FIXED UNIT PRICE SIMULATION FOR DISPOSAL OF SPENT FUEL FROM NUCLEAR POWER STATIONS IN THE UK (FUPSIM)

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Research Report

Fixed Unit Price Simulation for Disposal of Spent Fuel from New Nuclear Power Stations in the UK (FUPSIM)

Independent Report for Greenpeace UK • 15th June 2010

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This report was written by Ian Jackson with research assistance from Shehnaz Jackson.

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Executive Summary

This Research Report provides a realistic and impartial appraisal of the government's proposed Fixed Unit Price (FUP) scheme for spent fuel disposal from new nuclear power stations. To help visualise and better communicate how the Fixed Unit Price scheme works we developed an easy-to-use interactive computer simulation called FUPSIM. The FUPSIM model is freely available online at the Wolfram Mathematica Demonstrations Project.

- **Spent fuel disposal is 44% of EPR reactor build cost**. The full price charged by the government to energy utility companies for disposal of spent fuel from a new nuclear power station will be about £1.2bn for an AP1000 or £1.5bn for an EPR.[1] This is equivalent to 32% of the turnkey construction cost of an AP1000 or 44% of an EPR and is substantially higher than the economic assumptions underpinning the 2008 *Nuclear Energy White Paper*.

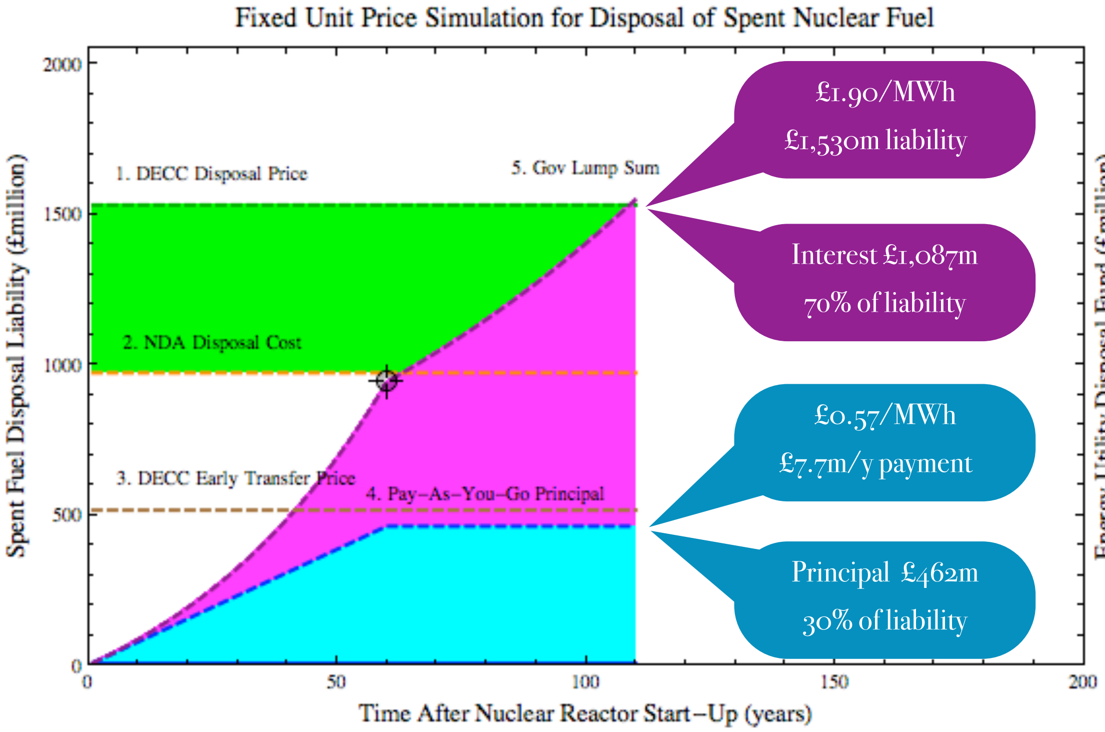
- **Levelised disposal costs are higher than they appear**. The true levelised cost (£/MWh) for spent fuel disposal is about £1.90/MWh but the effective levelised cost is reduced 70% to around £0.57/MWh, through financial engineering similar to an endowment mortgage.

- **Stock market pays for nuclear waste disposal**. The financial engineering designed to pay for disposal of spent fuel relies upon accrued interest funding around 70% of the total disposal cost. The energy utility would typically pay around 30% of the disposal cost over a 60 year period but then rely upon compound interest earned during the next 50 - 100 years to make up the shortfall. The arrangement transfers most funding risk to the stock market.

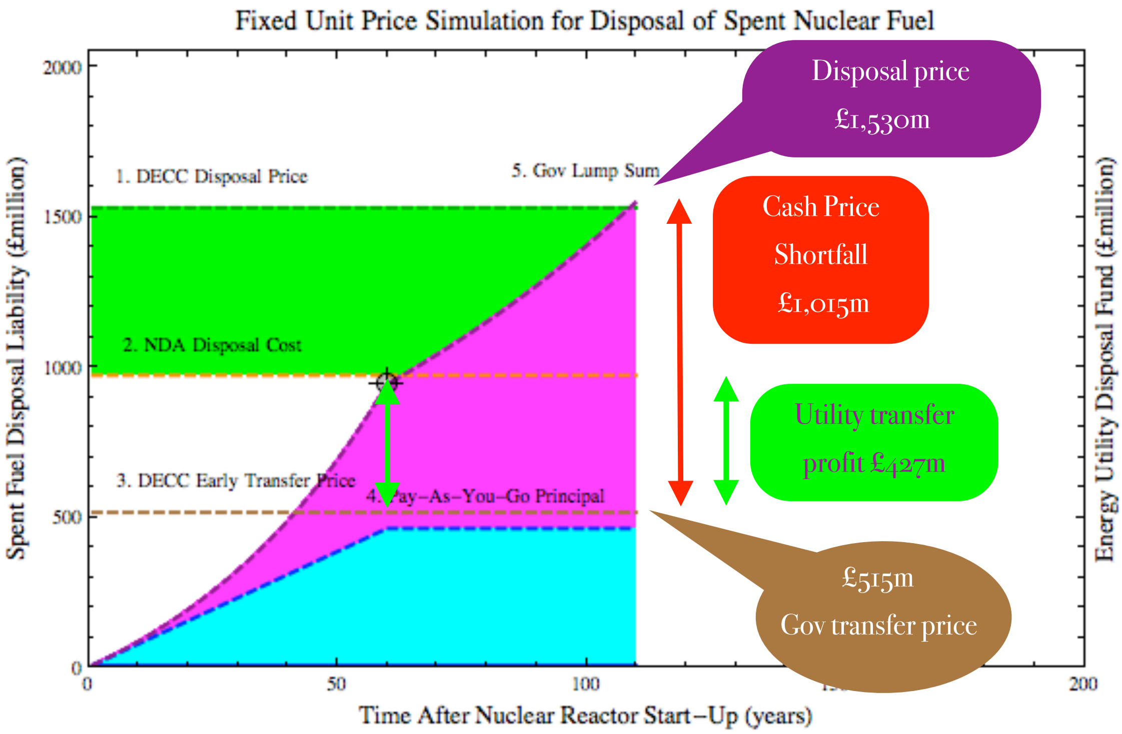
- **Early Transfer in 2080 reduces disposal cost by £1 billion per EPR**. Nuclear energy utilities have the option to transfer their spent fuel to government many decades before the waste can actually be disposed in a national deep geological repository. The 2080 transfer price is heavily discounted down to £515m for an EPR to avoid a future disposal liability of £1,530m, a price difference of £1,015m per EPR. There are good reasons for not discounting prices when faced with nuclear liability cash flows that are very long term. The discounted pricing assumes that £515m cash paid in 2080 is worth £1,530m in 2130. This may not necessarily be true in the real world, as much depends on future national economics.

[1] FUPSIM modeled @ 60 year reactor lifetime, reactor start-up 2020, reactor closure 2080, NDA repository disposal 2130, Quantity FUP £1.1m/tU, Output FUP 0.19p/kWh.

£1.5 billion Utility Spent Fuel Disposal Liability from a 1.65 GW EPR generating for 60 years (70% Paid For By Accrued Interest Earned from the Stock Market)



Discounted £0.5 billion Utility Spent Fuel Disposal Liability for Early Transfer of 1.65 GW EPR Spent Fuel to Government in 2080, Before Deep Disposal in 2130



- **Energy utility earns £0.4bn profit from EPR spent fuel transfer**. The energy utility could make a substantial profit of £427m between the value of the spent fuel investment fund at 2080 and the discounted early transfer price charged by government in 2080.

- **Spent fuel disposal price may rise to £1.9bn for an EPR**. The commercial profit margin between the disposal price charged to energy utilities by government and the actual cost of disposal borne by the NDA is effectively a project risk premium. The effective risk premium charged by government for spent fuel disposal is around 42% for an AP1000 or 58% for an EPR. This suggests that disposal prices may need to increase by between 42 to 58 percentage points in order to raise the overall risk premium level to a sensible 100% above the NDA's marginal disposal cost. This would mean that the government price for disposal of spent fuel may rise to around £1.5bn for an AP1000 or £1.9bn for an EPR.

- **Switching to actual disposal costs rather than fixed unit prices**. There is only one way to guarantee that energy utility companies pay the full costs of disposal and that is to make utilities pay the government's actual costs, not to charge them Fixed Unit Prices. Estimating realistic disposal prices perhaps 110 to 160 years into the future is fraught with difficulty. Moreover under present financial conditions stock market returns will not be sufficient to pay for the majority of an energy utility company's spent fuel liabilities. Under today's difficult economic conditions when interest rates are very low, there is little advantage in creating an investment fund to pay for nuclear waste disposal because the large increase in annual payments needed almost pay for the basic cost of spent fuel disposal anyway. We suggest that variable spent fuel disposal prices should be set based on the NDA's actual costs, indexed for NDA cost escalation and CPI price inflation.Variable Cost-Plus spent fuel disposal prices are better than Fixed Unit Prices, since they guarantee that the taxpayer will be paid in full without public subsidy. As well as being fairer to the taxpayer, there are also some commercial advantages for nuclear energy utilities because the levelised cost of disposal will actually be cheaper (although the utility bears the risk that future prices may escalate depending on out-turn costs for repository siting, construction and operation).

- **eFUP price is very close to the minimum NDA disposal cost**. The government has offered energy utilities the option of deferring their Fixed Unit Price for spent fuel disposal until repository costs are better understood. The government has suggested an expected Fixed Unit Price (eFUP) of 0.128p/kWh which is lower than the FUP of 0.194p/kWh. In practice FUPSIM modeling suggests the eFUP is actually very close to the NDA disposal cost and so might not include a sufficiently prudent risk premium to protect taxpayers.

- **Disposal costs may be underestimated**. FUPSIM and DECC use different approaches to modeling the likely costs of expanding the NDA nuclear waste repository to dispose of spent fuel from new nuclear power stations. Essentially FUPSIM predicts higher *full share* marginal disposal costs than DECC. Put another way, the extra (marginal) costs of spent fuel disposal appear to have been underestimated by government. Nevertheless it is encouraging that the government's Fixed Unit Prices are still high enough to cover the NDA's marginal costs predicted by FUPSIM, although the overall risk premium will be lower. This means that taxpayers will have less financial protection if things go wrong.

- **Problems with probabilistic modeling of nuclear costs**. We understand that DECC's pricing model is based on a Parametric Cost Model which looks at the (as yet unpublished) NDA costs for a range of different repository and nuclear power scenarios and then combines these using probabilistic (Monte Carlo) techniques. Of course in reality, the real world outcome will be just one or possibly two geological repositories with very specific costs that may or may not match the probabilistic estimate. Probabilistic techniques may not be very well suited to financial modeling of these first-of-a-kind nuclear facilities. For example, the government's 2001 financial assessment of BNFL's business case for the Sellafield MOX Plant (SMP) concluded that there was a 97% probability that the net economic benefit of SMP would be greater than zero and that the average benefit was expected to be +£216m (Mean NPV).[2] In fact by April 2009 SMP had lost £1,263m (£626m in running costs, £139m in commissioning costs and £498m in construction costs).[3]

Please Note:

The terms *EPR* (EPR™) and *AP1000* (AP1000™) used in this Research Report are Registered Trademarks of the nuclear reactor vendors companies Areva and Westinghouse respectively. *Mathematica* is a Registered Trademark of Wolfram Research Inc.

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[2] DEFRA and DOH. *Assessment of BNFL's Business Case for the Sellafield MOX Plant*. Public domain version prepared by Arthur D Little Limited. July 2001.

[3] Commons Hansard. *Sellafield*. Reply by the DECC Energy Minister Mr Mike O'Brien. Hansard Column 1368W. 2nd April 2009.

