5. THE CALCULATION OF TOTAL FUEL COSTS FOR PWR

5.1 Principles of assembling stage costs into overall fuel cost

The unit costs for the different stages of the fuel cycle are discounted to a selected base date and added together in order to arrive at a total fuel cost in present value terms. In order to obtain the levelised fuel cycle cost, net present values (npv's) are taken of the cost profile and the income profile (based on generation) to the commissioning date of the reactor. Setting the two npv's equal allows the levelised fuel cost to be calculated (see Annex 1).

5.2 Basic data

5.2.1 Choice of reactor parameters and base date

In addition to the fuel cycle cost data which are presented in Table 5.5, the basic assumptions adopted are given in Tables 5.1, 5.2, 5.3 and 5.4. The reference reactor is a 1 390 MWe PWR which is assumed to be commissioned in the year 2000. The load factor adopted is 75 per cent and the plant lifetime is 30 years with 25 and 40 years values for sensitivity analyses. The fuel mass balance for the reference reactor which is based on a fuel burn-up level of 42 500 MWd/t is shown in Table 5.6.

Table 5.1. **Reactor and fuel data**

Item	Reference	Sensitivity range
Reactor type	PWR (French N4)	
Thermal output	4 020 MWt	
Electric output	1 390 MWe	
Load factor[(a)]	75%	
Commissioning year	2000	
Plant lifetime	30 years	25-40 years
Fuel burn-up[(b)]	42 500 MWd/t	
Fuel mass balance	(see Table 5.6)	

a. Discounted average
b. At equilibrium

Table 5.2. **Cost data**

Item	Reference
Base date of monetary unit	Early 1991
Monetary unit	Front-end: US$ Back-end: ECU
Assumed exchange rate (long term)	US$1 = ECU 1

Note: Unit prices for each component are given in Table 5.5.

5.2.2 Tails assay for enrichment

The tails assay, i.e. the concentration of ^{235}U in the depleted uranium stream, is assumed to be 0.25 per cent, with 0.2 and 0.3 per cent being taken as variants for sensitivity calculations.

5.2.3 Lead and lag time

Lead time is the term referring to the date at which materials are obtained, services are performed and payments for front-end components occur, prior to the date of loading fuel into the reactor. Lag time is the date at which a payment for the back-end occurs, after the fuel discharge date. The full range of the selected reference and parametric lead and lag times for the various stages of the fuel cycle is shown in Table 5.3.

5.2.4 Loss factor

For costing purposes, the material losses in the different stages of the fuel cycle have been assumed to be 0.5 per cent for conversion, 1.0 per cent for fabrication and 2.0 per cent for reprocessing while no allowances have been assumed for losses in the other processes.

The actual losses which occur in practice are below these assumed values.

5.2.5 Unit price assumptions

The unit price assumptions for the component stages of the fuel cycle, which were presented in Chapter 4, are summarised in Table 5.5. The constant monetary units are the US dollar and the ECU, 1991 money values, for the front-end and the back-end of the fuel cycle, respectively.

Table 5.3. **Fuel cycle data**

Item	Reference	Sensitivity range
Tails assay for enrichment	0.25%	0.20%-0.30%
Lead time (relative to fuel loading date) for:		
- uranium purchase	24 months[(a)]	42 months[(a)]
- conversion	18 months[(a)]	34 months[(a)]
- enrichment	12 months[(a)]	22 months[(a)]
- fabrication	6 months[(a)]	12 months[(a)]
Lag time (relative to spent fuel discharge date) for:		
- spent fuel transport	5 years	
- reprocessing option[(b)]		
- reprocessing	6 years	
- VHLW disposal	56 years	
- direct disposal option[(c)]		
- interim storage	5 years	
- spent fuel encapsulation & disposal	40 years	
Loss factor for:		
- conversion	0.5%	
- fabrication	1.0%	
- reprocessing	2.0%	
- others	0%	

a. For initial fuel, 6 months are added.
b. Including 5 years storage time at reactor.
c. Including 5 years storage at reactor followed by 35 years storage at interim storage facilities.

