Research Report

Subsidy Assessment of Waste Transfer Pricing for Disposal of Spent Fuel from New Nuclear Power Stations

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Publication Disclaimer

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Executive Summary

The Coalition Government has sensibly proposed to revise the spent fuel disposal pricing basis from a *Fixed Unit Price* to what is effectively a *Variable Unit Price with Maximum Price Cap*. This more flexible arrangement is now called the *Waste Transfer Price* (WTP).

The Waste Transfer Price will increase over time as the final outturn costs of actually siting, building and operating the government's deep Geological Disposal Facility (GDF) are better understood.The Coalition Government has also proposed that the Waste Transfer Price should be deferred for a period up to 30 years after the start of nuclear reactor generation.

The variable unit pricing and the 30 year deferral period are important new principles introduced by the Coalition Government which potentially make spent fuel disposal pricing much fairer for taxpayers. The major advantage is that the government will have a very good idea of the actual costs of disposal by the end of the 2050 Deferral Period, because the government's Geological Disposal Facility (GDF) is planned to be fully operational by 2040. By 2050 the government will know the true outturn capital cost of siting and constructing the repository and will also have had 10 years practical operating experience running the repository.

However subsidy problems arise from DECC setting the level of the *Expected Price* and the *Price Cap* which appear to be too low. To help like-for-like comparison between FUPSIM and DECC cost calculations, we have used DECC's generic 1.35 GWe reactor assumptions. All calculations have been checked using a Hewlett Packard HP-12C Financial Calculator.

There are two potential *indirect subsidies* to energy companies for spent fuel disposal. The subsidies are indirect because the NDA would suffer the losses, not energy companies.

- **Maximum Price Cap**. Is the spent fuel disposal Price Cap (978 £k/tU) high enough to cover the government's costs, based on what we know about nuclear cost escalation trends?
- **Unit Disposal Cost**. Has the marginal cost to the government of spent fuel disposal (193 £k/tU) been underestimated compared with conservative modelling predictions?

Based on our Fixed Unit Price Simulation (FUPSIM) modelling analysis:

- **Price Cap Subsidy**. If the NDA repository experiences future nuclear cost escalation at the NDA's usual historic rate of 4.5% (above inflation) then actual unit costs of disposal will rise eventually exceeding the Price Cap by 2047. The disposal price paid by the energy utility will not fully cover the NDA's disposal costs, and so the NDA will require a government subsidy to make up the shortfall. The subsidy is around £131 million for a 40 year PWR but becomes significantly worse at around £1,127 million for a 60 year PWR.

- **Disposal Cost Underestimation Subsidy**. DECC may have underestimated the NDA's true disposal costs by 280 £k/tU, the difference between FUPSIM (473 £k/tU) and DECC estimates (193 £k/tU). The underestimation will mean that the NDA will not fully recover all of its disposal costs for new build reactor fuel, and so the NDA will require an indirect government subsidy to make up the shortfall. The subsidy will be around £296 million for a 40 year PWR and proportionally larger at £445 million for a 60 year PWR.

- **Overall Subsidy**. The total subsidy is of the order of £427 million (39% of the Capped Disposal Price) for a 40 year 1.35 GWe PWR. For a 60 year 1.35 GWe PWR the total subsidy is significantly worse of the order of £1,572 million (95% of the Capped Disposal Price), arising mainly because of the very severe effects of nuclear cost escalation on NDA losses.

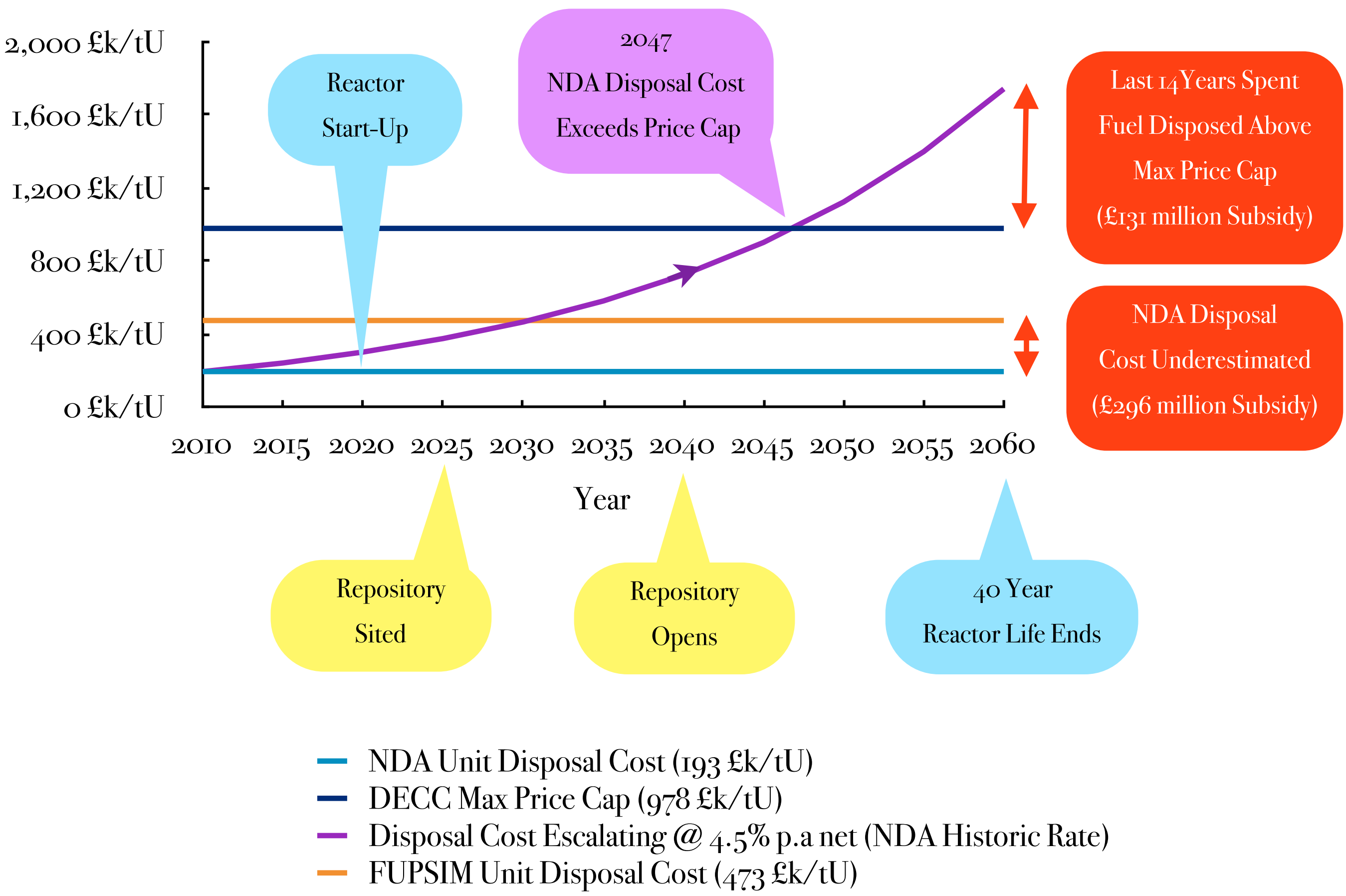
NDA Subsidies Needed to Recover Full Costs of Spent Fuel Disposal (Per Reactor)

DECC 1.35 GWe PWR	DECC 'Expected Price' Spent Fuel Disposal	DECC 'Capped Price' Spent Fuel Disposal	Estimated NDA Subsidies Needed	Comment
40 year lifetime	£670 million Price Paid By Energy Utility	£1,104 million Max Price Paid By Energy Utility	£131 million Price Cap Subsidy £296 million Disposal Cost Underestimation Subsidy **£427 million** **Total Gov Subsidy**	**39% government subsidy** needed by NDA on top of the Capped Price paid by energy utilities

DECC 1.35 GWe PWR	DECC 'Expected Price' Spent Fuel Disposal	DECC 'Capped Price' Spent Fuel Disposal	Estimated NDA Subsidies Needed	Comment
60 year lifetime	£1,005 million Price Paid By Energy Utility	£1,656 million Max Price Paid By Energy Utility	£1,127 million Price Cap Subsidy £445 million Disposal Cost Under-estimation Subsidy **£1,572 million** **Total Gov Subsidy**	**95% government subsidy** needed by NDA on top of the Capped Price paid by energy utilities

Based on 10 reactor fleet. Subsidy per reactor will be higher if fewer reactors are built. The Total Subsidy is in fact slightly underestimated here because the Disposal Cost Subsidy will also affect the Price Cap Subsidy but we have calculated the two subsidies separately.