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1. INTRODUCTION

1.1 Purpose of this Research Report

The previous government's *Consultation on a Methodology to Determine a Fixed Unit Price for [Nuclear] Waste Disposal*[4] was published on 25th March 2010 under the Energy Act 2008. Jackson Consulting was commissioned by Greenpeace UK to advise on the previous government's proposals for establishing a Fixed Unit Price (FUP) for the disposal of spent fuel from new nuclear power stations and to develop an independent economic model.

Our aim was to develop a well balanced Research Report on FUP that clearly communicated the major business issues and factors that might represent significant investment risk to British taxpayers and HM Treasury. The views expressed and conclusions reached are solely those of Jackson Consulting and do not necessarily represent those of Greenpeace UK.

1.2 Research Approach Using FUPSIM

This Research Report aims to provide a realistic and impartial appraisal of the proposed Fixed Unit Price scheme for spent fuel disposal and its financial implications for taxpayers. To help visualise and better communicate how the Fixed Unit Price scheme works we developed an easy-to-use interactive computer model called FUPSIM. FUPSIM calculates the approximate NDA repository cost and DECC disposal price for spent fuel disposal for any new nuclear power station project, the funding needed by energy companies to meet these spent fuel liabilities, and any potential funding shortfall that may need to be subsidised by the taxpayer. FUPSIM also calculates the handover price for Early Transfer of spent fuel from the energy utility to the government before eventual disposal in a future deep geological repository.

The FUPSIM model and its dashboard graphic display is fully user-interactive, controlled via the computer mouse. Users click-and-drag sliders which adjust 21 key model parameters such as power station output, generating lifetime, load factor, spent fuel burn-up, storage period, discount rates, etc. FUPSIM dynamically recalculates cost and price changes and displays results instantly on a dashboard screen and pricing graph. The impacts of changes in critical parameters such as rates of return can be seen graphically, making the Fixed Unit Price scheme simple to understand. Adjusting the FUPSIM sliders allows users to stress test the pricing regime under many different financial scenarios.

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[4] Department of Energy and Climate Change. *Consultation on a Methodology to Determine a Fixed Unit Price for Waste Disposal and Updated Cost Estimates for Nuclear Decommissioning, Waste Management and Waste Disposal*. 25th March 2010.

Ideally this Research Report should be read alongside the FUPSIM simulation running on a computer so that readers may directly interact and experiment with the model themselves.

- FUPSIM is a fully user-interactive research simulation of FUP using the state-of-art *Wolfram Mathematica* graphical computational programming engine.
- The FUPSIM model runs on Wolfram's *Mathematica Player* which may be freely downloaded for any Windows, Apple Mac or Linux computer.
- Greenpeace UK has kindly made FUPSIM publicly available on-line at the *Wolfram Demonstrations Project,* a free interactive scientific visualizations resource for researchers.
- A video demonstrating the major findings of this Research Report using the FUPSIM computer simulation is also available on the Greenpeace UK Channel of *YouTube*.

1.3 Downloading and Running FUPSIM under Mathematica Player

Users must first download and install the free Wolfram Mathematica Player 7 here:

http://www.wolfram.com/products/player/

FUPSIM is available as a free download at the Wolfram Demonstrations Project here:

http://demonstrations.wolfram.com/

1.4 Report Authors and Professional Standing

This Research Report was written by Ian Jackson with research assistance from Shehnaz Jackson, co-founders of Jackson Consulting (UK) Limited an independent nuclear consulting firm established in 2002. Ian Jackson is an Associate Fellow in the Energy, Environment and Development programme of the Royal Institute of International Affairs, Chatham House, a leading global think-tank. Ian is a GLG Scholar ranked in the Top 13% of nuclear market experts world-wide by financial management consultants Gerson Lehrman Group (GLG). He is a Chartered Radiation Protection Professional (CRadP) and a member of both the Society for Radiological Protection (MSRP) and the Nuclear Institute (MNucI). Ian Jackson is the author of *Nukenomics: The Commercialisation of Britain's Nuclear Industry* published in April 2008 by Nuclear Engineering International Special Publications. Shehnaz Jackson had a 14-year business administration career at the Atomic Energy Research Establishment Harwell from 1986 -2000, before co-founding Jackson Consulting in 2002.

2. FUPSIM USER GUIDE

2.1 Basic Modeling Questions

Despite the technical complexity of FUP, only four basic questions really matter:

- What is the extra cost (£m) of new reactor spent fuel disposal in a shared NDA repository?
- What disposal price (£m) will an energy utility be charged by the government?
- Has the energy utility company saved enough money to pay for this liability?
- What shortfall might need to be subsidised by the taxpayer?

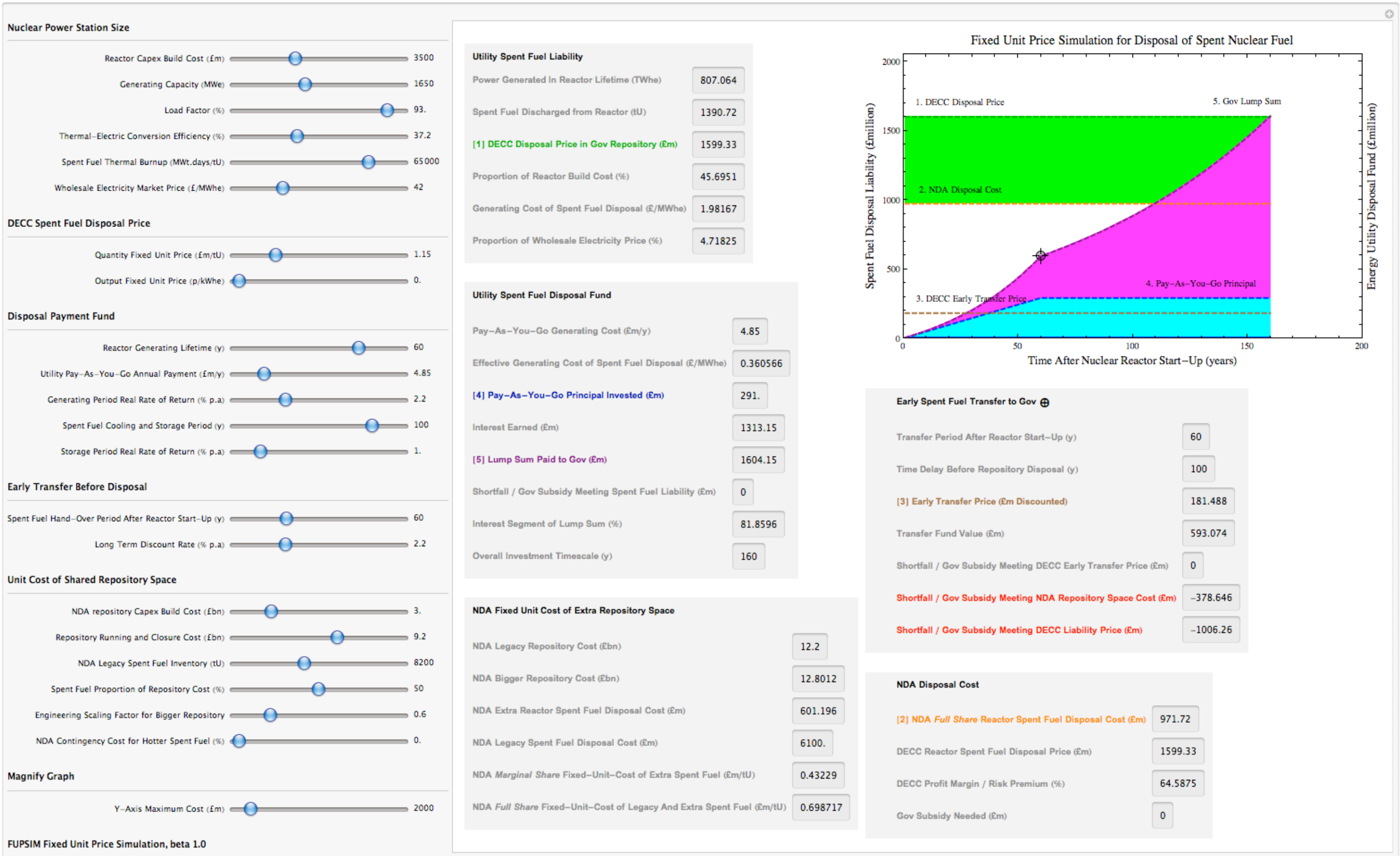
FUPSIM can answer these key questions and simulate waste disposal liabilities for any size of new nuclear power station. FUPSIM has 21 adjustable model input parameters and displays 31 separate calculation results. The model is fully dynamic. Users can adjust model settings and the results of calculations are displayed instantly on-the-fly. FUPSIM calculates the liability costs of spent fuel disposal expressing these as both a gross financial liability that the energy utility company must pay to government (£millions) and a levelised environmental disposal cost (£/MWh) spread over the nuclear reactor's generating lifetime. Calculations are expressed in 'real money' terms (disregarding inflation and cost escalation) in today's prices, and are undiscounted overnight costs except for the Discounted Early Transfer Price.

2.2 Dashboard Display

FUPSIM is operated through a simple interactive cockpit-style dashboard display on the computer screen (see screenshot overleaf). The model is controlled through 21 click-and-drag input sliders on the left of the screen. Financial calculation results are displayed in the centre and a summary graph is drawn on the right. Users can move a sniper-style crosswire to read-off detailed calculation results at any point in time on the graph. The value of the energy utility investment fund at that point and level of subsidy needed is calculated below the graph. FUPSIM automatically highlights any shortfalls or subsidies needed in **red text**.

When FUPSIM is ran for the first time, by default the model parameters are preset for a single 1,650 MWe Areva EPR nuclear power station, generating electricity for 60 years, with a load factor of 93%, spent fuel burn-up of 65,000 MWt.days/tU, with hand-over of spent fuel from the energy utility to government immediately after reactor closure, followed by geological disposal after 100 years cooling and storage (see screenshot overleaf).

Example FUPSIM Simulation Calculating Spent Fuel Liabilities for a Single EPR



2.3 Input Panels

FUPSIM has five input panels controlling 21 click-and-drag adjustable variables:

- **Nuclear Power Station Size.** This panel configures FUPSIM for any power station up to 4,000 MWe. The user inputs the reactor construction cost (£m), generating capacity (MWe), load factor (%), thermal-electric conversion efficiency (%), thermal spent fuel burn-up (MWt.days/tU) and the wholesale market price of electricity (£/MWh).

- **DECC Spent Fuel Disposal Price**. This panel allows the user to enter the DECC Fixed Unit Price, expressed as either £million per metric tonne of uranium spent fuel (£m/tU) or pence per kWh of reactor generation (p/kWh). Normally one slider should be set to zero but if both sliders are used FUPSIM adds the two prices together. This can be useful for example to investigate the effect of a p/kWh output tax on top of a £m/tU quantity charge.

- **Utility Disposal Payment Fund**. This panel configures FUPSIM to calculate the investment fund needed to pay-off the spent fuel disposal liability. The panel is important for financial stress testing of the energy utility fund under different interest rate and generating or storage scenarios. The user enters the generating lifetime (years), pay-as-you-go annual level payment into an investment fund (£m/y), the real rate of return during the generating period (% p.a.), the spent fuel cooling and storage period before disposal (years) and the real rate of return during the cooling and storage period (% p.a.).

- **Early Transfer Before Disposal**. This panel allows users to investigate the performance of the utility investment fund at different points in time and the effect of early hand-over of spent fuel from the energy utility to the government. The user enters the time period after reactor start-up when the fuel is transferred to government (years) and the government's long term discount rate (% p.a.). The discount rate is applied during the gap between the time when the fuel is handed over to government and then (perhaps many years later) eventually disposed in a deep geological repository after the cooling and storage period ends.

- **Unit Cost of Shared Repository Space**. This panel configures FUPSIM for the cost and size of the NDA's deep geological repository for legacy nuclear waste and legacy spent fuel. This information allows FUPSIM to calculate the extra cost needed to expand the repository to accommodate extra spent fuel from new nuclear reactors. The user enters the NDA repository's capital build cost (£bn), running and closure cost (£bn), legacy uranium spent fuel inventory (tU) and the spent fuel proportion of the repository lifecycle cost (%). The user must also select a fractal (power law) engineering scaling factor for expanding the repository and an extra cost increase (%) for disposing of higher burn-up spent fuel in the repository. The use of these parameters needs care and is explained in Section 2.6 below.

Two further sliders control the graph display:

- **Magnify Graph**. The magnify slider is used to adjust the graph scale so that none of the data points shoot off the graph. Because FUPSIM can calculate very large liabilities and investment fund values, some adjustment of the graph scale is occasionally needed, especially during stress testing under different scenarios. This does not affect FUPSIM calculations.
- **Sniper Crosswire**. Users can move a sniper-style crosswire to read-off detailed calculation results at any point in time on the graph. The movement of the crosswire is controlled by the spent fuel hand-over time slider in the Early Transfer panel.

