4. THE COSTS OF THE PWR FUEL CYCLE STAGES

4.1 The front-end of the fuel cycle

4.1.1 Uranium purchase

For the range of uranium prices considered in the 1985 study, uranium purchase contributed between 30 and 50 per cent of the total cost of the PWR fuel cycle. This represented between 5 and 20 per cent of the total electricity generation cost. With current data, Tables 5.7 and 5.8 show that uranium purchase contributes about the same level as enrichment services, while fabrication costs have also become important. The demand for uranium is now more predictable than it used to be. A number of technological advances such as increased fuel burn-ups, advanced fuel designs, improved plant efficiency, and the use of MOX fuel and reprocessed uranium have led to reduced uranium requirements.

Since the publication of the previous study, uranium market developments have made the highest of the price projections look less likely today. Although the uranium market is currently characterised by large global inventories and low prices, the future is uncertain[8]. As consumption of natural uranium is currently higher than production, the situation beyond the year 2000 is likely to be different after excess inventories are consumed. Some of the factors that might influence the uranium market are:

Demand side

- New reactor orders have stagnated since the late 1970s; the world total reactor capacity is, therefore, now plateauing and the annual growth rate of nuclear electricity production has become slower than in the past 20 years.
- Reactor retirements are small, but growing; however, if life extensions are developed, most of the reactors operating at present will also be operating up to the year 2000; uncertainty exists on the future of several reactors in Eastern Europe.
- Fossil fuelled plants make a significant contribution to global warming ("greenhouse effect") and may need to be replaced in significant numbers by systems which release no "greenhouse" gases. Nuclear systems are one such source.
- The world population growth will lead to the growth of the global energy consumption, even if energy will be utilised in a more rational way; as fossil fuels will become more expensive, more nuclear generated energy may be required.
- The 1980s were characterised by increasing fuel efficiency which will ultimately lead to a 10 to 15 per cent reduction in uranium demand; in addition, reprocessing activities will gradually grow, leading to further reductions in uranium fuel requirements.
- The long-term demand (after 2015) is highly speculative; it depends on the nuclear performance record, environmental considerations and the development of new technologies.

Supply side

– Theoretically, global inventories from all sources are adequate to make up a production shortfall beyond 2000.
– A part of the military inventory will eventually find its way to the market despite the technical and institutional difficulties; this part is likely to be less than 10 per cent of the global consumption up to 2030.
– Depleted enrichment tailings could be a significant source if new technology is developed.
– Significant undeveloped reserves are available at reasonable costs (less than $50 per kg U).
– No significant availability problem before 2015 is foreseen, although there could be big swings about the trend line from year to year.
– New regulations on the environment, radiological protection and decommissioning may increase production costs and may lead to some mine closures.

Long-term trend

– Significant future uranium market price rises may be limited by technological improvements (e.g. breeders and reprocessing), fuel substitution (e.g. the thorium cycle), new and alternate technologies (fusion, solar, wind, biomass, geothermal, tidal, etc.) and, as experience with other metals indicates, the discovery of new uranium.
– Based on resource analysis, there will most probably be an upper limit of about $130 per kg U throughout the entire period to 2030; new uranium discoveries may reduce this limit.

The previous NEA fuel cycle study used $83.2 per kg U escalating at 2 per cent per annum as the reference price and parametric evaluations were performed for an escalation rate of 0 and 4 per cent per annum. Ranges shown in the questionnaire replies vary between $40 per kg U in 1990 to around $105 per kg U in 2030. It was agreed to use the price of $50 per kg U (1990 money value), rising in real terms at a rate of 1.2 per cent per annum (i.e. $90 per kg U in 2040), as the reference value, which is in line with the recommendation of the NEA Uranium Group and for the sensitivity analyses the prices of $40 per kg U constant and $90 per kg U constant for the lower and the upper bounds, respectively. Additionally, further sensitivity analyses involving -50 to +100 per cent price changes are presented.

It should be noted that the average price of other metals (e.g. copper) has remained constant, in real terms, for more than 50 years despite heavy fluctuations over a number of years.