Price Cap Subsidy and Disposal Cost Underestimation Subsidy (Per Reactor)



We have also observed two interesting pricing anomalies:

- **Futures Market for Nuclear Waste.** An unintended consequence of setting fixed government price caps on nuclear waste disposal is the possible emergence of a tradable futures market. The combination of high NDA nuclear cost escalation combined with low DECC price capping may result in an unusual situation when the GDF repository first opens in 2040. Because of cost escalation the capped price for spent fuel disposal set for an energy company may already be cheaper than the through-the-door-price for new disposal customers entering the market. The Disposal Price would reach the Price Cap by 2036 (assuming 4.5% nuclear escalation), well before the 30 year price-setting Deferral Period ends in 2050. As a result, market players may trade spent fuel disposal capacity contracts with each other for a profit. This suggests that the DECC Price Cap has probably been set too low.
- **New Build Reactor Fuel Disposal is Half the Cost of Existing Reactor Fuel Disposal.** In DECC's pricing model we understand that new PWR nuclear reactor spent fuel disposal is half the cost of disposing of AGR spent fuel from Britain's existing reactor fleet. In other words PWR fuel disposal is half the cost of AGR fuel disposal on the same per-tonne basis. Presentationally this may perhaps give the appearance of favouring new nuclear build and so raises questions of balance and fairness in the pricing method. There are also technical and operational reasons why the pricing differential might not be valid in the real world.

There are two straightforward solutions to solve the subsidy issues identified in this Report:

- **Remove the Price Cap**. This would avoid most of the subsidy difficulties. We suggest that variable spent fuel disposal prices should be set based on the NDA's actual costs, indexed for both *NDA cost escalation* and *CPI price inflation*. At present DECC disposal prices would be indexed for inflation only but not nuclear cost escalation which causes most of the difficulty. Fully variable spent fuel disposal prices are better than Capped Prices since they guarantee that the taxpayer will be repaid in full without any public subsidy.
- **Set a Single Price for AGR, PWR and MOX Spent Fuel**. Most of the differences between FUPSIM and DECC unit cost modelling arise because of the way that DECC calculates lower disposal costs for PWR spent fuels. Setting one uniform (per-tonne uranium) disposal price for all major spent fuel types (AGR, PWR, MOX) would make more sense.

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1. Policy Background

In March 2010 the previous Labour Government consulted on proposals to set a Fixed Unit Price (FUP) for the disposal of radioactive wastes from new nuclear power stations that might be built in the UK.[1] In December 2010 the new Coalition Government published improved and more flexible proposals to set a Waste Transfer Price (WTP) for nuclear waste disposal.[2] The WTP consultation process must be seen within the wider background of the Coalition Government's objectives both to reduce the UK national deficit through better public spending controls and also to offer no direct subsidies for new nuclear power station development.[3]

2. Purpose of this Updated Research Report

Jackson Consulting was previously commissioned by Greenpeace to develop an interactive computer simulation of spent fuel disposal pricing called FUPSIM. The FUPSIM model and Research Report was published in June 2010.[4] Jackson Consulting has been commissioned by Greenpeace to briefly reassess the Coalition Government's new pricing proposals using FUPSIM and identify any potential subsidies that might favour nuclear energy development.

This updated Research Report is intended to be provide a realistic and impartial appraisal of spent fuel disposal pricing. The views expressed and conclusions reached are solely those of Jackson Consulting and do not necessarily represent those of Greenpeace.

3. DECC Generic 1.35GWe PWR Used in FUPSIM

To help like-for-like comparison between FUPSIM and DECC calculations, we have used DECC's generic reactor modelling assumptions as far as possible based on a 1.35GWe PWR reactor operating for 40 years lifetime, generation start-up 2020, end of generation 2060, average Load Factor 90%, with a lifetime generating output of 424,000 GWh over 40 years.

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[1] 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.

[2] Department of Energy and Climate Change. *Consultation on an Updated Waste Transfer Pricing Methodology for the Disposal of Higher Activity Waste from New Nuclear Power Stations*. 7th December 2010.

[3] Conservative Party. *Conservative Liberal Democrat Coalition Negotiations. Agreements Reached*. 11th May 2010.

[4] Greenpeace UK. *Fixed Unit Price Simulation For Disposal of Spent Fuel from New Nuclear Power Stations in the UK*. Research Report by Jackson Consulting. 15th June 2010.

4. Report Author

This Research Report was written by Ian Jackson, an independent nuclear consultant and currently an Associate Fellow in the Energy, Environment and Development Programme of the Royal Institute of International Affairs, Chatham House. Ian Jackson is the author of *Nukenomics: The Commercialisation of Britain's Nuclear Industry* (2008).

5. Downloading and Running FUPSIM

FUPSIM is a free-to-use fully interactive research simulation of nuclear reactor spent fuel disposal pricing using the state-of-the-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.

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

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

The FUPSIM model and User Guide is available as a free download here:

http://www.jacksonconsult.com/fupsim.html

6. Coalition Government's Revised Spent Fuel Disposal Pricing

The Coalition Government has sensibly proposed to revise the spent fuel disposal pricing basis from a *Fixed Unit Price* to what is effectively a *Variable Unit Price with Maximum Price Cap.* This more flexible arrangement is now called the *Waste Transfer Price* (WTP). The Waste Transfer Price will almost certainly increase over time as the final outturn costs of actually siting, building and operating the government's deep Geological Disposal Facility (GDF) are better understood. At present we can only have a hazy idea about what these lifecycle costs might be, although the current planning estimate by the Nuclear Decommissioning Authority (NDA) is £12.2 billion (undiscounted). The government has also very sensibly proposed that the Waste Transfer Price should be deferred for a period up to 30 years after the start of nuclear reactor generation. Assuming Britain's fleet of new nuclear reactors starts up around 2020 then the Waste Transfer Price would be deferred until 2050. The *Final Price* paid by an energy utility company will depend on the (variable) Waste Transfer Price at 2050, subject to an agreed maximum Price Cap set by the Secretary of State today.

The variable unit pricing and the 30 year deferral period are important new principles introduced by the Coalition Government which potentially make spent fuel disposal pricing much fairer for taxpayers. The major advantage is that the government will have a very good idea of the actual costs of disposal by the end of the 2050 Deferral Period, because the government's Geological Disposal Facility (GDF) is planned to be fully operational by 2040. By 2050 the government will know the true outturn capital cost of siting and constructing the repository and will also have had 10 years practical operating experience running the repository.

Table 1
DECC's Proposed Spent Fuel Disposal Pricing

Waste Transfer Price	Estimate	Comment
Unit Disposal Cost (Base Cost)	193 £k/tU	DECC estimate of the minimum unit cost today for disposing of one tonne of uranium spent fuel in the NDA's Geological Disposal Facility (GDF).
Combined Risk Premium and Risk Fee Cost	119 £k/tU	DECC estimate of combined Risk Premium and Risk Fee (62% overall) to compensate the government for taking on the risk that future disposal costs will escalate above the Price Cap after the Final Price is set.
Utility Disposal Price	312 £k/tU (1.6 x Base Cost)	DECC estimate today of the future price paid by the energy utility company to government to dispose of one tonne of uranium spent fuel in the NDA's Geological Disposal Facility (GDF).
Max Price Cap	978 £k/tU (5.1 x Base Cost)	DECC maximum price cap that the energy utility would pay to government for disposal of one tonne of uranium spent fuel. DECC estimate there is a 99% probability that the actual disposal cost will be below the Price Cap, and a 1% probability that the actual disposal cost will exceed the Price Cap.

Source: DECC Waste Transfer Price Consultation Document at Page 6. Costs are undiscounted and expressed in March 2008 prices. The most recent full lifecycle evaluation of GDF costs was £12,157 million (undiscounted) at 31st March 2008 [NDA 2008].

7. Potential Subsidies

The Oxford English Dictionary defines a subsidy as "a sum of money granted from public funds to help an industry or business keep the price of a commodity or service low". In practice *direct subsidies* paid in cash by government to an industry are rare. Instead governments usually prefer *indirect subsidies,* for example through artificially low pricing deals where a publicly funded body does not recover its full costs for providing a service to industry.

There are two potential indirect subsidies to energy companies for spent fuel disposal:

- **Maximum Price Cap**. Is the spent fuel disposal Price Cap (978 £k/tU) high enough to cover the government's costs, based on what we know about nuclear cost escalation trends?
- **Unit Disposal Cost**. Has the marginal cost to the government of spent fuel disposal (193 £k/tU) been underestimated compared with conservative modelling predictions? FUPSIM uses a well known power law scaling relationship to calculate per-tonne costs.[5]

8. NDA Nuclear Cost Escalation

Nuclear projects, especially unique first-of-a-kind (FOAK) facilities, have historically suffered from significant cost escalation well above national inflation rates. Nuclear cost escalation might mean that the actual unit costs of disposal in the future may exceed the Price Cap today. Public taxpayers would therefore subsidise any financial shortfall between the capped price paid by the energy utility and the actual cost of disposal in the Geological Disposal Facility. The NDA is a good comparison benchmark for likely cost escalation because the NDA itself has responsibility for developing the government's Geological Disposal Facility.

