FOREWORD

This subject was first studied by the NEA in 1983. Since then there have been significant developments in relevant technologies and associated costs. The NEA's Committee for Technical and Economic Studies on Nuclear Development and the Fuel Cycle (NDC) therefore believed it worthwhile to convene an ad hoc expert group to re-appraise this topic.

Experts from fourteen OECD countries and four international organisations participated in the working group; a full list is provided in Annex 12. This report has been prepared by the members of the expert group and is published under the responsibility of the Secretary-General of the OECD. It does not, however, necessarily represent the views of participating countries or international organisations.

ACKNOWLEDGEMENTS

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OVERVIEW

The results of this study show that a 40 per cent real terms reduction has occurred in projected fuel cycle costs for a large PWR since the previous OECD/NEA study undertaken in the early 1980s. This reduction is due to major reductions in the projected prices for the uranium and enrichment components and reductions in the prices for back-end services. Improved fuel and reactor performance contribute further to the reduction.

The results indicate that there is a small cost difference between the prompt reprocessing option compared with the long-term storage and direct disposal option. Based on best estimate data, the reference cases show a difference of approximately 10 per cent of the total nuclear fuel cycle cost, the cost of the direct disposal option being lower. In light of the underlying cost uncertainties, this small cost difference between the reprocessing and direct disposal options is considered to be insignificant, and in any event, represents a negligible difference in overall generating cost terms. It is likely that considerations of national energy strategy including reactor type, environmental impact, balance of payments and public acceptability will play a more important role in deciding a fuel cycle policy than the small economic difference identified.

A contemporary OECD/NEA study on the projected costs of generating electricity shows that for nuclear stations the proportion of the total generating cost taken up by the fuel component is, typically, 15-25 per cent at 5 per cent real discount rate. This is in contrast to fossil-fuelled generation where coal represents, typically, 40-60 per cent of the total cost and, typically, 70-80 per cent in the case of gas. Clearly, nuclear generation costs are far less sensitive to fuel price volatility compared with the fossil-fuelled alternatives.

1. Introduction

In early 1991, an expert group, with a membership drawn from fourteen countries and four international organisations, was formed to examine the economics of the fuel cycle with particular reference to a power station comprising a pressurised water reactor (PWR) commissioning in the year 2000. The expert group finalised its report at the end of 1993.

2. Study objective

The task of the expert group was to update the OECD/NEA 1983/84 study which was published in 1985. That study defined the levelised lifetime fuel cycle cost using internationally accepted investment appraisal methodology. Costs were derived for fuel cycles based on reprocessing and on long-term spent fuel storage followed by direct disposal.

The current study repeats that approach. Use of a 5 per cent reference case discount rate is still considered appropriate in reflecting the consensus of national practices. It also enables direct comparison to be made with previous results. Variations due to the use of different discount rates are also given.

3. Power station parameters

The reference reactor for the study is a French N4 type with a thermal output of 4 020 MW giving an electrical output of 1 390 MW. The power station is assumed to operate for 30 years with a levelised load factor of 75 per cent. The fuel costs were calculated for a four batch fuel cycle with annual refuels, the fuel being discharged at an average burn-up of 42.5 GWd/tU.

Experience shows that similar fuel cycle costs will be associated with a boiling water reactor (BWR) of similar size, commissioning and operating over comparable timescales. Fuel costs for the Canadian CANDU reactor and the Japanese ATR were also considered; they are reported in Chapter 8 but are not included in this summary.

4. Fuel cycle cost

4.1 General

The operations associated with the nuclear fuel cycle and the management of the corresponding waste typically extend over a period of between 50 to 100 years, from mining the uranium ore to finally disposing of the high level waste. The entire fuel cycle and its components are shown in Figure S.1. The overall fuel cycle cost comprises the aggregation of a series of prices for each of the fuel cycle components. Thus, it may be seen that the resulting fuel cycle cost covers all expenditure and liabilities in a comprehensive manner.

4.2 Front-end components and prices

The front-end of the fuel cycle consists of four stages: uranium purchase; conversion to uranium hexafluoride; enrichment; and fabrication. Relative to the date the fuel is loaded into the reactor, the lead time assumed for these components is 24, 18, 12 and 6 months, respectively.

A projection of prices for each of these components was derived from a survey of each expert group member's perception of future world market prices for term contracts. The study typically took the central value of the range that resulted from individual member inputs. All inputs were given in constant 1991 money value. The resulting values which were then used to calculate the reference fuel cycle cost are shown in Table S.1.