4.1.2 Conversion

The prices for conversion of natural uranium oxide to uranium hexafluoride for enrichment lie in the range $6 to $11 per kg U and there is no expectation of any significant increase in real terms in the future. A price of $8 per kg U was adopted as the reference case; $6 and $11 per kg U are the lower band and upper band values for sensitivity purposes.

The reference case in the 1985 study was $6 per kg U, corresponding to $7.6 per kg U in 1991 US$. The 1989 plutonium study adopted $7 per kg U as an illustrative value, which is $8.2 per kg U in 1991 US$. As regards the historical trend the conversion price is very stable. Conversion prices constitute only a few per cent of the total fuel cycle cost, therefore, their fluctuation would have insignificant effects on the cost of the overall fuel cycle.

4.1.3 Enrichment

Enrichment costs form a significant component of the total fuel cycle cost. In the 1985 study, enrichment costs contributed approximately one quarter of the total fuel cycle costs.

The gaseous diffusion and centrifuge processes are commercially well established. The introduction of new technologies, such as advanced centrifuge and laser enrichment, is expected to provide additional enrichment capability at prices substantially below those from existing plants due to lower energy requirements. Relevant research and development projects are carried out in France, Japan, the United Kingdom and the United States. The laser enrichment technology that is being developed in the United States (AVLIS) is projected to have a production cost for enriched uranium that is approximately one-half the cost of the existing gaseous diffusion plants.

Throughout the remainder of this century, and through the first decade of the 21st century, plant capacity is expected to exceed the demand for uranium enrichment services. Excess capacity is due to the slower than originally planned expansion of nuclear power on a worldwide basis. There is an expectation that supplies of enriched uranium from the former USSR may increase. The price of enrichment services is expressed per separative work unit (SWU), the quantity of SWUs necessary to obtain a quantity of enriched uranium at the required enrichment level being given by a complex formula (see Annex 1). Current enrichment prices vary between $70 and $160 per SWU. Potential new enrichment technologies, such as AVLIS, could lead to significantly lower values. It is possible that enrichment prices could decrease by 2 per cent per annum in real terms. However in this study it has been assumed prudently that enrichment prices will remain constant in real terms.

The reference case adopted was $110 per SWU with $80 per SWU and $130 per SWU being the lower and higher values for sensitivity calculations.

4.1.4 Uranium oxide fuel fabrication

There has always been high competition among fabrication services suppliers because the processes involved are well established, relatively straightforward and the market is over-supplied. Reported prices differ from country to country due, partly, to the existence of plants which have different sizes and ages, and, partly, due to the fluctuation of foreign currencies relative to the US dollar which forms a bench-mark for pricing purposes.

A few countries have reported high prices, but it is generally considered that prices for 43 000 MWd/t fuel lie in the range $200 to $400 per kg U. For the purposes of this study $275 per kg U was adopted as the reference case and for the sensitivity analyses $200 per kg U and $350 per kg U were used.

For comparison, in the 1985 study, the reference case was $190 per kg U ($242 per kg U in 1991 US$) and for the 1989 plutonium study $200 per kg U ($233 per kg U in 1991 US$). For both studies prices were for 33 000 MWd/t fuels.

The price of fuel fabrication has remained stable over the past decade. During the same period, fuel assembly design and construction has become more sophisticated, thus enabling better fuel utilisation, burn-up extension and better operational behaviour. This has led to an improved fuel cycle economy. Higher fuel fabrication prices are to be expected for the even higher burn-ups that are anticipated in future. It was reported that the price for advanced fuel assemblies capable of a burn-up of 50 000 MWd/t could reach approximately $400 per kg U.

4.2 Fuel at the reactor

The costs of storage of new or irradiated fuel at the reactor site and costs associated with the management or disposal of low level liquid and solid wastes produced during the reactor operations are not included in the costs of the fuel cycle.

4.3 The back-end of the fuel cycle

4.3.1 General

All back-end prices are levelised to the point of delivery to the respective plants for both the reprocessing and direct disposal options.

