Annex 1

METHOD OF CALCULATING A LEVELISED PRICE AND A FUEL CYCLE COST

1. Introduction

The purpose of this annex is twofold: firstly, to explain the method of calculating the levelised price for the back-end services. Secondly, it illustrates how this levelised price in conjunction with the front-end market prices are used to calculate the discounted fuel cycle cost per kilowatt hour (kWh) of electricity generated over the reactor lifetime, commonly known as the lifetime levelised fuel cycle cost.

2. Levelising to a price

All back-end services, such as reprocessing and waste disposal, can be defined in terms of plant cost estimates (see Annex 3). In order to charge the correct price the service provider must firstly decide the rate of return on capital that is required.

Having chosen this rate of return, the net present value of the cash flows associated with construction, operation, maintenance and decommissioning of the plant are calculated at the chosen reference date [e.g. when the material deliveries commence (see Figure 1.1)]. The net present value associated with the processing of the material, based on the levelised price (as yet unquantified) and the throughput profile, is expressed to the same reference date. The levelised price is then calculated by setting the two net present values equal. This levelised price ensures the plant operator can meet all his costs and obtain the required rate of return on the capital employed.

3. Fuel cycle costs

The cash out-flow for fuel cycle material and services commences before the reactor starts to generate electricity and continues well after the reactor ceases operation. The exact timing of payments for uranium, fuel fabrication, reprocessing, etc., depend on the fuel cycle chosen and the associated lead and lag times for each of the fuel cycle components.

In order to calculate the overall fuel cycle cost, the magnitude of each component cost and the appropriate point in time that it occurs must be identified. The quantities of fuel are obtained from reactor neutronics calculations (see Table 5.6 in the main text). These quantities of material and services are adjusted to allow for process losses in the various component stages of the nuclear fuel cycle and then multiplied by the unit costs (or levelised prices for back-end services) to obtain the component costs. Table 1.1 lists the notation of all the parameters needed for the calculations.

Table 1.1. **Parameter notation for fuel cycle cost calculations**

General

Discount rate	r
Time	t
Base date of monetary unit	t_b
Date of fuel loading	t_c
Fuel residence time	T_r

Materials

Mass of uranium feed (kg)	M_f
Mass of uranium charged in reactor (kg)	M_p
Mass of uranium in the tails (kg)	M_t
Mass of uranium discharged (kg)	M_d
Mass of plutonium (total) (kg)	M_{Pu}
Mass of plutonium fissile (kg)	M_{Puf}
Fraction of ^{235}U in the uranium feed	e_f (0.711 %)
Fraction of ^{235}U charged in reactor	e_p
Fraction of ^{235}U in the tails	e_t
Fraction of ^{235}U discharged	e_d
Conversion factor from kg U to lb U_3O_8 (a lbs U_3O_8 per kg U)	a (2.6)

For each component i of the nuclear fuel cycle:

Total component cost	F_i
Unit cost	P_i
Escalation rate	s_i
Material losses	l_i
Total loss factor	f_i
Lead or lag time	t_i

where:

i = 1	Uranium purchase
i = 2	Conversion
i = 3	Enrichment
i = 4	Fabrication
i = 5	Transportation of spent fuel
i = 6	Reprocessing or Interim Storage
i = 7	Disposal of VHLW or Encapsulation/Disposal of spent fuel
i = 8	Uranium credit
i = 9	Plutonium credit

and

P_1 = Monetary units per lb U_3O_8
P_2 = Monetary units per kg U
P_3 = Monetary units per SWU
$P_{4,7}$ = Monetary units per kg U
P_8 = Monetary units per kg U recovered
P_9 = Monetary units per kg Pu_f

For each component, the cost for a given fuel batch can be written as:

Cost of uranium

$$F_1 = M_f . a . f_1 . P_1 . (1+s_1)^{t-t_b}$$

where:

$$M_f = \frac{(e_p - e_t)}{(e_f - e_t)} . M_p$$

$$f_1 = (1+l_2)(1+l_3)(1+l_4)$$

From all front-end components: $t = t_c - t_1$

Cost of conversion

$$F_2 = M_f . f_2 . P_2 . (1+s_2)^{t-t_b}$$

where:

$$f_2 = (1+l_2)(1+l_3)(1+l_4)$$

Cost of enrichment

$$F_3 = S . f_3 . P_3 . (1+s_3)^{t-t_b}$$

where:

