Commission of the European Communities

energy

METHOD OF CALCULATING THE COST OF ELECTRICITY GENERATION FROM NUCLEAR AND CONVENTIONAL THERMAL STATIONS

Report

EUR 5914 DE, EN

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FINAL REPORT

At a request from the
Directorate-General for Energy
of the Commission of the European Communities
by the International Union of Producers and
Distributors of Electrical Energy (UNIPEDE)
Paris, France

1982

EUR 5914 DE, EN

Published by the
COMMISSION OF THE EUROPEAN COMMUNITIES

Directorate-General
Information Market and Innovation

Bâtiment Jean Monnet
LUXEMBOURG

LEGAL NOTICE

This publication is also available in the following language:

DE ISBN 92-825-3175-9

Cataloguing data can be found at the end of this publication

Luxembourg, Office for Official Publications of the European Communities, 1982

Printed in Belgium

ISBN 92-825-3176-7 Catalogue number: CD-ND-82-093-EN-C

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SUMMARY OF THE REPORT

1. TERMS OF REFERENCE OF THE GROUP OF EXPERTS

The Nuclear Energy Study Committee of UNIPEDE, in response to a request from the Directorate General for Energy of the Commission of the European Communities, has asked a group of experts to establish a model for calculating and comparing the cost of electricity generation from nuclear and conventional thermal stations. The model would allow the different European electricity utilities to provide data and results on a common and comparable international basis.

The model developed in this report can be applied to new nuclear stations of any type, to conventional thermal stations and even to gas turbines, but is not intended to be applied to combined heat and power stations.

Only future costs are considered, that is to say the costs of new stations, whether under construction or being planned, but not the costs of stations already operating, which would be evalutaed by accounting methods. Thus present costs are not considered.

The method presented in this report is not intended to be substituted for that used by each electricity utility for its own needs, in particular for establishing budgets and financial requirements. Nor is it intended to give the overall cost of supplying the consumers' electricity demand, which continually varies, as does the plant needed to meet the demand.

The overall cost can only be calculated taking into account all elements of the system, in particular the shape of the load curve, the generating plant mix and generating reserve margin, the network interconnections, etc. These factors must also be taken into account when making a full economic comparison of new generating stations of different types when added to a given system. The model presented in this report is not sufficiently sophisticated for such a comparison and is intended only for the purpose of comparing generating stations of the same type.

The Services of the Commission of the European Community were associated with the work of the Group of Experts.

2. PRESENTATION OF THE METHOD

The essentials of the proposed method are set out in this summary under three headings :-

(i) The principles and method of economic appraisal.

(ii) Definition of limits of supply and cash flows required by the method for the three components :

(a) Investment cost (capital cost).
(b) Operating cost other than fuel.
(c) Fuel cost.

(iii) Presentation of data and results.

Summary schedules and a short numerical example illustrating the essentials of the method are attached to this summary. The body of the report gives the detailed explanations and arguments underlying the adoption of the method.

3. THE PRINCIPLES AND METHOD OF ECONOMIC APPRAISAL

(Chapters 3 and 4 of the report)

3.1 Discounting :

The present-value method is used : all costs incurred by the electricity utility (investment, operating and fuel costs) are included at the time the utility incurs them and are at present valued to a given base date (see para 3.6 below). **They are then summed to give a total present value cost. When costs are incurred on a continuous basis (e.g. operating costs) it is considered adequate to lump them as a series of costs occurring at the middle of each year (see appendix 1 of the report).**

3.2 Constant money

All costs are expressed in constant money (real terms), that is to say in the same monetary unit, representing the value of money at a given reference date - if possible 1 January in the year the cost estimate is made.

3.3 Treatment of costs already incurred :

In the case of a station already under construction some costs will already have been incurred in previous years, and will have reflected the value of money in these previous years. A general price index is produced by the Government in all countries which relates the value of money at one date to the value of money at another date. Costs incurred in previous years are converted to costs in terms of the value of money at the reference date by multiplying them by the change in the general price index between the two dates (1).

3.4 Future costs and relative prices :

Estimates of future costs of individual factors, even though expressed in constant money terms, should still take account of expected future relative price changes, that is to say the change in cost (whether positive or negative) relative to the expected future change in the general price index (rate of inflation).

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(1) The index often used is that of the cost of the gross internal product. This index measures the depreciation of the monetary units over time (inflation).

These relative price changes occur in particular for wages (generally positive, reflecting the increase in purchasing power), taxes, raw materials (fuel-oil, uranium), certain industrial processes (e.g., decrease in the relative price of fabrication of fuel assemblies with series production and technological progress).

3.5 Discount Rate :

When working in constant money terms it is not appropriate to use current money financial interest rates. Nor for purposes of international comparison, is it possible, due to the different rates used in different countries, to choose a single "best" value of constant money terms discount rate. The Group of Experts therefore recommend quoting results for a range of discount rates and further recommend using rates of 5% and 10% p.a.

3.6 Choice of base date for discounting :

The base date for the present value of costs is the date of commercial commissioning of the unit considered. It is, in fact, the forecast date considered the most probable at the time of the estimation of the costs. In the case where costs are estimated globally for two or more units without being able to split them, the base date is mean commissioning date of the units. Most investment costs are incurred before the base date but a few after. Operating and fuel costs are mostly incurred after this date but can come before it.

3.7 Present value of energy output :

The net (sent-out) energy generated by the station in each year of operation is estimated and present valued to the base date, just as if they were costs (1). This calculation should include output prior to commercial commissioning. As energy generation is spread over the operating year, it is assumed to be concentrated at the mid-year point (operating years are not calendar years but are counted in twelve month periods from the commissioning date).

3.8 Average present-value of cost per kWh :

The average present value of cost per kWh is the ratio of the total present value of cost and the total present-value of energy. This cost is independent :

- of the base date for present-valuing

- and of choice of depreciation rule for the recovery of the investment cost over the station's lifetime, which is fixed by financial and fiscal considerations.

