designed to address the rundown of nuclear power in the UK, is not well suited to the changed situation involving new nuclear build and an expanded UK nuclear role, and that there is a need for realignment of policy across the sector.

It is also clear that, in the UK, there is now an opportunity to develop an holistic approach to nuclear power - combining the assessment of backend legacy materials with the opportunities offered by new-build development. The challenge is to seize this opportunity, maximising value for the UK, creating jobs, improving non-proliferation, reducing carbon emissions, increasing energy security, and addressing the long term management of nuclear materials and spent nuclear fuel.



## The UK's Nuclear Energy Landscape



The scientific evidence that global warming is happening is now beyond any doubt<sup>1</sup>. During the past twenty years there has been a massive step change in both the understanding of climate change and the need to address the challenges faced as a result of it. The understanding of the Earth's climate and the human-induced component of climate change is the result of extremely difficult and complex scientific work involving thousands of scientists globally. It is acknowledged that the scientific understanding is incomplete, and that significant uncertainties remain about the precise magnitudes, timing, and dangers of climate change.

Energy is an essential part of the UK's economic development but also a major contributor to carbon emissions. In order to move forward during this century there is a need to develop sufficient and secure low or zero carbon energy forms so that economic development and prosperity can continue.

The current energy market has, up to a point, served the UK well over the past four decades. However, unless a long term view is taken, carbon emissions could be locked into the system for decades to come. Furthermore the UK is now importing more of its energy, and competition for energy resources can make prices volatile, as the spike in oil prices in the summer of 2008 demonstrated. At the same time, to tackle climate change and meet UK emissions targets, there is a need to accelerate the move to low-carbon energy supplies.

In order to build the next generation of power stations, and ensure there will be enough capacity to meet UK's needs up to 2050, new gas-fired power stations and nuclear plants are required as well as developing Carbon Capture and Storage facilities and the deployment of more renewable technologies. Furthermore the UK must attract more than £100billion<sup>2</sup> of investment in new power stations and grid connections during the next decade.

Nuclear power has featured intermittently during the modern era of the UK's energy policy, with various nuclear power station designs over the years and a halt on new builds from the late 1990s. In 2003 the Energy White Paper<sup>3</sup> declared nuclear power to be uneconomical in the then current climate and foresaw the closure of all but one of the existing nuclear power stations by 2023.

The nuclear mission for the UK in the early 2000s thus became focused on the challenge of dealing with the legacy of facilities, spent nuclear fuel and radioactive waste from the early days of nuclear development and the operation of previous generations of reactors and their associated fuel cycle. The NDA was set up in 2004<sup>4</sup> with a mission to clean up the UK's civil nuclear legacy in a safe and cost-effective manner. In addition, the Managing Radioactive Waste Safely (MRWS) process was started in 2001 to make progress in the management and disposal of legacy wastes.

In 2006, a further Energy Review<sup>5</sup> re-examined the role of nuclear power. The current plan, set out in the Nuclear White Paper<sup>6</sup> of 2008 concluded that nuclear power generation had an important role to play in the development of a low carbon economy and that the UK should undertake a new build programme using modern commercially available reactors. The new-build reactors

are expected to deliver up to 16GW of power by the middle of the next decade, with Scenarios up to 146GW being examined as part of the 2050 Pathways Analysis<sup>7</sup>.

The UK Government has therefore implemented a number of facilitative measures to ensure that a new generation of nuclear power stations are constructed. These measures include:

- Carrying out strategic siting assessment and strategic environmental assessment processes to identify and assess suitable sites for new nuclear plants<sup>8</sup>.
- The establishment of the Generic Design Assessment (GDA) process to undertake non-site-specific aspects of the regulatory assessment of candidate reactor designs<sup>9</sup>.
- Introducing National Policy Statements for nuclear new build together with a major infrastructure planning process to ensure strategic delivery.<sup>10</sup>
- Ensuring that the operators of new nuclear power stations will have secure financing arrangements in place to meet the full costs of decommissioning and their full share of waste management and disposal costs<sup>11</sup>.
- Transfer of title for spent fuel to the Government in exchange for a payment from the utility sufficient to cover both disposal costs and risks of escalation<sup>12</sup>.
- A consultation on Electricity Market Reform including carbon pricing<sup>13</sup>.

While progress has been made on new nuclear power stations and legacy wastes, there has been little policy development in the field of the management of UK's nuclear materials. Furthermore the major spent fuel inventory from the AGR reactors is currently programmed to be split between reprocessing and storage for eventual disposal.

There is now a window of opportunity to examine the management of the UK's nuclear fuel and nuclear materials both from a clean-up viewpoint, and in the context of the ongoing commercial mission of nuclear new build. Such an exercise could examine Scenarios that may not only reduce the cost of dealing with discharging the UK's liabilities but also create opportunities for the UK in terms of energy production, job and skills development, improved nuclear non-proliferation and safe disposal of nuclear waste.

<sup>1</sup> IPCC Fourth Assessment Climate Change 2007 Report [http://www.ipcc.ch/publications\\_and\\_data/ar4/syr/en/spms1.html](http://www.ipcc.ch/publications_and_data/ar4/syr/en/spms1.html)

<sup>2</sup> Carbon Price Floor: Support and certainty for low carbon investment December 2010 [http://www.hm-treasury.gov.uk/d/consult\\_carbon\\_price\\_support\\_condoc.pdf](http://www.hm-treasury.gov.uk/d/consult_carbon_price_support_condoc.pdf)

<sup>3</sup> Energy White Paper: our energy future - creating a low carbon economy (CM5761)

<sup>4</sup> The Energy Act 2004 <http://www.legislation.gov.uk/ukpga/2004/20/contents>

<sup>5</sup> The Energy Challenge (CM 6887) <http://webarchive.nationalarchives.gov.uk/tna/+http://www.dti.gov.uk/files/file31890.pdf/>

<sup>6</sup> Meeting the Energy Challenge – A White Paper on Nuclear Power, Cm 7296, (January 2008).

<sup>7</sup> 2050 Pathways Analysis, HMG, July 2010 at [http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/lc\\_uk/2050/2050.aspx](http://www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/2050/2050.aspx)

<sup>8</sup> <http://webarchive.nationalarchives.gov.uk/+http://www.berr.gov.uk/files/file47136.pdf>

<sup>9</sup> <http://www.hse.gov.uk/newreactors/progress.htm>

<sup>10</sup> [http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/uk\\_supply/energy\\_mix/nuclear/new/siting/siting.aspx](http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/nuclear/new/siting/siting.aspx)

<sup>11</sup> [http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/uk\\_supply/energy\\_mix/nuclear/new/waste\\_costs/waste\\_costs.aspx](http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/nuclear/new/waste_costs/waste_costs.aspx)

<sup>12</sup> [http://www.decc.gov.uk/assets/decc/consultations/financingnuclear/1\\_20100324163031\\_e\\_@@\\_decr9574um10d574en.pdf](http://www.decc.gov.uk/assets/decc/consultations/financingnuclear/1_20100324163031_e_@@_decr9574um10d574en.pdf)

<sup>13</sup> Electricity Market Reform, Consultation Document, DECC, December 2010





# Nuclear Power as Part of the Energy Mix



## History

The UK's civil nuclear power programme grew out of the post-war military imperative of producing plutonium for nuclear weapons. From 1956 (see figure 1 below) the UK embarked on a major nuclear programme that saw the construction of nuclear research and development sites across the UK, and the construction of a complete suite of fuel cycle plants, from uranium conversion to

enrichment, fuel fabrication and spent fuel reprocessing serving both military and civil programmes.

The UK commitment to civil nuclear power production was intermittent and subject to frequent changes both in technology and policy.

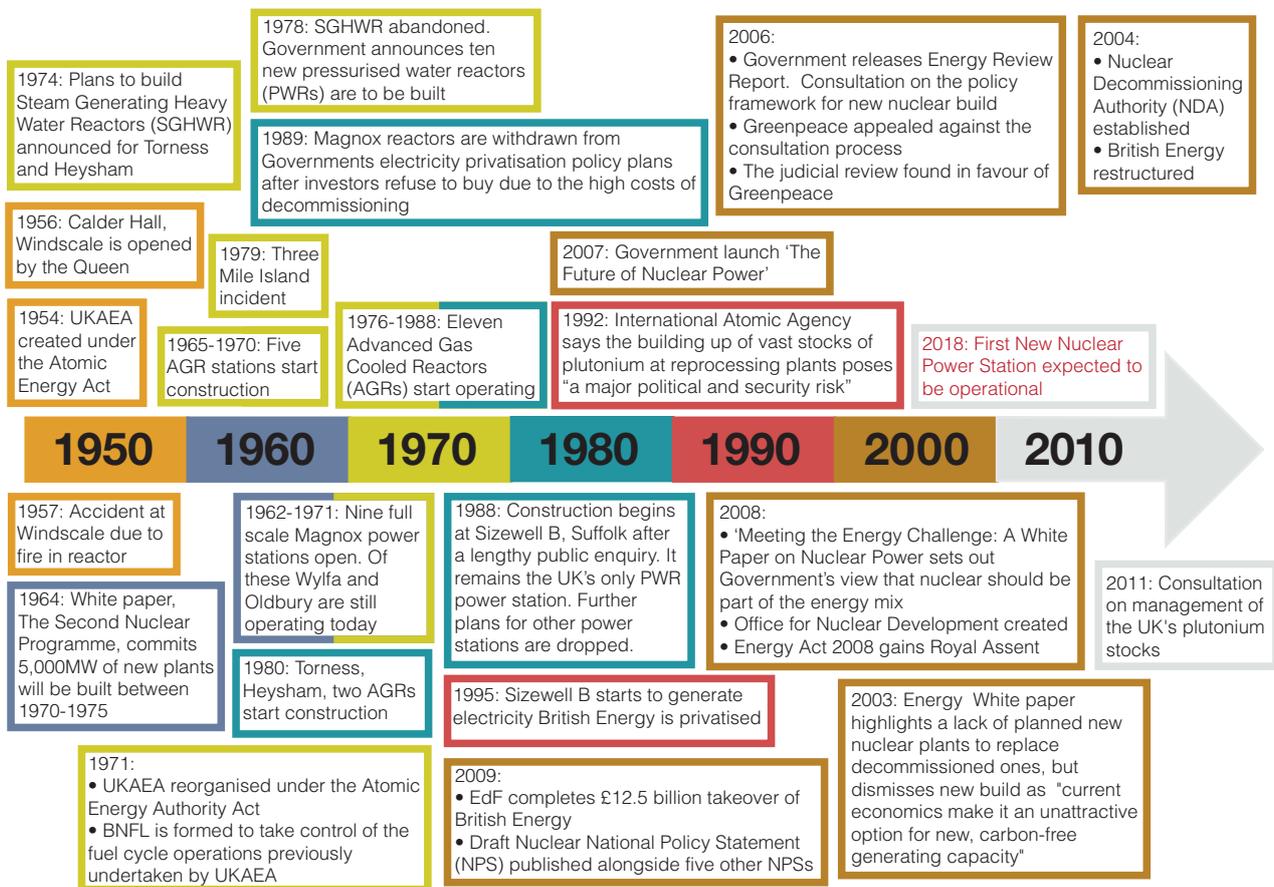


Figure 1 - Nuclear timeline from 1956 to present day.

The first phase of UK nuclear electricity generation came from the Magnox fleet of gas-cooled reactors, initially used for plutonium production but later developed into a purely generation role. The 11 Magnox stations, which came on line between 1956 and 1971, and between them have generated over 900 terrawatt-hours (TWh) of electricity: equivalent to powering 5 million homes for the last 45 years. Just two of these Magnox stations are still operating but are due to close within 2 years.

The UK's second programme of nuclear power stations, the Advanced Gas-cooled Reactors (AGRs) were commissioned between 1976 and 1989, and use slightly enriched ceramic uranium dioxide pellets in stainless steel cans. The most recent reactor built in the UK, the Sizewell B Pressurised Water Reactor (PWR), was commissioned in 1995 and uses low enriched uranium dioxide pellets in zirconium alloy cans.

The developments summarised above have led to a current situation where 19 reactors at ten nuclear power stations, provide up to 18% of the electricity generated in the UK as of early 2011. This is illustrated in Figure 2.

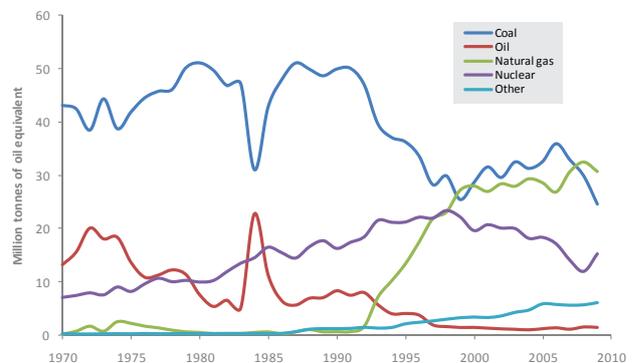


Figure 2 - Fuel used for electricity generation in the UK, 1970 to 2009: DECC, 2010<sup>1</sup>.

The Low-Carbon Transition Plan<sup>2</sup> (published in July 2009) committed the UK to reducing 'greenhouse gas' emissions by 34% by 2020. It is now considered that nuclear power is vital to achieving the UK's emission targets and reducing the fossil fuel contribution of UK's electricity generation<sup>3</sup>, and the Government has made it clear that nuclear power, without any specific public subsidy, has a role to play in the UK energy mix.

<sup>1</sup> <http://www.decc.gov.uk/en/content/cms/statistics/source/electricity/electricity.aspx>

<sup>2</sup> The UK's Low carbon Transition Plan, July 2009 [http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/lc\\_uk/lc\\_trans\\_plan/lc\\_trans\\_plan.aspx](http://www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/lc_trans_plan/lc_trans_plan.aspx)

<sup>3</sup> Climate Change Committee, 1st Report, <http://www.theccc.org.uk/reports/1st-progress-report>





## The Scope of the Study



This study examines four possible future Scenarios for the major UK stocks of plutonium, uranium and spent nuclear fuel. These stocks are comprised of:

- a. A UK-owned stockpile of separated plutonium that is predicted to reach around 100 tonnes (te) in the coming years. This plutonium mainly originates from the reprocessing of Magnox fuel (required as the cladding degrades over time when stored under water) and AGR spent fuel generated before 2007. Most of this material is currently owned by the NDA.
- b. The stock of UK-owned uranium from enrichment operations ('tails') and reprocessing ('REPU').
- c. A stock of more than 6,000teHM spent fuel produced by the AGR reactors after 2007. This is fuel in excess of that contracted for reprocessing, and the present plan is for storage under water until 2075, awaiting disposal in the future Geological Disposal Facility (GDF). The Sizewell B PWR spent fuel is also expected to be stored, either on-site or elsewhere without reprocessing.
- d. The spent fuel which will be produced by new build reactors from 2018 onwards. Current policy is to store this fuel until it can be disposed of in the future GDF sometime after 2075.
- e. The study also considers the possibility of providing further spent fuel reprocessing services for overseas utilities, with return to the country of origin of waste and separated uranium, and with plutonium returned as MOX fuel.

### Nuclear materials

Current stocks of nuclear materials can either be viewed as a resource for recycle into new fuel, or treated as a waste for eventual disposal. If materials are to be treated as waste, they will need at some stage to be converted into a form suitable for disposal. If treated as a resource, the plutonium would be recycled into Mixed Oxide Fuel (MOX), while the uranium from reprocessing (REPU) would need to be converted into uranium hexafluoride, enriched in uranium 235, and fabricated into REPU fuel.

Both these options would involve using major processing plants with significant capital and operational costs. Even continued storage would demand operation and renewal of facilities and associated spend. There is no 'cheap, do nothing' option.

Disposal of uranium stocks should be relatively straightforward, but would require an approved waste-form and a disposal route, presumably into the GDF currently targeted to be available from around 2040 under the MRWS programme. Disposal of plutonium would be much more challenging, with the only experience to date limited to defence plutonium waste disposal in the bedded salt deposits of the Waste Isolation Pilot Plant in New Mexico, USA. This has accepted only a tiny amount when compared to the UK inventory. Disposal in the UK would require the development of an approved plutonium waste-form and the construction and operation of a plant in which to make it. The proposed GDF could be made suitable to receive the plutonium waste, but only after a projected date of 2075. There would be pressure to convert the plutonium stocks, currently stored as plutonium dioxide powder, into the selected waste-form on an earlier timescale to reduce security and safety concerns.

Recycling plutonium as MOX would require a manufacturing facility with a capacity considerably higher than the current or projected achievement of the existing Sellafield MOX Plant (SMP). The recycle of REPU into fuel involves some modification to conventional uranium fuel cycle plants, but is considered to be part of the international fuel market, subject to economic and commercial arrangements.

The spent UK fuel not currently contracted to be reprocessed could also either be treated as a waste or a resource. As a waste, disposal would necessitate an approved waste-form capable of being emplaced in the GDF sometime after 2075. As in the case of plutonium, there would be pressure to move to the waste-form on an earlier timescale, particularly for spent AGR fuel, which is clad in stainless steel and is more difficult to maintain in a good condition during extended storage. The alternative to treating fuels as a waste would be to reprocess them and recycle the separated uranium and plutonium as fuel. This would require the fuel fabrication plants already discussed, but would also need the Thermal Oxide Reprocessing Plant (THORP) to be available. This plant is part of the highly integrated Sellafield site, so that its operation requires that other ancillary plants are also available for operations such as waste storage, waste and effluent treatment. As many of these plants are essential to support the clean-up of the site, it is the additional expenditure required to maintain THORP availability which needs to be estimated.

### Opportunity costs

All the options addressed above entail significant costs: for storage, waste-form development, processing and disposal, fuel plant design, construction and operation, and THORP and associated plant refurbishment and ongoing production. Where the options involve recycle, their costs will, to a greater or lesser extent, be offset by the value of the nuclear fuel which is produced.

The value of recycled fuels can be established by comparison with the cost of the fuels derived from natural uranium which they would replace, dependent upon the price of the uranium ore supply, and on the subsequent costs for conversion, enrichment and fuel fabrication. A range of feasible world market costs have been assessed to give a range of prices for uranium-derived PWR fuel.

The price that a given utility pays in the market will depend on the prices actually contracted by that utility for each

part of the fuel procurement. Though the uranium price on the spot market has varied greatly, from less than \$10/lb  $U_3O_8$ <sup>1</sup> to over \$130/lb  $U_3O_8$  in the last decade, individual utilities will have negotiated long term supply contracts giving much more stable prices. As such arrangements will vary from utility to utility, the price expectations for new fuel, and hence for MOX, will also vary. This should be taken into account if UK new reactor build is delivered by more than one utility or consortium.

The cost of producing the existing REPU and plutonium stocks has already been expended, so these materials may be considered as 'free issue' to further processing. The barrier to using the materials is then the processing costs of turning them into fuel.

For MOX fuel, the significant expense is its fabrication, but MOX prices are also subject to potential variation due to commercial and technical factors. Historically, the burn-up achieved for MOX has not matched that for uranium fuel, so more MOX has been required to generate a given amount of power. This effect has reduced as MOX has developed, but may still be a factor for UK new-build reactors. Loading MOX into a reactor necessitates some modifications in reactor control and operation in comparison to uranium fuel. Thus ideally MOX use should be planned in at an early stage of the reactor project. Retrofitting for MOX use in a reactor operating on uranium fuel will be more costly and technically challenging, will require an additional licensing process, and will be less likely to realise the full value of the fuel. Additional regulatory implications exist for the UK in that the process of Regulatory Justification and GDA have thus far explicitly excluded MOX, so these processes are likely to be on the critical path for MOX utilisation.

The worth of REPU fuel has been assessed using a range of world market prices for uranium, conversion, enrichment and fabrication, together with a range of assumptions on the additional costs for REPU processing in comparison to fuels made from natural uranium. The reasons for these additional costs are discussed in Appendix 2, and include the need for segregation from natural feeds, together with extra radiological precautions and timescale constraints during processing. For options which do not include recycle of REPU from THORP, this material has been treated as a zero value asset as it typically has a uranium 235 content high enough to give it a positive value at high natural uranium prices. It is therefore assumed to be sold for a price sufficient to cover its storage costs.

The costs of waste production and disposal in all Scenarios would almost inevitably fall to the Government and thence to the taxpayer. Scenarios involving income from fuel sales could use this income to offset UK costs. The economic results are relatively insensitive to disposal costs as these are incurred decades into the future and are thus much reduced by discounting. However, the currently envisaged regime of the Government taking title to spent fuel is on the basis of a price which will be set at the 95% level (i.e. there will be only a one in 20 chance of the actual cost paid by Government being higher). This risk premium will have the effect of raising costs to the utility and bringing them forward. MOX could exacerbate this effect as it requires longer cooling before disposal and may in any case attract higher disposal costs.

The current Government strategy is that spent fuel will be stored on individual reactor sites until it is ready for disposal. This might mean that MOX use could extend the period of spent fuel storage on an otherwise decommissioned reactor site, perhaps for decades. Extended MOX storage could be a serious stakeholder issue, as the vast majority of stakeholders are used to spent fuel being moved relatively promptly from reactor sites to Sellafield. It is also likely to reopen the debate on the price of MOX, with potential increases in the discount demanded. MOX storage reopens the debate on whether distributed spent fuel storage is sensible, and whether a centralised fuel store would reduce stakeholder concerns and cost to utilities and the UK.