Since the NDA was created in April 2005 its nuclear liabilities have escalated significantly, increasing 34% (£21. billion) in 4 years from £62.7 billion (2005/6 FY) to £83.8 billion today (2009/10 FY). This rise has been nearly continuous each year and suggests that NDA nuclear cost escalation has been approximately 4.5% annually, over and above the UK average inflation rate of 3.0% during the same 4 year period (YE 31 March 2006 to YE 31 March 2010)[6]. This sustained growth in NDA nuclear liabilities is shown in Graph 1 overleaf.

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[5] FUPSIM is based on the six tenths rule of cost estimation. See for example Chapter 20 of the US Department of Energy *Cost Estimating Guide* DOE G 430.1-1 (28 March 1997).

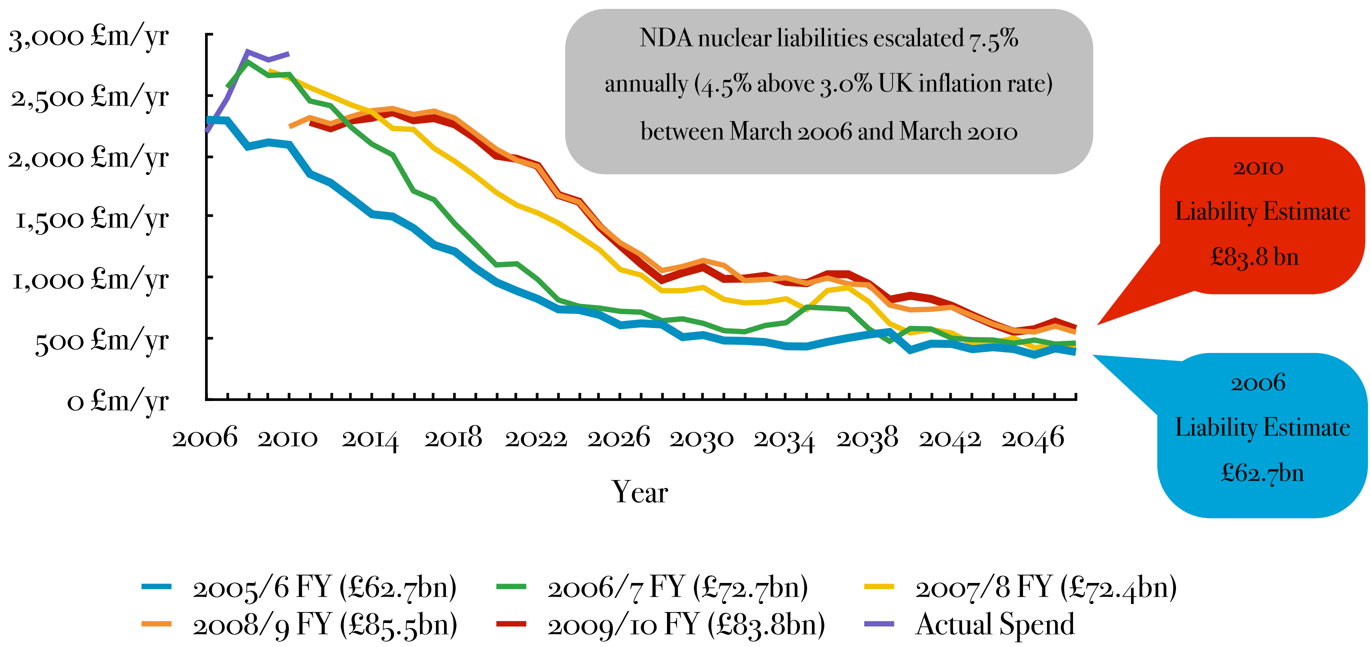
[6] Bank of England inflation calculator. UK inflation from 2005 to 2010 averaged 3.0% per annum. http://www.bankofengland.co.uk/education/inflation/calculator/flash/index.htm

NDA nuclear liability escalation trends are especially suggestive because they share key similarities with a GDF; the lifecycle costs are spread over similar very long timescales of at least 100 years into the future; and capital construction costs are a relatively small component (25%) of the overall lifecycle costs, which are dominated by facility running costs (75%).

There is some evidence that NDA cost escalation has peaked and is now slowing, because the past two years estimates are very similar (see the red and orange lines in Graph 1 below). However actual spending each year (shown by the purple line) has generally been higher than forecasted in previous years liability assessments. Overall the medium term trend does appear to be a gradual rise upwards at about 4.5% net annual cost escalation (above inflation). This level of cost escalation is fairly typical for nuclear projects and in fact similar to American experience developing the spent fuel repository at Yucca Mountain in New Mexico, USA.

Graph 1

4.5% Net Annual Cost Escalation in Nuclear Decommissioning Authority Liabilities



Source: NDA Annual Report & Accounts 2005/6 through to 2009/10. Spending and liability forecast data kindly provided by the NDA under the Freedom of Information Act.

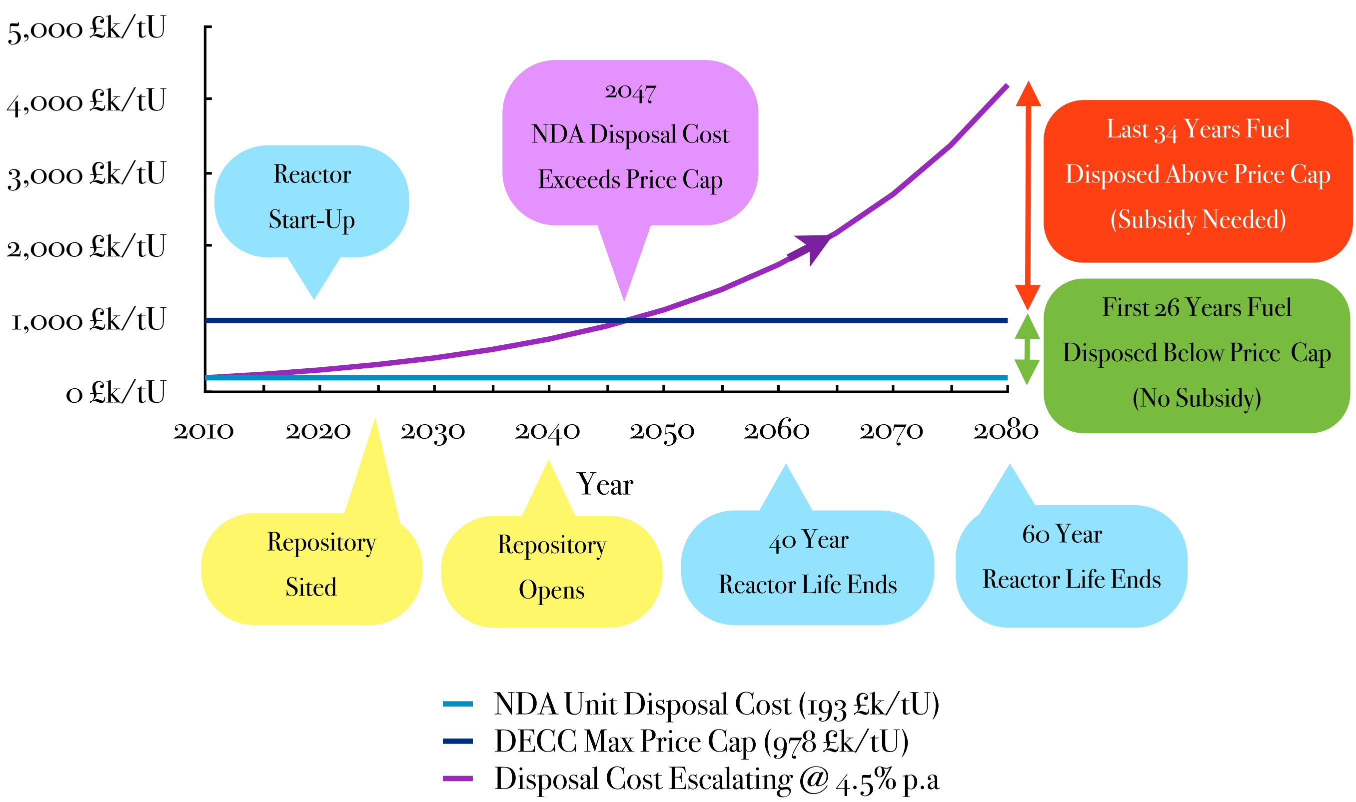
Note: For ease of display, Graph 1 shows a window of annual spending forecasts from 2006 to 2050 but total NDA lifecycle liabilities (currently £83.8bn) extend until 2135.

9. Price Cap Subsidy

DECC estimates the NDA's unit cost of spent fuel disposal to be 193 £k/tU in 2008 prices. This is the minimum unit cost (or base cost) that the NDA must be paid to fully recover its expenses for siting, building, operating and eventually closing the GDF disposal facility.