It is possible also to calculate an average annual cost of generation by apportioning the total present value cost over the station lifetime; similarly the average annual energy output can be calculated. The mean discounted cost per kWh is then seen to be equal to the ratio of the average annual cost and average annual energy output.

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(1) The reasons for this discounting are set out in section 3.2 of the report.

3.9 <u>Incidence of the utilisation (load factor) and breakdown of costs into fixed and proportional parts</u> :

The ratio of some energy output (e.g. for a given year, or total present value of energy output) to the net (sent out) capacity of the station gives a utilisation (load factor) expressed as "equivalent hours of operation at full power".

Since the generation cost depends on utilisation which in turn depends on the future operation of the station within the system, the group of experts recommends each electricity utility :

- to specify the utilisation for which the average **discounted cost per kWh is calculated**
- to give a breakdown allowing the cost to be varied as a function of utilisation, that is to say a **breakdown into a fixed cost and a cost proportional to** utilisation.

It is then easy to compare costs for the same load factor. The fixed part of the cost comprises :

- investment cost
- the major part of the operating cost
- a part of the fuel cost, especially for nuclear plant.

If this is expressed in terms of average annual cost, the fixed part becomes :

- capital charges (depreciation and interest; for nuclear stations the fixed part of the fuel charge is included) (1)
- the annual fixed operating cost

The proportional operating costs include :

- a part of the operating cost (certain maintenance costs, taxes or rents, etc.)
- for conventional thermal stations, virtually all the fuel costs and for nuclear stations, the most part.

In practice, making this breakdown is straightforward except for nuclear fuel costs; that is why these are discussed at length in the report (Chapter 7).

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(1) The average annual value of the capital charges does not imply any rule of depreciation, any more than the discounted average cost per kWh (see 3.8). Such a rule does not appear until an annual timetable of capital charges is fixed (e.g. if they are supposed constant at the average value).

4. LIMITS OF SUPPLY AND CASH FLOWS

4.1 General :

The above method is based on the inclusion of all costs at their correct time of occurance; once this principle is stated it is neither necessary or possible to give a detailed breakdown of costs.

However, the group of experts have agreed to separate costs not directly associated with the station but which depend on general policies in each country (dues, taxes, insurances, etc.) and general overheads (headquarters costs, etc.). Costs of this type should be excluded from international comparisons.

4.2 Investment cost (Chapter 5) :

The investment cost include all direct costs paid by the utility to manufacturers and sub-contractors for materials and services. They include all the utility's costs directly associated with the station, ranging from costs of preliminary site investigation, land purchase, off-site permanent and temporary works, site works, to costs of commissioning, final site clearance, engineering charges and allowances to cover unforseen conditions, etc. (1)

The cash flows for these costs can be given in more or less detail, but should include at least one cost per year of construction.

The difference between the sum of the costs present-valued to the date of commercial commissioning and the direct sum of the costs (not present-valued) constitutes the interest during construction (which can be expressed as a percentage of the direct sum of the costs).

Two categories of costs are set out separately and are not included in the calculation of costs for international comparisons :

- dues, taxes, insurance costs arising from contracts with outside bodies
- utility's indirect costs not directly associated with the station (central overheads, social costs etc.)

The estimation of investment costs in constant money terms requires making allowance for expected future relative price changes. This can be done by price adjustment formulae which use indices of future salaries and cost of materials, together with the general price index, over the period of construction. Using this method, the rate of inflation must be included as well as estimates of relative prices, since the price adjustment formulae includes a constant term, the rate of inflation is also required to convert basic cost estimates and possibly costs already incurred to monetary units at the reference date.

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(1) In a constant money calculation, no allowance for inflation needs to be included.

The limits of supply are formed by the high voltage terminals of the generator transformers but excluding the switching substation, lines and cables connecting the station to the system. In the case of a station extension on an already developed site, the costs exclude the costs of supply attributable to the first station. In the case of a nuclear station, the moderator costs are included but this report adopts the convention of including the initial fuel charge with the fuel cost.

The cost of dismantling a station is mentioned in a separate schedule if it is possible to give an estimate; if not this is stated, as a reminder.

4.3 Operating costs other than fuel (Chapter 6) :

These costs, generally estimated on a yearly basis, include a fixed part, independent of utilisation, and a part proportional to energy output.

The fixed costs include labour costs on site, costs of materials and services independent of utilisation, fixed repair and maintenance costs, etc.

The proportional costs include cost of materials consumed in operation and possibly the costs of labour and materials for a part of the repair and maintenance costs (particularly for gas turbines).

Taxes, dues, rents and insurance on the one hand, and overheads on the other hand, are put in a separate schedule and excluded from international comparisons.

The effect of relative price changes on operating costs is considerable and arises from two separate periods :

- firstly the period between the reference date defining the monetary unit and the first year of operation
- secondly the period of operation of the station

These effects can be calculated giving information on future operating modes, salaries, maintenance costs etc.

4.4 Fuel cost (Chapter 7 and Appendix 2) :

For a conventional thermal station, this cost includes the purchase, transport and handling of the fuel (coal, fuel-oil, natural gas, lignite etc.), and costs or revenue arising from ash and dust disposal. All these costs are proportional to utilisation. It is necessary also to allow for fuel stocks maintained on site-cost of initial stock less final stock, all discounted to the commissioning date. This cost is independent of utilisation.

The estimation of nuclear fuel cost is more complex because of the number and variety of operations on each batch of fuel, of its dwell time in the reactor, etc. Hence, it is necessary to simulate the complete fuel cycle over the reactor lifetime.