## Scenarios studied

Four Scenarios have been constructed and analysed, covering the spectrum from declaring all the materials as waste, to maximising their recycling and re-use. The Scenarios and their timescales are shown in Figure 3 below. The study has chosen not to include a 'sit and do nothing' Scenario as it is considered that this is not a realistic option in the medium to long term.

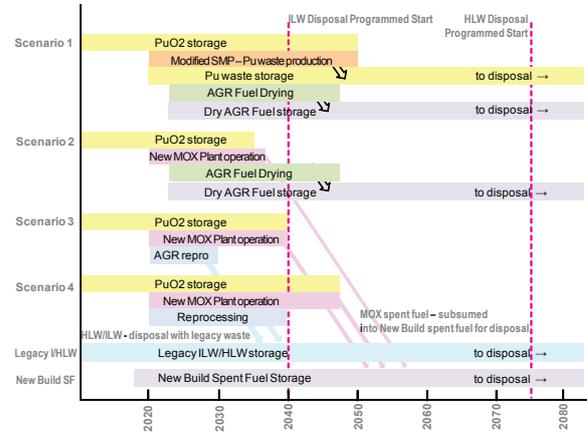


Figure 3 - Scenarios and Scenario timeline

### **Scenario 1. Initial storage, designation as waste, and disposal of plutonium and spent AGR fuels**

Scenario 1 considers ongoing storage of the existing and projected plutonium stocks, and ultimately declaring them as a waste. Existing recycled uranium from THORP is treated as a zero-value asset – stored and ultimately sold for a sum sufficient to offset storage costs. AGR and PWR spent fuel is stored until it can be disposed of in the projected GDF sometime after 2075. The AGR fuel is assumed to be dried for long term storage.

This Scenario envisages the continued secure storage of plutonium as plutonium dioxide powder in purpose-built facilities, with ongoing operational costs, and a programme of refurbishment and renewal of stores. Plutonium dioxide powder quality decreases with time and its processing becomes more difficult due to increased radiation from americium in-growth, particularly in plutonium from AGR reprocessing. The plutonium would inevitably be designated as a waste, and would need to be converted into a waste-form that could be disposed of in the GDF.

There is no industrial-scale process currently available for producing plutonium waste, though many have been proposed and experimented on at the laboratory scale. In this study a low-specification MOX 'fuel' has been adopted as the waste-form. This is technically not a particularly desirable material for disposal, as it lacks any real radiation barrier to hinder retrieval. However, it has been studied by the NDA and is the only process currently capable of even generic cost estimation.

The Scenario postulates a modified and simplified SMP to generate the low-specification MOX waste-form, and represents a minimum cost option.

NDA currently plans to store existing and projected stocks of AGR fuel not contracted for reprocessing (some 6,000teHM) until the GDF is available for their disposal. AGR spent fuel is stored under water in ponds at Sellafield, but it is not judged credible that wet storage would be viable until after 2075. This is especially true for the inventory of fuel which is already at risk from corrosion. Therefore, Scenario 1 postulates retrieving the AGR fuel from the ponds, drying it, and dry storing the fuel prior to conditioning for disposal.

The assumption in this study is that the development work on AGR fuel drying, dry storage and conditioning for disposal is successful, and that drying is carried out on dismantled fuel pins in a relatively low-cost facility installed in the existing Fuel Handling Plant. Such a programme would be subject to considerable technical, cost and timescale risks.

### ***Scenario 2. Conversion of plutonium into MOX fuel for new-build reactors, treating the spent AGR fuel as waste for disposal***

This scenario envisages the fabrication, from the UK plutonium inventory of around 100te, of approximately 1500te of MOX (each fuel assembly containing about 7% plutonium) in a new MOX plant to be sited at or adjacent to the existing Sellafield site<sup>2</sup>. The fuel is assumed to be used in UK new-build PWRs, and would power around 80GW-years of typical PWRs at 100% MOX loading, but would require around 275GW-years of reactor output if a 30% MOX charge was used. This equates approximately to a single 1.4GW reactor for its 60-year lifetime with 100% MOX usage, or around 4.6GW of reactors at 30% MOX.

Ideally, MOX manufacture needs to be flexible to be responsive to any variation in fuel loading requirements of the reactor(s). Thus MOX production would preferably match MOX consumption. The study assumes a 100teHM per annum MOX plant capacity, which in this Scenario would fabricate all the legacy MOX by around 2035, an earlier timescale than that required for loading the fuel into new build reactors. For Scenario 2, this would infer either (a) stockpiling of MOX or (b) a smaller MOX plant capacity. At the global level of cost estimation used, there is little justification for assuming a 'cost versus

capacity' function for a MOX plant. The plant costs have therefore been treated as a constant, and capacity/cost optimisation would need to be addressed in any more detailed study.

The UK plutonium stock consists of many small batches of variable quality: chemically because of contamination issues, ceramic quality issues such as particle size, and radiological issues caused by the reducing proportion of the plutonium 239 isotope with increasing spent fuel burn-up. This requires an increasing concentration of plutonium in MOX, and, as the plutonium 241 isotope decays to americium (which emits intense gamma radiation), leads to radioactive dose issues during fabrication. About 90% of the UK plutonium stock has been derived from Magnox fuel which has a low plutonium 241 isotope content, whereas the remaining 10% is from AGR fuel with a higher plutonium 241 isotope content and consequently greater dose impacts. This study makes a broad assumption that these materials are blended, without additional powder treatment or chemical cleaning before fabrication into MOX. However, a higher cost variant to cover such treatments is included.

As in Scenario 1, the AGR fuel stocks are assumed to be dismantled, and the fuel pins dried and stored prior to conditioning and disposal in the GDF sometime after 2075. As in Scenario 1, existing recycled uranium from THORP is treated as a zero-value asset – stored and ultimately sold for a sum sufficient to offset storage costs.

### ***Scenario 3. Conversion of plutonium into MOX, reprocessing of spent AGR fuel in a refurbished THORP, and using separated uranium and plutonium as fuel for new-build reactors.***

Scenario 3 would recycle the existing UK plutonium stockpile as MOX. Spent AGR fuel until the end of the reactors' lives is reprocessed with the High Level Wastes (HLW) and Intermediate Level Wastes (ILW) stored and disposed with the existing waste inventories. All plutonium and uranium from THORP is recycled as MOX or REPU fuel into new build PWR reactors. The NDA is assumed to derive an income from the sale of the fuel based upon the price of the natural uranium fuel displaced.

This Scenario would require a refurbishment of THORP and associated plants to enable its continued operation to around 2030. Scenario 3 avoids the need to provide long term storage of spent AGR fuel, and the development and operation of a suitable conditioning and disposal

route. A THORP throughput of 500teHM per annum is assumed as the base case.

The Scenario assumes a final date for generation of 2023 for the last AGR, but recognises that extensions to reactor lives are possible.

Plutonium blending is assumed as discussed in Scenario 2, together with a 100teHM per annum MOX plant. This would lead to a completion of MOX manufacture before 2040, with associated MOX throughput and programming considerations as in Scenario 2.

**Scenario 4. As 3 above, but with continued reprocessing of UK or overseas fuel in the refurbished THORP and recycling the separated plutonium and uranium as fuel.**

This Scenario would reprocess the spent AGR fuel as in Scenario 3, with the remaining capacity from the operational envelope of the refurbished THORP taken up by UK or overseas Light Water Reactor (LWR) fuel. As in Scenario 3, the NDA would gain an income from the sale of fuel made from REPU and plutonium from the reprocessing of spent AGR fuel. In the case of additional UK or overseas fuel reprocessing, NDA is assumed to

charge a market price for the reprocessing service, with full cost recovery for the production of recycled MOX and REPU fuels. In this Scenario THORP operates at around 500teHM per annum until 2040, processing slightly less than 5,000teHM of additional LWR fuel. In this Scenario, the MOX fuel campaign completes the fabrication of fuel from this additional reprocessing by 2050.

Scenario 4 avoids the expense of treating spent AGR fuel as a waste. The decision to reprocess UK PWR or overseas fuel requires an economic or strategic rationale from the fuel owners, but would raise the possibility of different ownership, commercial structures and risk/reward sharing.

### Costs and benefits

The Scenarios cover a range of costs and benefits. In the table below, increased costs/reduced benefits compared to the preceding Scenario are marked ↑, reduced costs/increased benefits are marked ↓, with unchanged parameters marked =.

Scenario 1	Plutonium storage	Number and cost of stores
	Plutonium wasteform	Low-specification MOX in modified SMP assumed – likely to represent a minimum cost
	AGR fuel drying	Equipment in existing plant assumed – could be avoided if wet storage until post-2075 is permitted
Scenario 2	Plutonium storage	↓ Number and cost of stores reduced c/f Scenario 1
	New MOX Plant	↑ Range of costs assumed to include plutonium dioxide treatment if required
	AGR fuel drying	= As Scenario 1
	Fuel sales	↓ Prices assumed based on a range of uranium and processing costs
Scenario 3	New MOX Plant	= As Scenario 2
	Fuel sales	= As Scenario 2
Scenario 4	THORP Refurbishment	↑ To 2030 – a range of costs assumed for THORP and ancillary plants
	New MOX Plant	= As Scenario 2
	Fuel sales	= As Scenario 2
	THORP Refurbishment	↑ To 2040 – a range of costs assumed for THORP and ancillary plants

Table 1 - Variations in costs between Scenarios

As both costs and benefits in all Scenarios appear over a long timescale (to at least 2075 in all cases), a key parameter is the use of discounting and the choice of discount rates. Discounting will favour Scenarios with lower initial spend on new plants in comparison to those with long term income streams. Variations in fuel and HLW disposal costs have been examined, but as these occur after 2075, they hardly affect any Scenario assessment based on discounted costs.

## The model

A model has been developed using assumed capital and operational costs for the Sellafield facilities involved in the various Scenarios. The detailed assumptions used are given in Appendix 1. In addition, charges have been assumed for services such as waste and spent fuel disposal, REPU conversion, enrichment, and fuel fabrication, and the provision of uranium feedstock for MOX. Income is included for fuel sales, and the price assumptions used are given in Appendix 2.

The model is relatively simple, due in no uncertain terms to keep it pragmatic in terms of effort and flexibility, but also minimises the chance of spurious accuracy being attributed to the results of assessments made on the basis of global assumptions.

## Model assumptions

The assumptions for all Scenarios are based on plants and operations meeting current regulatory criteria for safety of operations and discharges. The costs assumed are based on a combination of public domain figures and experience of nuclear plant costs, and are the responsibility of the authors. However, the range of costs used has been informally reviewed by NDA and Sellafield Ltd technical experts and are considered to be suitably representative for a high level review.

The capital cost assumptions used for the major plant items are:

- Plutonium and plutonium waste storage – based on a global cost of £650million per Sellafield Product and Residue Store (SPRS) module.
- Plutonium conditioning as Low-Specification MOX fuel - £500million based on a modified SMP.

- AGR spent fuel drying – base case of £100million for a plant module within the existing Fuel Handling Plant (FHP), with a variant at £1,000million for a stand-alone plant.
- New MOX fuel fabrication facility - £2,000million - £3,000million, with the higher figure including pre-treatment of the plutonium stocks.
- Refurbishment of THORP and ancillary plants – a range between a rolling refurbishment at £30million per annum, and capital projects between £1,000million and £4,000million.
- Suitably phased decommissioning costs are added at 20% to all capital expenditures

The income from fuel sales is based on the price of natural uranium fuel over a range of uranium prices and processing costs. Prices for MOX range between £1.5million and £2.5million per teHM, with prices for REPU fuel ranging between £0.6million and £1.1million per teHM. A summary of the pricing assumptions is given in Appendix 2.

For Scenario 4, which includes income from additional reprocessing services, a range of prices between £0.3million and £1.3million per teHM has been used.

A range of waste disposal costs has also been assumed, with a variant of increasing these assumed costs by a factor of 5. The earliest date for disposal (post 2075), much reduces the significance of these cost variations when discounted costs are used, though the transfer pricing mechanisms being developed by Government may shorten the timescale and increase the costs to be borne by new build utilities.

## Effects of programme changes

The Scenarios have been modelled using a series of assumptions about the UK reactor programme. Variations in these assumptions will feed back into the Scenario outcomes and, while these changes can be generally discussed, they have not been explicitly modelled. These potential changes include:

### ***Magnox fuel reprocessing extends substantially after the currently assumed date of 2016 or 2017.***

As production of Magnox fuel has ceased, the total amount of fuel is fixed, and a reprocessing programme extension could worsen the overall Sellafield cost

position. Conversely, it would mean that the period of THORP ancillary plant costs being shared with Magnox reprocessing activities would increase, reducing the incremental cost of running THORP over that period.

### ***AGR lifetimes are extended***

Lifetime extension for AGRs is likely, with 5-year extensions to Heysham 1 and Hartlepool nuclear power stations announced in December 2010. However, such extensions must be at risk from unforeseen developments in the ageing of these uniquely UK-developed reactor designs. Any extensions achieved would increase the total amount of fuel to be disposed of in Scenarios 1 and 2, by around 200teHM per annum of programme extension, increasing costs approximately pro rata. In the reprocessing Scenarios 3 and 4, the extra 200teHM per annum of fuel would take up around 5 months of the reprocessing campaign. Thus an overall 5-year extension would entail a 2 year extension to the reprocessing programme in Scenario 3, increasing costs, and in Scenario 4 would reduce the amount of overseas or UK LWR reprocessing by 1,000teHM, thereby reducing THORP income. This could, of course, be addressed by lengthening the overall THORP reprocessing campaign beyond the currently assumed 2040. The extended Scenario 4 might also require a slight increase in MOX plant capacity or a small extension to the MOX programme.

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<sup>1</sup> The international market in uranium is priced in dollars and measured in US units. Hence uranium prices are generally quoted as US dollars per US pound weight of uranium oxide (U<sub>3</sub>O<sub>8</sub>), the form in which uranium ore concentrate (UOC or 'yellowcake') is produced

<sup>2</sup> The role of the existing Sellafield MOX Plant (SMP) is assumed to be minimal – perhaps extending to manufacturing lead MOX assemblies for UK reactors.



# Scenarios



## Expenditure

Figure 4 below shows the form of cumulative expenditure for Scenario 1. The initial costs of storage lead into capital expenditure on plants and stores, and then to their operational costs. At the close of operations, there is a period of relatively low spending during waste storage, and then increased expenditure as wastes are conditioned for disposal and emplaced in the GDF.

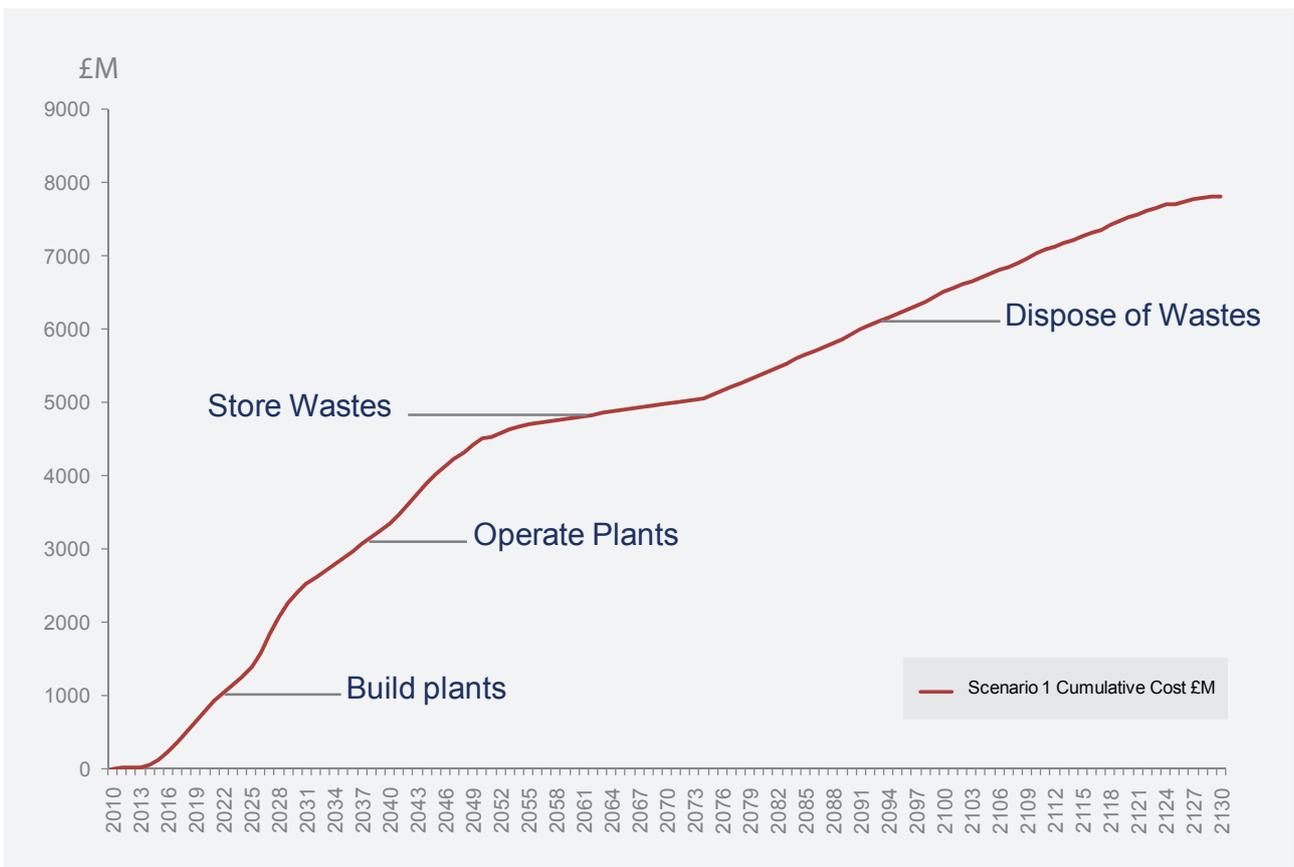


Figure 4 - General form of cumulative spending in Scenarios

For Scenarios 2-4, which have income streams from the sale of fuel, this income offsets the capital and operational expenditure, producing a cumulative net expenditure profile, as illustrated in Figure 5 overleaf.

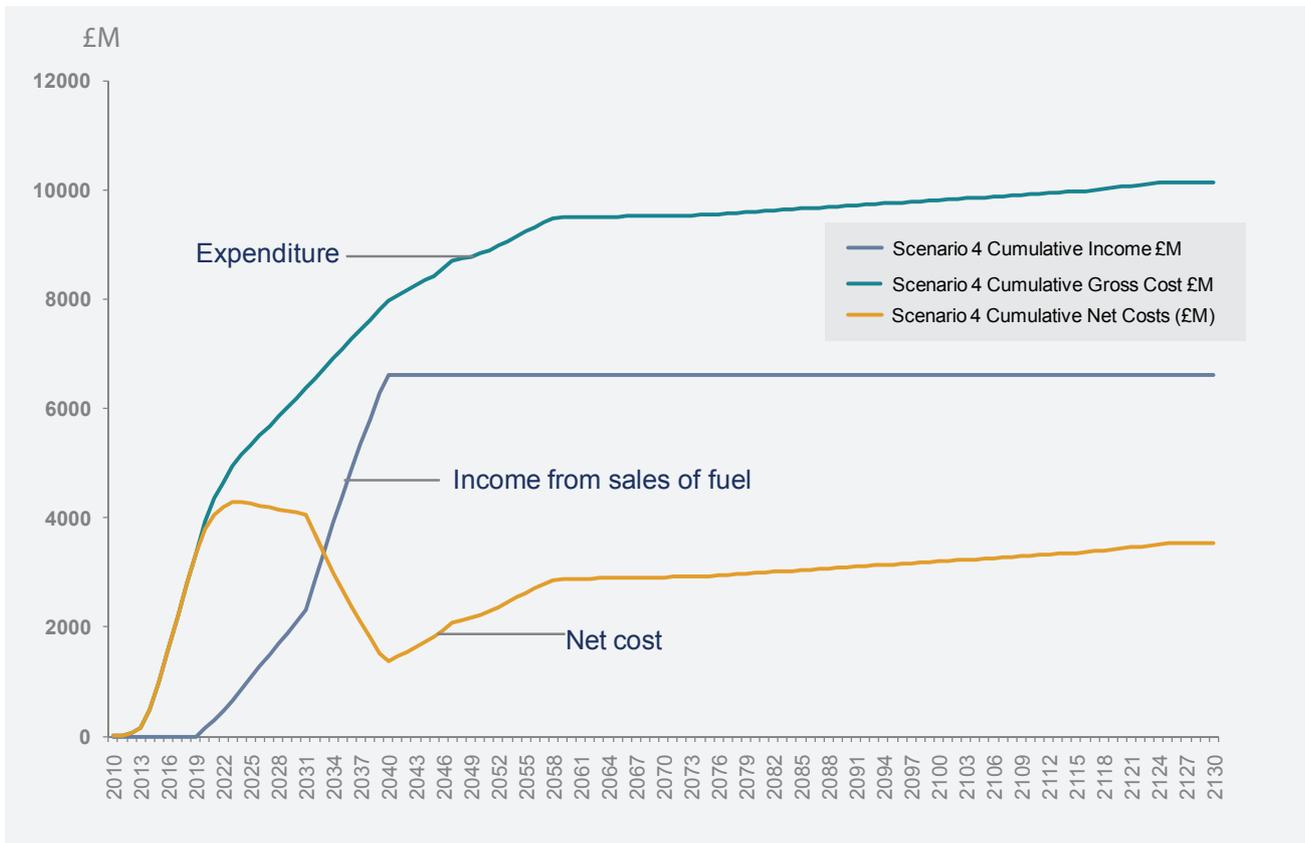


Figure 5 - General form of income and expenditure

For all Scenarios a key variable is the capital costs assumed for the plants and stores involved. For Scenario 2, the main facility is the new MOX fabrication plant, with the refurbishment of THORP and associated plants an additional cost in Scenario 4. The fuel price determines the income from fuel sales in Scenarios 2-4, and the reprocessing price fixes the additional income from THORP operation in Scenario 4.