Table S.1. **Front-end component unit prices**
(Reference case)

Component	**Price**
Uranium purchase	\$50/kg U (in 1990) (\$19.2/lb U_30_8) increasing at 1.2% p.a. in real terms
Conversion	\$8/kg U
Enrichment	\$110/SWU
Fabrication	\$275/kg U

4.3 Back-end components and prices

Two back-end options were considered in the study. The first was based on prompt reprocessing of the spent fuel and the recycle of recovered uranium and plutonium. The basic cost estimates used were supplied by BNFL who, in conjunction with COGEMA, indicated future expected trends. These estimates assumed that the fuel would be reprocessed in a newly constructed plant. In costing this plant, the experience gained from the design, construction and operation of the latest reprocessing plants of THORP at Sellafield, and UP3 at La Hague, has been taken into consideration.

The second option was based on long term storage followed by direct disposal. Cost estimates developed by the SKB company in Sweden were used as the reference case.

The timing of spent fuel deliveries from the power station and all subsequent processes for both options are shown in Figure S.2. Unit prices at the time of delivery were derived using cost estimates and the reference 5 per cent p.a. discount rate.

To enable a proper comparison of the costs of the reprocessing and direct disposal options, the associated prices were derived in a comparable way using the ECU monetary unit and the assumption that the service provider obtains a 5 per cent real rate of return on capital employed.

The resulting reference 5 per cent levelised unit prices at the time of delivery derived for the two options are shown in Table S.2.

Reprocessing option

Reprocessing is available on a competitive world market; the main suppliers being European based. For this reason back-end prices were given in ECU. A long-term exchange rate of 1 ECU = 1 US dollar was assumed. Reprocessing requires the use of large chemical plants with relatively large throughputs. Such plants are able to deal with the spent fuel from a large number of reactors, typically, 20-30 PWRs of the size considered in the study. Using cost estimates, unit prices were derived for reprocessing (which encompassed the associated spent fuel receipt, the waste conditioning/storage services and low and intermediate level waste disposal) and for the disposal of the vitrified high level waste (VHLW).

Direct disposal option

Direct disposal services are not currently available on the world market; each individual country pursues its own approach. This is influenced by the final stage, the disposal of the conditioned spent fuel.

Using cost estimates supplied by SKB, unit prices were derived for the transport and storage and for the encapsulation and disposal stages of the direct disposal option.

Table S.2. **Back-end service unit prices**
(Reference case)

Service	**Price**
Option: Reprocessing	
Transport (within European area)	ECU 50/kg U
Reprocessing (includes all processes except VHLW disposal)	ECU 720/kg U
VHLW disposal	ECU 90/kg U
Option: Direct disposal	
Transport/Storage	ECU 230/kg U
Encapsulation/Disposal	ECU 610/kg U

Notes:
- kg U refers to the mass of uranium in the fuel prior to irradiation.
- The above prices reflect discounting to appropriate delivery timing and as such they are not directly additive.

4.4 Environmental factors

Fuel cycle costs take full account of the investment and operating experience in meeting the strict regulatory requirements for environmental protection and public safety. They cover all expected costs over the 50 to 100 year period of the entire nuclear fuel cycle. Other non-nuclear forms of electricity generation have their own environmental impact which is the subject of studies being undertaken elsewhere.

5. Methodology

The investment appraisal method of deriving the lifetime levelised fuel cost requires the examination of the entire fuel cycle cash outflow based on component prices. The cash outflows are discounted to a base date using the selected discount rate which was set for the reference case at 5 per cent per annum (real). The levelised fuel cycle cost is derived in mills/kWh terms by equating the net present value of the entire fuel cycle cost and the net present value of the total electrical output over the station lifetime, where both have been discounted to the same date.

6. Sensitivity analysis

6.1 Front-end

A sensitivity analysis has been carried out with respect to lead times and unit prices. For lead times, an upper bound sensitivity was made by approximately doubling the reference lead times for uranium purchase, conversion, enrichment and fabrication. The sensitivity range for front-end service prices generally reflects the upper and lower bound values seen in the spread of perceptions given by members for future world market prices. The values used are shown in Table S.3.

Table S.3. **Front-end component unit prices**
(Sensitivity range)

Component	**Price sensitivity range**
Uranium purchase	$40-$90/kg U escalation 0% p.a.
Conversion	$6-$11/kg U
Enrichment	$80-$130/SWU
Fabrication	$200-$350/kg U

6.2 Back-end

Reprocessing option

The reference price relates to a new, as yet unbuilt plant, and so contains a degree of uncertainty. The capital estimates used are based on outturn costs related to design and construction knowledge gained through the THORP project. The prospect exists, however, that technology and design improvements will result from THORP and UP3 operation such that new plants will benefit and their costs will be reduced. The downside range in price that has been used for the sensitivity study takes this into account as well as anticipated process improvements leading to much reduced waste volumes. It does not cover major step changes in technology.