A levelised price is calculated in the same way as the total levelised fuel cost, i.e. by setting the net present values of the plant income (based on tonnes of uranium throughput) and cost profiles equal (see Annex 1). This ensures the correct price is charged for each tonne delivered to the plant, enabling the plant operator to meet all costs and also show a return on the capital employed. The discount rate used to obtain the levelised price reflects the rate of return that the plant operator requires on the capital employed (see Annex 2).

Following discharge from the reactor, the spent fuel undergoes a period of storage in the reactor pool. This stage of the fuel cycle is common to both the reprocessing and direct disposal options.

To ease transport requirements, fuel is usually held in the reactor pool for at least a few years prior to transport to allow significant reduction in heat output to occur. In this study a five years in reactor pool storage period is assumed for either option (the final core is assumed to be stored for only four years). The costs for this storage period are covered by the normal operating costs of the power station and they have not been included as a specific fuel cycle cost.

4.3.2 Reprocessing option costs

4.3.2.1 Transport of spent fuel

Based on the figures provided in the questionnaire responses a fixed price of $50 per kg U has been used as the reference price. This assumes relatively short transportation distances within the European area; it would not cover long distance sea transport such as Japan to Europe. For sensitivity purposes a range of $20 to $80 per kg U was used.

4.3.2.2 Interim storage of spent fuel

On receipt at the reprocessing site, spent fuel is subject to a further period of, usually, short storage. The length of this period can vary over a wide range of a few months to several years according to customers' requirements and plant availability. In this study it is assumed that spent fuel is stored at the reprocessing site for one year prior to reprocessing. The cost of this storage is included in the reprocessing price.

4.3.2.3 Reprocessing

Spent fuel reprocessing is offered commercially on an international basis by France and the United Kingdom. Japan is actively developing plans to build a commercial reprocessing plant.

The basic cost estimates used in this study were provided by British Nuclear Fuels plc (BNFL) and possible trends relating to future costs have been contributed by COGEMA.

Reprocessing plant cost estimates have been provided for a hypothetical modern reprocessing plant which is built and operated to coincide with the requirements of the study's reference PWR (see Annex 3). Experience gained from the design, construction and operation of the latest reprocessing plants, THORP at Sellafield and UP3 at La Hague has been taken into consideration in deriving the cost estimates for the hypothetical plant and for sensitivity analysis purposes.

Reprocessing permits the use of the recovered uranium and plutonium instead of burying it as waste, as exemplified by the direct disposal option. It is assumed that the fuel is stored one year at the reprocessing site prior to the reprocessing operations. High level waste (HLW) is assumed to be vitrified within a few years of production and the vitrified waste (VHLW) stored at the reprocessing site for 50 years prior to final disposal. LLW is assumed to be disposed shortly after production in common with current practice. ILW is assumed to be fixed in a cement matrix in metal containers and, after short interim storage, disposed in a deep geological repository. Account has been taken of the current operational experience with the Sellafield vitrification and waste conditioning plants.

The reference 5 per cent levelised unit price at time of delivery to the plant, covering all back-end costs after fuel delivery up to but not including final disposal of VHLW, is ECU 720 per kg U (this price is comparable to the post-baseload price currently on offer from BNFL and COGEMA). This price is based on the weight of fuel input to the reactor and not the weight of uranium and plutonium in spent fuel discharged from the reactor as in the 1985 study. This price includes research and development costs. Unlike the 1985 study, where the sensitivity analysis took into account possible increases as well as decreases in the reference price, the present study considers only a possible 25 per cent reduction. The argument supporting such a reduction is set out in Annex 3.

4.3.2.4 Waste disposal

The cost of disposing of low and intermediate level wastes forms a relatively small part of the price charged for reprocessing.

Cost estimates for the disposal of VHLW based on a hypothetical repository dedicated to the reprocessing plant using the latest UK perception regarding design and timing are detailed in Annex 3. These costs have been scaled from actual UK design studies using the appropriate quantity of VHLW assumed in the reference case. Noting the long timescales involved there is inevitably greater uncertainty in repository cost estimates compared with those for reprocessing plants. A reference 5 per cent levelised price of ECU 90 per kg U was used with an upper bound sensitivity price of ECU 580 per kg U [this price was derived using cost information from the OECD/NEA waste disposal costing study[6]].