## General observations and effect of discounting

All Scenarios have a period of income and expenditure extending over a century, so the effects of discounting are always important, and this is illustrated in Figures 6 and 7 below.

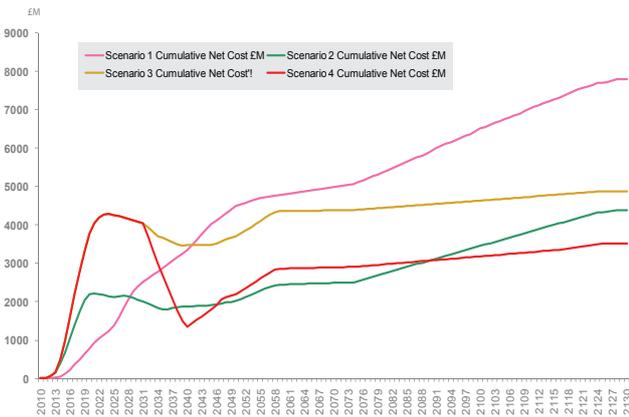


Figure 6 - Typical undiscounted model output

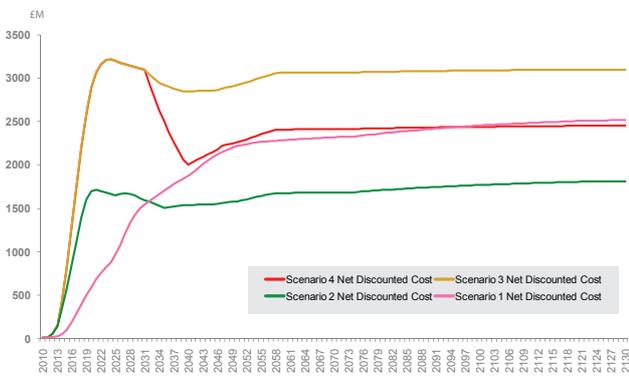


Figure 7 - Typical discounted model outputs

These figures show the typical profile of the model outputs using assumptions in the middle of the ranges for costs and prices. The following observations can be made:

1. The cost of all Scenarios reduces very markedly by the use of discounting. Here the Treasury discount rate has been applied: 3.5% for years 0-30, 3.00% for years 31-75, and 2.5% for years 76-125.
2. Scenario 1 is by far the most expensive option without discounting, because of its high volume of waste and consequent high conditioning and disposal charges. However, when discounting is applied, the cost of Scenario 1 reduces by over £6billion and becomes the median cost option.
3. Scenario 2 has a higher early spend because of the new MOX plant, but thereafter benefits from the MOX income and, in this case, becomes the cheapest option when discounted.
4. Scenario 3 has higher costs than Scenario 2, both discounted and undiscounted, reflecting the fact that the typical capital outlay to extend THORP reprocessing is greater than the income from MOX and REPU fuel sales and the avoided costs of drying, storing and disposing of spent AGR fuel.
5. Scenario 4 has the same capital costs as Scenario 3, and, using the mid-range assumptions for costs and prices, the income from additional reprocessing services makes it the least costly option in undiscounted terms. However, the early capital spend and delayed income stream lead to Scenario 4 being on a par with the median cost option in discounted terms.

### Effect of variations in capital expenditure (CAPEX)

In Figures 8 and 9, the effect of changing capital cost assumptions for the two major CAPEX plants is examined.

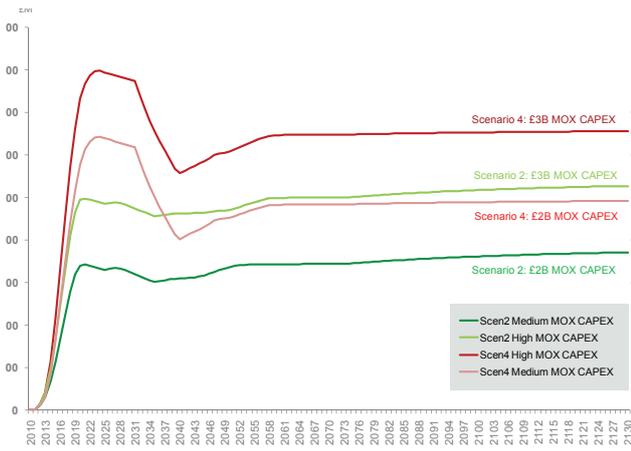


Figure 8 - Effect of CAPEX changes - MOX plant t

### Effect of variations in MOX, REPU fuel and reprocessing prices

In Figures 10 and 11, the effect of varying fuel and reprocessing prices on the outcomes for Scenarios 2 and 4 is examined.

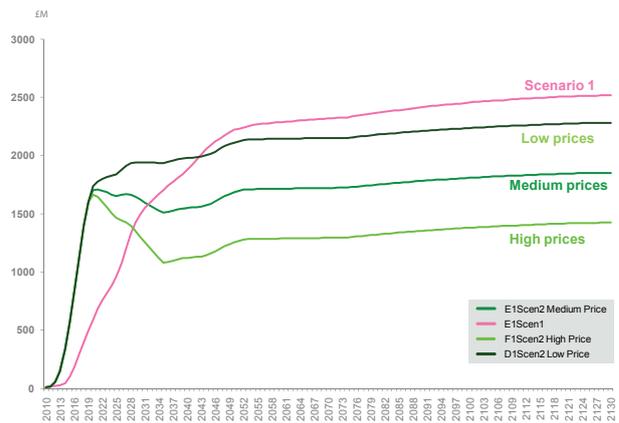


Figure 10 - Effect of price changes: Scenario 2

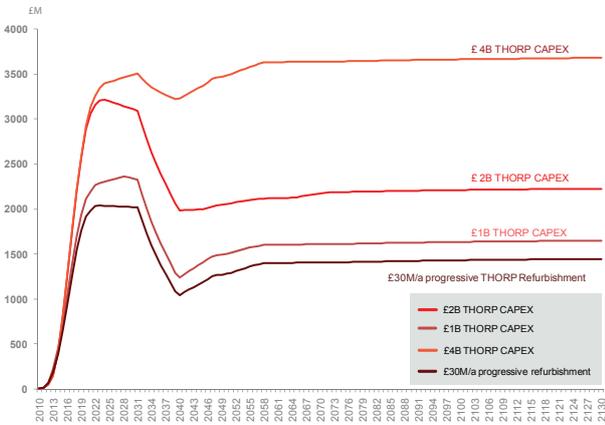


Figure 9 - Effect of CAPEX changes - THORP

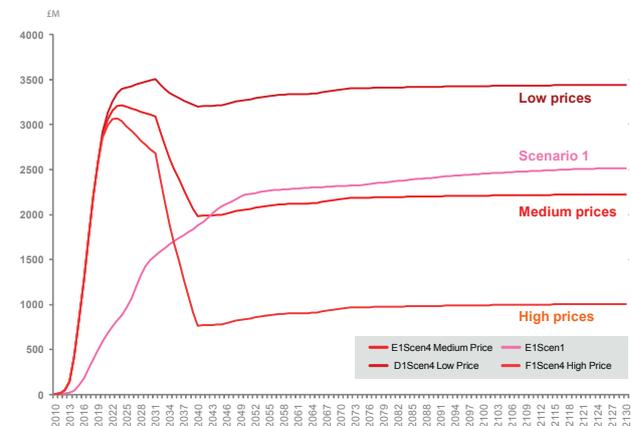


Figure 11 - Effect of price changes: Scenario 4

As the capital costs of plants are incurred early in the programme, the effect of increased capital costs is to raise costs pro rata in both discounted and undiscounted terms. Whether Scenario 2 or Scenario 4 is preferred will be a function of the relation between THORP capital cost and reprocessing price.

As would be expected, both Scenarios improve as prices rise. Scenario 4, having more sales income, improves more markedly than Scenario 2, and at high prices Scenario 4 becomes the preferred option.

## Effect of variations in reprocessing throughput

In Scenarios 3 and 4, THORP and its associated plants are refurbished to allow extended operation. For a given refurbishment outlay, the results of the Scenarios will improve as THORP throughput increases, as this will allow either minimisation of the reprocessing campaign and hence reduced operational costs (Scenario 3), or will allow more UK or overseas reprocessing and hence reprocessing income (Scenario 4). THORP throughput was examined in the model, and the results are given in Figure 12 below

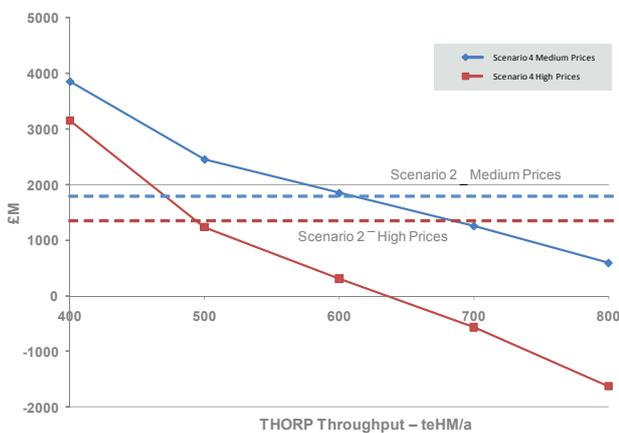


Figure 12.- Effect of THORP throughput on Scenario 4 discounted cost

This shows that when medium prices are assumed, a THORP throughput of around 600teHM per annum is necessary for Scenario 4 to be more economic than Scenario 2. However, high assumed prices will make Scenario 4 preferable to Scenario 2 at around 490teHM per annum.

Result sheets for all the model runs, with their assumptions, are provided in Appendix 3. These include sensitivity analysis of the effect of increasing the capital cost of spent AGR fuel drying, increasing disposal costs, reduced THORP throughput, and changes in discount rate.

## Effect of delays in MOX loading and income from MOX

Scenarios 2, 3 and 4 assume MOX loading into UK new-build reactors from around 2020. This timescale is challenging, especially as the Regulatory Justification and the GDA of the two candidate reactor systems have

not to date addressed the potential use of MOX. Delays in MOX loading and payment to 2025 and 2030 have been examined purely for the effect of discounting on later payments, and the results show that a delay from 2020 to 2025 at Treasury discount rate is equivalent to a reduction of 17.5% in price. This reduction increases to 28.5% if MOX fuel introduction is further delayed to 2030.

## Results summary

The economic analysis which has been carried out is based on broad assumptions but has been tested for credibility with some key stakeholders. This analysis is offered to inform the debate, and does not purport to recommend any one Scenario or variant over another. In particular, the analysis does not reflect detailed programmes which would be needed to implement the various Scenarios and their variants. For example:

- The assumption has been made that a uniform plutonium quality can be achieved by blending different batches of Magnox- and AGR-derived material, and that this will make most of the inventory acceptable for processing in the postulated MOX and waste plants.
- A detailed knowledge of the chemical and physical specification of plutonium dioxide powder would also be required to ensure that it could be fabricated in any particular MOX plant design and that the powder is capable of meeting final fuel specifications without pre-treatment and/or blending.
- However, the range of MOX plant capital costs used (£2billion - £3billion) can be considered to cover additional characterisation and/or off-line plutonium dioxide treatment.
- The throughput of the assumed MOX plant has been set at a notional 100teHM per annum, rather than by the rate of MOX burning in any assumed new-build PWR reactor program.
- The plutonium concentrations assumed for MOX are generally appropriate for new-build PWR reactors but have not been optimised for any particular reactor design or the percentage of the core taken up by MOX.
- Similarly, the isotopic composition assumed for uranium reprocessed from AGR fuel is thought to be representative of the non-contracted spent fuel inventory but would need further more detailed analysis, particularly if AGR reactor lives were extended.

The economic performance of all Scenarios and variants will vary strongly with the financial assumptions made, notably:

- The discount rate used in the assessment.
- The variability in uranium price and other 'world market' prices, notably uranium enrichment, which would determine the base price of uranium fuel to be replaced by MOX and REPU fuels.
- The variability in £:\$ exchange rate, noting that uranium prices are quoted in dollars and the proportion of the fuel cycle priced in £ sterling will vary according to commercial decisions made at the time.
- The level of surcharge levied on conversion, enrichment and fabrication of REPU fuel in comparison to the prices for processing fuel derived from natural uranium.
- The discount (if any) to be offered on the price of MOX and REPU fuels. This will in turn depend on the commercial situation, as a reactor project planned from the start to use recycled fuels could be expected to command smaller discounts than attempting to 'retrofit' these fuels into a reactor established in operation with natural uranium-derived fuel.

Against the context of these generic caveats, the following Scenario-specific observations are made:-

***Scenario 1. Initial storage, designation as waste, and disposal of plutonium and spent AGR fuels***

The Net Present Value of spending on this Scenario will be the lowest only under an extreme and unlikely set of assumptions which would involve for example, very low uranium prices or very high discount rates. The assumption regarding modifying the existing SMP to manufacture a waste-form based on low-specification MOX is likely to represent a minimum cost and a minimum timescale for implementation. Certainly, a move towards a higher specification waste-form such as plutonium vitrification or Hot Isostatic Pressing (HIP) would require an extensive research and development programme to underwrite a more sophisticated (and therefore presumably more expensive) waste conditioning plant. It could be judged that the extended timescale of such a programme might conflict with the international and national focus on addressing the security and proliferation issues associated with the UK's plutonium stockpile.

The plutonium and REPU are currently zero-valued nationally owned assets. Scenario 1 would convert plutonium into a waste liability and it is considered inevitable that the full cost of this conversion would fall to the public sector. REPU is assumed to be sold/disposed at zero value, which is likely to be achievable. Perhaps the only clear advantage of Scenario 1 is that for the length of time that the continued storage can be justified, the scale of early spend is likely to be lower than other scenarios. However, it is almost inevitably not the least total spend option, either undiscounted or discounted at the Treasury discount rates.

Spent AGR fuel is assumed to be retrieved from wet storage in ponds, dried in a new facility within the existing FHP, and stored in a new dry store until disposal in the GDF. This would represent a minimum cost but there must be a significant risk that a more expensive stand-alone drying facility would be required. The timescale assumed may also be challenging, particularly if there is any increase in the known corrosion risk to the wet-stored fuel. Existing regulatory concern is likely to increase the priority of identifying a proven fuel management route, the cost of which would also fall to the public sector. There is also a possible interaction between the timescale of assuring a spent fuel disposal route and any application to extend the lives of AGR stations beyond the currently assumed 2023 end date.

**Scenario 1 minimises commercial risk but introduces the certainty of the Government paying for the discharge of a liability, together with a risk of escalating costs due to technical uncertainty.**

***Scenario 2. Conversion of plutonium into MOX fuel for new-build reactors, treating the spent AGR fuel as waste for disposal***

For most sets of assumptions, both the undiscounted and discounted gross costs of Scenario 2 are lower than for Scenario 1. When the envisaged sale of the MOX manufactured in Scenario 2 is taken into account, this Scenario is generally less expensive except during the up-front capital expenditure of a new MOX fabrication plant.

The selling price of the MOX will be dependent on the perception of future price variations in the cost of natural uranium, the cost of other fuel cycle stages and the \$:£ exchange rate. It is considered unlikely that all the capital costs of the MOX plant would be met by the Public Sector.

This could give an opportunity for accessing private sector investment and the sharing of risk and reward between the current owner of the plutonium asset, any would-be MOX plant developer, and the utilities using the MOX in their reactors. Such a commercial arrangement could also ameliorate the short term spending increase in this Scenario in comparison with Scenario 1.

**Scenario 2 introduces an initial plant cost, but turns the UK plutonium liability into an energy asset and, offers the prospect of reduced cost compared to Scenario 1.**

***Scenario 3. Conversion of plutonium into MOX, reprocessing of spent AGR fuel in a refurbished THORP, and using separated uranium and plutonium as fuel for new-build reactors***

Scenario 3 relies on the refurbishment of THORP and associated facilities to treat spent AGR fuel using an existing and regulated process to produce established UK waste-forms. Although the Scenario benefits from the sale of MOX and REPU fuels, no income is assumed for reprocessing operations on the NDA-owned spent fuel. The Net Present Cost of this Scenario is generally greater than that of Scenario 2, as the income from the sale of MOX and REPU fuel is insufficient to offset the capital cost of the initial refurbishment of the reprocessing plants.

This plant refurbishment is the crucial cost parameter of the Scenario, and would need to be examined in the light of a detailed assessment of the interdependence of plants on the Sellafield site and current cost-sharing between Magnox and THORP reprocessing operations, especially after the scheduled completion of Magnox fuel reprocessing in 2016 or 2017.

Scenario 3 can perform better than Scenario 1 where low refurbishment costs and high fuel resale prices are assumed. However, its main benefit would seem to be the removal of the risks and costs associated with the development of a novel route for spent AGR fuel disposal involving new processes for drying, storage, and conditioning. It would also address, on a predictable timescale, regulatory and safety concerns about the open-ended storage of a relatively vulnerable spent fuel inventory.

**Scenario 3 optimises the energy asset of the main NDA-owned spent fuel inventory, whilst removing the requirement for new processes and a new waste-form to accommodate spent AGR fuel. It represents a commercial risk from the setting of fuel prices, but reduces technical and regulatory risk.**

***Scenario 4. As 3 above, but with continued reprocessing of UK or overseas fuel in the refurbished THORP and recycling the separated plutonium and uranium as fuel.***

This Scenario extends the THORP reprocessing campaign for around 7 years, ending around 2040. The spent fuel for this campaign is assumed to be from UK new-build PWR and overseas LWR fuel in unspecified proportions. Reprocessing is assumed to be charged at commercial rates, and the costs of MOX fabrication are assumed to be covered by the fuel owners.

The results from Scenario 4 indicate that combinations of low capital costs and high selling price can decrease the overall net cost to make the Scenario competitive with, or more favourable than, Scenario 2. Scenario 4 offers the opportunity to minimise costs, but at the expense of increased commercial and market risk.

**Scenario 4 can, in the right circumstances, provide the minimum cumulative net cost, but has the greatest dependence on commercial arrangements. It also relies on there being a strategic rationale for overseas and/or UK new-build utilities to contract for reprocessing services.**



## Scenario Attributes and Stakeholder Engagement



The study has taken cognisance of the views and concerns of relevant stakeholders, particularly those having a statutory responsibility for the areas concerned, or those directly impacted by them. These are taken into account in the following examination of the key attributes of the four Scenarios.

### Safety

The principal legislation for the safety of nuclear installations in the UK is the Nuclear Installations Act 1965<sup>1</sup>, which applies to all nuclear plants from design and construction through to operation and decommissioning. This is regulated by the Nuclear Directorate of the Health and Safety Executive (HSE)<sup>2</sup> independently of Government departments. Within the Nuclear Directorate, nuclear safety regulation, including licensing, is carried out by the Nuclear Installations Inspectorate (NII); nuclear security regulation is carried out by the Office for Civil Nuclear Security (OCNS); and nuclear safeguards functions are carried out by the UK Safeguards Office (UKSO).

The Ionising Radiation Regulations 1999 require employers to keep radiation exposure of workers and the public as low as practicable and within specified limits. The Nuclear Generating Stations (Security) Regulations 1996 and the Radioactive Material (Road Transport) Act 1991 are also relevant. Waste management and discharges to the environment are regulated by the Radioactive Substances Act 1993.

The main relevance of this regulatory regime to the Scenarios examined is that it sets a common standard of safety to be met by all the plants involved, both in their design and during their operation and decommissioning. Essentially this means that there will be no safety discriminators between the Scenarios once it has been shown that plants which meet the regulatory standards can be constructed. Table 2 below lists the main plants envisaged by each of the Scenarios and their 'regulatory' attributes.

Scenario(s)	Plant	Comments
1	Low-specification MOX fabrication	This plant is postulated as a simplification of the existing SMP. It is unlikely to offer regulatory challenges outside those already addressed for SMP in its present form. The regulators would have to be assured that low-specification MOX constituted a suitable waste form acceptable for emplacement within the GDF.
1, 2	AGR spent fuel drying and dry storage	AGR fuel drying and storage was proposed by Scottish Nuclear (SN) in the 1990s but was not carried through to the submission of a plant safety case. The plants considered here are considerably less challenging as AGR pins are the dried/stored medium, in comparison to the SN proposal which was to store complete fuel elements. Quality assurance of the drying process and ongoing atmosphere control during storage will be the main challenges, together with the storage of failed fuel, probably by providing a 'canning' facility. There seems no reason to doubt that a suitable plant safety case can ultimately be generated, but the costs and timescale of meeting this challenge must be uncertain.