Table 5.4. **Other data**

Item	Reference	Sensitivity range
Discount rate	5%	0%, 2%, 8%, 10%, 12% & 15%
Uranium credit	70% of the cost of new uranium at the same enrichment	
Plutonium credit	$5/g Puf	

Table 5.5. **PWR fuel cycle unit prices**[a]

Component	Basic assumptions for PWR: Reference unit price	Sensitivity range
Uranium purchase	\$50/kg U (in 1990) (\$19.2/lb U_3O_8) escalation 1.2% p.a.	\$40-\$90/kg U escalation 0% p.a.
Conversion	\$8/kg U	\$6-\$11/kg U
Enrichment	\$110/SWU	\$80-\$130/SWU
Fabrication	\$275/kg U	\$200-\$350/kg U
Reprocessing option:		
- spent fuel transport	ECU 50/kg U[b]	ECU 20-80/kg U
- reprocessing (including disposal of LLW & ILW & the vitrification & storage of VHLW)	ECU 720/kg U[c]	ECU 540-720/kg U
- VHLW disposal	ECU 90/kg U[d]	ECU 90-580/kg U
Direct disposal option:		
- spent fuel transport & storage	ECU 230/kg U[e]	ECU 60-290/kg U
- encapsulation & disposal	ECU 610/kg U[f]	ECU 140-670/kg U

a. Early 1991 money value.
b. Transportation within the European area.
c. Payable on delivery to the reprocessing site.
d. Payable on delivery to the VHLW disposal site.
e. Payable on delivery to the interim storage site and includes the price of transport.
f. Payable on delivery to the encapsulation and disposal site.

5.3 PWR cost calculations

All the fuel cycle cost calculations for both the reference and sensitivity analyses for both the reprocessing and the direct disposal options were carried out by PNC (Power Reactor and Nuclear Fuel Development Corporation), Japan. All calculations were performed using the PNC computer code PNC-REFCO and are based on the methodology indicated in Annex 1.

5.3.1 Costs for the reprocessing option

The fuel cycle costs for the reprocessing scenario of the reference PWR were calculated using the reference assumptions and unit prices as shown in Tables 5.3 and 5.5, respectively. Sensitivity calculations were made to analyse the impact of the variations in both the basic assumptions and unit prices on the total fuel costs and these are shown in Chapter 6.

Table 5.6. **Material balance (PWR, 42 500 MWd/t)**

Time (EFPY)	**Interval between reload (EFPY)**	**Total uranium (tonne)**	**^{235}U (%)**	**Fissile Pu (kg)**	**Total Pu (kg)**	**Burn-up (MWd/t)**
1. Non-equilibrium cycle charge data						
0		28.00	1.80			
0		9.16	1.80			
0		18.85	2.40			
0		17.77	2.40			
0		10.23	3.10			
0		26.39	3.10			
1.046		28.00	3.60			
1.724		28.00	3.60			
2.442		28.00	3.60			
2. Equilibrium cycle charge data						
3.240	0.798	28.00	3.60			
3. Non-equilibrium cycle discharge data						
1.046		27.44	0.84	130.00	172.64	13 900
1.724		8.82	0.60	54.40	76.50	22 000
1.724		18.19	0.78	119.00	164.50	23 000
2.442		17.01	0.53	119.46	175.56	32 000
2.442		9.75	0.85	72.20	102.60	33 000
3.240		26.50	0.64	208.00	312.00	41 000
4.037		26.53	0.94	214.24	309.40	39 000
4.835		26.47	0.88	216.32	316.16	40 600
5.632		26.40	0.81	218.40	322.92	42 500
4. Equilibrium cycle discharge data						
6.430	0.798	26.40	0.81	218.40	322.92	42 500
5. Final core discharge data						
		26.40	0.81	218.40	322.92	42 500
		26.77	1.24	202.80	275.60	31 900
		27.20	1.80	166.40	212.16	21 300
		27.54	2.50	109.20	127.40	10 700

Note: EFPY = effective full-power year.