4.3.2.5 Recovered uranium and plutonium credit

The monetary value of the credit of recovered uranium and plutonium contained in the spent fuel from the reference PWR assumes:

i) that the recovered material is recycled as soon as it is available in a reactor similar to the reference PWR and with the same design burn-up as the reference fuel; and

ii) that only one stage of recycling takes place.

As shown in Annex 8, a single recycle of the recovered material would allow approximately a 15 to 20 per cent core loading of MOX and approximately a 20 to 25 per cent reduction in natural uranium requirements. Together, these would reduce the reference fuel cycle cost by about 4 per cent (see Table 5.7).

Current PWR designs can be licensed to operate with up to a 50 per cent MOX core load, the balance in theory could comprise enriched UO_2 fuel from recovered uranium recycle. Thus, if the recovered plutonium and uranium were preferentially used in a limited number of PWRs, greater reductions in fuel cycle cost for these PWRs could be achieved.

The plutonium credits considered above assume that the plutonium is recycled once as MOX fuel in the reference PWR after only limited storage following its recovery from reprocessing. To the extent that recycle is delayed, additional costs could accrue through the need for additional storage and possibly a need for further processing to remove in-grown americium to meet the specification for MOX fabrication plants. Any need to transport plutonium prior to fabrication would also lead to higher costs. All of these aspects are considered in sections 4.3.2.6 et seq. hereafter.

The additional costs associated with the extended storage and purification of plutonium would tend to erode the credits identified in Annex 8. It is expected that on the time horizon of the current study, MOX fabrication plants will be available to accept the plutonium arisings from the assumed future reprocessing operations without further purification, even in the case of extended storage.

4.3.2.6 Plutonium storage

Published costs of plutonium storage vary widely owing to differences in the size of stores and the economic and financial differences which exist between countries. They are usually taken to be in the region of $1 to $2 per gram of total plutonium [Pu(t)] per year. Both BNFL and COGEMA include the cost of short-term storage as a minor component of the overall reprocessing price but some countries requiring longer-term storage are incurring additional prices of this order.

4.3.2.7 Plutonium purification

Long-stored plutonium may need to be purified, by the removal of in-grown americium before it can be recycled. The extent to which this will be necessary will depend upon the source of the plutonium, its period of storage and the design of the MOX fuel fabrication plant. The cost may vary[(5)] between $10 and $28 per gram Pu(t); a price of $18 per gram Pu(t) would be appropriate for plants treating about two tonnes Pu(t) per annum. This figure relates to americium removal from plutonium oxide; it would be less if the plutonium could be stored as a nitrate solution.

4.3.2.8 Plutonium transport

If plutonium transport is needed, the price is far higher per kg than that of spent fuel due to the more onerous criticality and physical security requirements. Indicative figures of around $500 to $900 per kg, which will vary with the mode of transport (air, land or sea), have been published[(5)]. Plutonium transport costs within a single site would be trivial by comparison.

4.3.2.9 Plutonium recycling

The recycling of plutonium in PWRs requires the mixing of plutonium and uranium oxides and their fabrication into MOX fuel in plants specially designed for that purpose. A comprehensive study[(5)] deals with plutonium recycling in greater detail. It also addresses the technicalities associated with multiple recycling.

MOX fuel fabrication costs are higher than those of enriched uranium oxide fuels. This is due to the higher investment cost of a MOX plant and to the latter's modular nature which does not confer the same advantages of scale that apply to a uranium plant. As the use of MOX fuel increases and the new MOX fabrication plants reach higher commercial throughputs, the present MOX fabrication prices will fall. The industry expects that, on current plans, the MOX fabrication price will have fallen to about three times that for uranium fuel by 2010. However, the reference case in the 1989 NEA plutonium study assumed that by the late 1990s, MOX fabrication prices would be four times those for enriched uranium fuel. For the purpose of the present study it was agreed that the reference case would prudently use a ratio of four over the entire reactor lifetime. Thus, the reference price was set at $1 100 per kg HM with a corresponding range for sensitivity analyses of $800 to $1 400 per kg HM. This range corresponds to the use of fabrication price ratios of three and five, respectively. It also corresponds to the use of the low and high uranium fuel fabrication prices with the reference MOX fabrication factor of four. The values used in the study are considered to be very robust.