1,2	AGR spent fuel disposal	AGR spent fuel disposal is required by Scenarios 1 and 2, but is also the default state of any 'delay action' option. The disposal form would presumably be developed as part of the ongoing MRWS programme, and is presumed to contribute to cost and timescale uncertainty rather than present a pass/fail test for the Scenarios.
2,3,4	New MOX plant	By analogy with SMP there seems no doubt that a MOX plant could be constructed to meet a modern safety case, but there will be uncertainties in cost and timescale until this is done. Chapter 6 and Appendix 5 address issues around MOX fuel plant technology which could inform the design parameters of any new MOX plant and its accompanying safety case.
3,4	THORP refurbishment and extended operation	The current THORP plant operational permission gives assurance that a safety case for refurbishment and continued operation is possible. However, the restrictions in permitted THORP operations over the last several years resulting from reduced evaporator capacity and critical components give an insight into the sort of challenges that must be met to assure operation to 2040. These challenges will feed back both into the refurbishment timescale and its cost, which is reflected in variations in both these variables being examined by the model.

Table 2 - Regulatory attributes of proposed plants

## Nuclear reactor design and regulatory justification

All Scenarios apart from Scenario 1 require MOX to be burned in new-build reactors.

The NII and OCNS, together with the Environment Agency, are currently undertaking the GDA process for new nuclear reactor designs.

The GDA process allows the generic safety, security and environmental aspects of new nuclear reactor designs to be assessed before applications are made for licences and permits to build particular designs of reactor on particular sites. Separately, a number of sites have been nominated as the potential hosts for new nuclear power stations. GDA is a facilitative process, intended to speed up the subsequent site-licensing and consents process, together with providing more certainty to investors at an earlier stage. The GDA process remains an essential step on the critical path for delivering safe and secure nuclear new-build in the UK. Two new nuclear reactor designs are currently being assessed:

- the UK EPR developed by AREVA and Electricité de France
- the AP1000 developed by Westinghouse Electric Company

The GDA process is progressing towards a June 2011 date for completion, but has acknowledged that there may be some issues that:

*'are unresolved at the end of the GDA and are considered by the regulators to be significant, but resolvable, and which require resolution before the .....construction of such a reactor could be considered. Where there are GDA issues, and (HSE) were content generally with the design, the Design Acceptance Confirmation of Design Acceptability would be provided, but designated as 'Interim'.<sup>3</sup>*

The GDA process has been predicated on the use of uranium-derived fuel and, in accordance with the 2008 White Paper, has specifically excluded examination of the potential use of MOX within the EPR and AP1000 designs. It is understood that both reactors are designed to accept MOX (including up to 100% MOX core loading). However, any utility developer would have to submit a separate application, over and above the current GDA process, if it was proposed that MOX should be deployed in new build reactors.

The other process which new build reactors need to satisfy is that of Regulatory Justification: ensuring that the benefits of processes using ionising radiation exceed

the detriments involved. Regulatory Justification has been carried out for both reactor designs, with positive decisions for both taken by the Secretary of State in October 2010. In both cases the decision was made on the basis of using “oxide fuel of low enrichment in fissile content” i.e. uranium-derived fuel. This implies that a varied or separate Regulatory Justification assessment and decision would be required before new build reactors could be operated with MOX.

The timing of the adoption of MOX and the extent of MOX loading would be determined both by the priority given to the necessary work by the reactor operator, and the extent and timing of the regulatory interactions required to achieve acceptance of the relevant operational safety case, plus the approval of transport of MOX to the reactor and the storage and assurance of disposal of the spent fuel after use.

## Environmental discharges and carbon benefits

### Discharges

All Scenarios require processing of the UK’s stock of plutonium from its current oxide powder form into MOX pellets, either for disposal as waste or for use as fuel in new-build reactors. The ‘waste’ or ‘fuel’ MOX plants will raise the same discharge concerns as the current SMP. Discharges from SMP have been shown to be very small<sup>4</sup>, and any new plant operating under the UK’s regulatory regime would similarly be expected to meet standards that represent the “Best Available Techniques” (BAT).

Scenarios 3 and 4 rely on the refurbishment and extended use of THORP. This is more contentious when considered against the provisions of the Oslo-Paris Convention (OSPAR) which states that “*by the year 2020, the OSPAR Commission will ensure that discharges, emissions and losses of radioactive substances are reduced to levels where the additional concentrations in the marine environment above historic levels, resulting from such discharges, emissions and losses, are close to zero*”<sup>5</sup>. In the 2009 UK Strategy for Radioactive Discharges, reductions to total beta discharges from 165 terabequerels per year (TBq/year) to around 50 TBq/year are expected to be made by 2020, with alpha discharges from reprocessing reducing from 0.31 TBq/year to about 0.2 TBq/year over the same period.

The effect of THORP operation on these reductions would need to be examined, and the level of discharges involved will to some extent depend on the details of the refurbishment programme of THORP and its associated plants. In any case a major reduction in Sellafield discharges will take place when Magnox fuel reprocessing ceases, scheduled for March 2016 with a fallback date of March 2017<sup>6</sup>.

### Carbon benefits

The carbon generated from all the processes involved in producing the current UK plutonium and spent fuel stocks are ‘sunk’ insofar as the uranium for the fuel has been mined; its enrichment carried out; and the carbon detriment of the fuel cycle plants and reactors has already occurred. Therefore in comparing MOX use against using fuel from newly mined uranium, the carbon generation from the MOX will only derive from the carbon detriment of the MOX plant construction, the MOX fabrication process, and the transport of the fuel to the power station. MOX from existing plutonium will avoid all the carbon dioxide from mining, conversion and enrichment – and it is very likely that the carbon detriment of MOX manufacture will be, at most, similar to the fabrication of uranium fuel.

The 2008 White Paper<sup>7</sup> concluded that the carbon footprint of the uranium nuclear fuel cycle is in the range of 7-22 grammes of carbon dioxide per kilowatt-hour generated. In Appendix 4, a calculation is made of the carbon saved by using MOX, using this range with a selection of figures from the literature on the carbon detriment of uranium fuel fabrication. The estimates for carbon dioxide saved range from 3.8x10<sup>6</sup> to 1.4x10<sup>7</sup> tonnes.

The recent Treasury Consultation Document on Carbon Pricing<sup>8</sup>, gives three illustrative carbon price Scenarios for the UK power sector, namely: £20, £30 and £40 per tonne of carbon dioxide in 2020 rising to £70 per tonne in 2030 (all in real 2009 prices). Taking the 2030 figure as representative of the period of MOX use, Appendix 4 indicates a carbon saving from the use of MOX of between £346million and £1,240million. However, these savings would be made on a global, rather than UK, basis, and most of the uranium carbon dioxide detriments avoided, and particularly those of uranium mining and milling, would not be incurred by operations in the UK.

These calculations are appropriate for the net savings between MOX used in Scenario 2 in comparison with

the use of uranium. They will underestimate the carbon dioxide savings between Scenarios 1 and 2, as Scenario 1 will have additional carbon detriment from the low-specification MOX manufacture which will not be mitigated by any savings. Scenarios 3 and 4 will have greater savings than Scenario 1, because of the use of recycled uranium, and the further reductions in uranium fuel in the UK driven by the additional MOX and REPU fuel from AGR spent fuel reprocessing. These are likely to be significant, but smaller than the reductions estimated for Scenario 2.

### Non-proliferation and security

UK is a nuclear weapons state, party to the Nuclear Non-Proliferation Treaty (NPT) which it ratified in 1968 and under which a safeguards agreement has been in force since 1972. The Additional Protocol in relation to this was signed in 1998. International Atomic Energy Agency safeguards are applied on all civil nuclear activities.

Though the assessment of the non-proliferation and security attributes of different plutonium Scenarios is complex, some general observations can be drawn:

- Continued long term storage leaves the plutonium in a form which is potentially accessible to diversion or theft, and could be dispersible if used in a 'dirty bomb'.
- Scenario 1 converts the powder into a sintered pellet form, which reduces dispersibility, but gives little change in the accessibility for diversion or theft.
- Scenarios 2, 3 and 4, however, reduce the amount of plutonium somewhat by burning it as MOX in a reactor, and leave the remainder as a constituent of highly radioactive spent fuel. The radiation and heat given off by this spent fuel will provide an increased resistance to diversion or theft. In the USA, this has been developed into a measure of theft/proliferation resistance termed the 'Spent Fuel Standard'.
- Scenarios 3 and 4 do continue to separate plutonium as plutonium dioxide powder during the operation of THORP, but this is stored for a relatively short time before fabrication into MOX and loading into a reactor.

All Scenarios thus represent an improvement on continuing storage, and therefore address the commitments entered into by the UK at the 2010 Washington Nuclear Security Summit. Non-proliferation and security considerations would, of course, be key parameters in the further evaluation of the UK's options for the long term management of plutonium and other nuclear materials.

### Spent fuel storage

As currently proposed, all spent fuel is to be stored on its host reactor site until its heat generation has reduced sufficiently to allow its transport and disposal. In the case of MOX, the increased heat generation will mean a longer cooling time, and hence longer storage on site, with associated cost implications and increasing stakeholder concerns depending upon the number of sites where MOX has been loaded into new build reactors. An alternative option would be the establishment of a national centralised spent fuel store, which would have the potential to reduce costs and avoid the additional MOX storage time at individual reactor sites.

### Transport

All Scenarios have issues of conventional transport as all Scenarios require new plants to be built and operated, with associated construction and operational traffic. These would increase with the size of the capital and operational programme, being lowest for Scenario 1, increased for Scenario 2, and highest for Scenarios 3 and 4. From this conventional point of view, local stakeholders would evaluate the likely nuisance against the jobs and other socio-economic benefits which each Scenario would offer.

The major concern in nuclear materials transport would be the movement of plutonium dioxide powder from its current stores to the plant processing it to waste or to MOX. In all four Scenarios these plants are assumed to be situated on or adjacent to the Sellafield site, thereby minimising plutonium dioxide transport in all cases. After this, the most significant transport concern would be the movement of MOX to the reactor, or of the MOX waste-form to the GDF. Regulation would ensure that safety and security standards were met, but this would involve additional costs in terms of packages and containers, monitoring and security escorts. More generally, the number of stakeholders involved would depend on the destination of the MOX or waste-form, which would

in turn depend on the location of the GDF or of the reactor(s) in which the MOX was to be used. This could be a significant consideration, or even constraint, if plans included multiple reactors remote from Sellafield.

Current arrangements would require the establishment of transport routes from dispersed reactor sites to the GDF some time after its scheduled availability to receive HLW and spent fuel in 2075. As the MOX will be both of higher burn-up and greater heat evolution than the current spent fuel inventory, it may not be disposable until into the 22nd century, extending the time over which transportation must take place.

### Socio-economic aspects

The differences in socio-economic benefits between the Scenarios are centred on the magnitude of capital investment and operational effort at Sellafield in West Cumbria. The nuclear fuel cycle and nuclear power production has been part of the local economic activity in West Cumbria for over 60 years. The Sellafield site is renowned internationally for the scope and scale of activities in one location, and the site has seen a range of research, power generation, reprocessing and now decommissioning activities from the 1940's to the present day. Arguably, it houses the largest body of nuclear expertise and skills in the UK and hosts 70% of the UK civil nuclear legacy.

Some 22% (approx. 12,000) of all jobs in West Cumbria (54,000) are currently nuclear related<sup>9</sup>. In the last 10 years the nuclear sector has seen a significant shift from public sector ownership to private sector management. The dominant public sector organisations (e.g. BNFL) no longer exist and the sector has become much more fragmented. Since the Energy Act 2004 and the formation of the NDA, the prospects for the nuclear sector have focused on the decommissioning of legacy assets at the Sellafield site. As the decommissioning process gathers pace it is projected that by 2018 a total of 17,000 jobs (i.e. over 30% of all jobs in Copeland, West Cumbria) will disappear. This process is underway now with 800 redundancies already announced and approximately 1,000 planned in the next year.

In the 'Meeting the Energy Challenge' White Paper<sup>10</sup>, the Government introduced a revised energy policy identifying the need for a significant proportion of the UK's future energy needs to be provided by nuclear power. The construction of up to 8 new nuclear power stations

is envisaged by 2025 at various locations across the UK with a site identified adjacent to the current Sellafield complex.

A key aspect of the rationale for new nuclear power stations is the availability of a GDF to receive the spent fuel. As part of the MRWS process which is charged with identifying a volunteer community to host the GDF, the local authorities in West Cumbria have declared an interest in potentially hosting such a repository. It has been estimated that this would involve over £14billion of investment, generating up to 500 jobs through the construction process from 2025 to 2040, 300 jobs during operations (2040 to 2130) and 50 jobs post-operation.

A 2003 Socio-economic study<sup>11</sup> examined a range of Sellafield operational futures and modelled the employment and associated socio-economic effects in West Cumbria. One operational future included the construction of a new MOX plant, and this allows the socio-economic impacts of the current Scenarios to be broadly compared with the 2003 estimates.

The new MOX plant in the 2003 study assumed around 500 extra permanent jobs for the plant itself. In 2006/7 NDA costs for Sellafield Ltd (excluding capital spend) was £993million<sup>12</sup>. In the same year the Sellafield Lifetime Plan<sup>13</sup> showed equivalent full time employees (FTE's) of around 15,000, giving a gross employment cost of some £66,000 per annum, which can be escalated to around £73,000 per annum today.

In Table 3, the total operational spend from 2016-2050 for each Scenario is converted into direct man years of effort, using this global figure, and an 'Direct plus Indirect' figure produced using the jobs multiplier of 1.22 derived in the 2003 study.

Scenario	Operational Spend (2016-2050) £M	Total Operational Employment (2016-2050) man-years	Total Direct + Indirect Employment (2016-2050) man-years
1	2634	36,000	44,000
2	1680	23,000	28,000
3	2873	39,000	48,000
4	4309	59,000	72,000

Table 3 - Outline estimate of Sellafield and West Cumbria employment by Scenario

Of the current 54,000 jobs in West Cumbria, the average additional employment from the various Scenarios over the 34 years considered would vary from 1.5% to 3.9% of the current workforce.

It should be noted that the West Cumbria Partners (including Cumbrian local authorities) are undertaking an update of the 2003 ERM socio-economic assessment<sup>14</sup> to include additional baseline socio-economic analysis of West Cumbria. This should enable the broad brush results above to be put into a more accurate context.

## Skills and suppliers

The Scenarios and their associated capital and operational spend profiles present opportunities to capitalise on, and contribute to the revitalisation of, the UK's nuclear scientific and technological base. In particular, the nuclear sector is a key employer across the North West region of the UK, which is also the leading region in respect of nuclear research and development activities. In total the sector and its supply chain employ over 23,000 people (in over 300 businesses) which is close to half of all of the UK's nuclear civil workforce. The sector is also a significant contributor to the regional economy with Gross Value Added (GVA) per worker (£63,712 in 2006) higher than the manufacturing average and double the regional average of £32,000. Total GVA for the sector in the region is estimated at £1.5 billion.

When combined with the developing prospects for nuclear new build and progress on MRWS, the Scenarios analysed provide an opportunity for the UK, and particularly the North West region, to arrive at an holistic sustainable vision for the next several decades.

1 <http://www.legislation.gov.uk/ukpga/1965/57>

2 <http://www.hse.gov.uk/nuclear/>

3 Generic Design Assessment Progress Report Reporting Period 1 July 2010 – 30 September 2010, HSE and EA

4 " The radiation dose from the SMP to the most exposed group among the general public is estimated at 0.002 microsieverts per year for discharges to air and at 0.00003 microsieverts per year for liquid discharges" – Government decision on Justification of SMP, 3rd October 2001, at [http://www.gov-news.org/gov/uk/news/sellafield\\_mox\\_plant\\_manufacture\\_of\\_mox\\_fuel/10576.htm](http://www.gov-news.org/gov/uk/news/sellafield_mox_plant_manufacture_of_mox_fuel/10576.htm).

5 As quoted in 'UK Strategy for Radioactive Discharges' DECC et al, July 2009.

6 The Magnox Operating Plan, MOP8, Rev 2, August 2010

7 A White Paper on Nuclear Power, DECC, Cm7296 (January 2008) <http://www.official-documents.gov.uk/document/cm72/7296/7296.pdf>

8 Carbon price floor: support and certainty for low-carbon investment, HM Treasury, December 2010 [http://www.hm-treasury.gov.uk/d/consult\\_carbon\\_price\\_support\\_condoc.pdf](http://www.hm-treasury.gov.uk/d/consult_carbon_price_support_condoc.pdf)

9 Communication from Cumbria Partners, January 2011

10 Meeting the Energy Challenge: A White Paper on Nuclear Power, Cm7296, January 2008 <http://www.official-documents.gov.uk/document/cm72/7296/7296.pdf>

11 The Environment Council: BNFL National Stakeholder Dialogue: West Cumbria: Socio-economic study, 2003 update [www.the-environment-council.org.uk%2Findex.php%3Foption%3Dcom\\_docman%26task%3Ddoc\\_download%26gid%3D11%26Itemid%3D64&rct=j&q=west%20cumbria%202003&ei=NI9mTcTrKtSbhQeO46neDQ&usg=AFQjCNHbEWnCOQlf6SFpO0avHpEI9VEABQ&cad=rja](http://www.the-environment-council.org.uk%2Findex.php%3Foption%3Dcom_docman%26task%3Ddoc_download%26gid%3D11%26Itemid%3D64&rct=j&q=west%20cumbria%202003&ei=NI9mTcTrKtSbhQeO46neDQ&usg=AFQjCNHbEWnCOQlf6SFpO0avHpEI9VEABQ&cad=rja)

12 NDA Report and Accounts, 2006/7 <http://www.nda.gov.uk/news/annual-report06-7.cfm>

13 2006/7 Lifetime Plan, Sellafield Site Summary, NDA-British Nuclear Group

[http://www.nda.gov.uk/documents/upload/Annual\\_Plan\\_2006\\_7.pdf](http://www.nda.gov.uk/documents/upload/Annual_Plan_2006_7.pdf)

14 The Environment Council: BNFL National Stakeholder Dialogue: West Cumbria: Socio-economic study, 2003 update [www.the-environment-council.org.uk%2Findex.php%3Foption%3Dcom\\_docman%26task%3Ddoc\\_download%26gid%3D11%26Itemid%3D64&rct=j&q=west%20cumbria%202003&ei=NI9mTcTrKtSbhQeO46neDQ&usg=AFQjCNHbEWnCOQlf6SFpO0avHpEI9VEABQ&cad=rja](http://www.the-environment-council.org.uk%2Findex.php%3Foption%3Dcom_docman%26task%3Ddoc_download%26gid%3D11%26Itemid%3D64&rct=j&q=west%20cumbria%202003&ei=NI9mTcTrKtSbhQeO46neDQ&usg=AFQjCNHbEWnCOQlf6SFpO0avHpEI9VEABQ&cad=rja)





## Policy Implications



### Political

Over recent years, policy development in the UK has focused increasingly on new-build, including its radioactive waste and spent fuel management. However, there has not been similar attention paid to nuclear materials management, especially plutonium management. This has resulted in parts of the UK nuclear sector being set up for the '2003 nuclear end game' mission rather than the '2011 renaissance'.

In the field of security and non-proliferation, the 2010 Washington Nuclear Security Summit has emphasised that the ongoing indefinite possession of around 102 tonnes of separated plutonium is likely to become politically untenable. It is also incompatible with UK's ongoing role in seeking to reduce nuclear proliferation risks and to increase security of nuclear material. The Royal Society<sup>1</sup> and the Royal Academy of Engineering<sup>2</sup> are both on record urging action to find a way forward. Though the disposition of the existing plutonium stockpile will be controversial, there appears to be a growing acceptance that long term inactivity is no longer an option, and that the end result will involve all three main options, with elements of storage, re-use, and disposal.

Scenario 1 as modelled processes plutonium into a waste-form which is not highly resistant to diversion or theft, whereas Scenario 2 produces highly radioactive spent MOX. Scenarios 3 and 4 require ongoing reprocessing with separation of plutonium, but have limited plutonium storage and end with spent MOX as the final waste form.

New reactor build has been predicated on the use of uranium fuel and there is a policy tension which must be resolved if re-use as MOX is decided upon. The earlier this tension is resolved, the wider will be the choice of MOX-burning reactors and the greater the chance of the UK obtaining value for its plutonium stocks.

### Environment

As discussed in Chapter 5, the radiological detriments of the UK operations envisaged in all Scenarios are likely to be small, and will have to meet standards that represent the Best Available Techniques. The carbon benefits of MOX re-use are considerable, and there will be overall reductions in global radiological detriment, but these benefits will largely be realised by reductions in uranium mining and milling which take place outside the UK.

### Social

All Scenarios offer the prospect of direct jobs through construction and operation, and indirect employment through the supply chain. The possible benefits have been assessed in Chapter 5.