5.3.2 Time flow of costs for the reprocessing option

The cash flow of payments for the entire fuel cycle based on the reference reprocessing option is shown in Figure 5.1. The payments for the various components of the fuel cycle are made at discrete points in time, corresponding to the refuelling interval plus or minus lead or lag times. The payments depend on the amount of material or service required and the unit price of each component. In this study the levelised prices for reprocessing and disposal of a batch of fuel are charged at the time of delivery of the fuel to the respective facility. The reprocessing price covers all services up to the time of final disposal, i.e. vitrification, ILW disposal and HLW storage. Both prices are levelised to ensure that the reprocessor can meet all costs and financial targets (see Annex 1). Figure 5.2 gives an example of the relative fuel cycle component costs and the time flow for a typical reprocessing fuel batch. Credits for plutonium and uranium are deducted from the cash flows.

From the above, the reference reactor, which is commissioned on the 1st January 2000, has a typical time flow of payments commencing in 1997 (with the purchase of uranium for the initial core) which extends out to 2085 when the final core is disposed (see Figure 5.3).

In order to obtain the levelised fuel cycle cost, net present values (npv's) are taken of the cost profile (Figure 5.3) and the income profile (based on generation) to the commissioning date of the reactor. Setting the two npv's equal allows the levelised fuel cost to be calculated (see Annex 1). The levelised fuel cost that results from the reprocessing cycle is 6.23 mills/kWh. The contribution of each fuel cycle component for the initial core and refuels in the total fuel cycle cost is shown in Table 5.7.

5.3.3 Costs for the direct disposal option

As with the reprocessing option detailed above, the costs for the direct disposal option were calculated using reference assumptions and unit prices shown in Tables 5.3 and 5.5, respectively. Timings of back-end services used those appropriate to Sweden (the reference case).

5.3.4 Time flow of costs for the direct disposal option

The cash flow of payments for the reference direct disposal option is shown in Figure 5.4. Due to the country specific nature of the reference case, timings of payments, as displayed in Figures 5.5 and 5.6, are different to those of the reprocessing scenario.

The levelised fuel cycle cost over the reactor life is 5.46 mills/kWh for the chosen reference case. The split of this cost into each fuel cycle component for both initial core and refuels is shown in Table 5.8.

5.4 BWR fuel cycle cost

Recent bid comparisons(9) confirmed that the lifetime levelised fuel cost for a modern future BWR is about the same as that for a modern PWR, when the equilibrium burn-up value of the BWR fuel is approximately 90 per cent the burn-up value of the PWR fuel. This applies to the direct disposal fuel cycle. If the reprocessing fuel cycle option is considered, the BWR fuel cost would, due to the slightly lower burn-up, be marginally higher than the PWR fuel cost. While the share of the uranium cost is typically lower for modern BWR fuel, fabrication costs are higher than those of the PWR fuel. Individual plant and fuel design features are, however, more important in determining fuel cycle costs than is the reactor type.

Table 5.7. **Levelised PWR fuel cycle cost for the reprocessing option**
(Reference case)

Component	(mills/kWh) Initial core	Reloads	Total
Uranium	0.17	1.47	1.64
Conversion	0.03	0.18	0.21
Enrichment	0.18	1.67	1.85
Fuel fabrication	0.19	0.81	1.00
Subtotal for front-end	**0.57**	**4.13**	**4.70**
Transport of spent fuel	0.02	0.09	0.11
Reprocessing & vitrification	0.32	1.34	1.66
Waste disposal	0.003	0.02	0.02
Subtotal for back-end	**0.34**	**1.45**	**1.79**
Uranium credit	-0.01	-0.17	-0.18
Plutonium credit	-0.01	-0.07	-0.08
Subtotal for credit	**-0.02**	**-0.24**	**-0.26**
Total cost	**0.89**	**5.34**	**6.23**

Table 5.8. **Levelised PWR fuel cycle cost for the direct disposal option**
(Reference case)

Component	(mills/kWh) Initial core	Reloads	Total
Uranium	0.17	1.47	1.64
Conversion	0.03	0.18	0.21
Enrichment	0.18	1.67	1.85
Fuel fabrication	0.19	0.81	1.00
Subtotal for front-end	**0.57**	**4.13**	**4.70**
Transport/Storage of spent fuel	0.10	0.41	0.51
Encapsulation/Disposal of spent fuel	0.05	0.20	0.25
Subtotal for back-end	**0.15**	**0.61**	**0.76**
Total cost	**0.72**	**4.74**	**5.46**