4.3.2.10 Uranium recycling

The present economic situation of the uranium market limits the interest in uranium recycling. Nevertheless, some electric utilities (e.g. in France, Japan, Switzerland and Germany) show some interest in developing recycling programmes.

The technology for making reprocessed uranium fuel is well established so there should be no technical limits on these programmes. In addition, the development of laser enrichment will provide an efficient way of re-enriching reprocessed uranium.

The calculations in Annex 8 of the value of reprocessed uranium are based on the N4 reactor type fuel cycle, a reprocessing facility producing UO_3 as the end product and conversion of reprocessed uranium in large facilities where the cost of conversion will not be more expensive than the cost of conversion of natural uranium.

The value of the uranium credit on the above assumptions is 0.18 mills/kWh or approximately 3 per cent of the fuel cycle cost. The future trend towards higher burn-up together with improved utilisation of the ^{235}U content of the fuel through the use of gadolinia poisons could result in the spent fuel containing less ^{235}U and more ^{236}U compared with the reference case. In addition, if the conversion of the reprocessed uranium were to attract a price premium compared with conversion of natural uranium, then the uranium credit could be significantly reduced and possibly extinguished altogether.

4.3.3 Direct disposal option costs

Consistent with the reprocessing case, cost estimates have been provided for storage, encapsulation and disposal plants based on the well developed strategy currently being followed in Sweden (see Annex 4). For costing purposes in this study, the relative timings in the Swedish case were maintained but the start of the interim storage operation was adjusted to coincide with the needs of the hypothetical PWR under study. This is shown in Figure 5.6.

4.3.3.1 Transport of spent fuel

Based on the Swedish approach, the reference case assumes significant sea transport using a specially designed vessel (M.V. Sigyn) and supporting transport vehicles (see Annex 4). It is judged that inter-European rail costs would be comparable or lower than the reference case. The costs for spent fuel transport are included in the calculation of the levelised storage price to be charged on delivery of the fuel to the interim storage facility.

4.3.3.2 Interim storage of spent fuel

Relatively long interim storage times are a major feature of the direct disposal option. In the Swedish example, on which the reference case is based, a period of 35 years further storage is involved; the spent fuel being stored underwater at a central facility (CLAB).

To enable direct disposal costs used in the reference case to be directly compared with alternative country options (direct disposal and reprocessing), a 5 per cent levelised price that would be paid on delivery of the fuel to the plant was derived. The reference 5 per cent levelised transport and storage price to be charged on delivery to the storage site is ECU 230 per kg U (see Annex 4).

4.3.3.3 Spent fuel encapsulation and final disposal

After 35 years at the interim storage facility, the spent fuel is assumed to be transported to the final disposal site where it is encapsulated just prior to emplacement in a deep, hard-rock geology. The 5 per cent reference levelised price for encapsulation and disposal that is to be charged on delivery to the repository is ECU 610 per kg U.

It should be noted that the SKB cost estimates used to derive this levelised price include a contingency of 27 per cent to reflect the uncertainty associated with the current state of the cost estimates for the encapsulation plant.

4.3.3.4 Comparison with other countries' plans

Unlike reprocessing which is available on the world market, the direct disposal option for spent fuel involves country-specific facilities for the entire back-end of the fuel cycle.

The reference case has been based on the Swedish example, the detailed costings of which are shown in Annex 4. Germany and the United States are also developing the direct disposal option. The state of development and the relative timing of the transport/storage and encapsulation/disposal operations are different to the Swedish example on which the reference case is based. This is shown diagramatically in Figure 4.1.

In the German example, intervenor action has introduced a delay between the actual construction (capital spend) phase and operation of the storage facility. The levelised prices shown take into account the capital and decommissioning costs although their timescales are not shown in Figure 4.1.

The method used in this study is to derive unit prices, levelised to the time of delivery, for the transport/storage and encapsulation/disposal operations. These levelised prices are shown in Figure 4.1 and are tabulated in Table 4.1. This method allows those prices to be applied to the delivery timings assumed for the hypothetical PWR whose fuel cycle cost is being calculated.