With the advent of new players in the UK nuclear sector, the opportunity for increased international cooperation and knowledge transfer can be maximised by developing, and maintaining, a long term strategy for nuclear education, skills and enterprise development.

### Technical

Declaring the UK's plutonium as a waste would necessitate the development of an approved and qualified waste conditioning route in parallel with the ongoing MRWS search for a disposal site. There is no international experience in bulk plutonium waste disposition at anything above laboratory scale, and the timescale, deliverability and cost of such a programme must be highly uncertain. All these developments would depend on UK public funding.

The fabrication of MOX, on the other hand, gives an opportunity to develop technology in a business setting, while attempting to maximise the worth of the UK plutonium

stock. The physical properties of the UK plutonium inventory are subject to uncertainty, and this raises the possibility of further developments in MOX manufacturing techniques to maximise the ability to accept this material. These possibilities are outlined in Appendix 5.

The long term storage of spent AGR fuel presents a UK-specific technical challenge, and the Scenarios presented in this report offer a trigger to perform a fundamental evaluation of the disposition of this fuel, rather than accept the outcome of a continued period of inaction.

## Legal

All Scenarios will have to meet legal obligations and regulatory approvals. There may be challenges, both nationally and internationally in the context of European law and international treaty obligations.

## Economic

In the current UK economic climate and the imperatives and structures set up by the '2003 nuclear end game' mission, the longer term benefit of any option to the UK is likely to be considered as secondary to the amount of early Government spending required. If all options were public sector funded, this would lead inevitably to the choice of delaying any action for as long as possible – which is in effect what has happened over the past several decades.

Scenario 1 will involve adding considerable cost to produce a waste product. The UK's plutonium stock, currently a zero value asset, would become a significant UK liability, and would require significant ongoing spend to maintain secure safe storage.

Whilst Scenario 1 offers only spend, Scenarios 2-4 offer, in various degrees, both spend and income. The balance of spend, income and risk between the parties involved can be varied by the adoption of different commercial and operational models. The key factors for success will be the establishment of commercial structures and risk/reward sharing profiles to produce an optimum solution for the UK.

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<sup>1</sup> Royal Society. 1998. Management of Separated Plutonium. Available at <http://royalsociety.org/WorkArea/DownloadAsset.aspx?id=5918>.

<sup>2</sup> Royal Academy of Engineering, Engineering The Future, October 2010 [http://www.raeng.org.uk/news/publications/list/reports/Nuclear\\_Lessons\\_Learned\\_Oct10.pdf](http://www.raeng.org.uk/news/publications/list/reports/Nuclear_Lessons_Learned_Oct10.pdf)





## Conclusions



This report and its illustrative economic assessment has been undertaken at the time of a step change in UK nuclear power policy – from a position of ‘nuclear end game’ in 2003, to the current projected renaissance of new nuclear generation as we stand in 2011.

By examining four Scenarios and a range of sensitivities, from declaring and treating UK nuclear materials as wastes, to maximising their recycle as a fuel in nuclear reactors, it has allowed elements of the nuclear fuel cycle and the accumulated UK stocks of nuclear materials to be assessed against the new policy backdrop.

The range of discounted cost outcomes given by the cases examined is large, from over £5billion to less than £0.5billion depending on the Scenario and the assumptions made.

Apart from costs there are other important factors, notably

- The use and development of existing nuclear assets
- Increased energy security by generating electricity from UK existing materials stocks
- Improved nuclear security and proliferation resistance
- Carbon savings, mainly from a reduction in uranium mining and milling overseas
- Increased employment and socio-economic benefits, particularly in West Cumbria
- Increased nuclear skills and a greater UK stake in the ongoing development of nuclear power

The main conclusions are:

- The structure of the UK nuclear industry, having been designed to address the rundown of nuclear power in the UK, is not well suited to the changed situation involving new nuclear build and an expanded UK nuclear role, and that there is a need for realignment of policy across the sector.
- It is also clear that, in the UK, there is now an opportunity to develop a holistic approach to nuclear power - combining the assessment of backend legacy materials with the opportunities offered by new build development.
- The challenge is to seize this opportunity, maximising value for the UK, creating jobs, improving non-proliferation, reducing carbon emissions, increasing energy security, and addressing the long term management of nuclear materials and spent nuclear fuel.



## Acronyms

AGR	Advanced Gas Reactors
AP1000	A type of Pressurised Water Reactor
BAT	Best Available Techniques
CAPEX	Capital expenditure
EPR	A type of Pressurised Water Reactor
FHP	Fuel Handling Plant
FTE's	Full time equivalent
GDF	Geological Disposal Facility
GVA	Gross Value Added
GW	Gigawatts
HIP	Hot Isostatic Pressing
HLW	High Level Wastes
HSE	Health and Safety Executive
ILW	Intermediate Level Wastes
Magnox	A type of nuclear reactor
MRWS	Managing Radioactive Waste Safely
NDA	Nuclear Decommissioning Authority
NII	Nuclear Installations Inspectorate
NPT	Nuclear Non Proliferation Treaty
OCNS	Office for Civil Nuclear
OSPAR	Oslo Paris Convention
PWR	Pressurised Water Reactors
REPU	Reprocessed Uranium
Sellafield Ltd	Sellafield Ltd is a Nuclear Site Licence company
SGHWR	Steam Generating Heavy Water Reactor
SMP	Sellafield Mox Plant
SN	Scottish Nuclear
TBq	Terabequerels per year
teHM	Tonnes of Heavy Metal
THORP	Thermal Oxide Reprocessing Plant
TWh	Terrawatt-Hours
UKAEA	United Kingdom Atomic Energy Authority
UKSO	UK Safeguards Office

## Appendix 1. Description and Assumptions UK Nuclear Fuel and Materials Recycling

### Model description

The spreadsheet is based on manually entered capital and operational costs for Sellafield plants, plus outside spends on waste conditioning, disposal, provision of uranium feedstock, etc. This allows realistic distribution of spend with time ('S' Curves) but does entail manual re-entry to change plant capital and operational cases.

The plant and materials programming is also carried out off-line, with off-line checking that materials are available for processing when used in the model and the throughputs are manually entered. Some yearly costs within individual worksheets, particularly income from MOX/REPU sales are, however, calculated from costs, throughputs and prices entered on the sheet.

The MOX fuel and REPU prices are calculated off-line using a REPU and MOX Price Development model, which allows different uranium prices, processing costs, and REPU feeds to be examined to give stage costs and material flows. The results from this work is given in Appendix 2.

The remaining costs can be entered on the model front sheet and feed to all relevant Scenarios. These include:

- Costs of Spent Fuel and Waste Disposal
- MOX fuel Selling Price
- Cash surplus available from sales of REPU fuel
- Reprocessing price

Discount rates can also be varied from the front sheet, and are variable over six time periods as given in the Treasury Discount Rate (Green Book, 2003).

The output of the model consists of:

- The cumulative gross and net undiscounted cost of each scenario, and the discounted net cost at the discount rate selected.
- The key capital expenditures from the worksheets (these are read back from the worksheets, not entered from the front sheet). Note that all capital expenditures have had a 20% allowance added at appropriate times for decommissioning

- The timescales over which all expenditure is incurred is also read back from the worksheets – giving the period over which capital expenditures and decommissioning costs are incurred.
- The results are used to generate cumulative spend/income graphs for each of the Scenarios, both undiscounted and discounted.

### Assumptions

The Table below gives the key parameters assumed for the model, and the range of sensitivities examined.

Parameter	Value	Notes
Pu storage module CAPEX	£250M	Up to 4 modules in Scenario 1
PuO <sub>2</sub> storage OPEX	£6.25M/a/module	Up to 4 modules in Scenario 1
Low-spec MOC plant CAPEX	£500M	
Low-spec MOX plant OPEX	£60M/a	
Low-spec MOX plant throughput	50teHM/a	
Low-spec MOX storage OPEX	£3.0M/a/module	Up to 4 modules in Scenario 1
Low-spec MOX disposal	£0.13M/teHM	x5 examined
AGR spent fuel drying CAPEX	£150M	Module in existing Fuel Handling Plant
AGR spent fuel storage CAPEX	£250M	£1B examined for Drying + Storage CAPEX
AGR spent fuel condition + dispose	£0.27M/teHM	x5 examined
New MOX plant CAPEX	£2000M	£3,000M examined
New MOX plant OPEX	£80M/a	
New MOX plant throughput	100teHM/a	
MOX loading to UK new build reactor	2020	2025 and 2030 start dates examined
THORP refurbishment CAPEX	£2B	£30M/a to £4B range examined
THORP Reprocessing OPEX	£80M/a	
THORP Reprocessing throughput	500teHM/a	300-800teHM/a examined

## Appendix 2 Mixed Oxide (MOX) and Reprocessed Uranium (REPU) Fuel and Price Assumptions

The economics of Scenarios 2, 3 and 4 of the study depend on selling MOX and REPU fuel to the utilities owning and operating new build UK PWR reactors. This Appendix outlines the derivation of the prices used in the model.

### Price of fuel derived from natural uranium

The production of natural-derived uranium fuel involves mining and milling uranium ore, purification and conversion to uranium hexafluoride (UF<sub>6</sub>), enrichment, conversion from UF<sub>6</sub> to uranium dioxide (UO<sub>2</sub>), and fabrication into fuel. The processes are illustrated in the figure below.

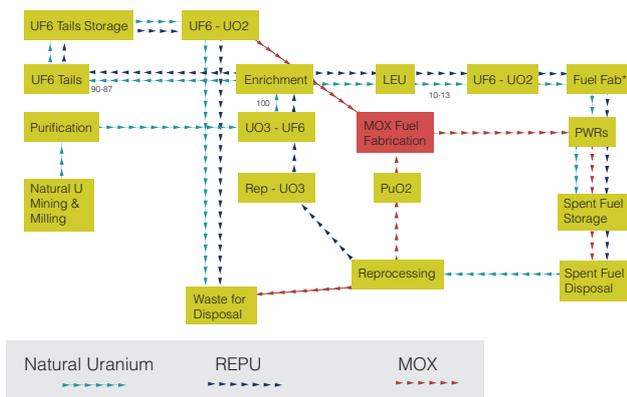


Figure A2.1 Fuel Material Flows

During enrichment, the UF<sub>6</sub> is separated into a product fraction higher in <sup>235</sup>U, and a tails fraction lower in <sup>235</sup>U. Depending on the relative costs of uranium and enrichment, the optimum <sup>235</sup>U content of the tails will change, with higher relative uranium costs driving more <sup>235</sup>U to be extracted into the product, with the tails <sup>235</sup>U content falling. This means that the amount of uranium required per unit of fuel changes with the relative prices, and the cost of any given fuel will need to be calculated for each particular set of price assumptions for each process stage.

The assumed price ranges for the fuel stages were chosen against the general background of prices over the last 30 years, and are shown in Table A2.1 below.

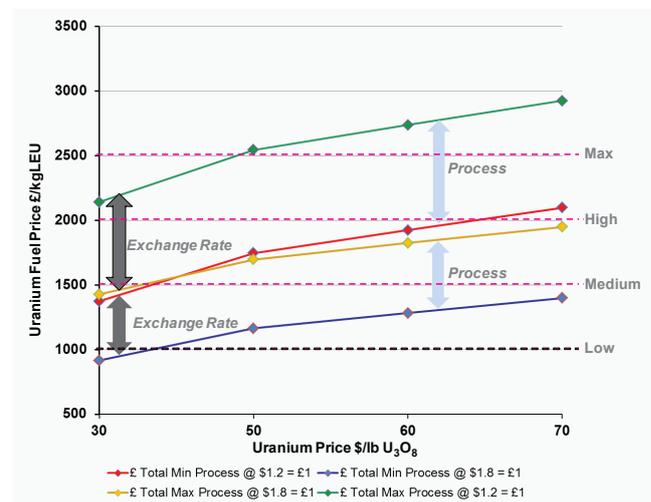
They represent a restricted subset of the values used in previous studies on NDA materials<sup>1</sup>. As uranium and most other process stages are priced in dollars, the \$:£ exchange rate is an important factor. Here too a relatively restrictive range has been chosen in comparison to actual variations over the last three decades.

Parameter	Max	Min
Exchange Rate US\$ = £1	1.8	1.2
Uranium (US\$/lbU <sub>3</sub> O <sub>8</sub> )	70	30
Conversion (Natural) \$/kgU	10	30
Enrichment (\$/kgSW) Natural	100	180
Fabrication (\$/kgU) Natural	150	300

Table A2.1 Price assumptions for natural-derived fuel

The prices of fuel were calculated across the range of the assumptions, for a fuel with a <sup>235</sup>U content of 4.5%. This is likely to be towards the bottom of the enrichment range expected for high burnup fuel for new build PWRs.

The results of the calculations are shown in Figure A2.2 below.



The figure shows that variations in exchange rate cause similar price changes to those caused by process charges, and the fuel prices can be seen to vary by a factor of three over the range of assumptions used. Three prices plus a 'maximum' variant were chosen for examination as seen in the figure and below.

- 'Maximum' variant £2.5M/te LEU

- 'High' £2.0M/te LEU
- 'Medium' £1.5M/te LEU
- 'Low' £1.0M/te LEU

### Price of MOX Fuel

Both the new build PWR reactor designs are stated to be capable of working with 100% MOX cores, or to be able to work with a proportion (typically 30%) of MOX fuel as achieved in most currently MOX-burning PWRs. Any differences between the performance of MOX and uranium fuel are likely to be relatively small, especially for the post-2020 fuel campaigns considered in Scenarios 2-4.

Provided, therefore, that MOX-burning is decided upon early in the reactor project, there seems no compelling reason why the price achieved for MOX fuel should be significantly different from that of the corresponding uranium-based fuel. As discussed elsewhere in this study, this parity of value is unlikely to persist where MOX burning is introduced as a modified scheme into an existing reactor, where the relative bargaining positions of the reactor owner and fuel vendor may be very different.

A case could be made for considering discounts of 10% or 20% on the uranium fuel price. These variations are small compared to the overall range of prices calculated for uranium fuel, so though the range of prices was not changed, it is pointed out that MOX fuel prices with a 20% discount would relate to U prices as shown in Table A2.2 below.

Uranium Fuel Price	MOX fuel Price with 20% discount	Level
£3.13M/teLEU	£2.5M/teHM	Max
£2.50M/teLEU	£2.0M/teHM	High
£2.00M/teLEU	£1.6M/teHM	
£1.88M/teLEU	£1.5M/teHM	Medium
£1.50M/teLEU	£1.2M/teHM	
£1.25M/teLEU	£1.0M/teHM	Low
£1.0M/teLEU	£0.8M/teHM	

Table A2.2 Equivalent MOX prices at 20% discount from uranium fuel

The bulk of MOX fuel is made up of uranium dioxide (UO<sub>2</sub>), and notionally some allowance would need to be made for the cost of supply of this material. However, NDA owns

very significant quantities of enrichment tails UF<sub>6</sub>, which has a very low value at current uranium prices, and would cost at most a few £K/teU to convert it to ceramic grade UO<sub>2</sub>. This would introduce an extremely small variance into the price, which was deemed to be insignificant compared with the price ranges being examined.

### Price of REPU Fuel

Uranium from oxide fuel reprocessing, either currently in stock or when generated from future reprocessing programmes from NDA-owned fuel, can be considered as a free issue into the REPU manufacturing process. The <sup>235</sup>U content of this uranium varies with reactor and burnup. For the AGR fuel which makes up most of the higher <sup>235</sup>U content NDA holding, the REPU feed examined was an AGR THORP product with 0.95% <sup>235</sup>U and 0.35% <sup>236</sup>U. This is a reasonable average, but of a wide range of spent fuel predictions between 0.7% for full-burnup robust fuel, 0.55-0.8% for normal fuel, and 1.5 – 1.8% for final cores. The resulting values should therefore be taken as indicative only.

Having started with 'free issue' REPU, the fuel fabrication process follows the same stages as natural uranium-derived fuel, as seen in Figure A2.1. The presence of <sup>236</sup>U is important, because it is a neutron poison and is enriched into the product, and requiring the REPU fuel to have a higher <sup>235</sup>U content to compensate. The presence of other uranium isotopes, <sup>232</sup>U and <sup>234</sup>U, also add challenges to processing, and at the very least owners of natural uranium-based fuel will require assurance that cross-contamination with REPU will not occur. Extra processing precautions, the need for segregation, and the lower amounts of REPU to be processed compared to natural uranium feed, means that the prices for conversion, enrichment and fuel fabrication are all likely to be higher than for natural-based fuel.

A general review of likely surcharges was carried out and has been informally tested with knowledgeable stakeholders. These surcharges are included in Table A2.3 below, and are quoted together with the ranges for natural uranium quoted in Table A2.4.

Parameter	Max	Min
Exchange Rate US\$ = £1	1.8	1.2
Uranium (US\$/lbU3O8)	70	30
Conversion (Natural) \$/kgU	10	30

Conversion (REPU) \$/kgU	30	75
Enrichment (\$/kgSW) Natural	100	180
Enrichment (\$/kgSW) REPU	100	198
Fabrication (\$/kgU) Natural	150	300
Fabrication (\$/kgU) REPU	200	360
MOX price discount (c/f U fuel) %	0	25

Table A2.3 Surcharges

These parameters have been used to calculate processing costs for making the equivalent of the 4.5% enriched natural fuel. This was done using a programme derived by Peter Wooders of ERM which was itself developed from the Urenco UK program, 'PASREF', as used for the first enrichment trails of oxide-derived REPU. In all cases the <sup>235</sup>U content of the fuel was raised by 0.3% for every 1.0% <sup>236</sup>U, a fairly typical value for PWRs.

With a large number of variables and with a large range for each, it was decided for each uranium price (\$30, \$50, \$60 and \$70/lb U3O8) to vary all costs upwards in five steps from minimum to maximum, for both high and low exchange rates. The resulting 'net income per tonne' results are seen in Figure A2.3 below.

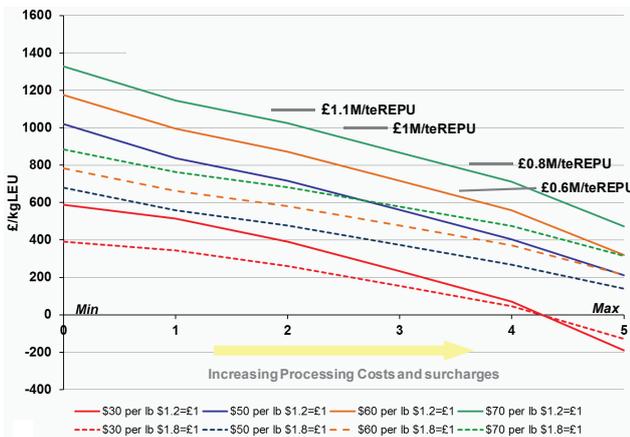


Figure A2.3 'Price minus Processing cost' for fuel from free issue REPU

Understandably in view of the large range of prices and exchange rates used, the resulting 'net income per tonne' varies from £200K/teU loss at high costs and low uranium prices, to over £1,300K/teU net income at high U prices and low costs. The response to a cost regime of high processing prices and low uranium costs would almost certainly be to store the REPU and await improved conditions. This is in fact the predominant outcome to date worldwide. However, with uranium spot prices once

more over \$60/lbU<sub>3</sub>O<sub>8</sub> it is sensible to examine some recycle options, and the values below were examined by the model.

- 'Maximum' variant £1.1M/te LEU
- 'High' £1.0M/te LEU
- 'Medium' £0.8M/te LEU
- 'Low' £0.6M/te LEU

<sup>1</sup> Uranium and Plutonium: Macro-economic Study Final Report – Public Version, ERM-IDM, April 2007, at <http://www.nda.gov.uk/documents/upload/Uranium-and-Plutonium-Macro-Economic-Study-June-2007.pdf>

### Appendix 3 UK Nuclear Fuels and Materials Recycling – Model Results Summary

This Appendix lists all the model runs which have been carried out in support of the study. The graphic below shows the main parameters involved, the base case, and the range of variations examined.