Even so, all that is necessary, in applying the present value method, is to calculate correctly the timing of costs of initial and replacement fuel incurred by the utility - including uranium ore costs, conversion to UF_6, enrichment, fabrication, reprocessing (all including transport costs and treatment and storage of radioactive waste), credits for recovery of uranium and plutonium from spent fuel (or economies of natural uranium and separative work for new fuel).

The fixed component of these costs is largely due to the storage in the reactor of fuel which, under average burn-up conditions, equals half the fuel used under equilibrium operating conditions; it is therefore not equal to the cost of the initial charge.

The component proportional to the energy produced corresponds to the costs of replacing spent fuel in the reactor.

Chapter 7 (para.75) and Appendix 2 of the report give a detailed analysis of this breakdown in fixed and variable components.

5. PRESENTATION OF DATA AND RESULTS

In order that costs quoted by different utilities can be consistent and comparable, the following minimum data and results are required :

(a) Basic data :

- reference date for the monetary unit and exchange rates, if possible 1 January of the year in question
- discount rates, working in constant money : 5 and 10%
- date of commercial commissioning of each unit in the station, or mean date where relevant
- assumed lifetime of each unit

(b) Technical description of the station :

A short description of all the technical characteristics of the site and station significantly affecting or helping to explain costs, in particular costs incurred for safety or environmental protection.

(c) Basic results :

- average discounted cost per kWh for given utilisation assumption, broken down into investment costs, operating costs other than fuel, and fuel cost
- the fixed cost per kW net (sent out), split into investment, operating and fuel cost

- costs proportional to kWh, broken down into operating and fuel cost.

This gives minimum information which does not allow a complete analysis of results or a full explanation of differences thrown up by comparisons. The complete set of assumptions, information and results necessary or helpful for this purpose are set out in the attached schedules, which utilities are recommended to fill in as fully as possible.

- Schedule 1 : basic data
- Schedule 2 : technical description of the station
- Schedule 3 : investment cost
- Schedule 4 : operating cost
- Schedule 5 : fuel cost
- Schedule 6 : summary of results.

Finally, it should be noted that, in parallel with the method presented in this report, each electricity producer can apply the methods of his choice for his own needs, in particular for preparing budgets and financial requirements, which must include expenses in current money terms.

SCHEDULE NO. 1

Basic Data

(Chapters 3 & 4 of report)

- Base date of monetary unit (UA) and rates of exchange
- Discount rate in constant money : 5% and 10%
- Date of commercial commissioning of the station (or of each unit)
- Unit lifetime
- Assumed power station utilisation, in equivalent hours of service at full power
  - 1st year of operation, from a date to be specified (1)
  - 2nd "
  - 3rd "

    etc.
- Number of hours present valued to the date of commercial commissioning
  - at 5%
  - at 10%
- Number of years of utilisation present valued to the date of commercial commissioning
  - at 5%
  - at 10%

(1) Part of the output in the first year is generated prior to commissioning. The start date of this year must be precisely defined.

This assumed utilisation should correspond to the mean present valued cost per kWh given in Schedules 5 and 6.

SCHEDULE 2

TECHNICAL DESCRIPTION OF POWER STATION

(Chapter 5 of Return 5.1)

- Site characteristics; geographical location, new site or already in use, etc.
- Number of units, boilers and turbo alternators.
- Operating concept: independent or coupled units, common or independent circuits, etc.
- Type of cooling: open circuit, closed circuit, mixed circuit, type of refrigerant, mean temperature and pressure conditions within the condenser, etc.
- Net electric power (less all auxiliaries) at mean conditions of cooling and over a range of variation.
- Possible capacity margin
- In the case of nuclear plant
    - boiler type
    - thermal power of reactor
    - type of containment and security provisions (electrical supply to auxiliaries, emergency cooling, earthquake, aircraft or missile impact, sabotage, etc.)
    - measures to protect the environment (thermal pollution, effluents, noise, etc.)
- In the case of fossil plant
    - fuel used
    - principal steam conditions (pressure, temperature, etc.)
    - specific consumption of fuel (in gross or net calories/kWh)
    - measures to protect the environment (chimneys, dust control, desulphurisation, noise etc.)
- In the case of Gas Turbine Plant
    - fuel used
    - Principal temperature and pressure characteristics under ambient conditions.
    - Measures to protect the environment (chimneys, noise, etc.)

SCHEDULE NO. 3

Investment Cost per KW net electrical

(Chapter 5 of the report, section 5.2 to 5.6)

Cat. 1: construction cost in constant money terms, excluding taxes, interest during construction, insurance expenses, etc... but including the electricity utility's expenses directly incurred in constructing the station.

Cat. 2: taxes, duties, contingency fees, insurance costs arising from contracts with outside bodies.

Cat. 3: interest during construction at 5% and 10%

Cat. 4: general expenses of the utility (central services, overheads, etc.)

Categories 1 and 3 which give the basic data for comparison purposes will be completed by the following information :

- formulae for the revision of construction cost
- future values for the indices in these formulae (salaries, raw materials, etc)
- future escalation of the general price index used in calculating the construction cost in constant money
- schedule of construction cost payments (at least one per year) used in the calculation in Category 3.

The discounting cost for the station should be given separately if it is taken into account in calculating the cost of energy generation.

SCHEDULE NO. 4

Operating costs, excluding fuel

(Chapter 6 of the report)

1. Fixed operating costs (independent of utilisation) average discounted cost in constant money terms, per net kW of electricity per annum, using 5 & 10% discount rates.