Based on the above factors, the reprocessing price range used for sensitivity purposes is ECU 540 to ECU 720 per kg U as shown in Table S.4, i.e. a downside sensitivity of 25 per cent. The reference value of ECU 720 per kg U is comparable to the post-baseload price currently on offer from BNFL and COGEMA.

The costs in the reprocessing option are partly offset by credits for the recycled uranium and plutonium; the derivation of these credits is explained in the main part of this report.

While reprocessing services are available on the world market, the disposal of the resulting wastes, particularly the vitrified high level waste (VHLW), will be the responsibility of the customers' country. A wide sensitivity range has been used for VHLW disposal. This reflects the different possible geologies involved, the different timescales envisaged and the different size of the national nuclear programmes giving rise to the high level wastes. The sensitivity range chosen is representative of the range of values provided by the individual countries involved in a separate OECD/NEA study on the cost of high-level waste disposal in geological repositories. Although the reference VHLW disposal price is at the lower bound of the range,

this fuel cycle component makes a very small contribution to the overall, levelised fuel cost, and hence any distortion this introduces is negligibly small. A similar comment is applicable to the direct disposal option where the reference disposal price was towards the upper bound of the range.

Direct disposal option

The direct disposal option is country specific. The reference case uses the Swedish system that has been well developed by SKB who possess detailed costing information. The cost estimates include normal engineering and construction contingency allowances which can be seen as providing against upside risk. The costs for the reference case are based on the use of 100 mm thick solid copper canisters in which the fuel will be encapsulated and disposed. Alternative canister designs and process engineering improvements could lead to a 15 per cent reduction in the reference cost estimates.

However, noting that the direct disposal option is country specific, in coming to a view on the appropriate sensitivity range to be used, recognition was given to the results of cost estimates provided by Germany and the United States. This led to a much wider sensitivity range for the two main components of the option, as shown in Table S.4.

Table S.4. **Back-end service unit prices**
(Sensitivity range)

Service	**Price sensitivity range**
Option: Reprocessing	
Transport (within European area)	ECU 20-ECU 80/kg U
Reprocessing (includes all processes except VHLW disposal)	ECU 540-ECU 720/kg U
VHLW disposal	ECU 90-ECU 580/kg U
Option: Direct disposal	
Transport/Storage	ECU 60-ECU 290/kg U
Encapsulation/Disposal	ECU 140-ECU 670/kg U

Notes: – kg U refers to the mass of uranium in the fuel prior to irradiation.
– The above prices reflect discounting to appropriate delivery timing and as such they are not directly additive.

6.3 Combination of sensitivities

Sensitivity price ranges were derived for each fuel cycle component as shown above. In practice, the out-turn price for each component would be expected to lie within those ranges. Not all prices will be at the upside or downside extreme. Indeed, the nature of the fuel cycle allows management steps to be taken to ameliorate the effects of adverse price movements, for example, adjustment of tails assay to optimise the price of enriched uranium or increased fuel burn-up to reduce the costs of spent fuel management.

A rectangular distribution of prices within each component range was assumed. A statistical analysis was used to combine a large number of samples. This resulted in fuel cycle cost ranges shown in the next section.

7. Results

Based on reference prices, the lifetime levelised fuel cycle cost for each option is:

- reprocessing option: 6.23 mills/kWh;
- direct disposal option: 5.46 mills/kWh.

Using the results of the above-mentioned statistical analysis and taking two standard deviations around the mean value, the following ranges are derived:

- reprocessing option: 5.17-7.06 mills/kWh;
- direct disposal option: 4.28-6.30 mills/kWh.

Figures S.3 and S.4 show the sensitivity of the fuel cycle cost to changes in each component price over a wide range encompassing a doubling or halving of the reference prices used in the study. This will enable other values to be selected that the reader may consider more appropriate.

8. Comparison with the 1985 NEA study

Figures S.5 and S.6 show the results from the present study compared with those from the 1985 NEA study. A 40 per cent real term reduction in levelised fuel cycle cost has occurred. This is due to two main factors:

a) major reductions in the projected price for the uranium and enrichment components, and reductions in the price for back-end services; and
b) improved fuel and reactor performance.