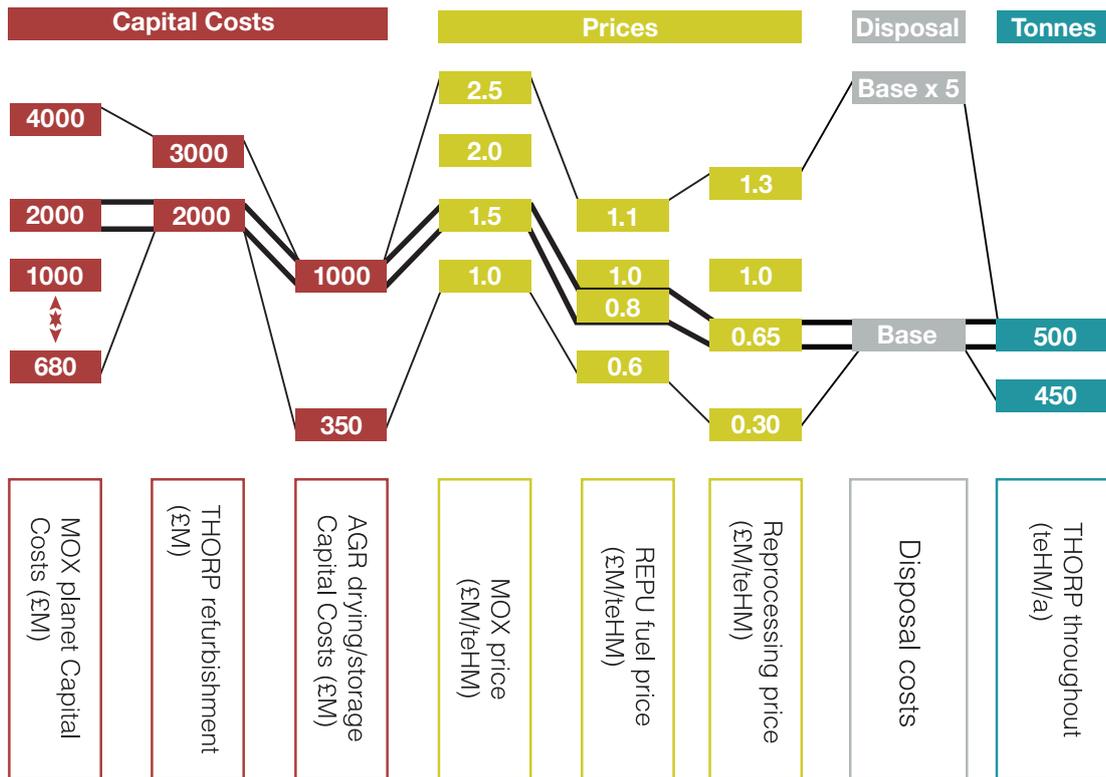


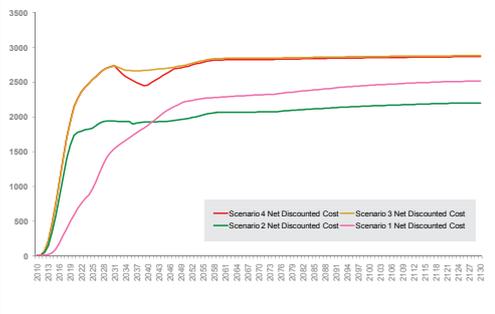
Figure A1. Main variables modelled and ranges examined

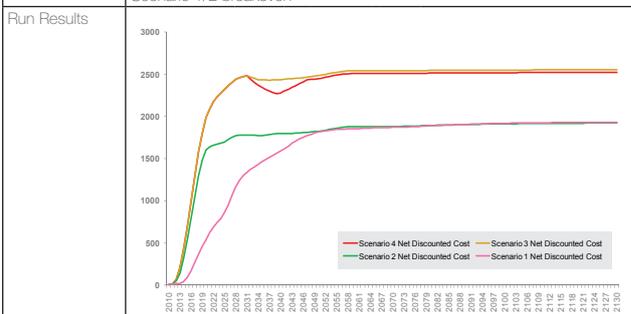
**Table A1. Model Runs used in the Report**

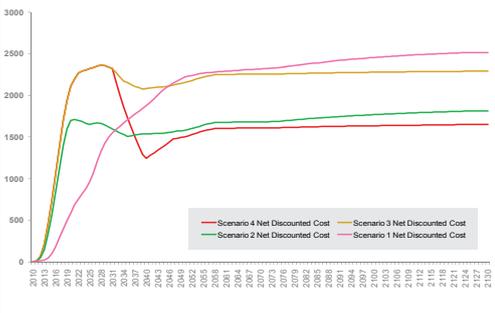
Run	CAPEX £Bn		Price (£M/teHM)			Discount Rate	Notes	NPV Scen 1	NPV Scen 2	NPV Scen 3	NPV Scen 4	Derivation
	MOX	THORP	MOX	REPU	REPRO							
A1	2.00	1.00	1.00	0.60	0.30	Treasury	Low THORP CAPEX, medium MOX CAPEX, low prices	-2,515	-2,201	-2,881	-2,867	
A2	2.00	1.00	1.00	0.60	0.30	4.60%	Low THORP CAPEX, medium MOX CAPEX, low prices, discount to Scen1 = Scen2	-1,931	-1,921	-2,552	-2,522	
B1	2.00	1.00	1.50	0.80	0.65	Treasury	Low THORP CAPEX, medium MOX CAPEX, medium prices	-2,515	-1,812	-2,289	-1,650	
B2	2.00	1.00	1.50	0.80	0.65	6.75%	Low THORP CAPEX, medium MOX CAPEX, medium prices. Discount to Scen1 = Scen2	-1,312	-1,310	-1,763	-1,438	
C1	2.00	1.00	2.00	1.00	1.00	Treasury	Low THORP CAPEX, medium MOX CAPEX, high prices	-2,515	-1,383	-1,697	-433	
C2	2.00	1.00	2.00	1.00	1.00	9.00%	Low THORP CAPEX, medium MOX CAPEX, high prices Discount to Scen1 = Scen2	-932	-928	-1,286	-947	
D1	2.00	2.00	1.00	0.60	0.30	Treasury	Medium THORP CAPEX, medium MOX CAPEX, low prices	-2,515	-2,240	-3,692	-3,678	
E1	2.00	2.00	1.50	0.80	0.65	Treasury	Base Case: Medium THORP CAPEX, medium MOX CAPEX, medium prices	-2,515	-1,812	-3,100	-2,454	
E3	2.00	2.00	1.50	0.80	0.65	Treasury	As E1, Medium THORP CAPEX, medium MOX CAPEX, medium prices – but x5 on disposal costs	-2,995	-2,258	-3,205	-2,576	
F1	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, medium MOX CAPEX, high prices	-2,515	-1,383	-2,507	-1,243	
G1	2.00	4.00	2.00	1.00	1.00	Treasury	High THORP CAPEX, high prices	-2,515	-1,383	-3,979	-2,716	
H1	2.00	4.00	2.50	1.10	1.30	Treasury	High THORP CAPEX, maximum credible prices	-2,515	-954	-3,431	-1,632	
J1	3.00	2.00	1.50	0.80	0.65	Treasury	High MOX CAPEX, Medium THORP CAPEX, medium prices	-2,515	-2,631	-3,919	-3,280	

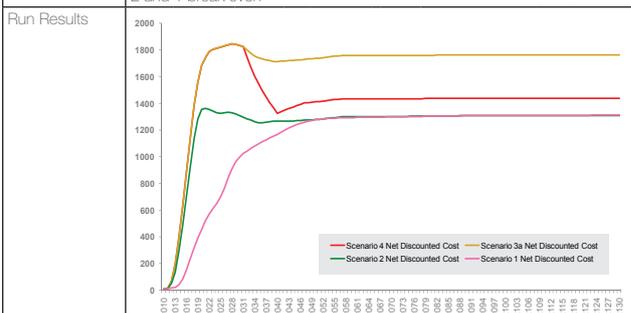
K1	2.00	~0.80	1.50	0.80	0.65	Treasury	Low cost, phased THORP refurbishment with 500teHM/a throughput, medium MOX CAPEX, medium prices,	-2,515	-1,812	-1,996	-1,447	
K2	2.00	~0.80	1.50	0.80	0.65	Treasury	Low cost, phased THORP refurbishment with 450teHM/a throughput and phased income, medium MOX CAPEX, medium prices	-2,515	-1,851	-2,084	-938	
K3	2.00	~0.80	2.00	1.00	1.00	Treasury	Low cost, phased THORP refurbishment with 450teHM/a throughput and phased income, medium MOX CAPEX, high prices	-2,515	-1,422	-1,491	+555	
K4	2.00	~0.80	1.00	0.60	0.30	Treasury	Low cost, phased THORP refurbishment with 450teHM/a throughput and phased income, medium Mox CAPEX, low prices	-2,515	-2,240	-2,671	-1,765	
L1	3.00	2.00	2.00	1.00	1.00	Treasury	High MOX CAPEX, medium THORP CAPEX, high prices	-2,515	-2,202	-3,327	-2,063	
L2	3.00	2.00	1.00	0.60	0.30	Treasury	High MOX Capex, medium THORP CAPEX, low prices	-2,515	-3,060	-4,511	-4,497	Change price in L1
M1	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, medium MOX CAPEX, increased AGR drying/storage costs, high prices	-2,982	-1,845	-2,507	-1,243	
N1	2.00	2.00	1.50	0.80	0.65	Treasury	Medium THORP CAPEX, medium MOX CAPEX, increased AGR drying/storage costs, medium prices	-2,982	-2,274	-3,100	-2,461	
O1	2.00	4.00	1.50	0.80	0.65	Treasury	High THORP CAPEX, medium MOX CAPEX, medium prices	-2,515	-2,240	-5,068	-4,436	
P1	3.00	4.00	2.50	1.10	1.30	Treasury	High THORP CAPEX, high MOX CAPEX, maximum credible prices	-2,515	-1,774	-4,251	-2,452	Raise MOX capital in H1 (MOX Capital from L1)
P2	3.00	4.00	2.00	1.00	1.00	Treasury	High THORP CAPEX, high MOX CAPEX, high prices	-2,515	-2,202	-4,799	-3,535	Change price from P1
Q1	3.00	1.00	1.50	0.80	0.65	Treasury	Low THORP CAPEX, high MOX CAPEX, medium prices	-2,515	-2,631	-3,109	-2,470	Raise MOX CAPex in B1 (MOX Capital from L1)

R1-400	2.00	2.00	1.50	0.80	0.65	Treasury	Medium THORP CAPEX, medium prices, THORP Throughput 400 teHM/a	-2,515	-1,812	-3,202	-3,856	Changed THORP throughput in E1
R1-500	2.00	2.00	1.50	0.80	0.65	Treasury	Medium THORP CAPEX, medium prices, THORP Throughput 500 teHM/a	-2,515	-1,812	-3,100	-2,454	As E1
R1-600	2.00	2.00	1.50	0.80	0.65	Treasury	Medium THORP CAPEX, medium prices, THORP Throughput 600 teHM/a	-2,515	-1,812	-3,025	-1,851	Changed THORP throughput in E1
R1-700	2.00	2.00	1.50	0.80	0.65	Treasury	Medium THORP CAPEX, medium prices, THORP Throughput 700 teHM/a	-2,515	-1,812	-2,968	-1,258	Changed THORP throughput in E1
R1-800	2.00	2.00	1.50	0.80	0.65	Treasury	Medium THORP CAPEX, medium prices, THORP Throughput 800 teHM/a	-2,515	-1,812	-2,924	-593	Changed THORP throughput in E1
S1-400	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, high prices, THORP Throughput 400 teHM/a	-2,515	-1,383	-2,610	-3,155	Changed THORP throughput in F1
S1-500	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, high prices, THORP Throughput 500 teHM/a	-2,515	-1,383	-2,507	-1,237	As F1
S1-600	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, high prices, THORP Throughput 600 teHM/a	-2,515	-1,383	-2,433	-309	Changed THORP throughput in F1
S1-700	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, high prices, THORP Throughput 700 teHM/a	-2,515	-1,383	-2,376	+566	Changed THORP throughput in F1
S1-800	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, high prices, THORP Throughput 800 teHM/a	-2,515	-1,383	-2,332	+1,628	Changed THORP throughput in F1
T1-2020	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, medium MOX CAPEX, high prices	-2,515	-1,383	-2,507	-1,243	As F1
T2-2025	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, medium MOX CAPEX, high prices	-2,515	-1,653	-2,821	-1,557	F1 - MOX payment delayed to 2025 - equivalent to reducing MOX price to £1.65M (17.1%)
T2-2030	2.00	2.00	2.00	1.00	1.00	Treasury	Medium THORP CAPEX, medium MOX CAPEX, high prices	-2,515	-1,876	-3,079	-1,815	F1 - MOX payment delayed to 2030 - equivalent to reducing MOX price to £1.43M (28.5%)

Run	A1							
Description	Low THORP CAPEX, low prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	1,000				
	£M/teHM MOX price	1.0	£M/teHM REPU fuel price	0.6				
	£M/teHM Reprocessing price	0.3	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-2,201	Scen 3	-2,881	Scen 4	-2,867
Commentary on Results	Scenario 2 has lower costs than Scenario 1 due to income from MOX fuel sales, but has higher initial spend because of early MOX plant investment. Scenario 3 is not competitive because cost of refurbishing and operating THORP is higher than the assumed discounted cost of AGR becoming a waste, and low prices mean Scenario 4 still has higher costs than Scenario 1.							
Summary Key Points	Capital costs and length of plant programme are the key variables – decreased costs and increased income favour Scenario 2 over Scenario 1, but would break even at a MOX price of £0.73M/teHM, or by increasing the discount rate to 4.6% as illustrated in Run A2. Scenario 3 will improve relative to Scenario 2 as AGR used fuel waste costs increase.							

Run	A2							
Description	Low THORP CAPEX, low prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	1,000				
	£M/teHM MOX price	1.0	£M/teHM REPU fuel price	0.6				
	£M/teHM Reprocessing price	0.3	Discount rate (%)	4.6				
	Additional assumptions: As Run A1, but discount rate increased to Scenario 1/2 breakeven							
Run Results								
NPV £M	Scen 1	-1,931	Scen 2	-1,921	Scen 3	-2,552	Scen 4	-2,522
Commentary on Results	At the discount rate chosen (4.6%) the early costs and later income of Scenario 2 combine to give the same net present cost as Scenario 1. This discounting also worsens the costs of Scenarios 3 and 4 in comparison to Scenario 1.							
Summary Key Points	Illustrates that increasing discount rate significantly favours low early spend – in this case Scenario 1.							

Run	B1							
Description	Low THORP CAPEX, medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	1,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,812	Scen 3	-2,289	Scen 4	-1,650
Commentary on Results	Scenario 2 has lower costs than Scenario 1 due to income from MOX fuel sales, but has higher initial spend because of early MOX plant investment. At these medium prices and low THORP refurbishment costs Scenario 3 becomes competitive with Scenario 1, but not Scenario 2. Median prices allow low THORP CAPEX to be overcome by sales revenue, and Scenario 4 is the lowest cost option.							
Summary Key Points	Capital costs and length of plant programme are the key variables – decreased costs and medium income favour Scenarios 2 and 3 over Scenario 1, with Scenario 4 the best option by some £160M NPV.							

Run	B2							
Description	Low THORP CAPEX, medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	1,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	6.75%				
	Additional assumptions: As B1, but discount rate increased until Scenarios 2 and 1 break even							
Run Results								
NPV £M	Scen 1	-1,312	Scen 2	-1,310	Scen 3	-1,763	Scen 4	-1,438
Commentary on Results	Scenario 2 has lower costs than Scenario 1 due to income from MOX fuel sales, but has higher initial spend because of early MOX plant investment. Raising the discount rate to 6.75% makes Scenarios 1 and 2 break even, with Scenario 4 some £130M more costly.							
Summary Key Points	Higher discount rates favour later spend, so Scenario 1 improves relative to the others.							

Run	C1							
Description	Low THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	1,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,383	Scen 3	-1,697	Scen 4	-433
Commentary on Results	With high price assumptions, income from MOX fuel sales leads to Scenario 2 dominating Scenario 1, but Scenario 2 has higher initial spend because of early MOX plant investment. At these high prices and low THORP refurbishment cost Scenario 2 is preferred to Scenario 3, but Scenario 4 is very dominant overall, and would achieve a positive NPV at a reprocessing charge of £1.1M/teHM.							
Summary Key Points	Capital costs and length of plant programme are the key variables – decreased costs and high income favour Scenarios 2 and 3 over Scenario 1, with Scenario 4 the best option by some £1B NPV.							

Run	C2							
Description	Low THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	1,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	9.00				
	Additional assumptions: As C1, but discount rate increased until Scenarios 2 and 1 break even							
Run Results								
NPV £M	Scen 1	-932	Scen 2	-928	Scen 3	-1,286	Scen 4	-947
Commentary on Results	With the same cost and price assumptions as C1, a discount rate of 9% gives very similar results for Scenarios 1, 2 and 4 – with the significant effect of high early spend at this discount rate balanced by the income from high prices.							
Summary Key Points	At high discount rates timing of spend increases in significance in comparison to magnitude. This run well illustrates the large sensitivity to discount rate.							

Run	D1							
Description	Medium THORP CAPEX, low prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.0	£M/teHM REPU fuel price	0.6				
	£M/teHM Reprocessing price	0.3	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-2,240	Scen 3	-3,692	Scen 4	-3,678
Commentary on Results	Even with low price assumptions and income from MOX fuel sales, Scenario 2 is less costly than Scenario 1, but Scenario 2 has higher initial spend because of early MOX plant investment. At these low prices and £2B THORP refurbishment, Scenario 2 is dominates both Scenario 3 and Scenario 4.							
Summary Key Points	Capital costs and length of plant programme are the key variables – medium costs and low income favour Scenario 2 over all other scenarios.							

Run	E1							
Description	Medium THORP CAPEX and medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,812	Scen 3	-3,100	Scen 4	-2,454
Commentary on Results	Scenario 2 has lower costs than Scenario 1 due to income from MOX fuel sales, but has higher initial spend because of early MOX plant investment. Scenario 3 is not competitive because cost of refurbishing and operating THORP is higher than the assumed discounted cost of AGR becoming a waste. Scenario 4 begins to be competitive as reprocessing income compensates for THORP costs.							
Summary Key Points	Capital costs and length of plant programme are the key variables – decreased costs and increased income favour Scenario 2 over Scenario 1, then will begin to favour Scenario 4 over Scenario 2. Scenario 3 will improve relative to Scenario 2 as AGR used fuel waste costs increase.							

Run	E3							
Description	Medium THORP CAPEX, medium prices – but x5 on all disposal costs							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,995	Scen 2	-2,258	Scen 3	-3,205	Scen 4	-2,576
Commentary on Results	This run shows the effect of an extreme (x5) increase in all disposal costs. This makes Scenarios 1 and 2 relatively less favourable than 3 and 4, but the effect of discounting and the timing (2070+) of HLW/Spent fuel disposal means that the overall effect is limited, emphasising that disposal costs have little effect on choices using the current programme timescales.							
Summary Key Points	The cost increase in disposal gives a large change in undiscounted cost, but a much smaller change in discounted cost, and as shown in the table below							

Run	F1							
Description	Medium THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,383	Scen 3	-2,507	Scen 4	-1,243
Commentary on Results	Scenario 2 has very much lower costs than Scenario 1 due to high income from MOX fuel sales, but has higher initial spend because of early MOX plant investment. Scenario 3 is competitive with Scenario 1, but high prices lead to Scenario 4 being the favoured option.							
Summary Key Points	Capital costs and length of plant programme are the key variables – decreased costs and increased income favour Scenario 1, and high prices/THORP CAPEX ratio favours Scenario 4 over Scenario 2. Scenario 3 will improve relative to Scenario 2 as AGR used fuel waste costs increase.							

Effect of x5 Increase in Disposal Costs from Run E1 to Run E3

Scenario	E1 Undiscounted	E3 Undiscounted	% Change	E1 Discounted	E3 Discounted	% Change
1	7,800	14,800	+90%	2,515	2,995	+9.5%
2	4,377	10,857	+148%	1,812	2,258	+24.6%
3	4,877	6,419	+31.6%	3,100	3,205	+3.4%
4	3,531	5,345	+51.4%	2,454	2,576	+5.0%

Run	G1							
Description	High THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	4,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,383	Scen 3	-3,979	Scen 4	-2,716
Commentary on Results	Scenario 2 has very much lower costs than all other scenarios due to high income from MOX fuel sales and absence of (high) THORP CAPEX. Initial spend is higher than Scenario 1 because of early MOX plant investment. High THORP costs make Scenario 3 uncompetitive, but Scenario 4 is little more costly than Scenario 1.							
Summary Key Points	Capital costs and length of plant programme are the key variables – decreased costs and increased income favour Scenario 2 over Scenario 1, and THORP CAPEX favours Scenario 2 over Scenario 4.							

Run	H1							
Description	High THORP CAPEX, maximum credible prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	4,000				
	£M/teHM MOX price	2.5	£M/teHM REPU fuel price	1.1				
	£M/teHM Reprocessing price	1.3	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-954	Scen 3	-3,431	Scen 4	-1,632
Commentary on Results	Scenario 2 has very lower costs than all other scenarios due to high income from MOX fuel sales and absence of (high) THORP CAPEX. Initial spend is higher than Scenario 1 because of early MOX plant investment. High THORP costs make Scenario 3 uncompetitive, but these highest prices enable Scenario 4 to approach comparability with Scenario 2.							
Summary Key Points	Capital costs and length of plant programme are the key variables – decreased costs and increased income favour Scenario 2 over Scenario 1, with high THORP costs preventing Scenario 4 from being the most favoured option.							

Run	J1							
Description	High MOX CAPEX, Medium THORP CAPEX, medium prices							
Run Parameters	£M MOX Capital	3,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-2,631	Scen 3	-3,919	Scen 4	-3,280
Commentary on Results	The high MOX plant CAPEX makes Scenario 2 more expensive than Scenario 1. High MOX costs also make Scenarios 3 and Scenario 4 uncompetitive at the medium prices assumed..							
Summary Key Points	Capital costs and length of plant programme are the key variables – increased MOX costs dominate in Scenarios 2-4.							