If the NDA repository experiences nuclear cost escalation at the NDA's usual historic rate of 4.5% (above inflation) then actual unit costs of disposal in the future will eventually exceed the Price Cap. The disposal price paid by the energy utility will not fully cover the NDA's disposal costs, and so the NDA will require a government subsidy to make up the shortfall. The subsidy is around **£131 million for a 40 year PWR** or **£1,127 million for a 60 year PWR**.

Graph 2
The Effect of 4.5% Nuclear Cost Escalation on the NDA's Spent Fuel Unit Disposal Costs, Compared with DECC's Unit Disposal Price Cap



Assuming the GDF experiences the NDA's 4.5% per annum net cost escalation then:

- **First 26 years of 40 year PWR lifetime (2020 - 2046)**. For the first 26 years of PWR reactor operation the NDA's actual disposal cost is below the DECC Price Cap. The Price of spent fuel disposal paid by energy companies will gradually increase but no public subsidy will be needed because the NDA will fully recover all of its actual disposal costs.

- **Last 14 years of 40 year PWR lifetime (2047 - 2060)**. For the final 14 years of PWR reactor operation the NDA's actual disposal cost will rise *above* the DECC Price Cap. Because the Final Price of spent fuel disposal paid by energy companies will remain fixed at the Price Cap, the NDA will not fully recover all of its actual disposal costs. The NDA will make a yearly loss which will gradually become worse over time (because of the effects of escalation). The government will therefore need to pay the NDA to cover these losses, making-up the shortfall. This provides an indirect subsidy of **£131 million** to the energy company.

- **Last 34 years of 60 year PWR lifetime (2047 - 2080)**. In reality both the AP1000 and EPR reactors planned to be built in the UK have 60 year design lifetimes. If the lifetime of the PWR is extended to 60 years then for the final 34 years of PWR reactor operation the NDA's actual disposal cost will be significantly above the DECC Price Cap. Under these circumstances the NDA would make a severe **£1,127 million** loss requiring a subsidy.

Table 2
NDA Subsidies Needed From Setting a Price Cap on Spent Fuel Disposal

DECC 1.35 GWe PWR	DECC 'Expected Price' Spent Fuel Disposal	DECC 'Capped Price' Spent Fuel Disposal	Additional NDA Subsidy Needed	Comment
40 year lifetime	£670 million Energy Utility	£1,104 million Energy Utility	**£131 million Government**	Government subsidy is 12% on top of the max Capped Price paid by energy utilities
60 year lifetime	£1,005 million Energy Utility	£1,656 million Energy Utility	**£1,127 million Government**	Government subsidy is 68% on top of the max Capped Price paid by energy utilities

Source: The total Expected Price and Capped Price are given in the DECC Waste Transfer Price Consultation Document at Page 6. (These include a small contribution from ILW). The size of the NDA Subsidy required as actual disposal costs escalate above the Price Cap is calculated in Table 3 and Table 4 below. All calculations are approximate.

Table 3
Subsidy Needed From Setting a Price Cap on Spent Fuel Disposal

Generic 1.35GWe, 40-Year PWR Reactor, 2020 - 2060

Date	NDA Unit Cost of Disposal (£k/tU)	DECC Price Cap on Disposal (£k/tU)	NDA Loss (£k/tU)	PWR Fuel Discharged (tU/yr)	Subsidy Needed (£k)
2010	**193**	**978**	**0**	**0**	**0**
2046	941	978	0	26.5	0
2047	984	978	-6	26.5	159
2048	1,028	978	-50	26.5	1,325
2049	1,074	978	-96	26.5	2,544
2050	1,123	978	-145	26.5	3,843
2051	1,173	978	-195	26.5	5,168
2052	1,226	978	-248	26.5	6,572
2053	1,281	978	-303	26.5	8,030
2054	1,339	978	-361	26.5	9,567
2055	1,399	978	-421	26.5	11,157
2056	1,462	978	-484	26.5	12,826
2057	1,528	978	-550	26.5	14,575
2058	1,596	978	-618	26.5	16,377
2059	1,668	978	-690	26.5	18,285
2060	1,743	978	-765	26.5	20,273
				Total Subsidy	**£131 million**

Note: Assumes actual NDA Unit Cost of Disposal (£k/tU) escalates at the NDA's historic nuclear escalation rate of 4.5% per annum net (above inflation). FUPSIM estimates that DECC's Generic 1.35 GWe PWR will discharge 1060 tU over 40 years (26.5 tU/yr). NDA cost escalation calculations performed on an HP 12C Financial Calculator.

Table 4
Subsidy Needed From Setting a Price Cap on Spent Fuel Disposal

Generic 1.35GWe, 60-Year PWR Reactor, 2020 - 2080

Date	NDA Unit Cost of Disposal (£k/tU)	DECC Price Cap on Disposal (£k/tU)	NDA Loss (£k/tU)	PWR Fuel Discharged (tU/yr)	Subsidy Needed (£k)
2010	**193**	**978**	**0**	**0**	**0**
2046	941	978	0	26.5	0
2047	984	978	-6	26.5	159
2048	1,028	978	-50	26.5	1,325
2049	1,074	978	-96	26.5	2,544
2050	1,123	978	-145	26.5	3,843
2051	1,173	978	-195	26.5	5,168
2052	1,226	978	-248	26.5	6,572
2053	1,281	978	-303	26.5	8,030
2054	1,339	978	-361	26.5	9,567
2055	1,399	978	-421	26.5	11,157
2056	1,462	978	-484	26.5	12,826
2057	1,528	978	-550	26.5	14,575
2058	1,596	978	-618	26.5	16,377
2059	1,668	978	-690	26.5	18,285
2060	1,743	978	-765	26.5	20,273
2061	1,822	978	-844	26.5	22,366
2062	1,904	978	-926	26.5	24,539
2063	1,989	978	-1,011	26.5	26,792
2064	2,079	978	-1,101	26.5	29,177
2065	2,172	978	-1,194	26.5	31,641

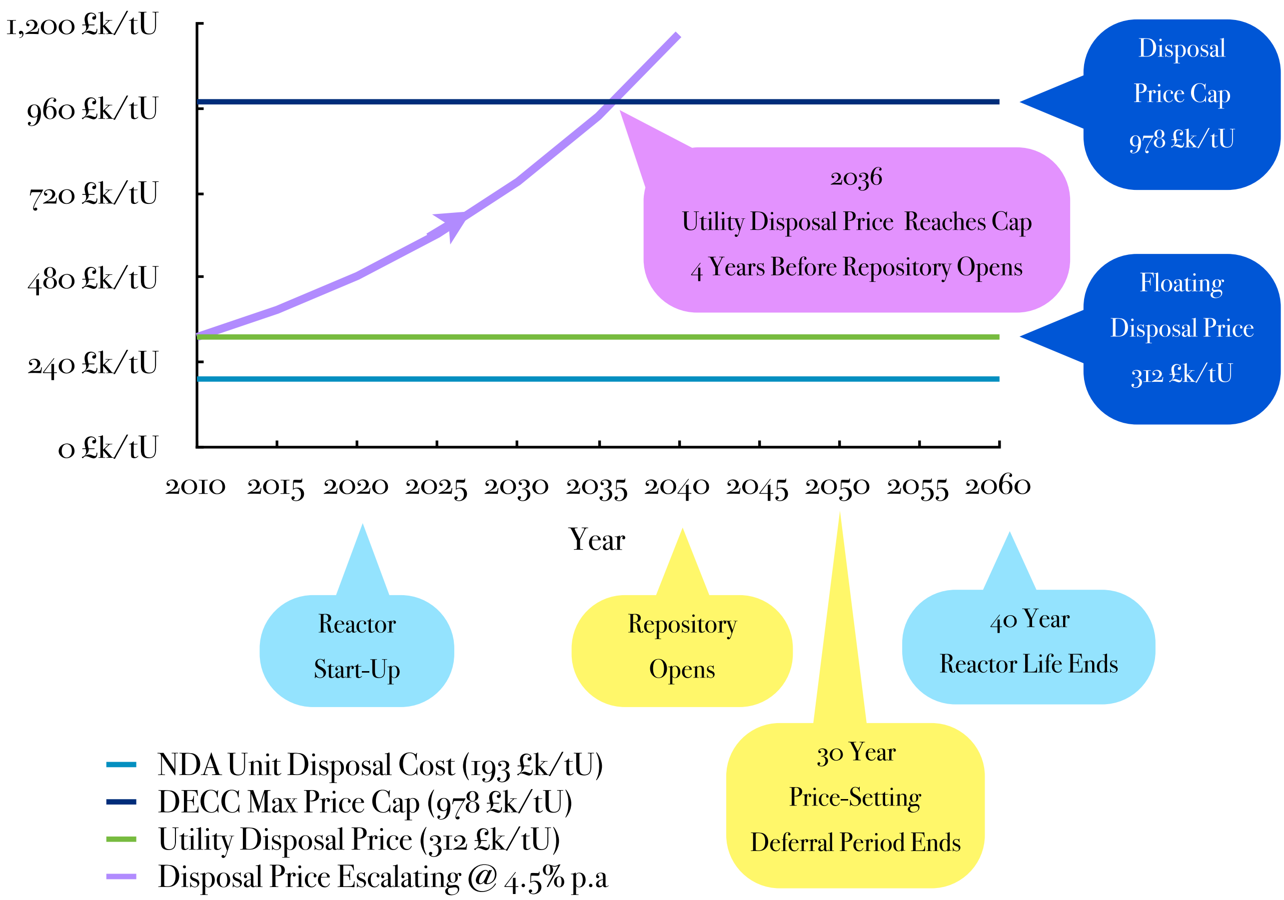
Date	NDA Unit Cost of Disposal (£k/tU)	DECC Price Cap on Disposal (£k/tU)	NDA Loss (£k/tU)	PWR Fuel Discharged (tU/yr)	Subsidy Needed (£k)
2066	2,270	978	-1,292	26.5	34,238
2067	2,372	978	-1,394	26.5	36,941
2068	2,479	978	-1,501	26.5	39,777
2069	2,591	978	-1,613	26.5	42,745
2070	2,707	978	-1,729	26.5	45,819
2071	2,829	978	-1,851	26.5	49,052
2072	2,956	978	-1,978	26.5	52,417
2073	3,089	978	-2,111	26.5	55,942
2074	3,228	978	-2,250	26.5	59,625
2075	3,374	978	-2,396	26.5	63,494
2076	3,526	978	-2,548	26.5	67,522
2077	3,684	978	-2,706	26.5	71,709
2078	3,850	978	-2,872	26.5	76,108
2079	4,023	978	-3,045	26.5	80,693
2080	4,204	978	-3,226	26.5	85,489
				Total Subsidy	**£1,127 million**