9. Conclusions

A 40 per cent real term reduction in estimated lifetime levelised costs has occurred since the 1985 study. This reduction is due to improved fuel and reactor performance factors and reductions in the projected prices of certain fuel cycle components.

This study shows that the reference lifetime levelised fuel cycle cost for a large PWR power station commissioning around the turn of the century is expected to lie in the range 5.5 to 6.2 mills/kWh depending on the spent fuel management option used. It is considered unlikely that the fuel cycle cost will lie outside the range 4.3 to 7.1 mills/kWh. Similar fuel cycle costs would be expected for a comparable BWR power station.

Figure S.1 **The nuclear fuel cycle**

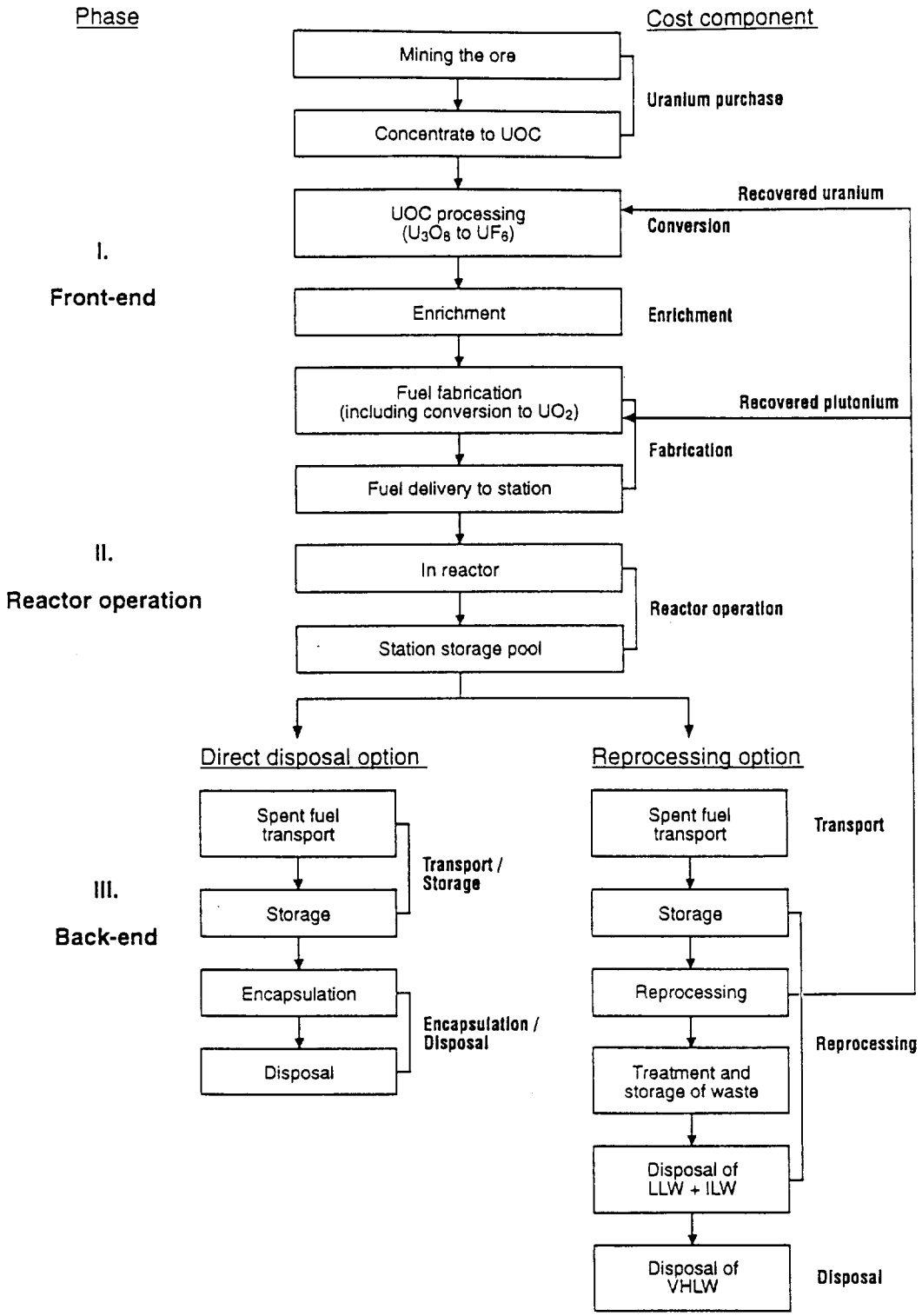


Figure S.2 **Back-end options and operation timings**

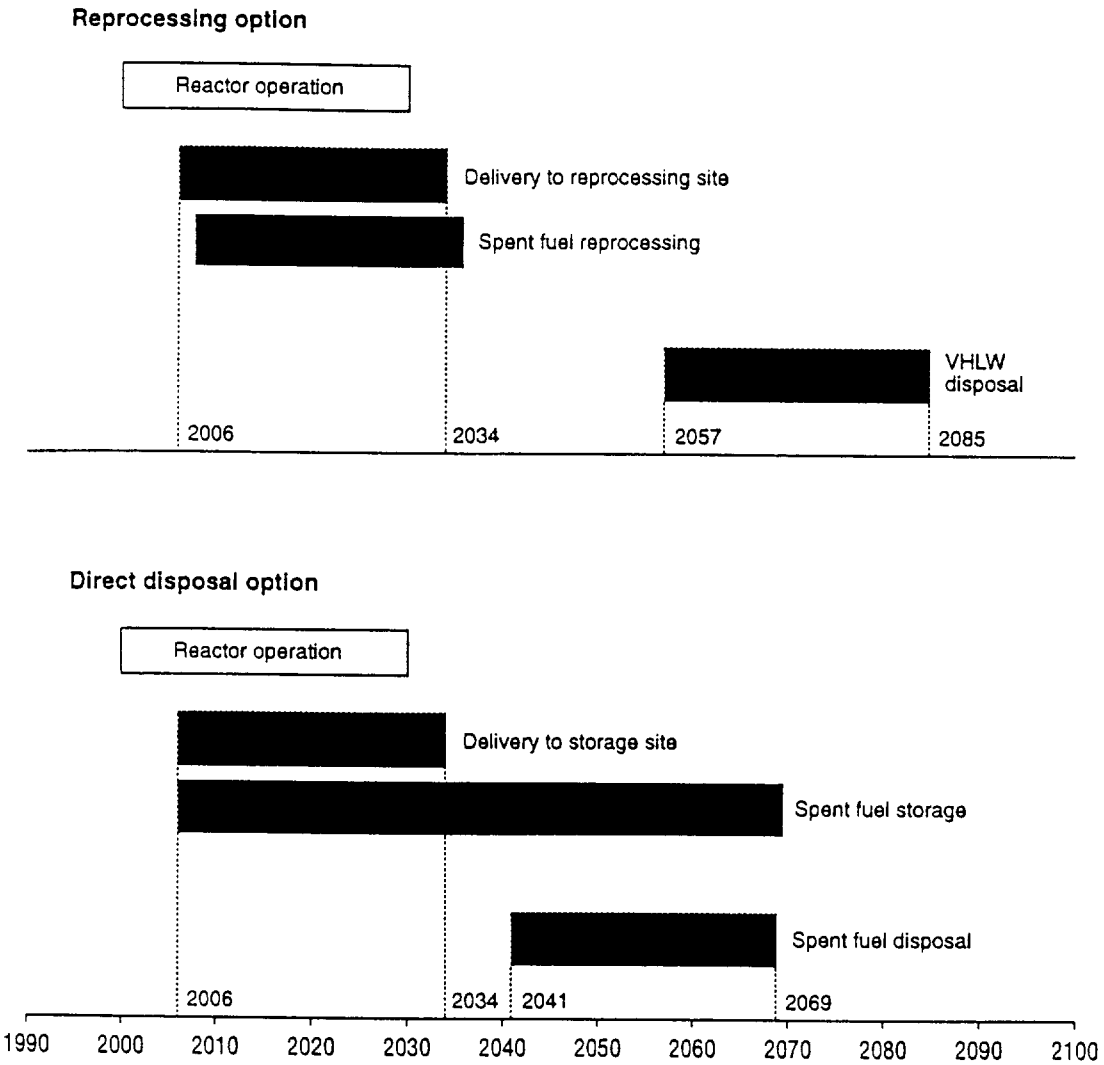


Figure S.3 **Fuel cycle components – Sensitivity to price variations**
(reprocessing option)