Run	K1							
Description	Low cost, phased THORP refurbishment, medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	£680-1,000M at £30M/a during programme				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: THORP refurbishment assumed as £30M/a cost throughout operational life, but with a shutdown between finish of current contracts and end 2019.							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,812	Scen 3	-1,996	Scen 4	-1,447
Commentary on Results	Lower, phased THORP refurbishment costs improve all reprocessing options, with Scenario 4 dominant.							
Summary Key Points	Capital costs and length of plant programme are the key variables – reduced THORP costs allow Scenario 4 to be preferred.							

Run	K2							
Description	Low cost, phased THORP refurbishment with 450teHM/a throughput and phased income, medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	£680-1,000M at £30M/a during programme				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: THORP refurbishment assumed as £30M/a cost throughout operational life (as Run K1), but with production reduced from 500teHM/a to 450teHM/a immediately after current contracts from 2016, and with total income from non-NDA reprocessing paid pro rata across entire THORP campaign i.e brings some income forward. Medium Prices.							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,851	Scen 3	-2,084	Scen 4	-938
Commentary on Results	Lower, phased THORP refurbishment costs improve all reprocessing options, and uniform spread of income more than compensates for 50teHM/a throughput reduction, leaving Scenario 4 more dominant.							
Summary Key Points	Capital costs and length of plant programme are the key variables – compared to Run K1, the phasing of income improves Scenario 4 by ~£275M.							

Run	K3							
Description	Low cost, phased THORP refurbishment with 450teHM/a throughput and phased income, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	£680-1,000M at £30M/a during programme				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	3.5/3.0/2.5				
	Additional assumptions: THORP refurbishment assumed as £30M/a cost throughout operational life with production reduced from 500teHM/a to 450teHM/a immediately after current contracts from 2016 (as Runs K1, K2), and with total income from non-NDA reprocessing paid pro rata across entire THORP campaign i.e brings some income forward. High Prices.							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,422	Scen 3	-1,491	Scen 4	+555
Commentary on Results	Lower, phased THORP refurbishment costs improve all reprocessing options, and uniform spread of income and high prices dominate THORP throughput reduction, leaving Scenario 4 dominant, with a positive NPV at these prices.							
Summary Key Points	Capital costs and length of plant programme are the key variables – reduced and spread THORP costs and income lead to Scenario 4 being preferred.							

Run	K4							
Description	Low cost, phased THORP refurbishment with 450teHM/a throughput and phased income, medium MOX CAPEX, low prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	£680-1,000M at £30M/a during programme				
	£M/teHM MOX price	1.0	£M/teHM REPU fuel price	0.6				
	£M/teHM Reprocessing price	0.3	Discount rate (%)	Treasury				
	Additional assumptions: THORP refurbishment assumed as £30M/a cost throughout operational life with production reduced from 500teHM/a to 450teHM/a immediately after current contracts from 2016 (as Runs K1, K2, K3), and with total income from non-NDA reprocessing paid pro rata across entire THORP campaign i.e brings some income forward. Low Prices.							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-2,240	Scen 3	-2,671	Scen 4	-1,765
Commentary on Results	Lower, phased THORP refurbishment costs improve all reprocessing options, and with uniform spread of income even low prices leave Scenario 4 dominant.							
Summary Key Points	Capital costs and length of plant programme are the key variables – reduced and spread THORP costs and income lead to Scenario 4 being preferred even with low prices.							

Run	L1							
Description	High MOX CAPEX, medium THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	3,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-2,202	Scen 3	-3,327	Scen 4	-2,063
Commentary on Results	Higher MOX costs (without increasing 'MOX waste' costs in Scenario 1) give Scenario 2 only a small advantage over Scenario 1, but high prices make Scenario 4 slightly preferred.							
Summary Key Points	Capital costs and length of plant programme are the key variables – increased MOX plant make Scenario 1 closer to 2 and 4.							

Run	L2							
Description	High MOX CAPEX, medium THORP CAPEX, low prices							
Run Parameters	£M MOX Capital	3,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.0	£M/teHM REPU fuel price	0.6				
	£M/teHM Reprocessing price	0.3	Discount rate (%)	Treasury				
	Additional assumptions:							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-3,060	Scen 3	-4,511	Scen 4	-4,497
Commentary on Results	Low prices dominate when combined with high MOX capital							
Summary Key Points	Increased capital costs and low prices see Scenario 1 preferred – but note capital and operating costs of 'MOX Waste' plant not increased in Scenario 1.							

Run	M1							
Description	Base case THORP and MOX CAPEX, increased AGR drying/storage costs, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: Increase in AGR drying and storage CAPEX to £1B from £350M							
Run Results								
NPV £M	Scen 1	-2,982	Scen 2	-1,845	Scen 3	-2,507	Scen 4	-1,243
Commentary on Results	Increase in AGR drying costs worsens Scenarios 1 and 2 compared to 3 and 4. Scenario 1 worst scenario.							
Summary Key Points	Capital costs and length of plant programme are the key variables – increased AGR drying costs give significant effect.							

Run	N1							
Description	Base case THORP and MOX CAPEX, increased AGR drying/storage costs, medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: Increase in AGR drying and storage CAPEX to £1B from £350M							
Run Results								
NPV £M	Scen 1	-2,982	Scen 2	-2,274	Scen 3	-3,100	Scen 4	-2,461
Commentary on Results	Increase in AGR drying costs worsens Scenarios 1 and 2 compared to 3 and 4. Scenario 2 still significantly better than Scenario 1.							
Summary Key Points	Increased AGR drying costs affect Scenarios 1, 2, with Scenario 2 worsened by £462M compared to the base case drying in run E1.							

Run	O1							
Description	High THORP CAPEX, medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	4,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: High THORP CAPEX of £4B, medium prices							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-2,240	Scen 3	-5,068	Scen 4	-4,436
Commentary on Results	Scenarios 3 and 4 are much more costly because of high THORP costs, defrayed only by medium reprocessing prices.							
Summary Key Points	Capital costs and length of plant programme are the key variables, with increased THORP CAPEX making Scenarios 3 and 4 much more costly.							

Run	P1							
Description	High THORP CAPEX, High MOX CAPEX, maximum credible prices							
Run Parameters	£M MOX Capital	3,000	£M THORP Refurbishment	4,000				
	£M/teHM MOX price	2.5	£M/teHM REPU fuel price	1.1				
	£M/teHM Reprocessing price	1.3	Discount rate (%)	Treasury				
	Additional assumptions: High THORP CAPEX of £4B, High MOX CAPEX of £3B							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,774	Scen 3	-4,251	Scen 4	-2,452
Commentary on Results	High THORP and MOX capital spend is largely compensated by highest prices.							
Summary Key Points	Increased capital costs and price approximately balance, but high THORP cost disadvantages Scenario 4 in comparison to Scenario 2.							

Run	P2							
Description	High THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	3,000	£M THORP Refurbishment	4,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: High THORP CAPEX of £4B, High MOX CAPEX of £3B							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-2,202	Scen 3	-4,799	Scen 4	-3,535
Commentary on Results	Scenarios 3 and 4 are much more costly because of high THORP costs, Scenario 2 still better than Scenario 1 even at high MOX CAPEX.							
Summary Key Points	THORP CAPEX making Scenarios 3 and 4 much more costly, even £3B MOX CAPEX leaves Scenario 2 less costly than Scenario 1.							

Run	Q1							
Description	High MOX CAPEX, low THORP CAPEX (as L1), medium prices							
Run Parameters	£M MOX Capital	3,000	£M THORP Refurbishment	1,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: High MOX CAPEX of £3B, Low THORP CAPEX							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-2,631	Scen 3	-3,109	Scen 4	-2,470
Commentary on Results	High MOX CAPEX and low THORP CAPEX with medium prices leave Scenarios 2 and 4 with similar costs. Note that no increased 'MOX waste' costs have been applied to Scenario 1.							
Summary Key Points	Approximate 'triple point' where Scenarios 1, 2, and 4 give similar results.							

Run	R1-400							
Description	Medium THORP CAPEX and medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput reduced to 400teHM/a compared to run E1 at 500teHM/a							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,812	Scen 3	-3,202	Scen 4	-3,856
Commentary on Results	Scenario 3 less costly than Scenario 4 – extra operating costs and reduced reprocessing capacity dominate income.							
Summary Key Points	Reduced reprocessing throughput reduces viability of Scenario 4							

Run	R1-500 = E1							
Description	Medium THORP CAPEX and medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput 500teHM/a as E1							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,812	Scen 3	-3,100	Scen 4	-2,454
Commentary on Results	As E1, Scenario 2 has lower costs than Scenario 1 due to income from MOX fuel sales, but has higher initial spend because of early MOX plant investment. Scenario 3 is not competitive because cost of refurbishing and operating THORP is higher than the assumed discounted cost of AGR becoming a waste. Scenario 4 begins to be competitive as reprocessing income compensates for THORP costs.							
Summary Key Points	Scenario 4 not yet favoured by this price/throughput combination							

Run	R1-600							
Description	Medium THORP CAPEX and medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput increased to 600teHM/a							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,812	Scen 3	-3,025	Scen 4	-1,851
Commentary on Results	Increased throughput/income brings Scenarios 2 and 4 to parity.							
Summary Key Points	Scenario 4 breaks even with Scenario 2 at this price/throughput combination							

Run	R1-700							
Description	Medium THORP CAPEX and medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput increased to 700teHM/a							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,812	Scen 3	-2,968	Scen 4	-1,258
Commentary on Results	Increased throughput/income favours Scenario 4.							
Summary Key Points	Scenario 4 dominates at this price/throughput combination							

Run	R1-800							
Description	Medium THORP CAPEX and medium prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	1.5	£M/teHM REPU fuel price	0.8				
	£M/teHM Reprocessing price	0.65	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput increased to 800teHM/a							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,812	Scen 3	-2,968	Scen 4	-1,258
Commentary on Results	Increased throughput/income favours Scenario 4.							
Summary Key Points	Scenario 4 dominates by over £1B at this price/throughput combination							

Run	S1-400							
Description	Medium THORP CAPEX and high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput reduced to 400teHM/a compared to run F1 at 500teHM/a							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,812	Scen 3	-2,610	Scen 4	-3,155
Commentary on Results	Scenario 3 less costly than Scenario 4 – extra operating costs and reduced reprocessing capacity dominate income.							
Summary Key Points	Reduced reprocessing throughput reduces viability of Scenario 4							

Run	S1-500 = F1							
Description	Medium THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput 500teHM/a as F1							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,383	Scen 3	-2,507	Scen 4	-1,237
Commentary on Results	Scenario 2 has very much lower costs than Scenario 1 due to high income from MOX fuel sales, but has higher initial spend because of early MOX plant investment. Scenario 3 is competitive with Scenario 1, but high prices lead to Scenario 4 being the favoured option.							
Summary Key Points	Parity between Scenarios 2 and 4 reached at THORP throughput of 500teHM/a at high prices, compared to ~600teHM/a at medium prices							

Run	S1-600							
Description	Medium THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput increased to 600teHM/a							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,383	Scen 3	-2,507	Scen 4	-1,243
Commentary on Results	Scenario 2 has very much lower costs than Scenario 1 due to high income from MOX fuel sales, but has higher initial spend because of early MOX plant investment. Scenario 3 is competitive with Scenario 1, but high prices and throughput lead to Scenario 4 being much the favoured option.							
Summary Key Points	Increased THORP throughput and reprocessing income make Scenario 4 clearly the most economic							

Run	S1-700							
Description	Medium THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput increased to 700teHM/a							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,383	Scen 3	-2,376	Scen 4	+566
Commentary on Results	High prices and throughput lead to Scenario 4 being much the favoured option, with a positive NPV.							
Summary Key Points	Increased THORP throughput and reprocessing income make Scenario 4 very clearly the most economic							

Run	S1-800							
Description	Medium THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: THORP throughput increased to 800teHM/a							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,383	Scen 3	-2,332	Scen 4	+1,628
Commentary on Results	High prices and throughput lead to Scenario 4 being much the favoured option, with a positive NPV.							
Summary Key Points	Increased THORP throughput and reprocessing income make Scenario 4 very clearly the most economic							

Run	T1-2020 = F1							
Description	Medium THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: Base case with MOX income from 2020							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,383	Scen 3	-2,507	Scen 4	-1,243
Commentary on Results	Scenario 2 has very much lower costs than Scenario 1 due to high income from MOX fuel sales, but has higher initial spend because of early MOX plant investment. Scenario 3 is competitive with Scenario 1, but high prices lead to Scenario 4 being the favoured option.							
Summary Key Points	Scenarios 2 and 4 similar, and over £1B better than Scenario 1.							

Run	T1-2025							
Description	Medium THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: Base case with MOX income delayed 5 years to 2025							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,653	Scen 3	-2,821	Scen 4	-1,557
Commentary on Results	Later payment for MOX leads to ~£300M worsening in NPV for Scenarios 2 and 4							
Summary Key Points	Later payment for MOX leads to discounted NPV reductions equivalent to price reduction of 17.1%							

Run	T1-2030							
Description	Medium THORP CAPEX, high prices							
Run Parameters	£M MOX Capital	2,000	£M THORP Refurbishment	2,000				
	£M/teHM MOX price	2.0	£M/teHM REPU fuel price	1.0				
	£M/teHM Reprocessing price	1.0	Discount rate (%)	Treasury				
	Additional assumptions: Base case with MOX income delayed 10 years to 2030							
Run Results								
NPV £M	Scen 1	-2,515	Scen 2	-1,876	Scen 3	-3,079	Scen 4	-1,815
Commentary on Results	10 year delay in payment for MOX leads to £493M worsening in NPV for Scenario 2 and £572M for Scenario 4							
Summary Key Points	10-year delay in payment for MOX leads to discounted NPV reductions equivalent to price reduction of 28.5%							

## Appendix 4 Worth of Carbon saved by MOX fuel from UK stockpile

### Parameters and assumptions

The Table below gives estimates of the electrical generation from MOX fuel made from the UK plutonium inventory and burned in typical new build PWR reactors. This will be used to estimate the amount of carbon dioxide saved in Scenario 2 by the use of MOX as a substitute for uranium fuel.

Parameter	Assumption/ Calculation	Result
1 Pu Inventory	100teHM	
2 Pu content of Fuel	7%	
3 MOX fuel yield	100/0.07 [A2/A7]	1,429teHM
4 MOX fuel burnup	50GWd(th)/teHM	
5 Total thermal generation	50*1,429GWd(th) [R3*A4]	71,450GWd(th)
6 Reactor thermal efficiency	35%	
7 Total Electrical generation from MOX	71,450*0.35GWd(e) [R5*A6]	25,008GWd(e)

Table A4.1. Parameters and assumptions for calculating carbon savings

### Carbon savings

If MOX use from existing plutonium is compared against using fuel from uranium, then the carbon generated from all the processes involved in generating the plutonium is already 'sunk'. The carbon generation from MOX fuel will then only derive from its manufacture in the MOX plant and its transport to the power station. The carbon detriment of the reactor itself, and its decommissioning, will also be 'sunk' as it would otherwise run on uranium fuel.

MOX from existing Pu will avoid all the CO<sub>2</sub> from mining, conversion and enrichment – and it is very likely that the carbon detriment of MOX manufacture will be similar to, but less than, the fabrication of uranium fuel

The 2008 White Paper<sup>1</sup> concluded

"2.18 We continue to believe that the range of figures presented in the consultation document – 7-22 gCO<sub>2</sub>/kWh emissions – represents a prudent and conservative judgement which is fully in line with authoritative research published by the OECD and the IAEA."

Therefore a realistic estimate for the range of carbon savings from MOX will be to subtract the carbon detriment of fuel manufacture from the range of savings calculated by using the total electrical generation from MOX and the 7-22 gCO<sub>2</sub>/kWh range of emissions from the whole fuel cycle.

Estimates of the carbon detriment of fuel manufacture range between around 0.1 gCO<sub>2</sub>/kWh<sup>2</sup> via 0.27g/kWh<sup>3</sup> to 0.58 gCO<sub>2</sub>/kWh<sup>4</sup>. Compared to the 7-22 gCO<sub>2</sub>/kWh range of the total range considered, these differences, even though spanning a factor of 5, are not significant to the savings postulated. The range of savings is given in Table A4.2, and is seen to lie between 3.8x10<sup>6</sup> and 1.4x10<sup>7</sup>teCO<sub>2</sub>.

### Carbon pricing and valuation of savings

Since the policy of decarbonising the UK's electricity supply relies at least in part on a monetisation of carbon emissions, it is instructive to estimate the deemed worth of the carbon emissions which could be avoided by using the UK stocks of plutonium as MOX fuel. The current Treasury Consultation Document on Carbon Pricing<sup>5</sup> quotes scenarios as below:

4.44 Three illustrative carbon price scenarios for the UK power sector are used: £20, £30 and £40/tCO<sub>2</sub> in 2020 rising to £70/tCO<sub>2</sub> in 2030 (all in real 2009 prices).

With MOX use in Scenarios 2-4 commencing in 2020 and carrying on for over 30 years, the £70/teCO<sub>2</sub> will give the most relevant estimate of the carbon cost avoided. The results of this calculation are seen in Table A4.2.

Parameter	Assumption/ Calculation	Result
1 Total Electrical generation from MOX	71,450*0.35GWd(e) [R5*A6]	25,008GWd(e)
2 Carbon Price	£70/teCO <sub>2</sub>	
3 Total electrical generation kWh	25,008(GWde)*106(GW to MW)*24(days to hours)	6x10 <sup>11</sup> kWh
4 Maximum saving per kWh	22 gCO <sub>2</sub> /kWh - 0.1 gCO <sub>2</sub> /kWh	22.9gCO <sub>2</sub> /kWh
5 Minimum saving per kWh	7 gCO <sub>2</sub> /kWh - 0.58 gCO <sub>2</sub> /kWh	6.4gCO <sub>2</sub> /kWh
6 Total maximum saving (teCO <sub>2</sub> )	6x10 <sup>11</sup> *22.9g*10 <sup>-6</sup>	1.4x10 <sup>7</sup>

7	Total minimum saving (teCO <sub>2</sub> )	$6 \times 10^{11} \times 6.4 \times 10^{-6}$	$3.8 \times 10^6$
8	Total maximum at £70/teCO <sub>2</sub>		$3.46 \times 10^8$
9	Total minimum at £70/teCO <sub>2</sub>		$1.24 \times 10^9$

Table A4.2. Valuation of carbon savings

Using the £70/teCO<sub>2</sub> valuation, the total carbon savings will be valued at between £346M and £1,240M.

<sup>1</sup> Cm7296, A White Paper on Nuclear Power, DECC, January 2008

<sup>2</sup> Vattenfall AB Generation Nordic Certified Environmental Product Declaration of Electricity from Ringhals Power Plant, 2007

<sup>3</sup> Environmental Product Declaration of Electricity from Tomes Nuclear Power, Station Technical Report, AEA Technology for British Energy, 2005

<sup>4</sup> S. van Leeuwen, Ceedata Consultancy, 2007

<sup>5</sup> Carbon price floor: support and certainty for low-carbon investment, HM Treasury, December 2010

## Appendix 5 MOX Plant Technology Optimisation Possibility

A common element in all Scenarios except Scenario 1 is the construction of a new MOX plant. In the economic analysis, a major variation in capital spending has been examined, changing the total sum from £2B to £3B. Part of the rationale for this is the uncertainty in capital cost of novel, one-off, highly regulated plants, but much of the potential variation is due to the requirement for the plant to utilise the existing UK plutonium stocks, which covers plutonium dioxide powder produced in a variety of plants across several decades. Of the two operating MOX plants in Europe, the French MELOX plant has a fine record of throughput upgrades and reliable production, whereas the UK Sellafield MOX Plant (SMP) has been beset with problems and has never produced at more than a small fraction of its designed capacity. However, in future examinations of potential MOX fabrication projects, there is still value in a broad assessment of the feed-technology-product 'package' which might be optimal for the UK situation. The following paragraphs outline the two MOX routes and suggest some possible evaluations.

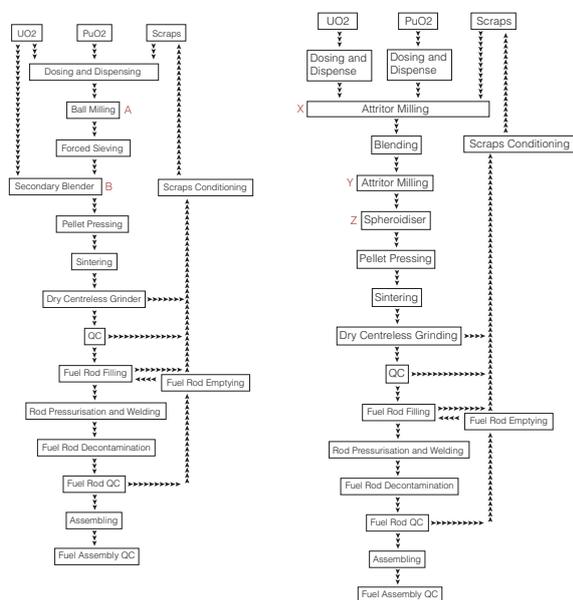


Figure 1. MIMAS Route (MELOX, left) and Short Binderless Route (SMP, right)

In the MIMAS route, a 'master blend' of PuO<sub>2</sub> and UO<sub>2</sub> (25 – 30% PuO<sub>2</sub>) are milled together (stage A) and this is then blended with more free-flowing UO<sub>2</sub> (stage B)

to the correct plutonium level. This secondary blend is then pressed into pellets. The second stage of mixing is carried out gently in a mechanical mixer to protect the flow properties of the added UO<sub>2</sub> diluent; the final mixture is fed directly to the press without a granulation stage – one of the advantages of the MIMAS route. However, the plutonium is distributed exclusively in the agglomerates of the primary mixture and the process relies on the gentle mixing to reduce these to small enough zones rich in plutonium which can be made homogeneous by diffusion mechanisms during sintering at high temperatures. MIMAS fuel has demonstrated good fuel performance but it is suggested that the process depends very much on the homogeneity of the master blend, which will probably be dependent on the physical properties of the PuO<sub>2</sub> powder.