Note: Assumes actual NDA Unit Cost of Disposal (£k/tU) escalates at the NDA's historic nuclear escalation rate of 4.5% per annum net (above inflation). FUPSIM estimates that DECC's Generic 1.35 GWe PWR will discharge 1590 tU over 60 years (26.5 tU/yr). NDA cost escalation calculations performed on an HP 12C Financial Calculator.

10. Futures Market from Price Cap and Deferral Period

The combination of NDA nuclear cost escalation combined with DECC price capping may also result in a strange situation when the GDF repository first opens in 2040. Because of cost escalation the capped price for spent fuel disposal paid by an energy company may already be cheaper than the through-the-door-price for new customers entering the market. And in fact the Disposal Price would reach the Price Cap by 2036 (assuming 4.5% nuclear escalation), well before the 30 year price-setting Deferral Period ends in 2050. Overall this suggests that the DECC Price Cap has probably been set too low.

Graph 3
The Effect of 4.5% NDA Nuclear Cost Escalation on the Spent Fuel Disposal Price Actually Paid By Energy Utilities



The NDA's Strategy Director warned in May 2010 that this price difference might inadvertently create a *futures market* in radioactive waste disposal.[7] A futures market is a trading market where participants buy and sell future contracts for delivery or supply of a service (such as radioactive waste disposal for example) on some specified future date.

The 312 £k/tU Disposal Price charged by DECC (which is about 62% higher than the NDA's 193 £k/tU unit cost) will escalate reaching the maximum Price Cap by 2036, some 4 years *before* the repository first opens in 2040. This means that early contracts for spent fuel disposal will be cheaper than the normal NDA door price paid by later repository customers.

A market trader (such as a new energy company) could then buy the right to dispose of a certain amount of spent fuel (from another energy company trader) at slightly below the future door price. This is basically a system of tradable futures contracts. It would also encourage energy companies to sign disposal contracts with DECC early on for rather more disposal capacity than perhaps needed, so that this might be sold for a profit later to new market players. An energy company trader might also choose to sell their disposal allowance if they did something else with the spent fuel instead such as transfer it to a store or reprocess it.

The creation of a futures market in spent fuel disposal is not necessarily a bad thing. It might even result in much better spent fuel management strategies to reduce disposal volumes and so maximise trading profits from selling spare disposal capacity. But it does serve to illustrate the unintended consequences of setting fixed government price caps on nuclear services. The possible emergence of a futures market strongly suggests that the Price Cap is too low.

[7] Nuclear Decommissioning Authority. *Nuclear Decommissioning Authority Response to Fixed Unit Price Consultation*. Dr Adrian Simper (Strategy Director). May 2010. The NDA was concerned that awarding a disposal capacity contract at fixed price (now capped price) might give the energy utility an asset if the future price has been underestimated. The energy utility could then sell their disposal capacity allowance later for a profit. The NDA Strategy Director was clearly well aware and mindful of the NDA's 4.5% cost escalation trajectory.

11. Reliability of DECC and FUPSIM Modelling

We are grateful to DECC for providing helpful comments on the FUPSIM model.[8] This has improved our understanding of how DECC models disposal costs and the key sensitivities.

The total cost of a GDF repository is very sensitive to the total quantity of spent fuel it contains. For example the NDA's historic legacy of spent fuel represents only 2% of the total volume of waste in a repository but is responsible for around 50% of the gross repository cost. This makes it difficult to reliably model unit disposal costs because even small changes in the spent fuel inventory can significantly increase the total lifecycle cost of the repository.

Table 5
2007 MRWS Waste Inventory[9] and 2005 Nirex Repository Cost Estimates[10]

Nuclear Waste	Packaged Volume (m3)	Packaged Volume (%)	NIREX Repository Cost (£m 2003)	NIREX Unit Cost (£k/tU)
Spent Fuel HLW	11,200 1,400	2.3% 0.3%	Single SF/HLW GDF £5,035m	952 £k/tU
ILW Others	364,000 100,300	76.3% 21.1%	Shared SF/HLW/ILW/O GDF £10,100m	952 £k/tU
	476,900	100%		

Note: The average unit cost of spent fuel disposal was approximately = £5035m/(3,500tU AGR + 1,200tU PWR) x 11,200 m3 / (11,200 m3 + 1,400 m3) = £0.952m/tU to dispose of the CoRWM inventory of 3,500tU AGR + 1,200tU PWR = 4,700tU [NIREX, 2005][CoRWM,2006]. The latest DECC legacy spent fuel inventory has now increased to 7,000tU AGR + 1,200tU PWR = 8,200tU [DECC, 2010].

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[8] Department of Energy and Climate Change. *OND Analysis of Independent Report for Greenpeace by Jackson Consulting: Fixed Unit Price Simulation for Disposal of Spent Fuel from Nuclear Power Stations in the UK (FUPSIM)*. Internal Note to File. November 2010.

[9] Department for Environment, Food and Rural Affairs. *Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal*. Cm7386. June 2008.

[10] NIREX. *Summary Note for CoRWM on Cost Estimates for CoRWM Option 7 (Deep Geological Disposal) and Option 9 (Phased Deep Geological Disposal)*. NIREX Technical Note 484432. September 2005.

The development of a brand new first-of-a-kind (FOAK) Geological Disposal Facility will be a difficult technical challenge. A fully costed and Peer Reviewed site-specific development and construction plan has yet to be prepared. Britain has not yet selected its disposal site nor disposal technology although the reference concept is KBS-3V, a system involving the disposal of spent fuel within copper canisters. KBS-3V looks a promising option but recently the NDA has investigated different alternative spent fuel packaging and repository emplacement arrangements.[11] It is interesting that this technical management review was triggered by the need to reduce 160-year spent fuel cooling and storage times at proposed nuclear reactor build sites. Feedback from public meetings strongly opposed this during the 2010 Nuclear National Policy Statement (Nuclear NPS) consultation process for siting new reactors.[12] A solution has been proposed involving the judicious mixing of different ages of irradiated PWR spent fuel which might cut on-site storage times to around 50 years. In future the Site Licence Company (SLC) responsible for construction and operation of the GDF repository will probably drive further innovations and improvements in radioactive waste management. For example the US consortia running other nuclear sites in the UK have already introduced new operational innovations with the aim of improving efficiency and reducing costs.

In the light of this uncertainty, FUPSIM uses a conservative approach to calculate unit disposal costs for new nuclear reactors by scaling upwards from known NDA costs based on the total mass of legacy AGR and PWR uranium fuels needing disposal. The method involves a mathematical power law which is well known in process cost estimation.[13] The method is conservative because it assumes that one tonne of uranium AGR fuel will be packaged and disposed in much the same way as one tonne of uranium PWR fuel. Both fuels contain the same one tonne mass of uranium, the only difference is the physical geometry of the fuel rod assembly and its outer cladding. AGR fuel rods sit within a circular honeycomb structure whereas PWR fuel rods sit within a very long and square shaped fuel assembly grid.

To make the most efficient use of repository space it is likely that AGR spent fuel assemblies would be size-reduced in some way (by stripping off the outer cladding), then treated and encapsulated before emplacement in a copper canister. This general approach to waste optimi-

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[11] Nuclear Decommissioning Authority. *Feasibility Studies Exploring Options for Storage, Transport and Disposal of Spent Fuel from New Nuclear Power Stations.* November 2010.