	5%	10%
Cat. 1 : direct operating cost, excluding taxes, including: total expenses for site personnel, raw materials, various supplies and materials, repair and maintenance.		
Cat. 2 : taxes, duties, rents and insurance costs arising from contracts with outside bodies etc...		
Cat. 3 : general expenses (regional and central services outside the site).		
TOTAL		

2. Proportional cost per kWh (excluding fuel) at 5 and 10% discount rate:

	5%	10%
Cat. 1 : materials used in operation, repair and maintenance :		
Cat. 2 : duties, taxes and rents :		
TOTAL		

This breakdown should be supplemented by the following information:

- the portion of salaries in categories 1 and 3 of fixed cost
- relative price changes in constant money, in particular of salaries (categories 1 and 3 of fixed expenses) and of duties (category 2 of fixed expenses)
- the overall relative cost change of the fixed and proportional costs.
- number of workers on site, and optionally:-
  - breakdown of manpower on site into : operation, repair and maintenance, administration and site management
  - repair and maintenance costs as a percentage of the capital cost of the equipment,
  - etc.

SCHEDULE NO. 5

Fuel cost (Chapter 7 of the Report)

Conventional Thermal Stations

- specific fuel consumption (using gross or net calorific value) per kW(e) net
- cost of fuel (per therm using gross or net calorific value)
- assumed future relative price change for fuel cost

Proportional cost = specific consumption times fuel cost

Fixed cost = fuel stock on site

Nuclear

1. Basic Assumptions

- price of ore concentrates in $/lb of U_3O_8 and in UA per kg of U contained in the concentrates
- cost of conversion of concentrates into UF_6, per kg of contained U
- enrichment cost, in $ and UA per kg of U
- fuel element fabrication cost per kg - SWU
- reprocessing cost of irradiated fuel, per kg of U contained in new or irradiated assemblages (say which) (transport, basic reprocessing, treatment and storage of radioactive waste, etc.).
- plutonium credit, per fissile gramme
- relative price change, in constant money, of each of these costs
- schedule of payments associated with each fuel cycle operation
- main physical characteristics, including for each fuel batch, for example (1) :-

---

(1) The characteristics given here apply to reactors with off-load refuelling, in particular PWR and BWR. For reactors with on-load refuelling, in particular gas-graphite, it is necessary to give quantities consumed or produced for a given quantity of energy (generally expressed in equivalent days operation at full power), and the isotopic composition of new and irradiated fuel.

SCHEDULE NO. 5 (Cont'd)

- date of fuel loading
- initial uranium mass
- initial enrichment
- date of refuelling
- final uranium mass
- final enrichment in U_{235}
- fissile Pu contained in the irradiated fuel
- discharge level of irradiation (MWD/te)
- etc....

SCHEDULE NO. 5 (Cont'd)

- fabrication	5 15 25 25 30	24 13 7 2 1
- recovery of fabrication losses	100	0
Irradiated fuel		in months following unloading
- reprocessing	100	18
- credits for uranium and plutonium	100	20

Physical characteristics of each batch of elements: see attached table (identical to the table in annex 2 of the report)

2 - Results (average discounted cost/kWh)

	5 %	10 %
Breakdown No. 1 in cUC/kWh		
- natural uranium	0,16	0,18
- enrichment	0,16	0,17
- fabrication of elements	0,05	0,06
- recovery of losses of fabrication	- 0,01	- 0,01
- reprocessing	0,07	0,06
- credit for uranium	- 0,03	- 0,03
- credit for plutonium	- 0,03	- 0,03
total cost	0,37	0,41
Breakdown No. 2 in cUC/kWh		
- initial charge	0,07	0,10
- refuelling	0,30	0,31
- reserve stocks	p.m.	P.m.
total cost	0,37	0,41
Breakdown No. 3		
- proportional cost at equilibrium in cUC/kWh	0,33	0,34
- fixed cost in UC/kW	32,4	39,2

2. Results

Average present valued cost per kWh : c, for the utilisation given in Schedule 1, with the following breakdowns:

	5%	10%
Breakdown No. 1		
- natural uranium		
- enrichment		
- fuel element fabrication		
- reprocessing		
- uranium credit (natural U enrichment)		
- plutonium credit		
TOTAL : c =		
Breakdown No. 2		
- initial charge		
- refuelling		
- reserve fuel		
TOTAL : c =		
Breakdown No. 3		
- proportional cost per kWh at equilibrium		
- fixed cost in UA per kW(e) net		

If U is the total discounted utilisation, we have :

$$c = \frac{\text{fixed cost}}{U} + \text{proportional cost.}$$

SCHEDULE NO. 6

Synthesis of results

(Chapter 8 in the report)

	5%	10%
Fixed Cost in MU per kW(e) net		
- investment		
- fixed operating cost		
- fixed portion of fuel cost		
Total fixed cost		
Proportional cost MU per KWh		
- proportional operating cost		
- proportional fuel cost		
Total proportional cost		
Average cost in MU per kWh, for data in Schedule 1 **Schedule 1** :		
- investment		
- operating (excluding fuel)		
- fuel		
TOTAL COST		

For each category of cost (investment, operating, fuel), and for the total, the following relationship holds :

$$\text{Average cost} = \frac{\text{fixed cost}}{U} + \text{proportional cost}$$

where U is the total discounted utilisation

CALCULATION OF THE COST OF ELECTRICAL ENERGY PRODUCTION FROM FOSSIL AND NUCLEAR POWER STATIONS

A practical example consistent with the summary of the report and given only as an illustration of the method

SCHEDULE NO. 1

Basic Data

- Monetary unit : European unit of account (UA) (1)
- base date of monetary unit : 1 January 1976
- discount rate in constant money : 5 and 10%
- commercial commissioning date for station: 1.7.82
- life of station : 20 years
- station operating assumptions in operating hours equivalent to full output, for the years beginning 3 months before commissioning :
  - 1st year of operation : 3000 hours
  - 2nd year of operation : 5000 hours
  - 3rd - 20th year of operation : 6600 hours
- number of hours present-valued to commercial commissioning date :
  - at 5% : 80300 hours
  - at 10% : 55400 hours
- number of years operation present-valued to commercial commissioning date :
  - at 5% : 12.77
  - at 10% : 8.93

---

(1) For schedules 4, 5, 6 use the following :

cUA = 10^{-2} UA

UA = Unit of Account

SCHEDULE NO. 2

Technical Description of the Station (1)

Nuclear station with two similar reactors, sited on a river, with closed circuit cooling provided by natural draught cooling towers, with one tower per unit.