By contrast, the SMP route uses high energy attritor milling at two stages, an initial milling (stage 'X') followed by further milling (stage 'Y'). This means that the UO<sub>2</sub>/PuO<sub>2</sub> in the final product goes through two milling stages, which is possible because the route relies on spheroidisation (stage 'Z') as the means of preparing the mix for pelleting, where the MIMAS route essentially relies on the existing flow properties on the UO<sub>2</sub> used.

The ability to modify the MOX raw materials by two stages of high-energy milling might well allow a greater flexibility in the physical properties of the initial PuO<sub>2</sub> feedstock. Feedstock variability has not been examined to any great extent to date in SMP, as the well-documented throughput challenges have understandably kept unnecessary studies of powder variables to a minimum.

Another factor in the Short Binderless Route as currently employed, is the use of Integrated Dry Route (IDR) UO<sub>2</sub> powder. This has a low specific surface area and small particle size, and gives a low initial sintering rate (giving an opportunity for the removal of volatile impurities) but high final densities, which are controlled to meet the pellet specification by the addition of a pore former. This might also allow greater control of chemical quality fluctuations in the input PuO<sub>2</sub> by varying sintering conditions or perhaps adding a pre-sintering stage.

Of course, pursuing these possibilities will have little merit if there is confidence that the MIMAS route can deal, unmodified, with the large bulk of the UK PuO<sub>2</sub> inventory. If, however, there is acceptance that the PuO<sub>2</sub> quality is a significant issue, it may be well worth examining whether some quality correction within the MOX fabrication route might be more optimal than separate PuO<sub>2</sub> quality improvement processes.

## Bibliography

**(all web-links live as of March 2011)**

Institute of Physics Report: The Role of Physics in Renewable Energy RD&D  
[http://www.iop.org/activity/policy/Publications/file\\_4145.pdf](http://www.iop.org/activity/policy/Publications/file_4145.pdf).

UK Health and Safety Executive.  
 Available at: <http://www.hse.gov.uk/nuclear/safeguards/muf.htm>.

Nirex. **1977**. "An Assessment of the Post-closure Performance of a Deep Waste Repository at Sellafield Volume 3: The Groundwater Pathway", Science Report S(97)12-3, **1997** This document indicates that the total inventory of Pu239 considered in the assessment is 11,700 TBq, which is equivalent to 5.1 tons.

Alesso, H. P. **1981**. Proven commercial reactor types: An introduction to their principal advantages and disadvantages. Energy, V 6, I 6, June 1981, Pages 543-554.  
[http://www.sciencedirect.com/science?\\_ob=MIimg&\\_imagekey=B6V2S-498M021-1S-1&\\_cdi=5710&\\_user=126524&\\_pii=036054428190058X&\\_origin=search&\\_coverDate=06%2F30%2F1981&\\_sk=999939993&view=c&wchp=dGLbVtz-zSkzV&md5=35bc4ecc6dd01705f019770c274dee0&ie=/sdarticle.pdf](http://www.sciencedirect.com/science?_ob=MIimg&_imagekey=B6V2S-498M021-1S-1&_cdi=5710&_user=126524&_pii=036054428190058X&_origin=search&_coverDate=06%2F30%2F1981&_sk=999939993&view=c&wchp=dGLbVtz-zSkzV&md5=35bc4ecc6dd01705f019770c274dee0&ie=/sdarticle.pdf).

Sizewell B enquiry. **1983-1985**.  
 Available at: <http://www.nationalarchives.gov.uk/nra/searches/subjectView.asp?ID=O56818&tabType=HISTORY>

US National Academy of Sciences. **1994**. "Management and Disposition of Excess Weapons Plutonium, National Academy Press, 1994.  
 Available at: [http://www.nap.edu/catalog.php?record\\_id=2345](http://www.nap.edu/catalog.php?record_id=2345)

Nuclear Utilities Chairmen's Group Submission to the **1994** Nuclear Review.

Organization for Economic Co-operation and Development. **1994**. The Economics of the Nuclear Fuel Cycle, Paris.  
 Available at: <http://www.oecd-nea.org/hdd/reports/efc/EFC-complete.pdf>

ExternE. **1998**. 'Power Generation and the Environment, a UK Perspective, AEA3776.  
 Available at: [http://www.regie-energie.qc.ca/audiences/3526-04/MemoiresParticip3526/Memoire\\_CCVK\\_81\\_Externe\\_UnitedKingdom.pdf](http://www.regie-energie.qc.ca/audiences/3526-04/MemoiresParticip3526/Memoire_CCVK_81_Externe_UnitedKingdom.pdf)

Royal Society. **1998**. Management of Separated Plutonium.  
 Available at: <http://royalsociety.org/WorkArea/DownloadAsset.aspx?id=5918>.

US DOE. **1998**. "Surplus Plutonium Disposition Draft Environmental Impact Statement", DOE/EIS-0283-D.  
 Available at: [http://elibrary.unm.edu/doe/DOEreport\\_1.php](http://elibrary.unm.edu/doe/DOEreport_1.php)

IAEA (International Atomic Energy Agency). **1998**. International Atomic Energy Agency GENERAL Distr. INFORMATION CIRCULAR: Communication Received from Certain Member States Concerning their Policies Regarding the Management of Plutonium.  
<http://www.iaea.org/Publications/Documents/Infcircs/1998/infcirc549a8.pdf>.

Küppers, C. **1999**. "The disposition of civil plutonium in the UK". ÖKO Institute, various references quoted by Barker and Sadnicki, 2001.

Simon Lobdell. **2002**. The Yucca Mountain Repository and the Future of Reprocessing, Washington Internships for Students of Engineering.  
 Available at: <http://www.wise-intern.org/journal/2002/simonlobdell.pdf>.

Energy White Paper: our energy future - creating a low carbon economy (CM5761)  
<http://products.ihc.com/cis/Doc.aspx?AuthCode=&DocNum=262824> IEAE. 2002.

BNFL National Stakeholder Dialogue. **2003**. Plutonium Working Group final report.  
 Available at: [http://www.the-environment-council.org.uk/index.php?option=com\\_docman&task=doc\\_download&gid=10&Itemid=64](http://www.the-environment-council.org.uk/index.php?option=com_docman&task=doc_download&gid=10&Itemid=64).

BNFL National Stakeholder Dialogue. **2004**. Security Working Group final report.  
 Available at: [http://www.the-environment-council.org.uk/index.php?option=com\\_docman&task=doc\\_download&gid=15&Itemid=64](http://www.the-environment-council.org.uk/index.php?option=com_docman&task=doc_download&gid=15&Itemid=64).

NNC Limited. **2004**. "The Immobilisation of Plutonium and Uranium as Wastes, Committee on Radioactive Waste Management", CoRWM Document No: 776, November 2004.

The Energy Act **2004** <http://www.legislation.gov.uk/ukpga/2004/20/contents>

Bunn, M., S. Fetter, J. Holdren and B. van der Zwaan. **2005**. "The economics of reprocessing versus direct disposal of spent nuclear fuel," *Nuclear Technology* 150, p. 209.  
Available at: <http://belfercenter.ksg.harvard.edu/files/repro-report.pdf>.

Jones, D. W. **2005**. Economic Aspects of Nuclear Fuel Reprocessing, Statement of Donald W. Jones, Vice President, RCF Economic and Financial Consulting, U.S. House of Representatives, House Science Committee, Subcommittee on Energy, July 12, 2005.  
Available at: <http://www.house.gov/science/hearings/energy05/july%2012/index.htm>.

IAEA/OECD. **2005**. Uranium: Resources, Production and Demand, June 2006

NIREX. **2005**. Cost estimate for a reference repository (NIREX technical note Sept 05).

WorldWatch Institute. **2005**. State of the World 2005: Redefining Global Security. New York: Norton. p. 107. ISBN 0-393-32666-7. Zangger Committee.  
Available at: <http://www.zanggercommittee.org/Seiten/default.aspx>

Boston Consulting Group, The. **2006**. Economic Assessment of Used Nuclear Fuel Management in The United States, July 2006, Prepared by The Boston Consulting Group for Areva.  
Available at <http://www.bcg.com/publications/files/>.

House of Commons Trade and Industry Committee, New nuclear? Examining the issues, Fourth Report of Session **2005–06**. Volume I. July 2006

Andra. **2006**. "Synthesis: Evaluation of the feasibility of a geological repository in an argillaceous formation. Meuse/Haute-Marne site", Dossier 2005.

Sustainable Development Commission. **2006**. The Role of Nuclear Power in a Low Carbon Economy, Paper 2: Reducing CO2 emissions – Nuclear and the Alternatives, March 2006.

Bunn, M. **2006**. Assessing the Benefits, Costs, and Risks of Near-Term Reprocessing and Alternatives, 2006.  
Available at: [http://belfercenter.ksg.harvard.edu/files/bunn\\_gnep\\_testimony.pdf](http://belfercenter.ksg.harvard.edu/files/bunn_gnep_testimony.pdf).

Australian House of Representatives. **2006**. Standing Committee on Industry and Resources, Australia's Uranium — Greenhouse Friendly Fuel for an Energy Hungry World, November 2006. Available at: <http://www.aph.gov.au/house/committee/isr/uranium/report/fullreport.pdf>.

CoRWM. **2006**. Sub-Criterion 9a: Radiological Pollution – short term.  
Available at: [http://www.corwm.org.uk/Pages/Plenary%20Meetings/Pre%20November%202007/2006/28-30%20March%202006/1670%20-%20Scoring%20Scales%20\(4\).doc](http://www.corwm.org.uk/Pages/Plenary%20Meetings/Pre%20November%202007/2006/28-30%20March%202006/1670%20-%20Scoring%20Scales%20(4).doc)

DTI (Department of Trade and Industry). **2006**. The Energy Challenge: Energy Review Report 2006, Department of Trade and Industry.  
Available at: <http://www.official-documents.gov.uk/document/cm68/6887/6887.pdf>

Euratom Supply Agency. **2006**. Annual Report.  
Available at: <http://ec.europa.eu/euratom/ar/ar2006.pdf>

European Commission: Energy.  
Available at: [http://ec.europa.eu/energy/nuclear/euratom/euratom\\_en.htm](http://ec.europa.eu/energy/nuclear/euratom/euratom_en.htm).

NEA, IAEA. **2006**. Uranium 2005 – Resources, Production and Demand. OECD Publishing. ISBN 9789264024250.  
Available at: <http://www.oecdbookshop.org/oecd/display.asp?sf1=identifiers&st1=662006031P1>

World Nuclear Transport Institute (WNTI). **2006**. Nuclear Fuel Cycle Transport.  
[http://www.wnti.co.uk/UserFiles/File/publications/factsheets/wnti\\_fs-QuickFacts.pdf](http://www.wnti.co.uk/UserFiles/File/publications/factsheets/wnti_fs-QuickFacts.pdf)

BERR. **2007**. Digest of UK Energy Statistics 2007, Tables 1.1 and 5.6.  
<http://www.berr.gov.uk/energy/statistics/publications/dukes/page39771.html>.

CBO TESTIMONY, Statement of Peter R. Orszag, Director. **2007**. Costs of Reprocessing Versus Directly Disposing of Spent Nuclear Fuel before the Committee on Energy and Natural Resources United States Senate November 14, 2007  
<http://www.cbo.gov/ftpdocs/88xx/doc8808/11-14-NuclearFuel.pdf>.

DTI. **2007**. The Role Of Nuclear Power In A Low Carbon UK Economy.  
Available at: <http://webarchive.nationalarchives.gov.uk/+http://www.berr.gov.uk/files/file39197.pdf>

- Massachusetts Institute of Technology. **2007**. The Future of Nuclear Power: an interdisciplinary MIT study, 2003 R.E.H. Sims, et al, 2007: Energy supply. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, et al], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.  
Available at: <http://web.mit.edu/nuclearpower/>
- NDA. **2007**. "Uranium and Plutonium: Macro-Economic Study, Final Report", Strategy options for the UK's separated plutonium, Royal Society. June 2007. Available at: [www.nda.gov.uk/documents/upload/Uranium-and-Plutonium-Macro-Economic-Study-June-2007.pdf](http://www.nda.gov.uk/documents/upload/Uranium-and-Plutonium-Macro-Economic-Study-June-2007.pdf).
- NDA. **2007**. The 2007 UK Radioactive Waste Inventory. Available at <http://www.nda.gov.uk/ukinventory/>.
- World Energy Council, Energy and Climate Change. **2007**. International Energy Agency, World Energy Outlook 2006.  
Available at: <http://www.iea.org/textbase/nppdf/free/2006/weo2006.pdf>
- IPCC Fourth Assessment Climate Change **2007** Report [http://www.ipcc.ch/publications\\_and\\_data/ar4/syr/en/spms1.html](http://www.ipcc.ch/publications_and_data/ar4/syr/en/spms1.html)
- Baldwin, T., N. Chapman, F. Neall. **2008**. Geological Disposal Options for High Level Waste and Spent Fuel. January 2008.  
Available at: <http://www.nda.gov.uk/documents/upload/Geological-Disposal-Options-for-High-Level-Waste-and-Spent-Fuel-January-2008.pdf>
- 2008**. Meeting the Energy Challenge – A White Paper on Nuclear Power, Cm 7296, (January 2008).  
<http://webarchive.nationalarchives.gov.uk/tna/+http://www.dti.gov.uk/files/file31890.pdf/>
- BERR (Department for Business, Enterprise & Regulatory Reform). **2008**. Meeting the Energy Challenge. A White paper on Nuclear Power.  
<http://webarchive.nationalarchives.gov.uk/+http://www.berr.gov.uk/files/file43006.pdf>.
- Gilchrist, P. **2008**. Plutonium Disposition Roadmap Briefing Paper, in advance of NDA National Stakeholder Group Meeting , May 2008 Ref NSG 65. Available at: <http://www.nda.gov.uk/documents/upload/NSG65-Briefing-Paper-on-Plutonium-Disposition-Roadmap-for-National-Stakeholder-Group-May-2008.pdf>.
- Iberdrola. **2008**. Reply to Consultation on Funded Decommissioning Programme guidance for new nuclear power stations, May 2008.  
Available at: <http://webarchive.nationalarchives.gov.uk/+http://www.berr.gov.uk/files/file48076.pdf>.
- NDA. **2008**. Plutonium: Options for Comment, August.  
Available at: <http://www.nda.gov.uk/documents/upload/Plutonium-Options-for-Comment-August-2008.pdf>.
- NDA. **2008**. Stakeholder Responses to Plutonium Options for Comment August 2008, December 2008.  
Available at [http://www.nda.gov.uk/documents/upload/Stakeholder\\_Responses-to-Plutonium-Options-for-Comment-August-2008-b.pdf](http://www.nda.gov.uk/documents/upload/Stakeholder_Responses-to-Plutonium-Options-for-Comment-August-2008-b.pdf).
- NDA. **2008**. "NDA Plutonium Options: For Comment August 2008 – October 2008", page 11.  
Available at: <http://www.nda.gov.uk/documents/upload/Plutonium-Options-for-Comment-August-2008.pdf>
- NDA. **2008**. Plutonium Options Stakeholder Workshop, 15 October 2008.  
Available at: <http://www.nda.gov.uk/documents/upload/Plutonium-Options-Stakeholder-Workshops-Report-October-and-November-2008.pdf>.
- NDA. **2008**. Macro-economic study quotes 550 TW-h,  
Available at: <http://www.publications.parliament.uk/pa/cm200708/cmselect/cmberr/293/29306.htm>
- UK Energy White Paper, **2008**, paras 2.188 and 2.221,  
Available at: [http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/uk\\_supply/energy\\_mix/nuclear/white\\_paper\\_08/white\\_paper\\_08.aspx](http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/nuclear/white_paper_08/white_paper_08.aspx)
- NDA. **2009**. NDA Plutonium Topic Strategy - Credible Options Technical Analysis, January 2009.  
Available at <http://www.nda.gov.uk/documents/upload/NDA-Plutonium-Topic-Strategy-Credible-Options-Technical-Analysis-January-2009.pdf>.
- NDA. **2009**. NDA Plutonium Topic Strategy - Credible Options Technical Summary, January 2009.  
Available at <http://www.nda.gov.uk/documents/upload/NDA-Plutonium-Topic-Strategy-Credible-Options-Technical-Summary-January-2009.pdf>.
- WNA. **2009**. "Mixed Oxide (MOX) Fuel", updated March 2009, Available at: <http://www.world-nuclear.org/info/inf29.html>
- Von Hippel, F. **2009**. Why reprocessing persists in some countries and not in others: The Costs and Benefits of Reprocessing, 9 April 2009.  
Available at: <http://www.npec-web.org/Essays/vonhippel%20-%20TheCostsandBenefits.pdf>.
- DECC (Department of Energy and Climate Change). **2009**. DECC Plutonium workshop, transcript, May 2009. ©The Environment Council 2009/ DECC Plutonium Management Workshop/ 21 May 2009. Reference: URN 09D/615.  
Available at: [http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/nuclear/plutoniummanagement/1\\_20090902103846\\_e\\_@@\\_plutoniummgmtworkshopsummary.pdf](http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/nuclear/plutoniummanagement/1_20090902103846_e_@@_plutoniummgmtworkshopsummary.pdf).

DECC. **2009**. Plutonium: factors in decision making, July 2009.

Available at: [http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/nuclear/plutoniummanagement/1\\_20090902105255\\_e\\_@@\\_preconsultationdiscussionpaperplutoniummanagement.pdf](http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/nuclear/plutoniummanagement/1_20090902105255_e_@@_preconsultationdiscussionpaperplutoniummanagement.pdf)

NDA. **2009**. Press Release (UK Nuclear Decommissioning Association). 2009. Sellafield MOX Plant (SMP) Current Position, October 2009.

British Pugwash Group. **2009**. The Management of Separated Plutonium in the UK, November 2009.

Available at: [http://www.pugwash.org/uk/documents/Manage\\_Sep\\_Plutonium\\_2009\\_fin\\_Color\\_2.pdf](http://www.pugwash.org/uk/documents/Manage_Sep_Plutonium_2009_fin_Color_2.pdf).

2050 Pathways Analysis, HMG, July **2010**.

Available at: [http://www.decc.gov.uk/en/content/cms/what\\_we\\_do/lc\\_uk/2050/2050.aspx](http://www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/2050/2050.aspx)

DECC. **2010**. Digest of UK Energy Statistics 2010. 29 July 2010.

<http://www.decc.gov.uk/assets/decc/Statistics/publications/305-pn10-086.pdf>.

DECC. **2010**. Data from file "Fuel input for electricity generation, 1970 to 2009 (DUKES 5.1.1)"

Available at: <http://www.decc.gov.uk/en/content/cms/statistics/source/electricity/electricity.aspx>.

IAEA. **2010**. <http://www.iaea.org/Publications/Documents/Conventions/cppnm.html>.

WNA (World Nuclear Association). **2010**. World Nuclear Power Reactors & Uranium Requirements.

Available at: <http://www.world-nuclear.org/info/reactors.html>

WNA. **2010**. Nuclear Power in the United Kingdom. Available at: <http://www.world-nuclear.org/info/inf84.html>.

WNA. **2010**. The Economics of Nuclear Power. Available at: [http://www.world-nuclear.org/info/inf02.html?ekmense1=c580fa7b\\_702\\_729\\_410\\_1](http://www.world-nuclear.org/info/inf02.html?ekmense1=c580fa7b_702_729_410_1).

WNA. **2010**. World Nuclear Power Reactors & Uranium Requirements.

<http://www.world-nuclear.org/info/reactors.html> and World Nuclear Association. 2010. Nuclear Power in the United Kingdom.

<http://www.world-nuclear.org/info/inf84.html>.

Carbon Price Floor: Support and certainty for low carbon investment December **2010**.

Available at: [http://www.hm-treasury.gov.uk/d/consult\\_carbon\\_price\\_support\\_condoc.pdf](http://www.hm-treasury.gov.uk/d/consult_carbon_price_support_condoc.pdf)

Electricity Market Reform, Consultation Document, DECC, December **2010**.

Available at: <http://www.decc.gov.uk/en/content/cms/consultations/emr/emr.aspx>

Consultation on management of the UK's plutonium stocks (February **2011**)

Available at: <http://www.decc.gov.uk/en/content/cms/consultations/plutonium/plutonium.aspx>