Figure 5.1 **Cash flow of the PWR fuel cycle**
(reprocessing option)

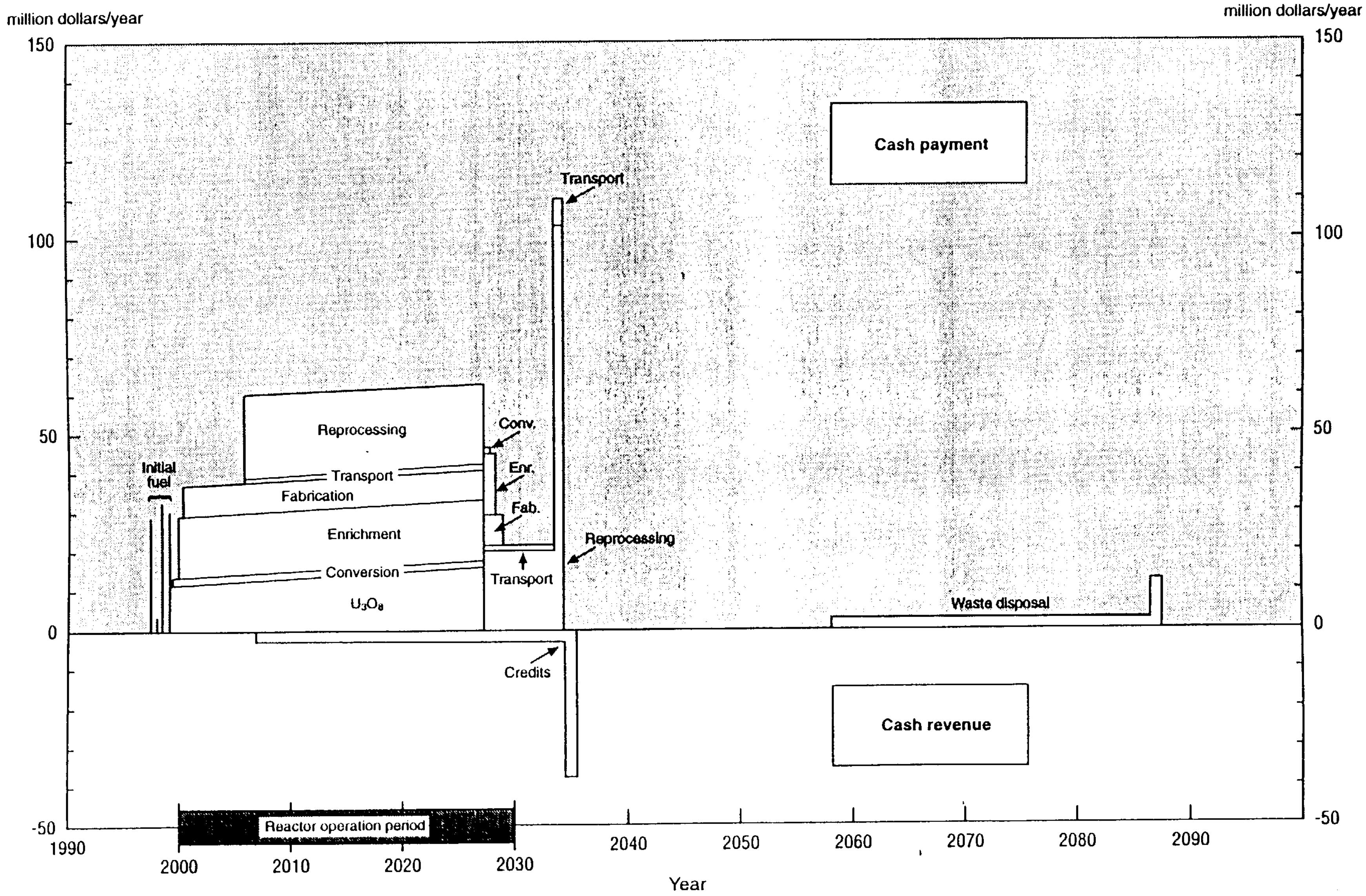

Figure 5.2 **Time flow of nuclear fuel cycle cost**
(PWR reprocessing option)