2.4 Results Panels

FUPSIM has five output panels displaying 31 calculation results plus a graphic display :

- **Utility Spent Fuel Liability**. FUPSIM calculates the total electrical power generated (TWh) and the total amount of spent fuel discharged from the reactor (tU) during the operating lifetime of the new nuclear power station. FUPSIM calculates the total price that the utility must pay to DECC for disposal of the spent fuel (£m) and also expresses this as a fraction of the capital build cost of the reactor (%). FUPSIM calculates the levelised cost of spent fuel disposal (£/MWh) and the proportion of the electricity market price (%).
- **Utility Spent Fuel Disposal Fund**. FUPSIM calculates the performance of the energy utility's investment fund needed to pay-off the spent fuel disposal liability. FUPSIM calculates the growth of level annual payments (£m/y), the principal invested (£m), the levelised effective cost of spent fuel disposal (£/MWh) and the compound interest earned (£m). FUPSIM also calculates if there is any shortfall between the lump sum at the end of the investment period and the DECC liability price that the utility must pay to the government. Any underpayment, which by implication may need a government subsidy, is highlighted in **red**.
- **NDA Fixed Unit Cost of Repository Space**. FUPSIM calculates the cost for an NDA legacy repository (£bn) and the extra cost for a bigger repository to dispose of extra spent fuel (£bn). FUPSIM calculates the *marginal share* cost (£m/tU) of increasing the repository size, which is just the basic minimum unit cost of the extra spent fuel space. FUPSIM also calculates the *full share* cost (£m/tU) of increasing the NDA repository size, which combines or spreads the unit cost of disposal of both new and legacy spent fuel together.

- **NDA Disposal Cost**. FUPSIM calculates the total *full share* disposal cost (£m) of spent fuel from the the new nuclear power station based on the NDA's Fixed Unit Cost. FUPSIM compares the NDA cost with the DECC disposal price and calculates the profit margin (%). The profit margin is effectively the risk premium between the actual cost of the government's disposal service and the fixed price charged to energy utility customers.

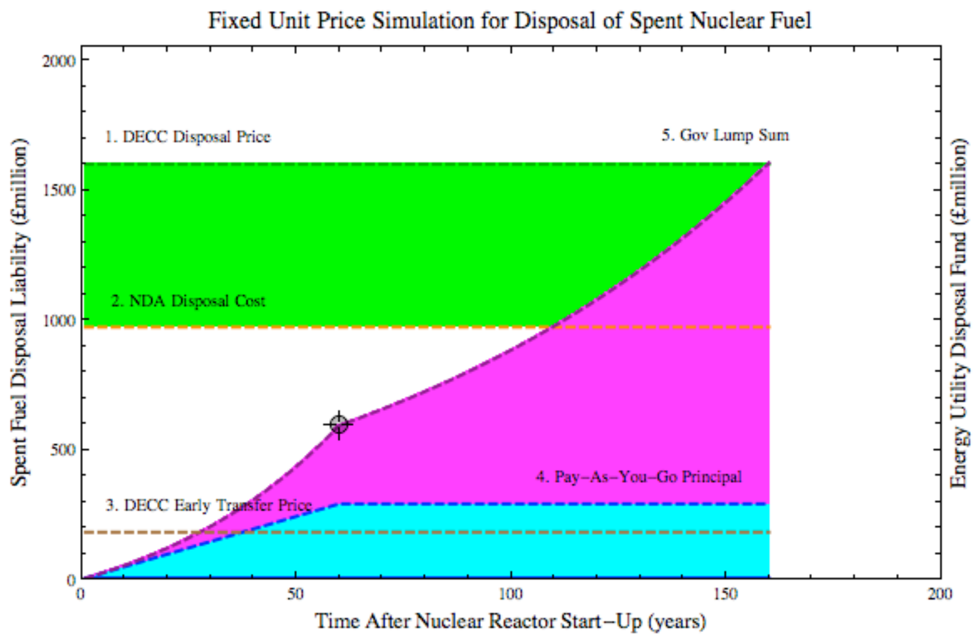
- **Early Spent Fuel Transfer to Government**. FUPSIM calculates the accumulated transfer value of the investment fund at the time when the spent fuel is handed-over to government. FUPSIM calculates any shortfall (£m) between the value of the investment fund compared with the DECC disposal price, the discounted DECC early transfer price, and the NDA disposal cost. By implication any shortfall in the fund value to meet these costs may need a government subsidy and is highlighted in **red** text.

2.5 Graph Plot

FUPSIM displays a plot of the five most important FUP curves:

1. **DECC Disposal Price**. This is the total price charged by DECC to the utility for disposal of spent fuel from the new nuclear reactor and appears as a **green horizontal line** across the graph. The area of the graph between the DECC Price and NDA Cost is shaded green if the price is higher than the cost (profit), or red if the price is lower than the cost (loss).

2. **NDA Disposal Cost**. This is the total cost incurred by the NDA for expanding the repository to dispose of spent fuel from the energy utility company's new nuclear reactor. The cost appears as an **orange horizontal line** across the graph.



3. **DECC Early Transfer Price**. This is the discounted price charged by DECC to the utility for early transfer of spent fuel to government before a disposal repository is available. The sniper crosswires show the transfer point on the graph and the value of the investment fund at that time. The transfer price appears as a **brown horizontal line** across the graph.

4. **Pay-As-You-Go Principal**. This is the accumulated value of levelised payments made into the energy utility company investment fund. The payments are Pay-As-You-Go because the energy company must make regular payments into the fund every year that the nuclear power station operates. The value of the principal increases each year the reactor operates until the reactor reaches the end of its life and is shut-down. The principal invested then remains constant for the duration of the cooling and storage period. The Pay-As-You-Go Principal appears as a steadily increasing **linear blue line**, which then levels off horizontally when the reactor reaches the end of its generating lifetime.

5. **Government Lump Sum**. This is the final lump sum that is paid by the energy utility investment fund to the government to pay for spent fuel disposal at the end of the generating and storage period. The value of the fund appears as a **purple exponential curve** and gradually increases as the fund earns compound interest. The purple curve rises quite steeply during the reactor generating period, as regular Pay-As-You-Go payments are made into the investment fund. Afterwards the purple curve rises more slowly as the fund relies on compound interest alone to grow the principal and reach the final target fund value. When the purple Lump Sum curve is below the DECC Price there will not be sufficient money in the energy utility fund to pay the government for spent fuel disposal. (The arrangement is very similar to an endowment mortgage, where the endowment fund only accumulates enough to pay-off a home loan at the very end of the investment period).

2.6 Technical Parameters and Settings

FUPSIM has five input panels controlling 21 click-and-drag adjustable variables. The technical basis of these model parameters and their default settings are explained below, along with some suggestions for changing the default values to investigate different reactor scenarios. Technical data sources referenced are listed in the Bibliography at the end of this Research Report. When FUPSIM is ran for the first time, by default the model parameters are preset for a single 1,650 MWe Areva EPR nuclear power station with a 60-year generating lifetime. The settings can be reconfigured for any kind of nuclear reactor such as the 1,150 MWe Westinghouse AP1000 or even Small Modular Reactors such as the 165 MWe Eskom PBMR.

FUPSIM Parameters and User-Adjustable Settings

Model Parameter	Initial Value	Technical Comment
Reactor Capex Build Cost	£3,500 m	The EDF Energy capital build cost of the Flamanville-3 EPR (intended for UK deployment) is €4 bn (£3.5 bn). The Duke Energy capital build cost of the Lee-3 Twin AP1000 is approx $11 bn (£3.6 bn per AP1000 unit), excluding financing, fuel, land and transmission. FUPSIM allows power station build costs up to £10 bn. This parameter allows the back-end fuel disposal liability to be expressed as a % of the reactor capital build cost. EPR and AP1000 reactor build costs in France and the USA are likely to be the closest match to build costs in the UK.
Generating Capacity	1,650 MWe	Generating capacity of a single Areva EPR reactor. FUPSIM allows station generating capacities up to 4,000 MW e.g. to accommodate twin EPR units (3,300 MW) or triple Westinghouse AP1000 units (3,450 MW). FUPSIM also allows lower power outputs from Small Modular Reactors (SMR) such as the 165 MWe PBMR.
Load Factor	93%	Design-basis load factor for an EPR. The load factor is the ratio of actual generating output (MWh) to annual design basis output (MWh). World-wide commercial PWR nuclear power stations have achieved average load factors of 75% (lifetime) and 83% (2009) based on Nuclear Engineering International magazine load factor tables. FUPSIM allows load factors from 1% up to 100%.

Model Parameter	Initial Value	Technical Comment
Thermal-Electric Conversion Efficiency	37.2%	Ratio of the reactor electrical output (MWe) to the total reactor core thermal output (MWt). The Olkiluoto-3 Areva EPR design has an electrical power output of 1,600 MWe and a thermal power output of 4,300 MWt, with an electrical conversion efficiency of 37.2%. The AP1000 has an electrical output of 1,150MWe and thermal output of 3,400 MWt giving an efficiency of 33.8%. Generation IV Advanced High Temperature Reactor (HTR) designs such as the PBMR small modular reactor have better efficiencies around 41%. FUPSIM allows conversion efficiencies ranging from 1% up to 100%.
Spent Fuel Burn-Up	65,000 MWd/tU	Average thermal burn-up of discharged spent fuel from the EPR reactor core. NDA repository disposability assessment of EPR and AP1000 spent fuel assemblies assume a peak burn-up of 65,000 MWt.days/tU. In practice the average burn-up is likely to be lower around 48,300 MWt.days/tU. The Olkiluoto-3 EPR burn-up is initially expected to be licensed at 45,000 MWt.days/tU. The Sizewell-B PWR is designed to operate at much lower burn-up of 33,000 MWt.days/tU, the typical level for a commercial PWR reactor today. FUPSIM allows burn-ups up to 80,000 MWt.days/tU.
Wholesale Electricity Market Price	£42 /MWh	The price of electricity on the wholesale electricity market as of April 2010. This parameter allows the levelised back-end fuel liability (£/MWh) to be expressed as a % of the price of electricity on the wholesale market. FUPSIM allows wholesale electricity prices up to £150/MWh.
Quantity Fixed Unit Price	£1.15 m/tU	DECC Fixed Unit Price for spent fuel disposal expressed as a quantity-based price (£million per tonne uranium). DECC Discussion Paper No. 3 suggests prices in the range from a low of £0.985 m/tU (80% probability) to a high of £1.490 m/tU (99% probability). The FUPSIM default value is £1.15m/tU from DECC Variant 1 P99%. FUPSIM allows Fixed Unit Prices up to £5m/tU. The formulae used inside FUPSIM for its own internal calculations are based on £million per tonne of uranium.

Model Parameter	Initial Value	Technical Comment
Output Fixed Unit Price	0.0 p/kWh	DECC Fixed Unit Price for spent fuel disposal expressed as an output-based price (pence per kWh generated). This is an alternative way of setting the Fixed Unit price. DECC FUP Consultation Document suggests prices in the range from a low of 0.194 p/kWh to a high of 0.238 p/kWh. The FUPSIM default value is zero but FUPSIM allows Fixed Unit Prices up to 2.0 p/kWh. If the output Fixed Unit Price is used then FUPSIM's quantity Fixed Unit Price must normally be reset to zero, otherwise FUPSIM will add both the Quantity and the Output Fixed Unit Price values together. This can sometimes be useful for example to investigate the effect of an output tax. The formulae used inside FUPSIM for its own internal calculations are based on £million per tonne of uranium, so FUPSIM internally converts p/kWh prices to an equivalent £m/tU price for performing model calculations.
Reactor Generating Lifetime	60 y	The expected commercial generating lifetime of an EPR or AP1000 nuclear reactor unit. The DECC FUP Consultation Document assumes a generating lifetime of only 40 years but energy utility business cases are generally based on a more realistic 60 year design lifetime. FUPSIM allows generating lifetimes up to 80 years, e.g for allowing up to 20 years of Plant Life Extension (PLEX).
Utility Pay-As-You-Go Annual Payment	£4.85 m/y	Levelised annual payments made by the energy utility company into a spent fuel disposal investment fund. Payments are funded from electricity sales every year that the nuclear power station generates. The accumulated value increases each year the reactor operates until the reactor reaches the end of its life and is shut-down. FUPSIM allows Pay-As-You-Go payments up to £30m/y.