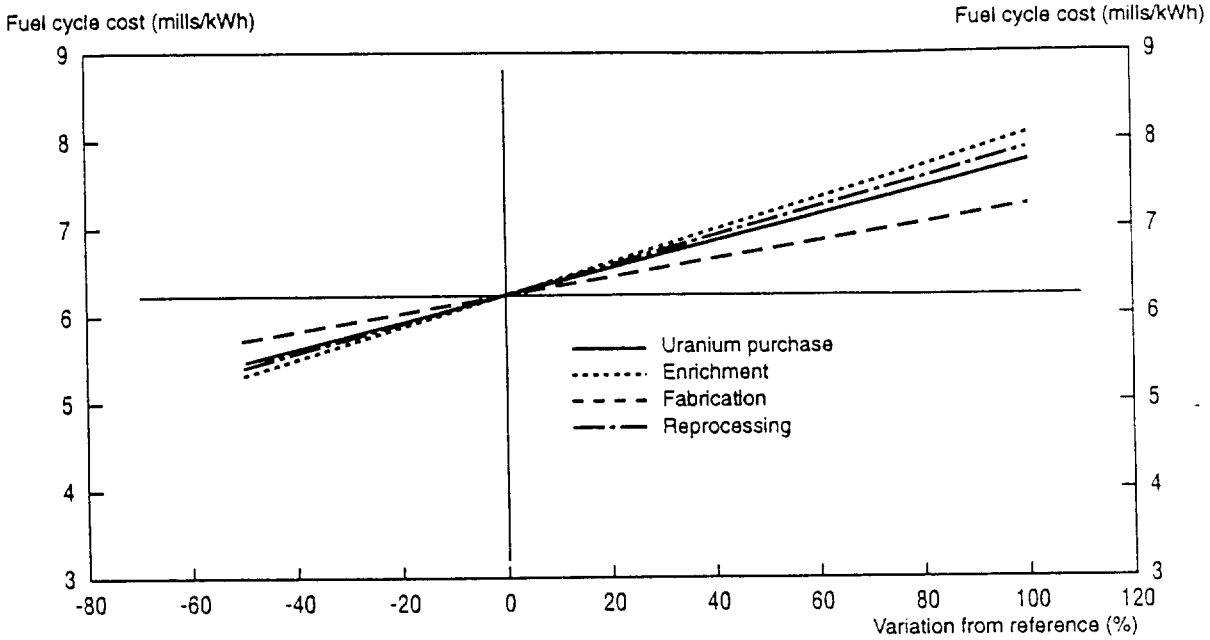


Figure S.4 **Fuel cycle components – Sensitivity to price variations**
(direct disposal option)

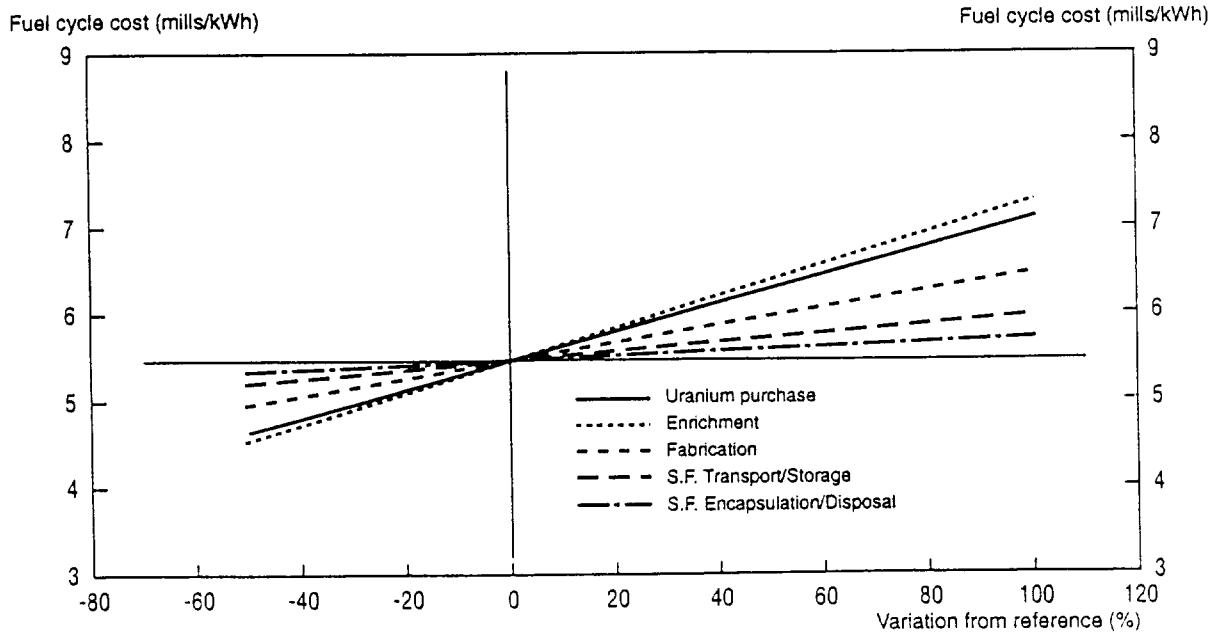


Figure S.5 **Levelised lifetime PWR fuel cost**
(reprocessing option)