PWR-Type, Westinghouse, 3 primary loops per reactor, a single heat exchanger and a single turbo-generator per unit, (unit system).

Total capacity : 905 MW electric net

Thermal Capacity of Reactor : 2775 MW

Capacity Margin : about 5%

Prestressed concrete containment with impervious inside steel skin.

Emergency cooling : two injection routes with independent security and 100% discharge from each.

(1) Given here very briefly and incompletely.

SCHEDULE NO: 3

Investment Costs per kW(E) Net

		5%	10%
Cat. 1:	:	340 UA/kw	340 UA/kw
Cat. 2:	:	0	0
Cat. 3: at 5%	:	45	
at 10%			95
Cat. 4:		15	15
Total Cost : at 5%	:	400	
: at 10%	:		450

Price Revision formula for category 1 cost :

$$\frac{P}{P_o} = 0.10 + 0.10\frac{PsdB}{PsdB_o} + 0.48\frac{S}{S_o} + 0.32\frac{M}{M_o}$$

with PsdB : index of generation and services

S : salary index

M : overall index of materials

$PsdB_o$, S_o, M_o, : same indices at 1.1.76

Assumptions of annual increase rates :

PsdB : 9%

S : 12%

M : 7%

General price index : 8%

Progress payment dates (for the construction of 2 units) :

2.5% 8% 15% 25% 24% 12% 9.5% 4%

synchronise — Commissioning

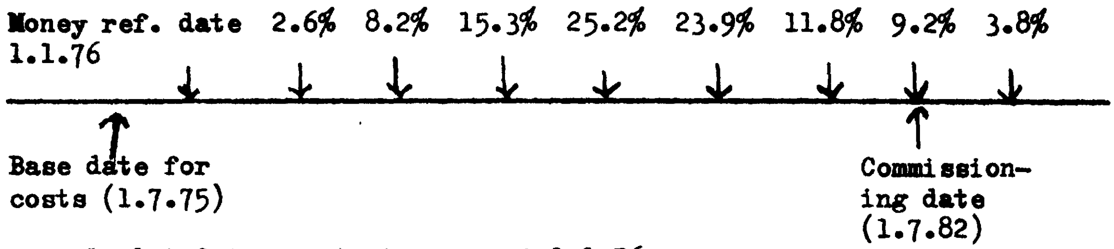
Cost of dismantling : to be recorded separately

SCHEDULE NO. 3 (SUPPLEMENT)

Detailed Calculation of Investment Costs in Constant Money Terms and of discounted hours of utilisation

Assume a turnkey contract, details as follows :

- Basic price at 1.7.75 = 312 UA/kW (1)
- Formulae for price revision : see Schedule No.3
- Assumptions of Annual price increases : see Schedule No.3
- Progress payments :



- calculated in constant money at 1.1.76
- commissioning date : 1.7.82
- dates of payments : at 12 monthly intervals, from 1.7.76 to 1.7.83.

The successive payments expressed in 1.1.76 money terms, are as follows:

$$1.7.76:\ 312 \times 0.026 \times \frac{0.10+0.10\times1.09+0.48\times1.12+0.32\times1.07}{1.08^{1/2}} = 8.50$$

$$1.7.77:\ 312 \times 0.082 \times \frac{0.10+0.10\times(1.09)^2+0.48\times(1.12)^2+0.32\times(1.07)^2}{1.08^{3/2}} = 27.07$$

$$1.7.78:\ 312 \times 0.153 \times \frac{0.10+0.10\times(1.09)^3+0.48\times(1.12)^3+0.32\times(1.07)^3}{1.08^{5/2}} = 51.02$$

$$1.7.79:\ 312 \times 0.252 \times \frac{0.10+0.10\times(1.09)^4+0.48\times(1.12)^4+0.32\times(1.07)^4}{1.08^{7/2}} = 85.02$$

---

(1) The price is assumed to comprise the actual expenditure of the electricity utility, except for some general expenses.

$$1.7.80:\ 312 \times 0.239 \times \frac{0.10+0.10\times(1.09)^5+0.48\times(1.12)^5+0.32\times(1.07)^5}{1.08^{9/2}} = 81.63$$

$$1.7.81:\ 312 \times 0.118 \times \frac{0.10+0.10\times(1.09)^6+0.48\times(1.12)^6+0.32\times(1.07)^6}{1.08^{11/2}} = 40.87$$

$$1.7.82:\ 312 \times 0.092 \times \frac{0.10+0.10\times(1.09)^7+0.48\times(1.12)^7+0.32\times(1.07)^7}{1.08^{13/2}} = 32.33$$

$$1.7.83:\ 312 \times 0.038 \times \frac{0.10+0.10\times(1.09)^8+0.48\times(1.12)^8+0.32\times(1.07)^8}{1.08^{15/2}} = 13.56$$

Total cost in 1.1.76 money terms : $= 340.00$

Progress payments, expressed in real terms, are then given in Schedule No. 3:

$\frac{8.50}{340} = 2.5\%$, $\frac{27.07}{340} = 8\%$, $\frac{51.02}{340} = 15\%$, etc.....

If we continue to express this in 1976 prices one finds :

$312 \times (1.08)^{1/2} = 324.2$ **instead of 340 UA/kW**

The difference is due to the effect of applying the revision formula to the successive payments.

