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): \( M_r \)
- 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): \( M_{Pd} \)
- Mass of plutonium fissile (kg): \( M_{Pfd} \)
- Fraction of \(^{235}\)U in the uranium feed: \( c_t \) (0.711 %)
- Fraction of \(^{235}\)U charged in reactor: \( c_p \)
- Fraction of \(^{235}\)U in the tails: \( c_t \)
- Fraction of \(^{235}\)U discharged: \( c_d \)

- Conversion factor from kg U to lb U\( _{3} \)O\( _{8} \)
  - (a lbs U\( _{3} \)O\( _{8} \) 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

\[ P_1 = \text{Monetary units per lb U}_3\text{O}_8 \]
\[ P_2 = \text{Monetary units per kg U} \]
\[ P_3 = \text{Monetary units per SWU} \]
\[ P_{4r} = \text{Monetary units per kg U recovered} \]
\[ P_s = \text{Monetary units per kg U recovered} \]
\[ P_r = \text{Monetary units per kg Pu} \]

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

**Cost of uranium**

\[ F_1 = M_t \cdot \mathbf{f}_1 \cdot P_1 \cdot (1 + g_1)^{t - c_b} \]

where:

\[ M_t = \frac{(e_p - e_c)}{(e_c - e_c)} \cdot M_p \]

\[ f_1 = (1 + I_2) (1 + I_3) (1 + I_4) \]

From all front-end components: \( t = t_c - t_4 \)

**Cost of conversion**

\[ F_2 = M_t \cdot \mathbf{f}_2 \cdot P_2 \cdot (1 + g_2)^{t - c_b} \]

where:

\[ f_2 = (1 + I_2) (1 + I_3) (1 + I_4) \]

**Cost of enrichment**

\[ F_3 = S \cdot f_3 \cdot P_3 \cdot (1 + g_3)^{t - c_b} \]

where:

\[ S = \text{Separative Work Units} \]
\[ = M_p V_p + M_t V_{t_c} - M_t V_{t_c} \]
\[ M_t = M_t - M_p \]

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

and \( x \) is subscript for \( f, p \) or \( t \)

\[ f_3 = (1+l_3)(1+l_4) \]

Cost of fabrication

\[ F_4 = m_p \cdot f_4 \cdot p_4 \cdot (1+s_4)^{t-t_b} \]

where:

\[ f_4 = (1+l_4) \]

Cost of transportation

\[ F_5 = m_p \cdot p_5 \cdot (1+s_5)^{t-t_b} \]

for all the back-end components: \( t = t_c + T_r + t_d \)

Cost of reprocessing or interim storage

\[ F_6 = m_p \cdot p_6 \cdot (1+s_6)^{t-t_b} \]

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

\[ F_7 = m_p \cdot p_7 \cdot (1+s_7)^{t-t_b} \]

Uranium credit

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

\[ F_8 = m_d \cdot p_8 \cdot f_8 \cdot (1+s_8)^{t-t_b} \]

where:

\[ f_8 = (1-l_8) \]

\[ F_8 = C_{rec} \]
Plutonium credit

\[ F_9 = M_{Pu} \cdot \mathcal{E}_6 \cdot P_9 \cdot (1+S_9)^{t-t_b} \]

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 levelling 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:

\[
\sum_{\tau_1} \sum_{t = t_o - T_2}^{t_o + L + T_3} \frac{F_i(t)}{(1+r)^{t-t_o}}
\]

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:

\[
\sum_{t = t_o}^{t_o + L} \frac{C \cdot E(t)}{(1+r)^{t-t_o}}
\]

where:

\( E(t) = \) net electrical output at time \( t \)

hence:

\[
\sum_{\text{stages}} \sum_{\text{time}} \frac{F_i(t)}{(1+r)^{t-t_o}} = \sum_{\text{time}} \frac{C \cdot E(t)}{(1+r)^{t-t_o}}
\]
hence:

\[
C = \frac{\sum_{s=0}^{\text{stages}} \sum_{t=0}^{\text{time}} \frac{F_s(t)}{(1+r)^{t-t_0}}}{\sum_{t=0}^{\text{time}} \frac{E(t)}{(1+r)^{t-t_0}}}
\]  

(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:

\[
\frac{1}{(1+r)^{t-t_0}} = \exp(-r't)
\]  

(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.

\[
\sum_{t=0}^{\text{time}} \frac{E(t)}{(1+r)^{t-t_0}} = \int_{t=0}^{\text{time}} \exp(-r't) \cdot E(t) \, dt
\]  

(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:

\[
E \int_{0}^{T} \exp(-r't) \, dt = E \cdot \frac{1 - \exp(-r'T)}{r'} = E \cdot \frac{1 - \exp(-r'T)}{r'T}
\]  

(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)

A = Base date for levelised storage price
B = Base date for levelised repository price

To obtain a levelised price:
NPV (costs) = NPV (income)