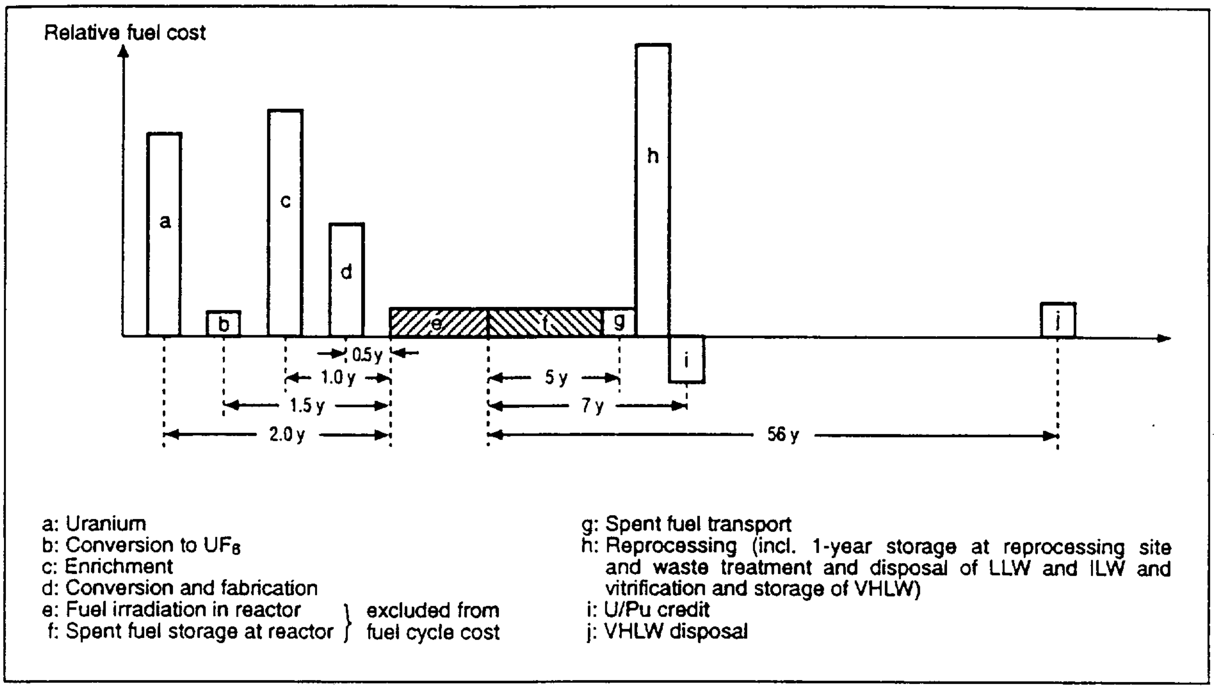

Figure 5.3 **Scenario for back-end of PWR reprocessing option**

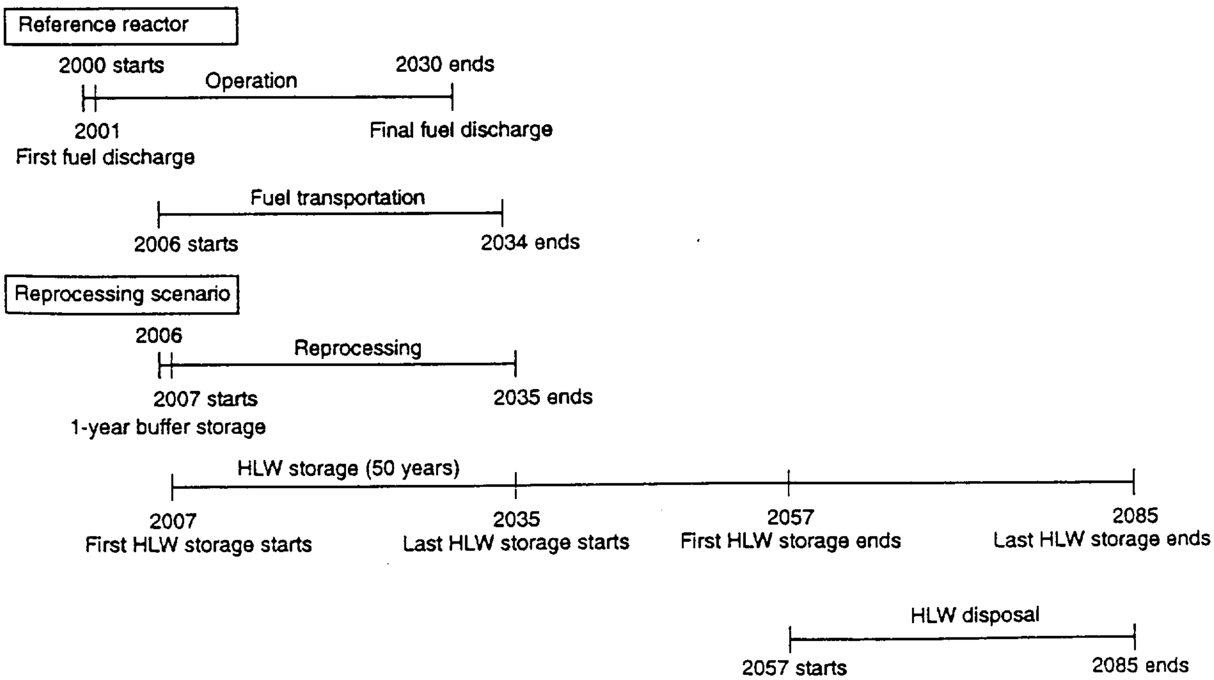

Figure 5.4 **Cash flow of the PWR fuel cycle**
(direct disposal option)