<u>Calculation of interest during construction at discount rate a:</u>

Let $r = 1 + a$

We apply to the value of 340 UA/kW the following coefficient:

$$0.025\, r^6+0.08\, r^5+0.15\, r^4+0.25\, r^3+0.24\, r^2+0.12\, r+0.095+\frac{0.04}{r} - 1$$

<u>Calculation of the present valued number of hours :</u>

The number of hours present valued to the date of commercial commissioning is equal to:

$$r^{3/12} \quad \frac{3000}{r^{1/2}} + \frac{5000}{r^{3/2}} + \sum_{n=3}^{20} \frac{6600}{r^{n-1/2}}$$

SCHEDULE NO. 4

Operating Cost, excluding fuel

1. Fixed operating cost (independent of utilisation), average annual cost per kW(e) net, taking into account relative price changes, in UA/kW p.a.

	5%	10%
Cat. 1 (direct costs) :	9.5	9.0
Cat. 2 (taxes):	7.0	6.5
Cat. 3 (overheads):	1.5	1.5
Total fixed charges	18.0	17.0

2. Fixed operating costs, present valued over the station lifetime (product of the annual charges times the present valued number of years given in Schedule 1) in UA/kW :

5%	10%
230	150

3. Proportional Cost (excluding fuel), in cUA/kWh (1) :

	5%	10%
Cat. 1:	0.001	0.001
Cat. 2:	0.032	0.030
Total proportional Cost:	0.033	0.031

Proportion for salaries in category 1 of fixed costs: about 70%
in category 3 of fixed costs: approaching 100%

Annual Rate of relative price changes in real money terms :

- for salaries : 4%
- for taxes and rents: 4.5%
- for materials : -1%
- for overall operating costs 3%

Number of workers on site : 235

(1) cUA = 10^{-2} UA (hundredths of UA)

SCHEDULE NO. 5

Fuel Costs

1. Basic Data:

- ore concentrate cost : 21.6 $/lb d'$U_3O_8$ = 48 UA/kg of contained U
- ore conversion cost in UF_6 : 3.5 kg of contained U
- enrichment cost : 93.5 $/kg-SWU = 80 UA/kg - SWU
- fuel element fabrication costs : 115 UA/kg of contained U
- overall reprocessing cost : 190 UA/kg of contained U
- plutonium credit : 11.5 UA/g fissile
- relative price change in constant money : nil
- payment schedules :

	Fraction of payment cost in %	Date of payment
		in months before the commissioning date
Initial fuel :		
- uranium ore	100	17
- enrichment	100	14
- fabrication	2	54
	3	45
	2	43
	2	37
	2	33
	2	27
	2	25
	3	23
	2	20
	12	26
	16	16
	12	12
	8	11
	8	10
	16	7
	4	4
	4	0
	100	
- recovery of the loss in fabrication	100	4

SCHEDULE NO.5 (Cont'd)

Refuelling costs:		in months before refuelling
- natural uranium	100	11
- enrichment	100	8
- fabrication	5	24
	15	13
	25	7
	25	2
	30	1
- recovery of losses in fabrication	100	0
Irradiated fuel		in months after unloading
- reprocessing	100	18
- credit for uranium and plutonium	100	20

Physical characteristics of each batch of fuel - see table in appendix 2 of the report.

2 - Results (average discounted cost/kWh) :-

Breakdown No. 1 in cUA/kWh

	5%	10%
- natural uranium	0.16	0.18
- enrichment	0.16	0.17
- fabrication of fuel elements	0.05	0.06
- recovery of losses in fabrication	-0.01	-0.01
- reprocessing	0.07	0.06
- credit for uranium	-0.03	-0.03
- credit for plutonium	-0.03	-0.03
Total cost	0.37	0.41
Breakdown No. 2		
- initial charge	0.07	0.10
- refuelling	0.30	0.31
- reserve stocks	p.m	p.m
Total cost	0.37	0.41

SCHEDULE NO. 5

Breakdown No. 3

	5%	10%
- proportional cost at equilibrium in cUA/kWh	0.33	0.34
- fixed cost in UA/kW	32.4	39.2

Notes: If U is the total present valued utilisation, we have:

$$\text{Total cost per kWh} = \frac{\text{fixed cost}}{U} + \text{proportional cost}$$

then for example, at 10% discount rate

$$0.41 = \frac{39.2 \times 100}{55400} + 0.34$$

On the other hand the cost of the initial charge expressed in UA per KWe net, is :

$$0.10 \times 10^{-2} \times 55\ 400 \sim 55 \ \text{UA/kW}$$

The fixed cost thus represents 70% (approx.) of the cost of the initial charge.

NUMERICAL EXAMPLE - CHARACTERISTICS OF CHARGED AND DISCHARGED BATCHES

New Fuel Charged					Irradiated Fuel Discharged						
Batch No.	Date of loading in years	Mass of U in kg	Enrich-ment %	Cost C in MUA	Batch No.	Date of unload-ing	Mass of U in kg	Enrich-ment %	Fissile Pu in g per kg of initial U	Irradiation of reject in MWD/t	Cost D in MUA
1		23,100	2.1		1	2.17	22,548	0.88	5.09	16,116	1.07
2		462	2.1		2	3.11	451	0.63	5.63	21,922	1.17
3		24,024	2.6		3		23,156	0.81	6.28	26,253	
4	0	462	2.1	50.77	4	4.16	451	0.63	5.63	20,194	
5		24,024	3.1		5		22,974	0.82	6.65	32,859	1.04
6		462	2.1		6		451	0.63	5.63	20,841	
7	2.17	24,024	3.25	20.81	7	5.23	22,972	0.92	6.63	32,714	0.65
8	3.11	24,178	3.25	20.95	8	6.30	23,090	0.88	6.68	33,735	0.77
9	4.16	24,178	3.25	20.95	9	7.37	23,090	0.88	6.68	33.735	0.77
10	5.23	24,178	3.25	20.95	10	8.44	23,090	0.88	6.68	33,735	0.77
11	6.30	24,178	3.25	20.95	11	9.51	23,090	0.88	6.68	33,735	0.77
12	7.37	24,178	3.25	20.95	12	10.58	23,090	0.88	6.68	33,375	0.77
13	8.44	24,178	3.25	20.95	13	11.64	23,090	0.88	6.68	33,735	0.77
14	9.51	24,178	3.25	20.95	14	12.71	23,090	0.88	6.68	33,735	0.77
15	10.58	24,178	3.25	20.95	15	13.78	23,090	0.88	6.68	33,735	0.77
16	11.64	24,178	3.25	20.95	16	14.85	23,090	0.88	6.68	33,735	0.77
17	12.71	24,178	3.25	20.95	17	15.92	23,090	0.88	6.68	33,735	0.77
18	13.78	24,178	3.25	20.95	18	16.99	23,090	0.88	6.68	33,735	0.77
19	14.85	24,178	3.25	20.95	19	18.06	23,090	0.88	6.68	33,735	0.77
20	15.92	24,178	3.25	20.95	20	19.12	23,090	0.88	6.68	33,735	0.77
21	16.99	24,178	3.25	20.95	21		23,090	0.88	6.68	33,735	0.77
22	18.06	24,178	3.25	20.95	22	20.19	23,450	1.66	6.19	22,587	-9.11
23	19.13	24,178	3.25	20.95	23		23,861	2.56	4.33	9,820	