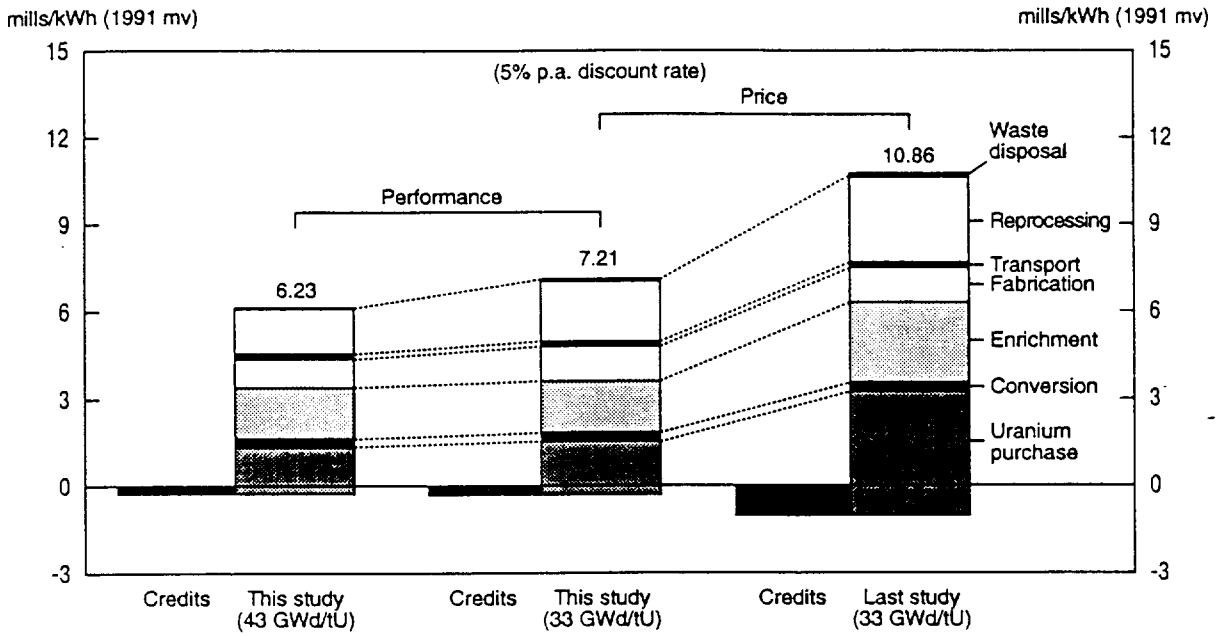
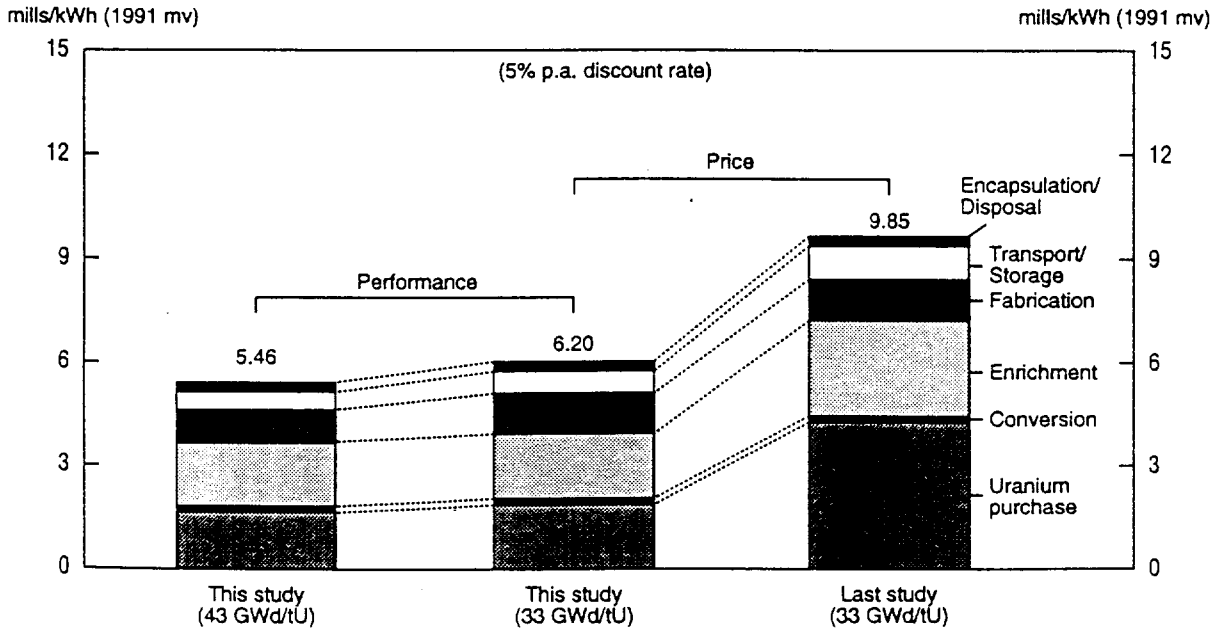