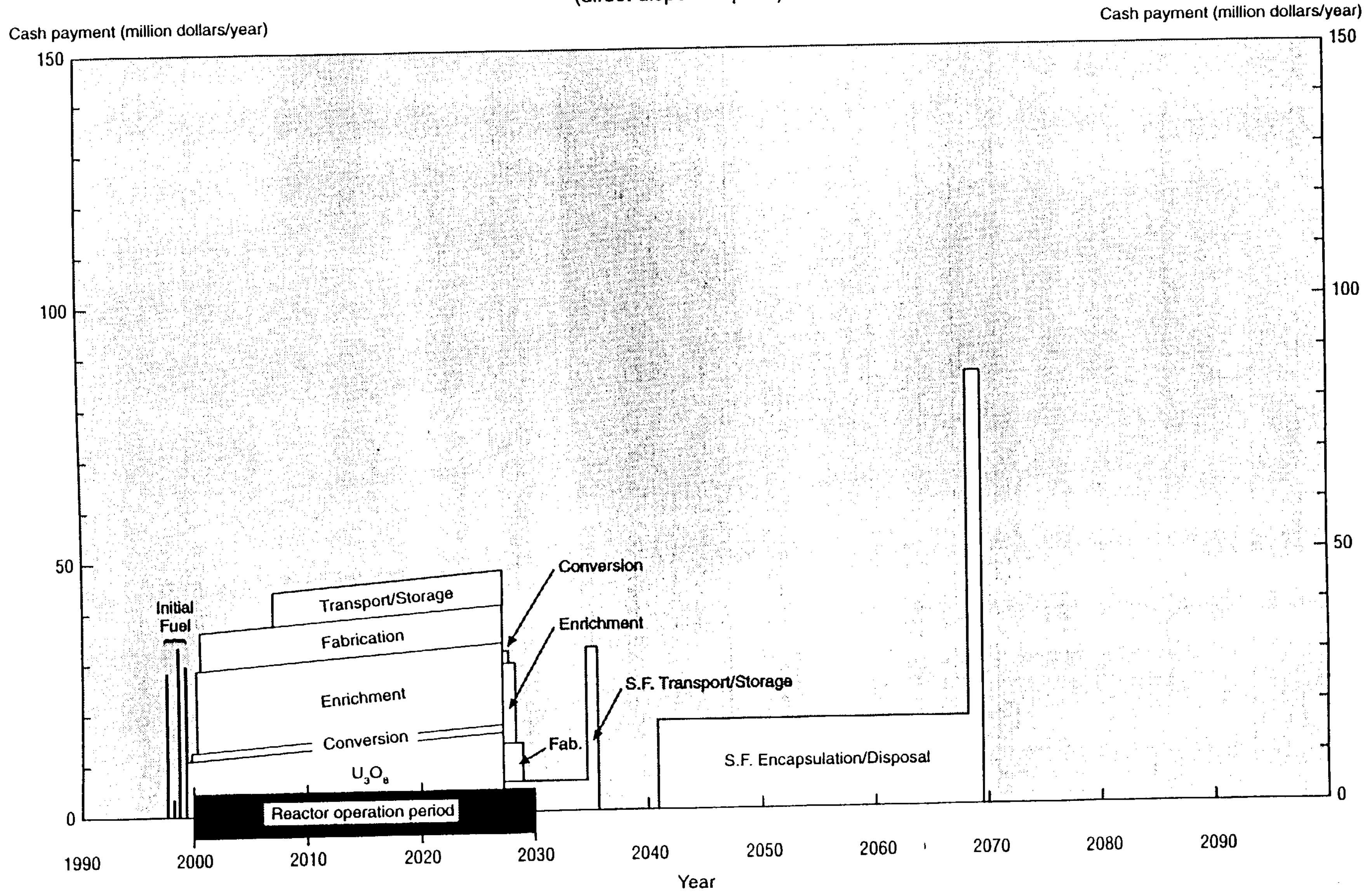

Figure 5.5 **Time flow of nuclear fuel cycle cost**
(PWR direct disposal option)