SCHEDULE NO. 6

SUMMARY OF RESULTS

	5%	10%
Fixed costs in UA per KWe net		
- Investment	400	450
- Fixed operating cost	230	150
- Fixed part of fuel cost (rounded)	35	40
Total fixed cost	665	640
Proportional costs per kWh in cUA/kWh		
- Proportional cost (operation)	0.03	0.03
- Proportional cost (fuel)	0.33	0.34
Total variable costs	0.36	0.37
Average discounted cost per kWh in cUA/kWh		
For utilisation given on Schedule No.1		
- Investment	0.50	0.81
- Operation (excluding fuel)	0.32	0.30
- Fuel	0.37	0.41
Total cost (rounded)	1.20	1.50

For each item (investment, operation and fuel) and for the total, we have

$$\text{average cost} = \frac{\text{Fixed cost}}{U} + \text{proportional cost}$$

where U is the total discounted utilisation

Method of Calculating the Cost of Electricity Generation

From Nuclear and Conventional Thermal Stations

1. TERMS OF REFERENCE OF THE GROUP OF EXPERTS

The Nuclear Energy Study Committee of UNIPEDE, in response to a request from the Directorate General for Energy of the Commission of the European Communities, has asked a Group of Experts to establish a model for calculating and comparing the cost of electricity generation from nuclear and conventional thermal stations. The model would allow the different European electricity utilities to provide data and results on a common and comparable international basis.

The model developed in this report can be applied to new nuclear stations of any type, to conventional thermal stations and even to gas turbines, but is not intended to be applied to combined heat and power stations.

Only future costs are considered, that is to say the costs of new stations, whether under construction or being planned, but not the costs of stations already operating, which would be evaluated by accounting methods. Thus present costs are not considered.

The method presented in this report is not intended to be substituted for that used by each electricity utility for its own needs, in particular for establishing budgets and financial requirements. Nor is it intended to give the overall cost of supplying the consumers' electricity demand, which continually varies, as does the plant needed to meet the demand.

The overall cost can only be calculated taking into account all elements of the system, in particular the shape of the load curve, the generating plant mix and generating reserve margin, the network interconnections, etc. These factors must also be taken into account when making a full economic comparison of new generating stations of different types when added to a given system. The model presented in this report is not sufficiently sophisticated for such a comparison and is intended only for the purpose of comparing generating stations of the same type.

The Services of the Commission of the European Community were associated with the work of the Group of Experts.

2. PRESENTATION OF REPORT

The report first of all describes the general principles of the discounting method used for calculating the cost of electricity generation, and in particular the discounted average cost per kWh (Section 3 and Appendix 1).

However, apart from the uncertainties inherent in long term forecasts, the practical application of the method involves considerable disparities between countries and raises some basic questions of economics, in particular :-

- Must costs be taken in terms of constant money or current money?
- What value of discount rate should be used? Is this primarily a financial or economic rate?

These questions are dealt with and discussed in Section 4, which attempts to provide an answer to them and presents the conclusions of the working group.

A detailed examination is then made of the three components of the cost of electricity generation, with an indication of the data necessary for establishing comparisons :-

- Cost of power station construction or capital cost (Section 5)
- Operating costs, excluding fuel (Section 6)
- Fuel costs, including the first charge in the case of nuclear power stations (Section 7).

Finally, the cost of generating electricity depends on one essential parameter : the utilisation of the power station during its life. This utilisation varies considerably depending on the nature and make-up of the generating system of which it is a part, and on the type of plant envisaged.

It is therefore essential to specify how the cost of the kWh varies as a function of the utilisation of the power station, i.e. to break down the generation cost between a fixed part and a part proportional to the utilisation.

In practice, this breakdown only poses a problem in the case of nuclear fuel costs: these are therefore examined at considerable length (Section 7 and Appendix 2).

Finally, Section 8 gives a brief summary of all the foregoing results and draws conclusions.

The report contains a summary and summary schedules and a numerical example illustrating the essential points of the method.

3. METHODOLOGICAL FRAMEWORK : DISCOUNTING

3.1 Principle of Discounting

The calculation of the cost of any product involves costs incurred at different times and modes of production which are also distributed in time (1).

The simplest expression for the cost of a unit of output is the quotient of the arithmetical sum of all the capital and operating costs and the arithmetical sum of the products. In this method, one adds up costs expressed in monetary units of different periods. However, these units constitute different goods, and such an addition is illegitimate.