[12] Department of Energy and Climate Change. *The Government Response to the Consultation on the Draft National Policy Statements for Energy Infrastructure.* October 2010.

[13] FUPSIM is based on the six tenths rule of cost estimation. See for example Chapter 20 of the US Department of Energy *Cost Estimating Guide* DOE G 430.1-1 (28 March 1997).

sation is now standard practice in the waste management sector. The only major operational constraints are radiation dose to workers handing the fuel and the risks of criticality if too many spent fuel rods are deliberately squeezed together during size reduction. Furthermore the NDA will now probably employ complex mixing of both long and short-cooled spent fuel together, increasing the operational radiological hazard dealing with canisters.

Together these factors mean that an *NDA Spent Fuel Packaging Plant* [14] is likely to be built with sufficient robotic capability for remote handling spent fuels, size reduction and packing in a copper canister. Some of the necessary technology for remote handling and size reduction of spent fuel is already used at THORP to strip and reprocess AGR spent fuels.

Because of the likely convergence of similar handling and treatment techniques for both AGR and PWR spent fuels explained above, the most conservative approach to model disposal costs is to assume similar unit costs for both AGR and PWR spent fuels. The FUPSIM model takes this approach, avoiding complications from differing fuel and canister geometries.

However DECC treats the unit disposal costs from legacy AGR spent fuel and new PWR spent fuel separately, with new PWR spent fuel being about half the cost of AGR spent fuel. The difference arises because DECC models costs based on the volume of a copper disposal canister. DECC assumes that the capacity of a copper canister is just over 1 tonne for uranium AGR spent fuel but 2.06 tonnes for uranium PWR spent fuel. Because AGR fuel assemblies are rather bulky, fewer will fit inside a disposal canister. This is a reasonable calculation approach but it does mean that the costs of expanding a repository to dispose of PWR fuel from new nuclear reactors will become very much cheaper. This is because DECC assumes relatively inefficient packing of bulky AGR fuels but highly efficient packing of PWR fuels.

In practice both AGR and PWR spent fuels ought to have very similar disposal footprints per tonne of uranium, provided that they have been properly size-reduced in a packaging plant to remove their excess cladding. Robotic size reduction is easier for AGR fuels because the assemblies are fairly short (about 1 metre in length) and their outer graphite cladding shell can be easily removed. Moreover AGR spent fuel rods can be size reduced and compressed together with fewer criticality risks because the enrichment of AGR fuel is lower than PWR fuel. These operational practices should significantly improve the canister packing efficiency and make overall AGR disposal costs broadly similar to that for PWR spent fuel.

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[14] A £500m Centralised Spent Fuel Packing Plant has recently been proposed as an option and provisionally costed in the NDA's *Spent Fuel Feasibility Study* (November 2010).

Another problem with DECC modelling is that high burn-up (65GWd/tU) PWR spent fuel assemblies radiate more heat than standard burn-up AGR spent fuels (35 GWd/tU). In order to accommodate high burn-up spent fuels, fewer PWR fuel assemblies per storage canister might be necessary to maintain a repository temperature limit of 100 degrees C. However the NDA's judicious mixing strategy combining both short and long-cooled PWR spent fuel assemblies within a single canister might exacerbate this temperature control problem. (Judicious mixing is a political solution to help avoid 160-year spent fuel storage on reactor sites). A copper canister has an assumed capacity of 4 PWR spent fuel bundles (2.06 tU/can) but it is possible that this might need to be reduced in some cases to make judicious mixing work better (for example down to 3 bundles at 1.55 tU/can). Judicious mixing could perhaps reduce the PWR packing efficiency down towards a similar level as AGR fuel (1.0 tU) making overall AGR canister disposal costs broadly similar to that for PWR spent fuel.

In summary, both the likely operational impact of optimised size reduction of AGR fuels and judicious mixing of PWR fuels strongly suggests that the more prudent approach to modelling disposal costs is to assume similar unit costs for both AGR and PWR spent fuels. This is the conservative approach used in the FUPSIM model which we believe is the better way forward given the significant technical uncertainties dealing with AGR and PWR spent fuels.

Table 6
Summary of Reasons Why DECC Should Not Assume
New Build PWR Fuel is Half the Disposal Cost of Legacy AGR Fuel

FUPSIM Reasons For Similar Disposal Cost 1tU AGR =1tU PWR	DECC Reasons For Half Disposal Cost 1tU AGR = 2.06 tU PWR
• Conservative given operational uncertainties. • UK has not selected final disposal technology. • No site-specific fully-costed GDF build plan. • Alternative SF packing arrangements possible. • NDA Spent Fuel Packaging Plant is planned. • Standardised packing treatment regimes likely. • Size reduction to remove AGR cladding possible, improving packing efficiency similar to PWR. • Compression of low enriched AGR bundles possible, improving packing efficiency similar to PWR. • NDA judicious mixing strategy may reduce packing efficiency of mixed cooled PWR fuels. • Fewer PWR assemblies per storage canister might be necessary to maintain GDF temperature limit.	• KBS-3V is reference disposal concept at present. • Assume direct disposal of AGR and PWR fuel assemblies without significant pre-treatment. • 4 PWR spent fuel bundles (2.06 tU) fit in canister. • Fewer AGR spent fuel assemblies (1 tU) fit in copper canister (without size reduction).

12. Spent Fuel Disposal Costs for Different Reactor Fleet Sizes

The Labour 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".[15] This is an important principle affecting cost calculations. 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) from new nuclear build. FUPSIM calculates the *marginal* 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. FUPSIM displays both marginal and full share results.

If just a few new reactors are built then it is much more expensive to dispose of reactor fuel. But as the size of a new build reactor fleet increases then unit disposal costs drop. The unit costs are lower because larger repositories have better economies of scale than small ones. Put another way, unit costs are cheaper as more radwaste is added to the repository, up to a certain point limited by the maximum radiological capacity of the disposal site.[16] DECC has assumed a large 10 reactor fleet which significantly dilutes unit costs by 28%. A 10 reactor fleet is about the largest fleet size that could all be accommodated within a single repository.

FUPSIM was designed to simulate waste disposal liabilities and costs for any size of new nuclear power station built in the UK up to a total site generating capacity of 4GWe. For example FUPSIM can model various Single and Twin AP1000 and EPR reactor combinations that might be built on any of the 8 disposal sites in the Nuclear National Policy Statement (NPS).

FUPSIM models the full share costs of slightly expanding the NDA's Geological Disposal Facility (GDF) to accept spent fuel waste from any single new nuclear power station up to 4GWe. However FUPSIM was not designed to model costs from the entire new UK reactor fleet, which will probably range from between 1 and 10 new build reactor units by 2025. The Nuclear National Policy Statement is based on new reactors being fully deployable by 2025.

As the NDA repository expands with new nuclear build fuel added, Spent Fuel Unit Disposal Costs may be approximated through iterations of the *six-tenths rule* cost estimating formulae:

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[15] Department for Business, Enterprise and Regulatory Reform. *Meeting the Energy Challenge: A White Paper on Nuclear Power*.Cm7296. January 2008. See pages 152 - 153.

[16] The radiological capacity of a GDF repository 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.)

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

Cost B (CB), Cost A (CA), Size B (SB), Size A (SA), Scale Factor (SF = 0.6)

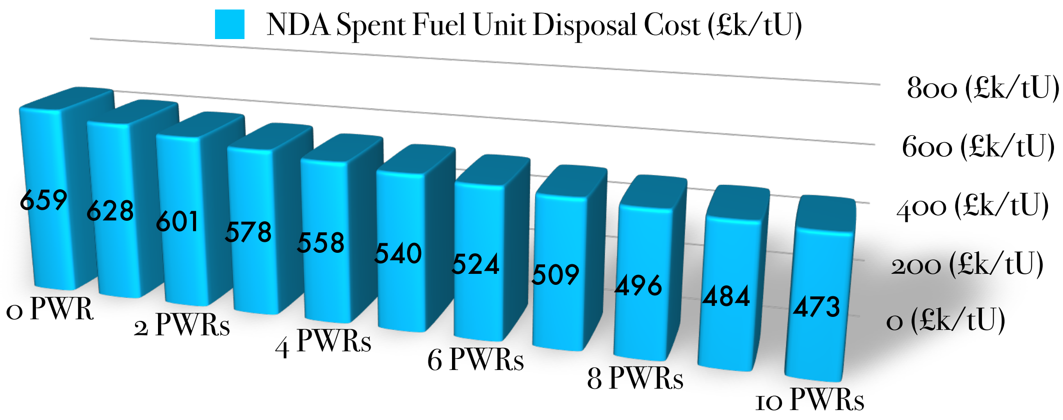
Table 7
Reduction in NDA Spent Fuel Unit Disposal Costs as Reactor Fleet Size Increases