Model Parameter	Initial Value	Technical Comment
Generating Period Real Rate of Return	2.2 % p.a	The net rate at which the spent fuel disposal investment fund earns interest above the level of inflation, during the reactor generating lifetime. The DECC FUP Consultation Document assumes real growth rates during the reactor generating period of 3.5%, 2.2% and 1%. The real rate of return is currently 0.5% in April 2010. UK inflation in April 2010 was 3.4% and the Bank of England interest rate has been 0.5% from March 2009 to April 2010. The FUPSIM default value is 2.2% used in DECC Discussion Paper 3 but FUPSIM allows real rates of return from zero up to 7.5% per annum. A zero % rate of return would mean that the spent fuel investment fund grows only in line with inflation, i.e. without increasing in real terms above the UK national inflation rate. Put another way, the investment fund would need to earn at least 3.4% annually just to keep up with today's inflation level, otherwise it would lose its value in real terms.
Spent Fuel Cooling and Storage Period	100 y	The Draft DECC Nuclear National Policy Statement assumes a spent fuel cooling and storage period of up to 100 years on the nuclear reactor site. Extended storage periods are necessary because disposal of new build spent fuel would not begin until priority disposal of all NDA historic legacy spent fuel has been completed first by 2130. This assumes that the NDA geological repository opens 90 years earlier in 2040. Extended storage periods may also be necessary to allow high burn-up spent fuels to cool sufficiently before disposal. FUPSIM allows a spent fuel cooling and storage up to 120 years and assumes the spent fuel is then disposed immediately.

Model Parameter	Initial Value	Technical Comment
Storage Period Real Rate of Return	1.0 % p.a.	The net rate at which the spent fuel disposal investment fund earns interest above the level of inflation, during the extended storage period. The DECC FUP Consultation Document assumes real growth rates during the spent fuel storage period of 1% and 0%. The real rate of return (Bank of England base rate) is currently 0.5% in April 2010. The FUPSIM default value is 1.0% used in the DECC FUP Consultation, but FUPSIM allows real rates of return from zero up to 7.5% per annum. A zero % rate of return would mean that the spent fuel investment fund grows only in line with the UK inflation rate. Put another way, the investment fund would need to earn at least 3.4% annually just to keep up with today's inflation level, otherwise it would lose its value in real terms.
Spent Fuel Hand-over Period After Reactor Start-Up	60 y	Energy utilities can hand-over their spent fuel to the government before a geological repository is available (Early Transfer). The DECC FUP Consultation Document assumes reactor start-up beginning in 2020 and a spent fuel Transfer Date of 2080 (60 years hand-over). FUPSIM allows spent fuel hand-over up to 200 years after the nuclear reactor is first powered-up on the grid.
Long Term Discount Rate	2.2 % p.a	The discount rate used by the NDA in its Annual Report & Accounts 2008/9 to discount its long term nuclear liabilities up to the year 2132 is 2.2%. If energy utilities pay government in advance for spent fuel disposal (Early Transfer) the spent fuel disposal price is discounted. The early transfer price is discounted according to the number of years delay between hand-over of spent fuel and actual disposal at the end of the extended storage period. The repository is assumed to accept and bury the fuel immediately after storage ends (Assumed Disposal Date). FUPSIM allows discount rates up to 7.5% per annum.

Model Parameter	Initial Value	Technical Comment
NDA Repository Capex Build Cost	£3 bn	The NDA repository lifecycle cashflows are £12,157m total expenditure between March 2009 to March 2138 (Detailed NDA spreadsheet data provided under FoI Request on NDA Annual Report & Accounts 2007/8). Nirex 2005 ILW/SF co-disposal repository lifecycle cost estimate for CoRWM was £10,100m assuming £2470m capex build cost (24.4%). The FUPSIM default value is £3bn capex today, based on 24.4% of £12,157m. FUPSIM allows up to £15bn cost of repository capex. FUPSIM also allows zero capex e.g for writing-off the sunk nuclear construction costs of the repository in the future.
Repository Running and Closure Cost	£9.2 bn	FUPSIM's default repository opex and closure cost is based on the NDA lifecycle cost of £12.2bn less £3bn capex to give £9.2bn. Note that the NDA £12.2bn repository cashflow does not seem to include any Community Benefit package (expected to be another £1.2bn). FUPSIM allows total running and closure costs of up to £15bn. This also allows the financial impact of a community benefit package to be simulated as an extra cost.
NDA Legacy Spent Fuel Inventory	8,200 tU	The DECC FUP Consultation Document gives an NDA legacy spent fuel inventory of 7,000 tU of AGR spent fuel and 1,200 tU of Sizewell-B PWR spent fuel (8,200 tU total). FUPSIM allows legacy spent fuel inventories of up to 20,000 tU, for example if THORP is shut-down early resulting in more unreprocessed AGR spent fuel needing disposal, or if the the lifetimes of AGR reactors are extended also resulting in more AGR spent fuel. The legacy inventory is a very important parameter because it drives the marginal cost of adding *extra* disposal capacity in the repository spent fuel deposition tunnels for accommodating spent fuel from new nuclear build.

Model Parameter	Initial Value	Technical Comment
Spent Fuel Proportion of Repository Cost	50%	FUPSIM's calculation algorithms separate the lifecycle cost of spent fuel disposal and ILW disposal, in order to calculate just the extra (marginal) cost of adding more spent fuel. Nirex Technical Note 484432 provided to CoRWM in September 2005 calculated £5,035m for a dedicated SF/HLW repository and £10,100m for shared co-located SF/HLW/ILW repository. This implies that the SF/HLW proportion of the total cost of an NDA shared repository is approximately 50%. (Put another way, a dedicated commercial repository for new nuclear build spent fuel could be built at about half the cost of a shared public-private NDA repository). FUPSIM allows the spent fuel proportion of the repository lifecycle cost to be varied from zero up to 100%.
Engineering Scaling Factor for Bigger Repository	0.6	FUPSIM estimates the approximate cost of a larger repository to dispose of extra spent fuel using an algorithm based on a power law equation with an engineering scaling factor. The method is based on the six-tenths rule of cost estimation and was used by Ontario Power Generation (OPG) to estimate geological repository disposal costs for NWMO in Canada. The FUPSIM scaling factor exponent is initially 0.6, well known as the six-tenths-rule in process engineering. The scaling factor is usually in the range from 0.3 to 1.0, but experience in the process industry shows the average is close to 0.6 for most situations. The margin of error of the cost estimate using this method is typically plus or minus 20%. The method is ideally suited to calculating small marginal size increases, provided that scaling is not extrapolated too far beyond the reference Base Case (the NDA historic spent fuel Base Case is currently 8,200 tU). FUPSIM allows engineering scale factors up to 3.0.

Model Parameter	Initial Value	Technical Comment
NDA Contingency Cost for Hotter Spent Fuel	0%	Depending on their storage period, high burn-up EPR and AP1000 spent fuel assemblies radiate more heat than standard burn-up AGR spent fuels, and so may need physically spacing wider apart inside repository tunnels. In order to accommodate high burn-up spent fuels, greater spacing of tunnels or fewer fuel assemblies per storage canister might be necessary. The marginal cost of disposing of EPR spent fuels is likely to be slightly larger than AGR spent fuels because the tunnels need to be longer to accommodate this extra spacing. These longer tunnels will cost more (per tU) to excavate than standard AGR tunnels. To correct for this, FUPSIM can add a contingency cost to the scaled-up cost of the extra repository space needed for new build spent fuel. For example, if the EPR tunnels need to be twice as long as standard AGR tunnels then FUPSIM could add a 100% cost increase. However this correction factor should be used cautiously depending on expert judgement by a mining engineer. FUPSIM sets the default correction factor to zero %, meaning that the cost of disposing of EPR fuel is the same as AGR fuel. However FUPSIM allows a contingency cost correction of up to 300% if this is judged necessary. The correction factor is not likely to be needed if the EPR spent fuel cooling and storage time is greater than 75 years. NDA Disposability Assessment concludes that 100 years cooling would be needed for 65,000 MWd/tU burn-up EPR spent fuel to maintain a repository temperature limit of 100ºC. For lower burn-ups, 75 years cooling would be needed for 50,000 MWd/tU burn-up EPR fuel, to meet the same repository temperature limit of 100ºC. A correction factor is only likely to be needed for early disposal of high burn-up spent fuels with less than 75 years cooling, but the % is a matter of judgement. The authors are grateful to Mr Hugh Richards for discussions on this issue.

2.7 Algorithms and Error Margin

FUPSIM is a black box empirical mathematical model that simulates the economics of spent fuel nuclear waste disposal based on generally observed engineering principles, without needing to know the detailed underlying cost structure of a deep geological repository. FUPSIM uses several algorithms to calculate simulation results, depending on input variables and certain correction factors. FUPSIM's internal algorithms are based on transformations and adaptations of the basic formulae explained below, with some modifications.

Financial Equations

FUPSIM's financial calculation results have been tested and are in good agreement with a Hewlett Packard HP-12C financial calculator. The *Mathematica* engine which powers FUPSIM calculates exact solutions for spent fuel disposal fund projections.

Future Value from Annual Level-Payment Cashflows During Station Generating Life:

$$FV = PMT \times \frac{[(1 + INT)^{YRS} - 1]}{INT}$$

Future Value (FV), Level Payment (PMT), Interest Rate (INT), Investment Period (YRS)

Future Value from Growth of Fund During Extended Storage Period:

$$FV = PV \times (1 + INT)^{YRS}$$

Future Value (FV), Present Value (PV), Interest Rate (INT), Investment Period (YRS)

Discounted Early Transfer Value for Early Payment Before Repository Disposal:

$$DV = \frac{FV}{(1 + DR)^{YRS}}$$

Discounted Value (DV), Future Value (FV), Discount Rate (DR), Discount Period (YRS)

Repository Engineering Equations

FUPSIM estimates the approximate cost of a larger repository to dispose of extra spent fuel using an algorithm based on a power law equation with an engineering scaling factor. The method is based on the six-tenths rule of cost estimation and was used by Ontario Power Generation (OPG) to estimate geological repository disposal costs for NWMO in Canada.[5]

The engineering margin of error of the cost estimate using this method is typically plus or minus 20% and is often used in the USA as a basis for a preliminary engineering budget estimate, when the costs of a smaller pilot plant (or in this case repository) are known.[6] (Googling the "six-tenths rule" of cost estimation gives over 10,000 web hits and has an entry on Encyclopaedia Britannica). The model is empirical and results are somewhat conservative, allowing approximate calculation of larger plant sizes without needing to know the detailed cost structure of the new plant. The method is ideally suited to calculating small marginal size increases provided that scaling is not extrapolated too far beyond the reference Base Case.

$$CB = CA \times (SB/SA)^{SF}$$

Cost B (CB), Cost A (CA), Size B (SB), Size A (SA), Scale Factor (SF)

Reactor Spent Fuel Equations

FUPSIM's reactor calculation results have been tested and are in good agreement with a Hewlett Packard HP-42S scientific calculator. The *Mathematica* engine which powers FUPSIM calculates an exact solution for the spent fuel discharged from the nuclear reactor.[7]

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5 OPG. *Cost of Alternative Approaches for the Long-Term Management of Canada's Nuclear Fuel Waste: Deep Geological Disposal Approach*. Ontario Power Generation et al. Submission to the Nuclear Waste Management Organisation (NWMO). March 2004.

6 Whitesides, R. *Process Equipment Cost Estimating By Ratio and Proportion*. PDH Center for Engineering Continuing Education. PDH Course G127. 2007.

7 The method for calculating tonnes of spent fuel discharged from a reactor is given in Eden, R. *Energy Economics: Growth, Resources and Policies*. Cambridge University Press. 1983.

$$SFD = \frac{LF}{100} \times MW \times \frac{100}{EF} \times \frac{365.24}{BU} \times YRS$$

Spent Fuel Discharged (SFD), Load Factor (LF), Generating Capacity (MW), Generating Period (YRS), Thermal Efficiency (EF), Thermal BurnUp (BU)

2.8 Data Entry Using Sliders

FUPSIM has 21 click-and-drag graphic sliders which are used to adjust input variables using a mouse. In some cases it is not always possible to enter an exact desired value into the FUPSIM model. For example when dragging the Real Rate of Return slider near a desired interest rate of exactly 0.5%, FUPSIM displays values of 0.47%, 0.51% or 0.56% but not 0.50% exactly. The user must select the closest approximation, which in this example is 0.51%.

2.9 Fund Overshoot / Undershoot

The FUPSIM calculated value of an investment fund will sometimes very slightly overshoot or undershoot the exact target price needed to pay a spent fuel disposal liability.(The variation is typically very small, less than 1% of the final target fund value needed to pay for spent fuel). This is because small changes in level payments and interest rates can make a difference to the fund value many years into the future. FUPSIM input values used in this Research Report have been selected which give the closest match to the liability cost, so fund results are approximately correct. Because of mathematical rounding convention a FUPSIM level payment of £4.65m is rounded upwards to £4.7m in this report, but calculated by FUPSIM as £4.65m.