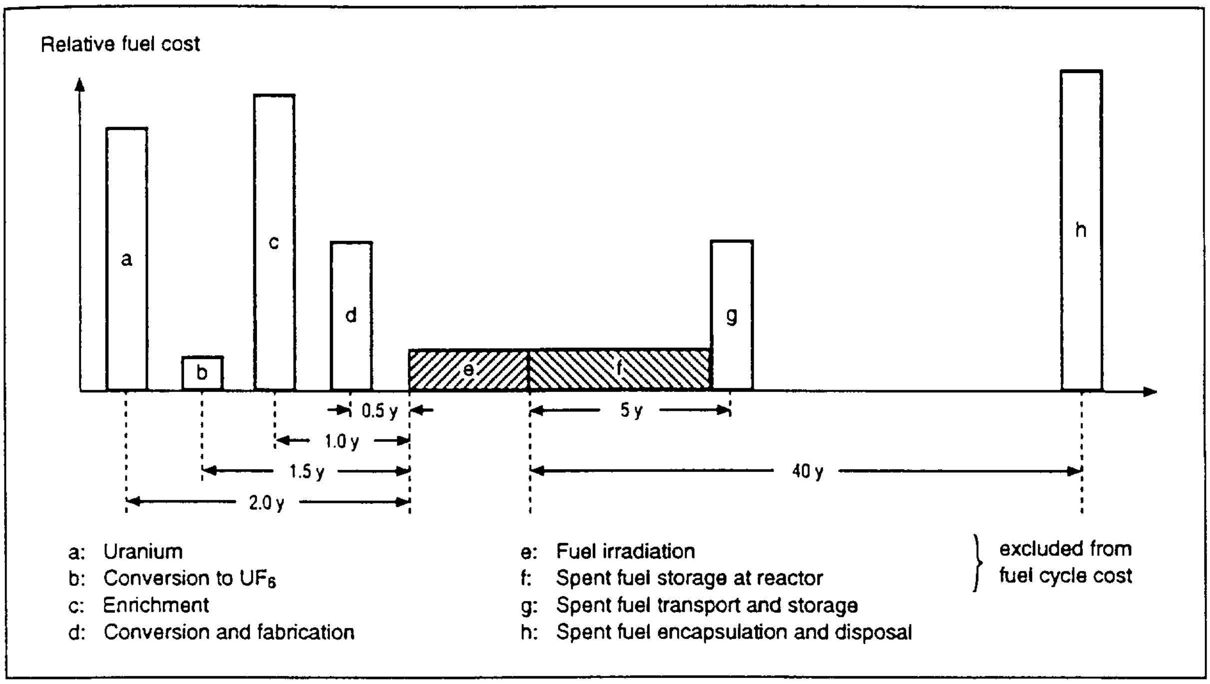

Figure 5.6 **Scenario for back-end of PWR direct disposal option**