1.35 GWe PWR Fleet Size	Spent Fuel Discharged (tU)	SIZE A Old Repository Inventory (tU)	SIZE B New Repository Inventory (tU)	COST A Old Spent Fuel Repository Cost Segment (£m)	COST B New Spent Fuel Repository Cost Segment (£m)	Shared Spent Fuel Unit Disposal Cost (£k/tU)
0	0	8,200	-	£5,404m	-	659
1	**1,060**	**8,200**	**9,260**	**£5,404m**	**£5,813m**	**628**
2	1,060	9,260	10,320	£5,813m	£6,204m	601
3	1,060	10,320	11,380	£6,204m	£6,579m	578
4	1,060	11,380	12,440	£6,579m	£6,940m	558
5	1,060	12,440	13,500	£6,940m	£7,289m	540
6	1,060	13,500	14,560	£7,289m	£7,627m	524
7	1,060	14,560	15,620	£7,627m	£7,955m	509
8	1,060	15,620	16,680	£7,955m	£8,275m	496
9	1,060	16,680	17,740	£8,275m	£8,587m	484
10	**1,060**	**17,740**	**18,800**	**£8,587m**	**£8,891m**	473

Note: The Spent Fuel and HLW proportion of the GDF repository cost is approximately 50% of the NDA gross lifecycle cost = £12,157m / 2 = £6,079m. The Spent Fuel cost segment is then split in proportion to the volume of SF packaged waste = £6,079 x 11,200 m3 SF / (11,200 m3 SF + 1,400 m3 HLW) = £5,404m. This is approximately the cost segment for disposal of the NDA's historic legacy of 8,200 tU Spent Fuel, without any new build fuel. The MRWS packaged waste volumes are given in Table 5 [MRWS, 2007].
Cost scaling margin of error using the six-tenths rule power law is typically +/- 20%.

Graph 4

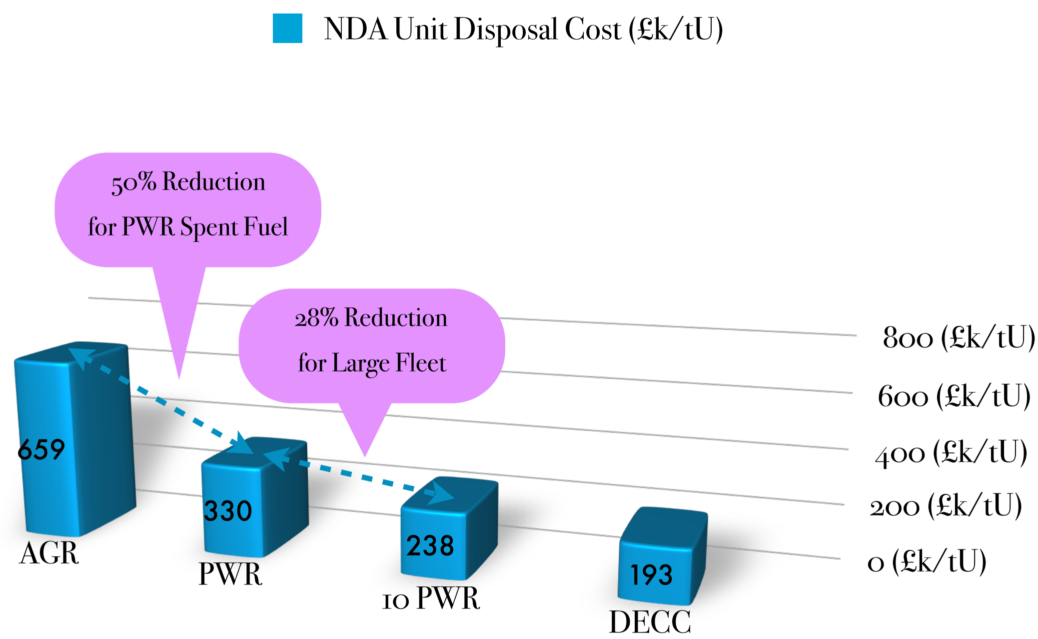
Reduction in NDA Spent Fuel Unit Disposal Costs as Reactor Fleet Size Increases



Note: FUPSIM modelled based on DECC's Generic 1.35GWe PWR reactor operating for 40 year lifetime, discharging 1060 tU. Calculations are shown in Table 7. A 10 PWR Fleet reduces unit disposal costs by 28% (from 659 £k/tU down to 473 £k/tU).

Graph 5

How DECC Calculates Low Unit Disposal Costs for New Build Spent Fuel



Note: Using this calculation method there is good agreement between FUPSIM's estimate of DECC unit cost (238 £k/tU) and DECC's stated unit cost (193 £k/tU) which is within FUPSIM's +/- 20% margin of error.

13. Disposal Cost Underestimation Subsidy for Large Fleet

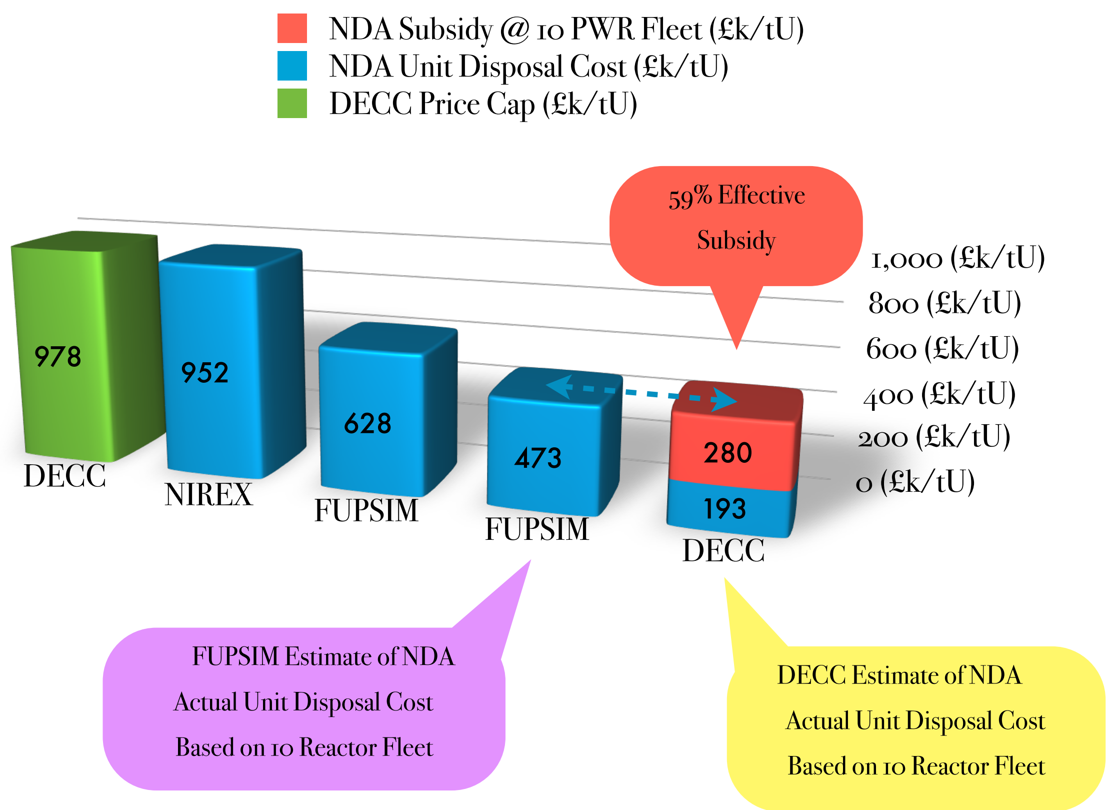
All computer models are a simplification of the real world. Both the FUPSIM simulation and DECC parametric models are approximate and will probably not be entirely correct. The best approach is to look at a range of unit cost predictions and make a sensible judgement. Table 8 and Graph 6 below show a range of modelled Unit Costs and the Price Cap for comparison.

Table 8
Range of Predictions for NDA Unit Costs of Spent Fuel Disposal
(The minimum unit cost needed to fully recover the NDA's actual disposal costs)

DECC Price Cap (£k/tU)	NIREX (£k/tU)	FUPSIM 1 PWR (£k/tU)	FUPSIM 10 PWR (£k/tU)	DECC Base Cost (£k/tU)
978	952	628	473	193

Note: FUPSIM unit cost estimates are given in Table 7 and Graph 4 based on DECC's 1.35GWe PWR with 40 year generating period. The NIREX estimate is in Table 5.

Graph 6
Range of Predictions for NDA Unit Costs of Spent Fuel Disposal



It is important to note that these are the minimum actual *Unit Costs* of spent fuel disposal not floating *Unit Prices* charged by DECC, which are set slightly higher subject to a maximum Price Cap. NIREX spent fuel disposal unit cost estimates are at the high end of the cost range, FUPSIM is towards the middle and DECC unit costs are at the bottom of the range.

DECC has assumed a large 10 reactor fleet which significantly dilutes unit costs. A 10 reactor fleet is about the largest fleet size that could all be accommodated in a single GDF. To calculate the subsidy from possible underestimation of NDA actual disposal costs it is fairest to compare the 10 reactor FUPSIM Unit Cost with the DECC Unit Cost (on like-for-like basis).