2.10 Resetting FUPSIM

FUPSIM can be reset to its default parameters at any time simply by clicking the plus symbol (+) in the top right hand corner of the FUPSIM dashboard above the graph plot and clicking *Initial Settings*. Alternatively simply shut-down FUPSIM and re-start the programme.

2.11 Beta User Feedback

FUPSIM has been released as a public beta software model for researchers at the Wolfram Demonstrations Project. Technical and academic feedback from users of the model is welcomed. Please email the authors at enquiries@jacksonconsult.com.

3. NUCLEAR POWER STATION ANALYSIS RESULTS

3.1 Reactor Scenarios

FUPSIM can analyse spent fuel disposal liabilities for any nuclear power station build project up to 4,000MW. This Research Report analyses the four most likely new nuclear power station configurations that energy utilities are proposing to build in the UK by 2025, the first wave of nuclear development forecast in the Draft Nuclear National Policy Statement (NPS).

- 1,650MW Single EPR generating for 60 years
- 3,300MW Twin EPR generating for 60 years
- 1,150MW Single AP1000 generating for 60 years
- 2,300MW Twin AP1000 generating for 60 years

Important: FUPSIM internally calculates exact values but results presented in this Research Report are *rounded* and are *approximate*. For example a FUPSIM level payment of £4.65m is rounded upwards to £4.7m. There will sometimes be minor data-entry related variations using the graphic sliders because they cannot always select the precise value needed for a calculation. For example 0.5% interest rate may need to be entered as 0.51% (see Section 2.8).

3.2 Fixed Unit Price Range

The behaviour of Fixed Unit Prices is complex and perhaps best illustrated by experimenting directly with the interactive FUPSIM simulation. For simplicity the analysis results presented in this Research Report are based on two illustrative DECC Fixed Unit Prices; a Quantity Fixed Unit Price(Q-FUP) of **£1.1m/tU** and an Output Fixed Unit Price (O-FUP) of **0.19 p/kWh**. These values approximately represent the high and low range of Fixed Unit Prices in the DECC FUP Discussion Paper 3 (May 2009) and the later DECC FUP Public Consultation (March 2010) which are summarised in the Table below.

DECC Fixed Unit Prices at 80% to 99% Probability

DECC FUP	P80%	P90%	P95%	P99%
Quantity FUP	985 £m/tU	1,049 £m/tU	1092 £m/tU	**£1,150 m/tU**
Output FUP	**0.194 p/kWh**	0.205 p/kWh	0.215 p/kWh	0.238 p/kWh

Sources: Quantity FUP estimates are given in the DECC FUP Discussion Paper 3 @ p35, Output FUP estimates are given in the DECC FUP Consultation Paper @ p61

3.3 Utility Spent Fuel Liability Higher Than Expected

The price charged by the government to energy utility companies for disposal of spent fuel from a new nuclear power station will be about £1.2bn for an AP1000 or £1.5bn for an EPR, equivalent to 32% of the turnkey construction cost of an AP1000 or 44% of an EPR. Disposal costs are much larger than previously indicated by government during its nuclear consultations, which assumed lifecycle back-end disposal costs of only 3% (4.5% of capex).[8] This means that FUP costs are about 7 to 10 times higher than was originally expected by the government in 2006. This is of some concern because the underestimated costs wrongly informed part of the economic analysis used for the 2008 *White Paper on Nuclear Power*.

Spent Fuel Liabilities for AP1000 and EPR Nuclear Power Stations

Power Station	Spent Fuel @ 60 Yrs	FUP	Disposal Price	% Reactor Build Cost
EPR	1,391 tU	1.1 £m/tU	£1,530m	44%
		0.19 p/kWh	£1,533m	44%
Twin EPR	2,781 tU	1.1 £m/tU	£3,060m	44%
		0.19 p/kWh	£3,067m	44%
AP1000	1,061 tU	1.1 £m/tU	£1,167m	32%
		0.19 p/kWh	£1,069m	30%
Twin AP1000	2,126 tU	1.1 £m/tU	£2,338m	32%
		0.19 p/kWh	£2,142m	30%

FUPSIM modeled @ 65,000 MWd/tU thermal burn-up, EPR 37.2% efficient, AP1000 34.0% efficient, EPR Flamanville-3 capex £3.5bn, AP1000 Lee-3 capex £3.6bn

An AP1000 produces less spent fuel waste than an EPR and as a consequence its back-end spent fuel disposal costs are about 30% lower (£1,069m vs £1,533m), in line with the reduced power output of a 1,150MW AP1000 compared with a 1,650 MW EPR. The government's

[8] DTI. *The Energy Challenge: Energy Review Report.* Cm6887. July 2006. The government assumed a lifecycle cost structure for a new nuclear power station of 66% capital cost, 20% operations and maintenance cost, 11% fuel cost and 3% back-end cost (see Page 115). The back-end cost expressed as a fraction of reactor construction cost was 3/66 x 100 = 4.5%. Actual back-end FUP costs are 7 times higher than the government expected for an AP1000 (32/4.5=7.1) and 10 times higher than expected for an EPR (44/4.5=9.8).

intention to established a Fixed Unit Price based on energy output (p/kWh) rather than quantity of spent fuel (£m/tU) also gives a slight advantage to the AP1000, reducing disposal costs by about 8% (£98m) (£1,069m vs £1,167m). There is no appreciable difference between an Output FUP and Quantity FUP for the larger EPR reactor (£3m).

3.4 Government Risk Premium Underestimated

The effective risk premium charged by government for spent fuel disposal is actually much less than 100% offered by utilities. It is around 42% for an AP1000 or 58% for an EPR. This suggests that disposal prices need to increase by 42- 58 percentage points in order to raise the effective risk premium level back to a sensible 100% above the NDA's disposal cost.

The major purpose of the government's FUP disposal scheme is to protect energy utilities from price escalation that is often experienced with public sector nuclear facility projects. For example the NDA's nuclear liabilities increased from £47.9bn[9] to £85.5bn[10] during the government's restructuring of civil nuclear liabilities between July 2002 and the latest civil nuclear liability estimate in March 2009. During this 7 year period the NDA's nuclear liabilities escalated 8.6% annually or 5.9% in real terms above the UK's 2.7% average rate of inflation.[11] Realistically it is likely that an NDA deep geological repository - a highly complex first-of-a-kind project - may well experience similar levels of cost escalation. The Fixed Unit Price offered to energy utility companies will protect them from exposure to this risk of cost escalation for disposal of their spent nuclear fuel within the NDA's repository. The commercial profit margin between the disposal price charged to energy utilities by government and the actual cost of disposal borne by the NDA is effectively a project risk premium.

The government's 2008 *White Paper on Nuclear Power* stated that "operators of new nuclear power stations will be obliged to meet their full share of waste management costs" and that "energy companies have indicated that they would be prepared to pay a significant risk premium over and above the expected cost of disposing of waste, in return for having the certainty of a fixed upper price".[12] Jackson Consulting understands that energy utility compa-

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[9] DTI. *Managing the Nuclear Legacy: A Strategy for Action*. Cm5552. July 2002.

[10] Nuclear Decommissioning Authority. *Annual Expenditure Profile for NDA in 2008/9 Annual Report & Accounts*. Response to Freedom of Information Act Request. October 2009.

[11] Bank of England. *Inflation Calculator*.Average CPI price inflation in the UK between 2002 and 2009 was 2.7% per annum. www.bankofengland.co.uk

[12] BERR. *Meeting the Energy Challenge: A White Paper on Nuclear Power*.Cm7296. January 2008, pages 152 - 153.

nies were broadly prepared to accept a risk premium of not more than 100%. To illustrate the commercial logic of this position, consider the following. If the NDA's £3bn capex repository was constructed over the next 10 years, and experienced the NDA's usual historic price escalation of 5.9% in real terms, the repository would actually cost £5.3bn, an overall price increase of 77% (£2.3bn). Given the technical complexity of building a repository and the NDA's poor track record in cost control, it seems likely that repository construction costs will indeed probably escalate in a similar way. (For example, before it was cancelled by US President Obama, DOE cost estimates for the the Yucca Mountain spent fuel repository escalated 7.6% annually from $57.5bn to $96.2bn between 2001 and 2008). Although the total £12.2bn lifecycle cost of the NDA repository (construction cost, running cost and closure cost) from which Fixed Unit Prices are derived might not increase by 77% overall, nevertheless the 100% risk premium suggested by energy utilities seems a sensible precaution.

DECC Risk Premium Above NDA Disposal Cost

Power Station	Spent Fuel @ 60 Yrs	FUP	NDA Disposal Cost	DECC Disposal Price	Risk Premium/ Profit Margin
EPR	1,391 tU	1.1 £m/tU	£972m	£1,530m	57%
		0.19 p/kWh	£972m	£1,533m	58%
Twin EPR	2,781 tU	1.1 £m/tU	£1,841m	£3,060m	66%
		0.19 p/kWh	£1,841m	£3,067m	67%
AP1000	1,061 tU	1.1 £m/tU	£751m	£1,167m	55%
		0.19 p/kWh	£751m	£1,069m	42%
Twin AP1000	2,126 tU	1.1 £m/tU	£1,442m	£2,338m	62%
		0.19 p/kWh	£1,442m	£2,142m	49%

FUPSIM modeled @ 8,200 tU baseline legacy spent fuel inventory in NDA repository

The government's effective risk premium is slightly better for a Twin AP1000 (49%) or a Twin EPR (67%), because their larger generating capacities mean the government charges a higher total price (£m) but the government's full share fixed unit costs are lower (£m/tU). The full share fixed unit costs are lower because larger repositories have better economies of scale than small ones. Put another way, unit costs become cheaper as more radwaste is added to the repository, up to a certain point limited by the maximum radiological capacity of the disposal site. The radiological capacity of a site is a radiation risk based upper limit on the total radioactive inventory and is intended to reduce the risk of death to members of the public from radiation exposure to less than one chance in one million per year (10^{-6} p.a.).[13]

3.5 Levelised Disposal Cost Underemphasised

The levelised cost (£/MWh) charged by the government to energy utilities for spent fuel disposal will be about £1.90/MWh for an EPR and £2.07/MWh for an AP1000. This means that levelised costs are actually about 3 to 8 times higher than the levelised costs of £0.26/MWh to £0.71/MWh that are usually presented by the government to City financial analysts.[14]

True Levelised Cost of Spent Fuel Disposal

Power Station	Spent Fuel @ 60 Yrs	FUP	Disposal Price	Levelised Cost
EPR	1,391 tU	1.1 £m/tU	£1,530m	£1.90/MWh
		0.19 p/kWh	£1,533m	£1.90/MWh
Twin EPR	2,781 tU	1.1 £m/tU	£3,060m	£1.90/MWh
		0.19 p/kWh	£3,067m	£1.90/MWh
AP1000	1,061 tU	1.1 £m/tU	£1,167m	£2.07/MWh
		0.19 p/kWh	£1,069m	£1.90/MWh
Twin AP1000	2,126 tU	1.1 £m/tU	£2,338m	£2.07/MWh
		0.19 p/kWh	£2,142m	£1.90/MWh

FUPSIM modeled @ 65,000 MWd/tU thermal burn-up,
EPR 37.2% efficient, AP1000 34.0% efficient

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[13] The Environment Agency sets a Risk Guidance Level of 10^{-6} in Requirement R6 of *Geological Disposal Facilities on Land for Solid Radiative Wastes: Guidance on Requirements for Authorisation*. Environment Agency. February 2009.

[14] DECC. *Consultation on a Methodology to Determine a Fixed Unit Price for Waste Disposal*. March 2010. Page 8, Table 2 of the DECC FUP Consultation Document gives an illustrative value of the operator's waste disposal cost of 0.26-0.71 £/MWh. Levelised costs are actually between 3 times higher (2.07/0.71 = 2.9) and 8 times higher (2.07/0.26=8.0).

Levelised costs of £1.90/MWh may seem small but can have a significant impact on the economic viability of nuclear power, especially when wholesale power prices are only marginally above generating costs. For example the European Commission concluded that a sustained power price fall of just £8.56/MWh from 2000 to 2002 was sufficient to trigger the financial collapse of the UK national nuclear electricity utility firm British Energy in July 2002.[15]

It is important that levelised costs are presented transparently on a level playing field. Private sector energy companies are preparing to make large capital investments in new coal, gas, nuclear and renewable electricity generating assets over the next decade. Decisions on what nuclear power stations may be built in the future will be taken by commercial energy utility companies, who must convince their private sector shareholders. In practice this means that City analysts and pension fund managers will have a big say in whether nuclear build actually goes ahead, as these tend to be the largest institutional investors in the energy sector. Levelised costs (£/WMh) are an important discriminating factor for City analysts to make informed comparisons between the costs of different low-carbon electricity generation technologies. In the investment community there is a great deal of market interest comparing the levelised cost of nuclear waste disposal for nuclear power stations with that of carbon capture and storage (CCS) for fossil-fueled power stations. The levelised cost of CCS vs FUP may well decide whether energy utilities choose to invest in either coal or nuclear power stations as low-carbon generation technologies. (A carbon floor price is also important but this will not differentiate between FUP and CCS because both have zero carbon emissions).