Figure S.6 **Levelised lifetime PWR fuel cost**
(direct disposal option)



1. INTRODUCTION

In most OECD Member countries which are committed to nuclear power generation, the nuclear programmes are fairly stable resulting in nuclear electricity generation share figures of the order of 20 to 73 per cent. Construction of new power plants is currently infrequent and limited only to a small number of countries. This situation is not expected to change in the near future. However, the safety and operational record of the nuclear industry and current environmental and economic considerations underline the present and future importance of the nuclear power option. Nuclear fuel cycle choices and costs are, therefore, important in considering energy policies, fuel diversity, security of supply and the associated social and environmental impacts.

An OECD/NEA expert group, with a membership drawn from fourteen OECD countries, the CEC, the IAEA and the IEA, has examined in detail the projected costs of the various stages of the nuclear fuel cycle for pressurised water reactors, considering both the reprocessing and the direct disposal options.

The following countries were represented at the expert group meetings: Australia, Belgium, Canada, Finland, France, Germany, Italy, Japan, Netherlands, Spain, Sweden, Switzerland, United Kingdom and United States. The list of group members is given in Annex 12. The expert group was chaired by Mr. D. J. Groom.

The NEA has been carrying out a number of studies concerning the economics of nuclear power. Electricity generation cost studies[1, 2, 3, 4] were published in 1983, 1986, 1989 and 1993. Since quantities of plutonium, both in spent thermal reactor fuel and as separated material recovered by fuel reprocessing, have been increasing for the past 30 years and will continue to increase in the future, at least in the short-term, interest is being shown in the use of MOX fuel, which led to the publication of the 1989 NEA study: *Plutonium Fuel - An Assessment*[5]. The NEA has also recently published a report on the costs of disposal of high level waste into deep geological repositories[6], the results of that report are compared with values used in this study.

The present study, which is an update of the 1985 OECD/NEA study on *The Economics of the Nuclear Fuel Cycle*[7] presents in a clear and concise way estimates of the prices utilities expect to pay for the different components of the fuel cycle for a typical PWR coming into service at the turn of the century. Developments in the economics of the fuel cycle and improvements in plant technology and their role in reducing overall fuel costs are presented and discussed. It should be noted, however, that national fuel cycle strategies are not necessarily influenced solely by financial aspects; a number of other considerations such as national energy strategy including reactor type, environmental impact, balance of payments and public acceptability also play an important role in deciding a fuel cycle policy.

The nuclear fuel cycle can be divided into three stages: front-end, at-reactor and back-end. These, in turn, can be sub-divided into more specific components. The costs and current developments related to these components are presented, analysed and compared with those used in the 1985 study.

Although a large, modern PWR has been taken as the reference plant for the study, the resulting fuel cycle costs are considered to be typical of those for a modern BWR. The fuel cycles and costs for the CANDU and ATR designs are also presented, although in less detail.

A competitive, diversified world market exists for uranium and front-end fuel cycle services. For the back-end, BNFL and COGEMA offer internationally commercial reprocessing services and some other countries have a limited, indigenous reprocessing capability. Nevertheless, a general feature of the back-end of the fuel cycle is that the onus is placed upon countries with nuclear power stations to provide disposal facilities for the resulting waste products, regardless of whether those products arise from reprocessing or from direct disposal of the spent fuel. In this study, the estimates of future reprocessing prices are in line with currently available contract prices, supported by cost data supplied by BNFL and future trend data from COGEMA. The estimates of direct disposal costs have been based primarily on data from Sweden with additional data from the United States and Germany to illustrate the effects of programme scale and timing. The use of mixed plutonium and uranium oxide fuel is discussed because of its importance in determining plutonium monetary values which may lead to plutonium credit in the reprocessing cycle. Similarly, the use of uranium fuel obtained by re-enrichment of the uranium recovered by reprocessing is also examined.