If FUPSIM modelling is correct then DECC may have underestimated the NDA's true disposal costs by 280 £k/tU (473 £k/tU - 193 £k/tU = 280 £k/tU). The underestimation will mean that the NDA will not fully recover all of its disposal costs for new build reactor fuel, and so the NDA will require an indirect government subsidy to make up the shortfall. The subsidy will be around **£296 million for a 40 year PWR** or **£445 million for a 60 year PWR**.

Table 9
NDA Subsidies Needed From Underestimating Actual NDA Disposal Costs of Spent Fuel (Subsidy Per Reactor, Based on a 10 PWR Reactor Fleet)

DECC 1.35 GWe PWR	DECC 'Expected Price' Spent Fuel Disposal	DECC 'Capped Price' Spent Fuel Disposal	Additional NDA Subsidy Needed	Comment
40 year lifetime	£670 million Energy Utility	£1,104 million Energy Utility	**£296 million Government**	Government subsidy is 27% on top of the max Capped Price paid by energy utilities
60 year lifetime	£1,005 million Energy Utility	£1,656 million Energy Utility	**£445 million Government**	Government subsidy is 27% on top of the max Capped Price paid by energy utilities

Source: The total Expected Price and Capped Price are given in the DECC Waste Transfer Price Consultation Document at Page 6. (These include a small contribution from ILW). The size of the NDA Subsidy required is calculated in Table 10 below.

Table 10
Subsidy From Underestimating Actual NDA Unit Disposal Costs of Spent Fuel
(Subsidy Per Reactor, Based on a 10 PWR Reactor Fleet)

Generic 1.35GWe PWR, 40-Year and 60-Year Generation

Model	NDA Unit Cost (£k/tU)	PWR Fuel Discharged 40 Years (tU)	NDA Disposal Cost (£m)	PWR Fuel Discharged 60 Years (tU)	NDA Disposal Cost (£m)
DECC	193	1060	£205m	1590	£307m
FUPSIM	473	1060	£501m	1590	£752m
Loss	-280	**Subsidy**	**£296 million**	**Subsidy**	**£445 million**

Note: FUPSIM estimates that DECC's Generic 1.35 GWe PWR will discharge 1060 tU over 40 years and 1590 tU over 60 years (26.5 tU/yr).
FUPSIM Unit Disposal Cost of 473 £k/tU @ 10 PWRs is calculated in Table 7.

14. Disposal Cost Underestimation Subsidy for Small Fleet

DECC's cost modelling assumes that 10 new nuclear reactors will be built and all their spent fuel disposed in the NDA's Geological Disposal Facility (GDF). However if just a few new reactors are built then it becomes much more expensive to dispose of spent fuel. Put another way the unit costs of disposal (£k/tU) are much higher for small reactor fleets (See Graph 4).

Another possibility is that utilities do build a large reactor fleet but decide not to dispose of all of their spent fuel in the NDA repository for strategic reasons. For example uranium reactor fuel might be supplied from abroad and returned to the country of origin (take back).

In the worst case, if the UK nuclear renaissance fails to materialise and only one new 1.35GWe PWR is actually constructed,[17] then the unit disposal cost rises to 628£k/tU (see Table 7). In this case DECC may have significantly underestimated the NDA's true disposal costs by 435 £k/tU (628 £k/tU - 193 £k/tU = 435 £k/tU). The underestimation will mean that the NDA will not fully recover all of its disposal costs for new build reactor fuel, and so the NDA will require an indirect government subsidy to make up the shortfall. The subsidy will be around **£461 million for a 40 year PWR** or **£692 million for a 60 year PWR**.

Table 11
NDA Subsidies Needed From Underestimating Actual NDA Disposal Costs of Spent Fuel (Subsidy Per Reactor, Based on a 1 PWR Reactor Fleet)

DECC 1.35 GWe PWR	DECC 'Expected Price' Spent Fuel Disposal	DECC 'Capped Price' Spent Fuel Disposal	Additional NDA Subsidy Needed	Comment
40 year lifetime	£670 million Energy Utility	£1,104 million Energy Utility	**£461 million Government**	Government subsidy is 42% on top of the max Capped Price paid by energy utilities
60 year lifetime	£1,005 million Energy Utility	£1,656 million Energy Utility	**£692 million Government**	Government subsidy is 42% on top of the max Capped Price paid by energy utilities

Source: The total Expected Price and Capped Price are given in the DECC Waste Transfer Price Consultation Document at Page 6. (These include a small contribution from ILW). The size of the NDA Subsidy required is calculated in Table 12 below.

[17] EDF Energy's business plans seem the most advanced at present, with proposals for a twin 1650 MWe EPR at Hinkley Point C (3.3GWe) and subsequently a Twin EPR at Sizewell C.

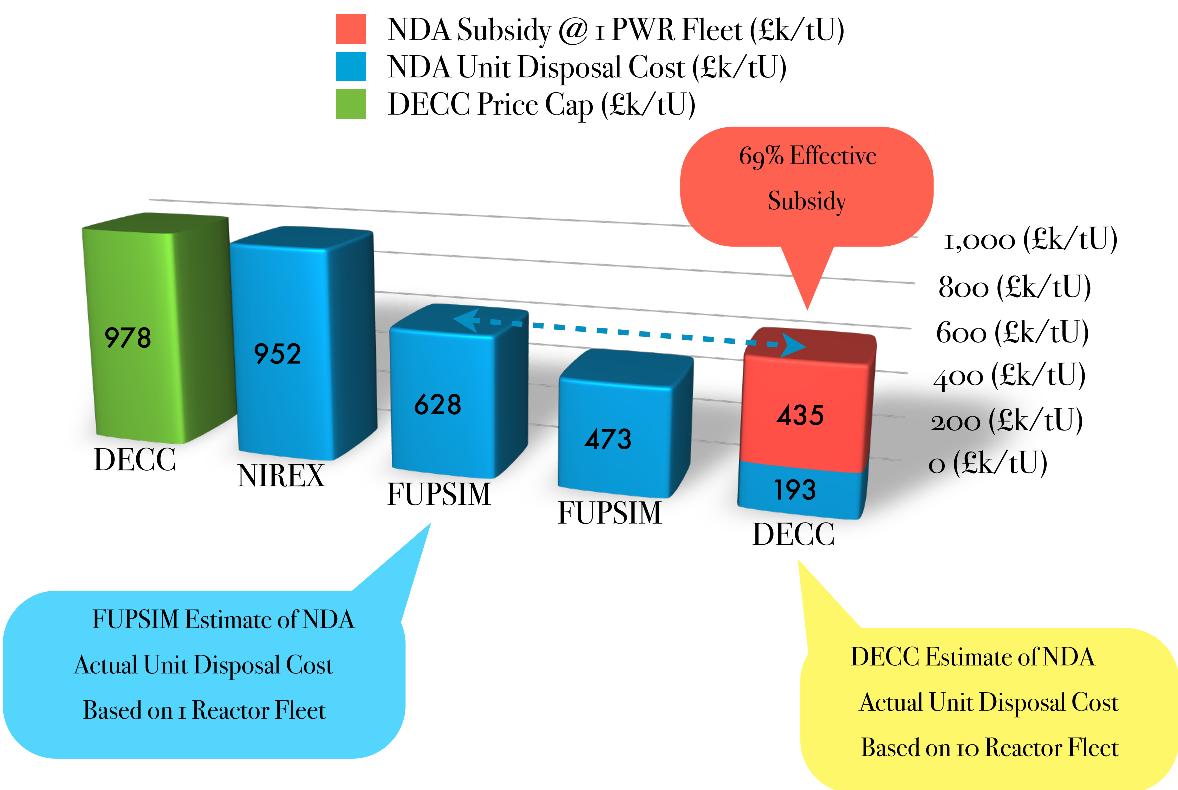
Table 12
Subsidy From Underestimating Actual NDA Unit Disposal Costs of Spent Fuel
(Subsidy Per Reactor, Based on a 1 PWR Reactor Fleet)

Generic 1.35GWe PWR, 40-Year and 60-Year Generation

Model	NDA Unit Cost (£k/tU)	PWR Fuel Discharged 40 Years (tU)	NDA Disposal Cost (£m)	PWR Fuel Discharged 60 Years (tU)	NDA Disposal Cost (£m)
DECC	193	1060	£205m	1590	£307m
FUPSIM	628	1060	£666m	1590	£999m
Loss	-435	**Subsidy**	**£461 million**	**Subsidy**	**£692 million**

Note: FUPSIM estimates that DECC's Generic 1.35 GWe PWR will discharge 1060 tU over 40 years and 1590 tU over 60 years (26.5 tU/yr). FUPSIM Unit Disposal Cost of 628 £k/tU @ 1 PWR is calculated in Table 7.

Graph 7
Range of Predictions for NDA Unit Costs of Spent Fuel Disposal



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