3.6 Investment Model Not Suitable for Nuclear Waste Disposal

The government has proposed that energy utilities adopt what amounts to a 160-year endowment mortgage scheme to pay for their spent fuel nuclear waste disposal liabilities. Nuclear operators must make regular small payments into an investment fund (about £4.7m/y for an EPR) which is assumed to grow earning compound interest. The arrangement is very similar to an endowment mortgage, where the endowment fund only accumulates enough to pay-off a home loan at the very end of the investment period. The major advantage of the scheme is that levelised spent fuel disposal costs are effectively reduced by a factor of 5 from £1.90/MWh to £0.35/MWh (for an EPR). The total value of the small payments (£279m for an EPR) is about 5 times less than the actual cost of spent fuel disposal (£1,530m for an EPR).

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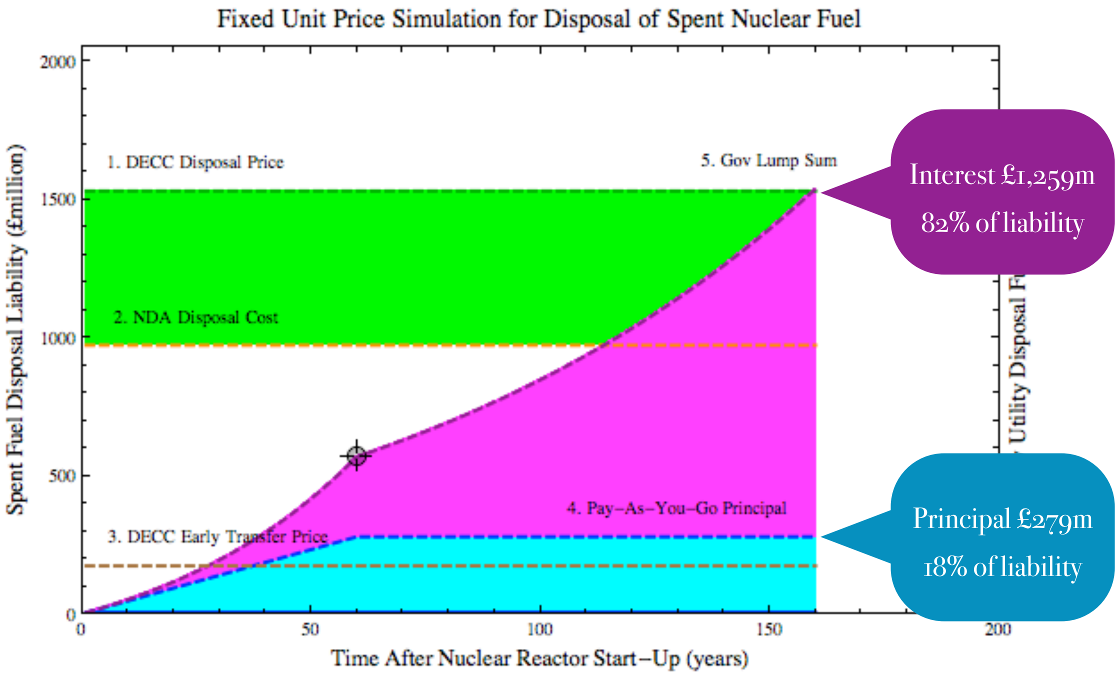
[15] Commission of the European Communities. *Commission Decision of the 22 IX 2004 on the State Aid Which the United Kingdom is Planning to Implement for British Energy plc*. Brussels, 22 IX 2004, c(2004) 3474 final. See Page 4 @ Para 14.

Utility Fund Needed to Pay-off Spent Fuel Liability Under DECC Interest Assumptions

Power Station	Spent Fuel @ 60 Yrs	Disposal Price	Levelised 'Mortgage' Payment	Principal	Interest
EPR	1,391 tU	£1,530m	£4.7m/y	£279m	£1,259m (82%)
Twin EPR	2,781 tU	£3,060m	£9.2m/y	£552m	£2,491 (82%)
AP1000	1,061 tU	£1,167m	£3.5m/y	£207m	£934m (82%)
Twin AP1000	2,126 tU	£2,338m	£7.2m/y	£429m	£1,936m (82%)

FUPSIM modeled @ 65,000 MWd/tU thermal burn-up, EPR 37.2% efficient, AP1000 34.0% efficient, 60 year generating period real rate return 2.2% p.a, 100 year storage period real rate of return 1.0%, FUP £1.1m/tU

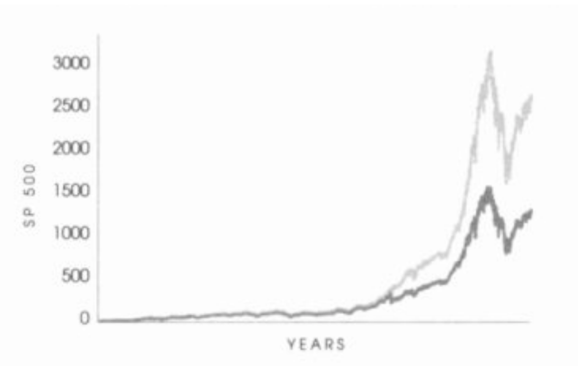
DECC Expects 82% of the Nuclear Waste Disposal Liability for an EPR to be Paid For by Interest Earned from the Stock Market over 160 Years



FUPSIM modeled @ £1,530m spent fuel liability for an EPR, £4.7m/y level payment, 60 year generating period, 100 year storage period

The major weakness of the FUP scheme is that it relies on the utility regularly earning interest from the stock market or from government bonds (which are paid by taxpayers). Depending on the spent fuel cooling and storage period, typically about 70% to 80% of the investment fund is made up of such interest payments. Moreover the investment fund must consistently and reliably earn interest over an extremely long period, typically 110 to 160 years. It is highly questionable whether this 160 year endowment funding model is sensible or appropriate to pay for nuclear waste disposal, a safety-critical function of national government. Relying on financial markets to fund 82% of nuclear waste disposal costs is too risky. For example consider the graph below of the Standard & Poor's 500 index of leading US companies, reproduced from Nassim Nicholas Taleb's *The Black Swan*. Half of all stock market returns were earned in just 10 trading days over the past 50 years. Put another way, 50% of stock market returns were earned in just 0.08% of lucky stock market trading days.[16] The financial markets are intrinsically volatile and unsuited to guaranteeing to pay for nuclear waste.

S&P 500 Index Showing the Skewed Financial Impact of the 10 Largest Trading Days in the Past 50 Years, Which Earned 50% of Returns



Source: Nassim Nicholas Taleb. "The Black Swan: The Impact of the Highly Improbable". Penguin. 2007. See Pages 275-276

[16] Assuming Wall Street trades 5 days per week, 52 weeks per year, the lucky trading days were just 10d/(5d x 52w x 50y) x 100 = 0.077% of all trading days in the past 50 years.

Problems with potential taxpayer losses under the FUP scheme can be better understood by comparison with the UK endowment mortgage crisis. Many homeowners lost substantial sums of money during the endowment mortgage crisis of the 1990s/2000s. In January 2010 *The Guardian* reported that Aviva (formerly known as Norwich Union) warned of expected shortfalls in 88% of its 700,000 home owner savings and endowment mortgages.[17] 88% of the group's endowment mortgages are now in the 'red' zone where there is a high risk they will not pay off the home loan they were bought to cover. Just 4% were 'green'. Banks always have the option of repossessing and selling-off homes if the homeowner fails to repay the bank loan in full. But the government has no such realistic alternative option for spent fuel disposal because nuclear waste <u>must</u> be safely managed and disposed. If an energy company spent fuel disposal fund suffered similar losses to endowment mortgages, with such losses perhaps occurring many decades into the future long after the reactor had shut-down, the shortfall would inevitably have to be paid for by taxpayers.

The National Audit Office has pointing out that if a private sector nuclear energy utility firm went bust, a liquidator would be entitled to disclaim its spent nuclear fuel liabilities, which would revert back to the Crown (the government).[18] The government remains ultimately responsible for spent fuel disposal. It is worth pointing out that spent fuel remains dangerously radioactive for many decades. Fifty years after removal of spent fuel from the reactor, the radiation dose to a person standing nearby an unshielded spent fuel assembly would still give a potentially fatal radiation dose of 5 Sieverts within four hours of exposure (radiation level 1,150 mSv/hr @ 30cm distance from a 50-year aged fuel bundle).[19] After 100 years the spent fuel assembly would still give the person their maximum permitted yearly radiation dose limit within 10 seconds (radiation level 360 mSv/hr @ 30cm distance from a 50-year aged fuel bundle).[20] Only after about 500 years does the spent fuel become less hazardous, giving a person standing nearby their yearly radiation dose limit after just over an hour exposure (radiation level 0.8 mSv/hr @ 30cm distance from a 500-year aged fuel bundle).

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[17] Rupert Jones. *Aviva warns of shortfall in 88% of its endowment mortgages*. The Guardian. 12th January 2010.

[18] National Audit Office. *The Restructuring of British Energy*. March 2006. Without a prospective purchaser a liquidator is entitled to disclaim nuclear liabilities (see Page 19).

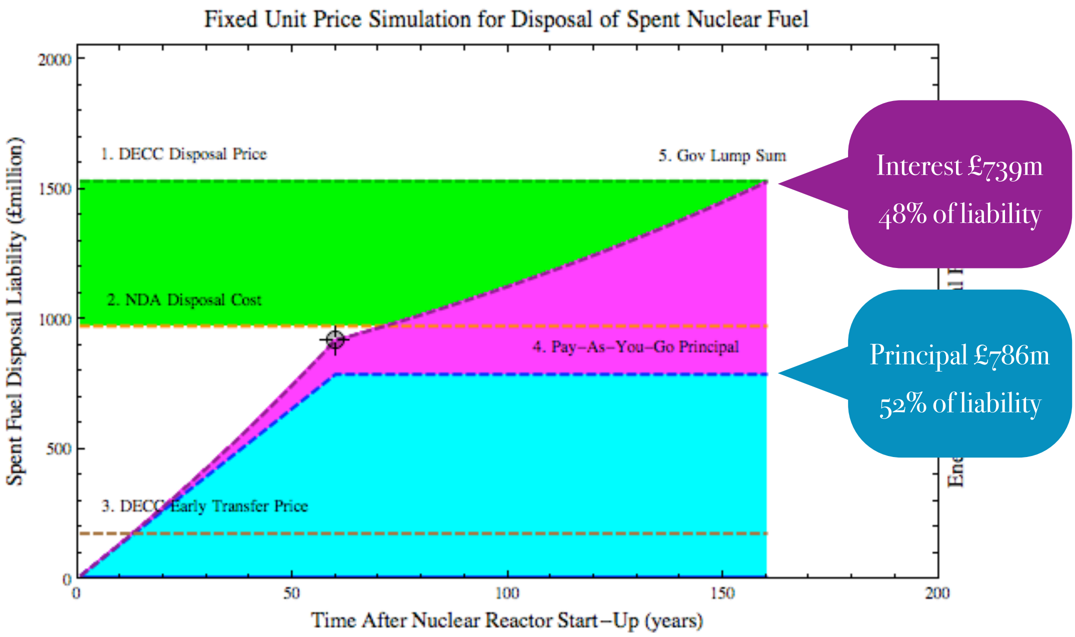
[19] NWMO. *Choosing A Way Forward: The Future Management of Canada's Used Nuclear Fuel.* Final Study Report. 2005. Spent fuel radiation doses are discussed at Page 344.

[20] The ICRP 2007 maximum radiation dose limit recommended for a member of the public is 1 mSv per annum, or 20 mSv per annum occupational limit for a trained radiation worker.

3.7 Financial Conditions Today Support Cost-Recovery Model

The DECC FUP Consultation Document and background Discussion Papers assume real rates of return during the reactor generating period of 3.5%, 2.2% and 1% per annum. But today the Bank of England base rate is currently at a historic low of 0.5% as of April 2010 and has remained at this level since March 2009. Under present financial conditions, stock market returns will not be sufficient to pay for the majority (82%) of an energy utility company's spent fuel liabilities. At 0.5% real rate of return the stock market will only pay for about 48% of an EPR's spent fuel liabilities, while the energy utility company must pay 52% through increased annual 'mortgage' level-payments made into the utility company's investment fund.