Table 4.1. **Comparison of country-specific direct disposal costing data**

Country	**Undiscounted Costs (ECU/kg U)**		**Levelised Price, 5% (ECU/kg U)**	
	Transport/ Storage	**Encapsulation/ Disposal**	**Transport/ Storage**	**Encapsulation/ Disposal**
Sweden	210	360	230	610
Germany[(a)]	290	500	290	670
US[(b)]	40	120	60	140

a. In the German case, the levelised price has been derived using a 4.3 per cent per year (real) rate of return. However, because of the timing of events, this introduces a negligibly small error and the values are a good approximation to the 5 per cent levelised price.

b. In the US case, the storage price is calculated for a quantity of approximately 87 000 tU of spent fuel alone, whereas the disposal price is calculated for this quantity of spent fuel and about 9 000 tU of equivalent defence programme wastes, i.e. a total of approximately 96 000 tU.

In the Swedish case the disposal repository is being engineered to take only encapsulated spent fuel. In the US and German cases the repository will be designed to accept both conditioned HLW from reprocessing and encapsulated spent fuel. In the US case, spent fuel comprises over 90 per cent of the waste, whereas in the German case it is assumed to represent about 30 per cent. The ability of the repository to take both types of high level waste makes it difficult to identify costs solely attributable to the spent fuel component. However, since the US and German cases are being used only to set boundary values for sensitivity purposes, this is not considered to be of major importance.

The SKB data are related to facilities for a total of 8 000 tU of spent fuel. The US data are related to 87 000 tU of spent fuel plus defence programme wastes equivalent to 9 000 tU, and the German example relates to 35 000 tU of spent fuel (70 per cent as VHLW and 30 per cent as encapsulated spent fuel). This quantity is higher than that currently assumed by the German utilities in setting financial provisions to cover disposal liabilities. Because of burn-up increases, the German utilities assume a lower quantity for disposal and hence use a prudently higher unit disposal price.

The Swedish and US cost estimates in the above table relate to plant costs and do not include supporting research and development costs. These could act to increase costs by about 20 per cent in the Swedish case to as much as doubling the cost in the US case. In the German case, supporting research and development has been included but as it sets the upper bound to the sensitivity range no attempt has been made to separate it out.

The back-end cost of the direct disposal option will be heavily influenced by country-specific regulatory and licensing requirements, by programme timing and by the engineering and design approach and nature of the geology into which disposal is made.

It is to be noted that the reference case (based on the Swedish experience) lies within the range shown. For sensitivity calculations the values for the German and the US cases have been taken to set the upper and lower bounds, respectively, for the range of encapsulated spent fuel disposal prices used in this study. In all instances, the relative timings set by the Swedish reference case have been consistently applied.

4.4 Environmental factors

The operation of nuclear power stations and associated nuclear fuel cycle service plants is carried out under strict regulatory requirements for environmental protection and public safety. These requirements cover all aspects of the fuel cycle including operation and decommissioning and cover transport of radioactive materials. Additionally, the aerial and liquid discharges from the sites containing fuel plants are subject to authorisations and monitoring whilst solid wastes must conform to specifications to meet regulatory requirements for transport, storage and ultimate disposal. The costs that have been used in this study take full account of the investment and operating experience that has been found to be necessary in meeting these comprehensive requirements.

It would be appropriate in all comparisons of costs with those of non-nuclear fuel cycles to acknowledge the comprehensive nature of the nuclear costs.

4.5 Safeguards

In the 1985 study, costs for implementing safeguards procedures were included in the cost of each component of the fuel cycle.

Safeguards procedures both for the front-end and for the reprocessing facilities in the back-end of the fuel cycle are well established and more efficient methods are currently being pursued. Safeguards procedures for the disposal of radioactive wastes have not yet been properly established; additional costs for the implementation of safeguards are expected for the direct disposal of spent fuel.

Costs for safeguards are negligibly small in comparison to the other cost components of the fuel cycle.

Figure 4.1 **Incidence of cash flow versus the spent fuel delivery profile of the three country-specific examples**