S = Separative Work Units

$= M_p V_p + M_t V_t - M_f V_f$

$M_t = M_f - M_p$

$$V_x = (2e_x - 1) \ln \frac{e_x}{1-e_x}$$

and x is subscript for f, p or t

$$f_3 = (1+I_3)(1+I_4)$$

Cost of fabrication

$$F_4 = M_p . f_4 . P_4 . (1+s_4)^{t-t_b}$$

where:

$$f_4 = (1+I_4)$$

Cost of transportation

$$F_5 = M_p . P_5 . (1+s_5)^{t-t_b}$$

for all the back-end components: $t = t_c + T_r + t_i$

Cost of reprocessing or interim storage

$$F_6 = M_p . P_6 . (1+s_6)^{t-t_b}$$

Cost of disposal of VHLW or Encapsulation/Disposal of spent fuel

$$F_7 = M_p . P_7 . (1+s_7)^{t-t_b}$$

Uranium credit

The value of recovered uranium (C_{rec}) is defined in detail in Annex 8:

$$F_8 = M_d . P_8 . f_8 . (1+s_8)^{t-t_b}$$

where:

$$f_8 = (1-I_6)$$
$$P_8 = C_{rec}$$

Plutonium credit

$$F_9 = M_{Pu_t} \cdot f_6 \cdot P_9 \cdot (1+s_6)^{t-t_b}$$

The component costs above are given for a typical batch. Over the reactor lifetime, these costs are time dependent and should be written as $F_i(t)$.

4. Discounting and levelising of fuel cycle costs

All the component costs are discounted back to a selected base date and added together in order to arrive at a total fuel cost in present value terms.

The total discounted cost of the nuclear fuel cycle can be written as:

$$\sum_i \sum_{t=t_o-T_1}^{t=t_o+L+T_2} \frac{F_i(t)}{(1+r)^{(t-t_o)}} \qquad (1)$$

where:

t_o = reference date (commissioning date)

L = reactor lifetime

T_1 = max. value of lead time (in front-end)

T_2 = max. value of lag time (in back-end)

If C is the constant levelised fuel cost per unit of electricity sent out by a reactor, the total cost of fuel is also:

$$\sum_{t=t_o}^{t_o+L} \frac{C \cdot E_{(t)}}{(1+r)^{t-t_o}} \qquad (2)$$

where:

$E_{(t)}$ = net electrical output at time t

hence:

$$\sum_{stages} \sum_{Time} \frac{F_i(t)}{(1+r)^{t-t_o}} = \sum_{Time} \frac{C \cdot E(t)}{(1+r)^{t-t_o}} \qquad (3)$$

hence:

$$C = \frac{\sum_{Stages} \sum_{Time} \frac{F_i(t)}{(1+r)^{t-t_0}}}{\sum_{Time} \frac{E(t)}{(1+r)^{t-t_0}}} \tag{4}$$

Because electricity is generated more or less continuously during the reactor life, a continuous discounting method can be employed. The discount rate r is then replaced by r' = ln(1+r), which is called the continuous discount rate, and the discount factor is replaced by the exponential form:

$$\frac{1}{(1+r)^{t-t_0}} = \exp(-r't) \tag{5}$$

The denominator of equation (4) is rewritten in the exponential form and the integration is made over the period in which electricity is generated.

$$\sum_{time} \frac{E(t)}{(1+r)^{t-t_0}} = \int_{time} \exp(-r't) \,.\, E(t) \; dt \tag{6}$$

If E(t) is assumed to be constant over a period of time from 0 to T and equal to E, the above integral then becomes:

$$\begin{aligned} E \int_0^T \exp(-r't)\, dt &= E.\, \frac{1-\exp(-r'T)}{r'} \\ &= E.\, T.\, \frac{1-\exp(-r'T)}{r'T} \end{aligned} \tag{7}$$

When the load factor of the plant varies from year to year or from cycle to cycle over the lifetime of reactor, E has different values for each operational year or cycle. In such a case, the above integral will be taken separately and will be added together in order to arrive at the total discounted electricity output.

The procedures mentioned above can be laborious if economic and technical parameters vary with time. In the present study a PNC computer code was used for the calculation of the levelised fuel cycle cost over the lifetime of reactor.

Figure 1.1 Assumed timescales used in calculation of a levelised price (direct disposal option)