The Stock Market Will Only Pay for 48% of Spent Fuel Liabilities from an EPR at Today's 0.5% Bank of England Interest Rate



FUPSIM modeled @ £1,530m spent fuel liability for an EPR, £13.1m/y level payment, 60 year generating period, 100 year storage period

Fund Needed to Pay-off Spent Fuel Liability at Today's 0.5% Bank of England Interest Rate

Power Station	Spent Fuel @ 60 Yrs	Disposal Price	Levelised 'Mortgage' Payment	Principal	Interest
EPR	1,391 tU	£1,530m	£13.1 m/y	£786m	£739m (48%)
Twin EPR	2,781 tU	£3,060m	£26.3 m/y	£1,575m	£1,480 (48%)
AP1000	1,061 tU	£1,167m	£10.0 m/y	£603m	£567m (48%)
Twin AP1000	2,126 tU	£2,338m	£20.2 m/y	£1,212m	£1,139m (48%)

FUPSIM modeled @ 65,000 MWd/tU thermal burn-up, EPR 37.2% efficient, AP1000 34.0% efficient, 60 year generating period real rate return 0.5% p.a, 100 year storage period real rate return 0.5% p.a, FUP £1.1m/tU

It is commercially very unlikely that the UK's national deep geological repository will be built by private contractors on a turnkey fixed price basis. The Boards of major publicly held construction companies and their City shareholders simply could not accept the financial risks involved of building such a highly uncertain advanced technical project at fixed price. During the 2000s the NDA's costs escalated 5.9% annually and Yucca Mountain costs escalated 7.6% annually. First-of-a-Kind (FOAK) nuclear plants have traditionally been built on a Cost Plus basis where the contractor agrees to carry out the work for whatever it actually costs to complete it, and then charges this amount plus a percentage fee based upon these costs.[21] In fact the Nuclear Decommissioning Authority's Sellafield site is ran on this basis by a consortium of private contractors under a 17 year Government-Owned, Contractor-Operated (GOCO) Management & Operation (M&O) contract. The military Atomic Weapons Establishment (AWE) at Aldermaston is also ran under a similar 25-year GOCO M&O contract. Cost Plus rather than Fixed Price contracting models are best suited to the nuclear industry.

[21] Bayliss, C and Langley K. *Nuclear Decommissioning, Waste Management and Environmental Site Remediation*. Elsevier. 2003. Modern contract strategies in the nuclear industry are are discussed in Chapter 13.

By the same logic, Variable Cost-Plus spent fuel disposal prices are better than Fixed Unit Prices, since they guarantee that the taxpayer will be paid in full without public subsidy. The Sellafield THORP reprocessing plant was partially financed in advance this way by cost-recovery contracts with Japanese and European energy utility companies in the 1970s.[22] Under today's difficult economic conditions when interest rates are very low, there is little advantage in creating an endowment mortgage fund to pay for nuclear waste disposal, because the large increase in level payments needed almost pay for the basic cost of spent fuel disposal anyway. Levelised utility payments of £13.1m/y, totaling £786m after 60 years, very nearly meet the NDA's basic cost of providing repository space for the EPR spent fuel (£972m).The creation of a stock market investment fund is an unnecessary gamble.

The Cost Plus nature of nuclear repository contracting and today's economic pricing signals both point towards the need for Variable Cost-Plus recovery pricing of spent nuclear fuel disposal. Disposal prices should be set based on the NDA's actual costs, indexed for NDA cost escalation and CPI price inflation. The government already seems to partly accept this argument because Fixed Unit Prices will be indexed for CPI inflation, although not NDA cost escalation. A similar argument supporting a mix of Variable Cost Phase and Fixed Cost Phase pricing was suggested by EDF Energy in its pre-consultation submissions to government, that were recently released to Greenpeace under the Freedom of Information Act.[23]

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[22] Walker, W, *Nuclear Entrapment: THORP and the Politics of Commitment*. Institute of Public Policy Research. 1999.

[23] EDF Energy. *Fixed Waste Cost and Schedule: Discussion Paper*. Powerpoint presentation for meeting with DECC 23/10/09. V5 231009. Released to Greenpeace by DECC under the Freedom of Information Act in June 2010.

3.8 Discounted Early Transfer Pricing Issues

Probably the most controversial aspect of the government's Fixed Unit Price scheme is the option for nuclear energy utilities to transfer their spent fuel to government many decades before the waste can actually be disposed in a national deep geological repository.

The presumption is that the NDA's geological repository is expected to open in 2040 and the disposal of the UK's historic legacy waste takes 90 years to complete by 2130. After 2130 the repository is available for the disposal of waste from new nuclear power stations.

For example, an energy utility company operating an EPR could pay £174m up-front 10 years after the reactor begins generation, to transfer title of its lifetime spent fuel liability to government and so avoid a future spent fuel disposal liability of £1,530m. The arrangement effectively saves £1,356m (89%) of lifetime spent fuel disposal costs for an EPR. A utility company could quite credibly set aside the necessary £174m Early Transfer Price (levelised cost £17.4m/y) from its electricity sales during the first decade of nuclear power generation.

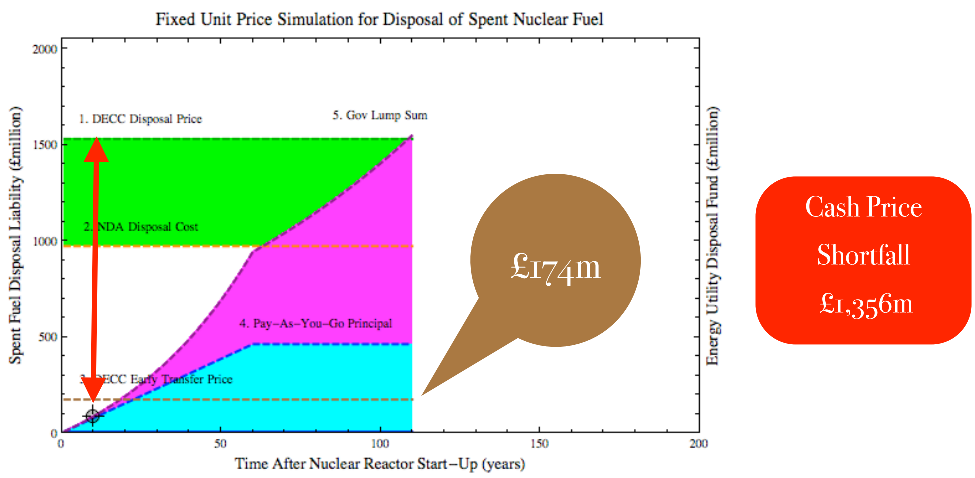
In practice, the government has suggested a later Transfer Date of 2080 which increases the Early Transfer Price to £515m. This still saves the energy utility company £1,015m, some 66% of the £1,530m lifetime EPR spent fuel disposal cost - an excellent deal for utilities. FUPSIM models these dates below with a 60 year generating life for an EPR and AP1000.

Price Shortfall from Early Transfer of Spent Fuel Liability

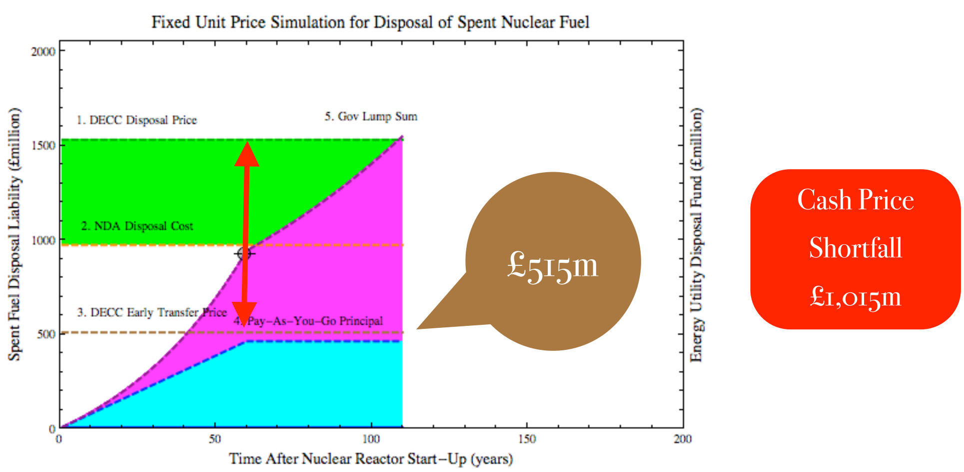
Power Station	Spent Fuel @ 60 Yrs	Early Transfer Price 2030	Early Transfer Price 2080	Full Disposal Price 2130	Shortfall/ Subsidy 2080 - 2130
EPR	1,391 tU	£174m	£515m	£1,530m	£1,015m (66%)
Twin EPR	2,781 tU	£347m	£1,031m	£3,060m	£2,029m (66%)
AP1000	1,061 tU	£132m	£393m	£1,167m	£774m (66%)
Twin AP1000	2,126 tU	£265m	£788m	£2,338m	£1,550m (66%)

FUPSIM modeled @ 65,000 MWd/tU thermal burn-up,
EPR 37.2% efficient, AP1000 34.0% efficient, 60 year generating period,
50 year storage period, 0% contingency for hotter spent fuel, FUP £1.1m/tU,
Early Transfer discount rate 2.2%, reactor start-up 2020

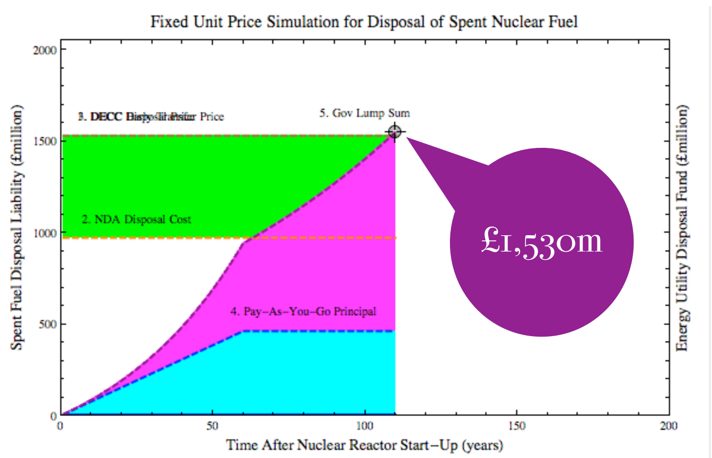
Discounted Early Transfer Price of EPR Spent Fuel at 2030



Discounted Early Transfer Price of EPR Spent Fuel at 2080



Full Disposal Price of EPR Spent Fuel Without Early Transfer, at 2130



4. RESEARCH CONCLUSIONS

4.1 Fixing The Government Risk Premium at 100%

The effective risk premium charged by government for spent fuel disposal is rather low at around 42% for an AP1000 or 58% for an EPR (see Section 3.4). The Fixed Unit Price could be adjusted to 100% risk premium that we believe the market is willing to bear.

The revised Quantity Fixed Unit Price (Q-FUP) will be approximately a £1.4m/tU and the revised Output Fixed Unit Price (O-FUP) will be approximately 0.24p/kWh.

DECC Fixed Unit Prices Required For 100% Risk Premium

Power Station	Spent Fuel @ 60 Yrs	NDA Disposal Cost	Profit Margin / Risk Premium	Required Disposal Price	Required FUP @100% Risk Premium
EPR	1,391 tU	£972m	100%	£1,944m	1.4 £m/tU
		£972m	100%	£1,944m	0.24 p/kWh
Twin EPR	2,781 tU	£1,841m	100%	£3,628m	1.3 £m/tU
		£1,841m	100%	£3,628m	0.23 p/kWh
AP1000	1,061 tU	£751m	100%	£1,502m	1.4 £m/tU
		£751m	100%	£1,502m	0.27 p/kWh
Twin AP1000	2,126 tU	£1,442m	100%	£2,884m	1.4 £m/tU
		£1,442m	100%	£2,884m	0.26 p/kWh

FUPSIM modeled @ 8,200 tU baseline legacy spent fuel inventory in NDA repository, 65,000 MWd/tU thermal burn-up, EPR 37.2% efficient, AP1000 34.0% efficient, 60 year generating period, 100 year storage period

4.2 Switching to a Disposal Cost Recovery Pricing Model

The government's very high reliance on stock market interest to pay for spent fuel liabilities under the Fixed Unit Price scheme is unsuitable for today's economic climate (see Section 3.6). We suggest that variable spent fuel disposal prices should be set based on the NDA's actual costs, indexed for NDA cost escalation and CPI price inflation (see Section 3.7). Variable Cost-Plus spent fuel disposal prices are better than Fixed Unit Prices, since they guarantee that the taxpayer will be paid in full without public subsidy.

As well as being fairer to the taxpayer, there are also some commercial advantages for nuclear energy utilities because the levelised cost of disposal will actually be cheaper (although the utility bears the risk that prices may escalate depending on repository out-turn costs).

For example using Cost Plus recovery pricing, the spent fuel disposal liability of an EPR would be £972m, compared with £1,530m under the government's Fixed Unit Price scheme. Similarly the levelised cost of spent fuel disposal from an EPR would be £0.7 m/tU using Cost Plus, compared with £1.1 m/tU under the Fixed Unit Price scheme.

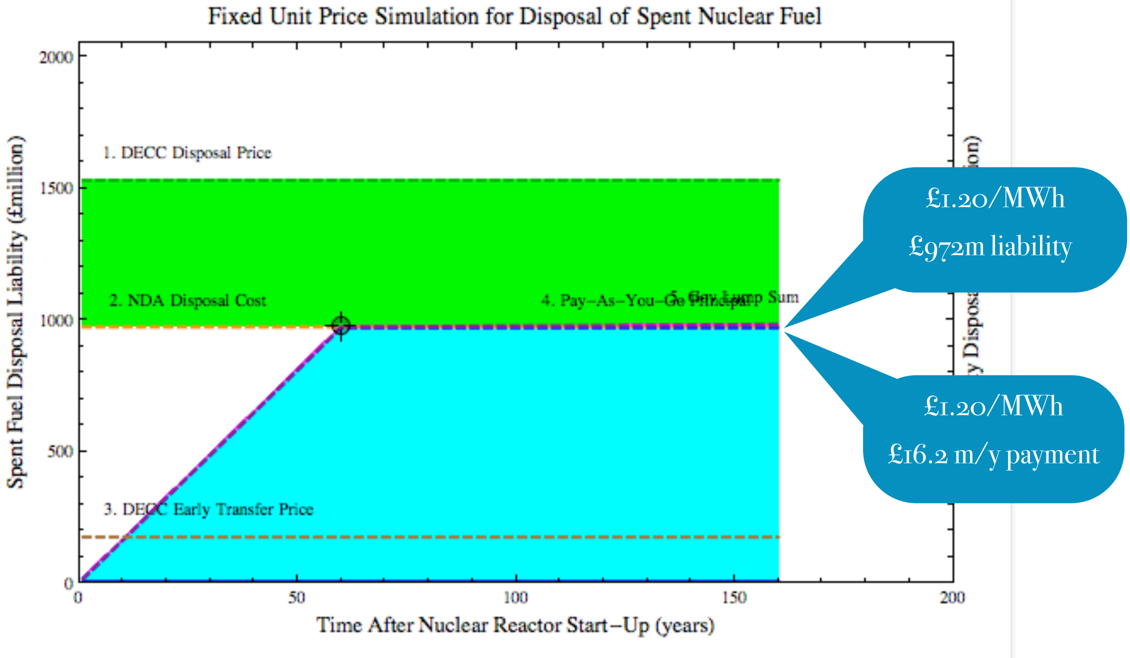
However the annual payments made by a nuclear energy utility would need to be larger under Cost Plus recovery. The energy company would need to pay £16.2 m/y compared with only £4.7m/y under the Fixed Unit Price scheme, which relies on interest payments to make-up the shortfall. (The exact FUP annual payment depends heavily on interest rate assumptions and would be around £13.1 m/y at today's Bank of England 0.5% base rate for example).

Spent Fuel Disposal Liabilities Using 'Cost-Plus' Recovery Pricing Model

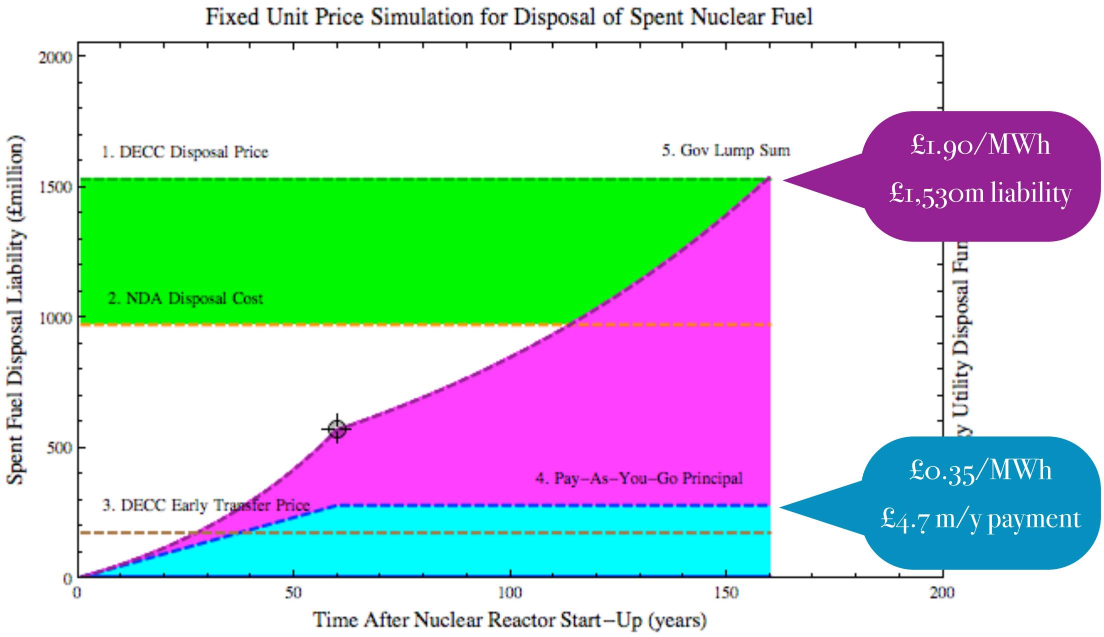
Power Station	Spent Fuel @ 60 Yrs	NDA Disposal Cost	Quantity Levelised Cost	Output Levelised Cost	Utility Annual Payment
EPR	1,391 tU	£972m	0.7 £m/tU	0.12 p/kWh	£16.2 m/y
Twin EPR	2,781 tU	£1,841m	0.7 £m/tU	0.12 p/kWh	£30.7 m/y
AP1000	1,061 tU	£751m	0.7 £m/tU	0.13 p/kWh	£12.5 m/y
Twin AP1000	2,126 tU	£1,442m	0.7 £m/tU	0.13 p/kWh	£24 m/y

FUPSIM modeled @ 8,200 tU baseline legacy spent fuel inventory in NDA repository, 65,000 MWd/tU thermal burn-up, EPR 37.2% efficient, AP1000 34.0% efficient, 60 year generating period, 100 year storage period

£972m EPR Spent Fuel Disposal Liability Using 'Cost-Plus' Recovery Pricing Model



£1,530m EPR Spent Fuel Disposal Liability Using DECC Fixed Unit Price Model



4.3 Early Transfer Price Should Not Be Discounted

Although we agree that the government is best placed to safely dispose of spent fuel from new reactors in the NDA's repository, we are concerned that the discounted pricing structure may disadvantage the taxpayer by around £1 billion for each reactor (see Section 3.8). The price is discounted by 2.2% annually over the 50 years between transfer of spent fuel to government in 2080 and disposal in the shared NDA geological repository from 2130 onwards. This discount rate and time period effectively reduces the cash price by around two thirds.

Prices are discounted because although the NDA's geological repository is expected to open in 2040 the disposal of new build spent fuel will not begin until 2130, 90 years later. Yet this commercial disposal timing is rather arbitrary because new build spent fuel could be disposed more or less immediately after reactor closure in 2080 provided that the repository has been sufficiently engineered to accept the extra heat load from higher burn-up PWR spent fuel.

High burn-up fuel may need 75 years cooling, meaning that spent fuel from a reactor starting-up in 2020 could be disposed in a geological repository from 2095 onwards. The final spent fuel core discharged after reactor closure in 2080 would be disposed around 2155.

Under the government's proposals an energy utility company operating an EPR in Britain from 2020 (EDF Energy for example) could pay £515m in 2080 after the reactor has shut-down, transferring title of its lifetime spent fuel liability to the government. The £515m early transfer payment would avoid a future spent fuel disposal liability of £1,530m. The discounted pricing assumes that £515m cash paid in 2080 is worth £1,530m in 2130. This may not necessarily be true in the real world as much depends on future national economics. Accurately forecasting national economic trends over the next 120 years (at 2130) is highly questionable and is one of the reasons why we suggest switching to 'actual costs' disposal pricing.

Furthermore, as noted in the Executive Summary of this Research Report, the energy utility could make a substantial profit between the value of the spent fuel investment fund at 2080 and the early transfer price charged by government in 2080. (The graphic in the Executive Summary shows a liability of £1,530m, a fund value of £942m, a transfer price of £515m, a net profit for the utility of £427m, and a loss for the taxpayer of £1,015m).

While we support the early transfer of spent fuel from energy utilities to government management control as soon as practicable, the utility should pay the disposal price in full in 2080 (without discounting) on the basis that the repository will already be fully operational. Indeed the geological repository will already be 40 years old at the 2080 transfer date.

4.4 Leasing and Take-Back of Spent Fuel Abroad

The high cost of spent fuel disposal in the UK may drive energy utilities to lease returnable fuel supplies from abroad. France, Russia and South Korea already offer such closed-cycle nuclear fuel services to the United Arab Emirates and other Middle Eastern countries. Uranium fuel leasing and take-back would avoid the need for disposing of spent fuel in the UK, essentially displacing the environmental problem overseas to the supplying country of origin.

For example, Areva of France could supply nuclear fuel to French-owned EDF Energy for burning in British EPR reactors. After 4 years irradiation and 5 years cooling the spent fuel could be returned to France for reprocessing and disposal in a French repository. Rosatom (Russia) and KEPCO (South Korea) may offer similar take-back arrangements for developing nuclear states.Western governments have made similar offers to Iran through the United Nations. We judge this commercial scenario to be quite plausible for the UK market because the three energy utility consortia that are proposing to construct new nuclear power stations in Britain are 85% foreign-owned by Continental European energy utility companies.[24]

The government's FUP Consultation Document gives nuclear energy utility companies the option of deferring the setting of their Fixed Unit Prices for 10 years until after the nuclear power station has started-up (effectively delaying the economic decision to 2030). This timing flexibility also seems to support the possibility of spent fuel leasing and take-back.

The commercial possibility of spent fuel leasing raises many practical questions over the possible details of any overseas reprocessing of UK-origin spent fuel and whether there would be returns of nuclear waste or separated nuclear materials (plutonium and uranium) extracted during reprocessing. This Research Report does not examine the policy or legal implications of overseas reprocessing either for the UK or those countries named above.

4.5 Further Research

This Research Report has briefly analysed typical nuclear reactor construction scenarios under the central (most likely) economic conditions assumed by the government in its March 2010 Fixed Unit Price Consultation Document. However in line with FSA best practice we would recommend that a financial stress test is undertaken using the FUPSIM model to assess the overall stability and robustness of the FUP scheme under a wider range of economic and technical conditions, and to perform a sensitivity analysis of modeling parameters.

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[24] Institution of Mechanical Engineers. *Nuclear Build: A Vote of No Confidence?* March 2010

GLOSSARY OF TERMS USED

AP1000™ - Advanced Passive 1,1150 MWe nuclear reactor designed by the American firm Westinghouse (owned by Toshiba).

CCS - Carbon Capture and Storage, a developing technology for disposal of carbon emissions from fossil-fueled power stations.

DTI - the UK government's former Department of Trade and Industry.

DECC - the Department of Energy and Climate Change created in October 2008.

EPR™ - Evolutionary Pressurised-water Reactor 1,650 MWe, designed and marketed by the French state-owned firm Areva.

FUP - Fixed Unit Price paid by energy companies to the government for disposal of spent nuclear reactor fuel in a national UK deep geological repository facility (GDF).

FUPSIM - Fixed Unit Price Simulation, a mathematical model of the government's Fixed Unit Price disposal scheme for spent nuclear reactor fuel.

GDF - Geological Disposal Facility, a proposed UK national repository for disposing of nuclear waste deep underground.

GWe - Gigawatt electrical, the electrical power output of a nuclear power station, equivalent to 1,000 MWe.

kWh - kilowatt hour, the electrical power output of a nuclear power station, usually expressed over a defined period of time.

MWe - Megawatt electrical, the electrical power output of a nuclear power station.

MWh - Megawatt hour, the electrical power output of a nuclear power station, usually expressed over a defined period of time.

MWt - Megawatt thermal, the total heat power output of a nuclear reactor core.

NDA - Nuclear Decommissioning Authority, a UK government-owned Non Departmental Public Body (NDPB) responsible for constructing a deep geological repository.

NIREX - Nuclear Industry Radioactive Waste Executive, a nuclear waste disposal research body, now part of the NDA.

p/kWh - pence per kilowatt-hour electrical, a price charged per unit of electricity.

£/MWh - pounds per megawatt-hour electrical, a price charged per unit of electricity.

£m/tU - million pounds per metric tonne of uranium spent fuel heavy metal.

tU - metric tonnes of uranium spent fuel expressed as the heavy metal.

£m - million pounds sterling.

£bn - billion pounds sterling.

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