In fact, in an economy which has not reached either saturation of demand, or the exhaustion of technical possibilities, "a MU immediately (2)" is generally preferred to "a MU in one year or in 10 years": one can always find a producer (1) who is prepared to invest this MU in order to obtain from it, in the long term, a higher value, and any consumer will only give up an immediate consumption in exchange for a future consumption of higher value.

In economies of the Western type, this preference for "liquid" or "fresh" money is normally shown by the existence of financial markets where operators meet who are prepared to exchange immediately available MU's against future MU's with additional interest. The interest in this transaction represents the cost of liquidity.

If there is in the economy a perfect financial market, such that all yearly loans are made at the same rate a, and it is always possible to borrow at this rate, it is equivalent for any person to possess one MU today or to have the certainty of possessing (1+a) MU in one year. Or again, one MU in one year is equivalent to:

$$V = \frac{1}{1 + a} \text{ MU today}$$

In the following report, 'a' will be called the "discount rate", and V the "present value" of 1 MU in one year's time.

---

(1) The words "production" and "producer" are employed in this section in the widest sense: the production of any product, and not only electricity.

(2) MU = monetary unit (DM, BF, FF, Lire, £, $, etc.)

If one now considers a unit available in 2 years, and if the rate remains a, the present value of this MU is $\frac{1}{(1+a)^2}$. More generally, a unit in n years time has a present value of $\frac{1}{(1+a)^n}$ (1)

<u>The values, discounted to a given date, of all the costs relating to one production unit can then be summated.</u>

Let D (t) be the cost incurred at instant t (the actual outgoing of funds, either capital or operating costs). The total cost, discounted to an arbitrary date taken as the time origin, and summed from this date to infinity, is expressed by :

$$D = \sum_{t=o}^{\infty} \frac{D(t)}{(1+a)^t}$$

In fact, the life of the implement of production (a power station for example) is not infinite : let T be this life. Let us suppose that the date of commissioning is taken as the origin, and that the construction costs extend over n years <u>before</u> commissioning. The <u>total cost discounted to the date of commissioning</u> is expressed as:

$$D = \sum_{t=-n}^{T} \frac{D(t)}{(1+a)^t}$$

Some practical methods of carrying out the discounting calculation for a schedule of costs are given in Appendix 1.

3.2 <u>Average Discounted Cost per kWh</u>

Let D be the total discounted cost of a conventional or nuclear thermal power station, covering all costs (capital, operating and fuel costs).

It is now necessary to distribute this cost uniformly over the energy produced by the power station throughout its life. In order to do this, each kWh is assigned an average cost c such that the discounted value of the power station output, valued at this average cost, is equal to the sum of the discounted costs D.

As the discounted value of the electricity generation is the product of a number of kWh's and a unit cost assumed to be constant throughout the lifetime of the power station, this leads to an expression which on first sight is a little unexpected: that of the "total discounted energy" or the "number of discounted hours".

---

(1) If the rate assumes different yearly values $a_1, a_2, \ldots\ldots, a_n, \ldots\ldots$, then MU today is equivalent to $(1+a_1)(1+a_2)\ldots(1+a_n)$ MU in n years time. Conversely, one MU in n years is equivalent to $\frac{1}{(1+a_1)\ (1+a_2)\ldots\ldots(1+a_n)}$ MU today.

In fact, if one designates by E (t) the energy supplied in the year t, the average discounted cost of the kWh c is defined by the equation:

$$D = \sum_{0}^{T} \frac{cE(t)}{(1+a)^{t}} \quad \text{or} \quad c \sum_{0}^{T} \frac{E(t)}{(1+a)^{t}} \qquad (1)$$

When c is made a common factor in the right hand side of the equation, a quantity appears which is the <u>total discounted energy</u> E.

The average discounted cost per kWh is therefore equal, by definition, to the ratio of the total discounted cost D and the total discounted energy E (2). One can also say that the cost c is the price at which the Company constructing and operating the power station should sell the energy at the station terminals to exactly balance its discounted costs and its discounted revenue.

In the case where all the costs are expressed per net electrical kW, the same must apply to the energy E (t) which is then equivalent to a number of hours H (t): these are not actual operating hours, but <u>equivalent hours of operation at full capacity</u>, giving the same energy.

The number of discounted hours is thus expressed, taking into account footnote (1):-

$$H = \sum_{t=1}^{T} \frac{H(t)}{(1+a)^{t-1/2}}$$

The time-schedule of energy E (t) or the number of hours H (t) may be of any type, and may take into account on the one hand teething troubles, and on the other hand variations in the power station output over time (for example, going off base-load and rising progressively in the load curve).

3.3 <u>Presentation in terms of annual amounts</u>

On the basis of a total discounted quantity (costs, energy or number of hours), a weighted annual average can be defined using the discount factors for successive years. For example, the discounted average annual utilisation is defined by the ratio:

---

(1) The energy E (t) is distributed uniformly in time, apart from minor random variations. It is shown in appendix 1 that, under these conditions, this equation can be written:

$$D = c \sum_{t=1}^{T} \frac{E(t)}{(1+a)^{t-1/2}}$$

(2) If the discounting date for costs and energy is shifted Δt, the two terms of the ratio are divided by $(1+a)^{\Delta t}$: hence the average discounted cost of the kWh does not depend on the discounting date. By convention, the date of commissioning is generally taken for this date.

$$\bar{H} = \frac{\sum_{t=1}^{T} \frac{H(t)}{(1+a)^{t-1/2}}}{\sum_{t=1}^{T} \frac{1}{(1+a)^{t-1/2}}}$$

The same would apply to costs or energy. The denominator of this ratio is the number of discounted years, or the discounted life of the power station. If one considers the ratio which defines the discounted average cost per kWh, and if the top and bottom of this ratio are divided by the number of discounted years, one can see that the discounted average cost per kWh is also equal to the ratio of the average yearly cost and the average yearly energy.

Now the total discounted cost comprises :-

- The capital cost I.
- The power station operating costs, F.

The average annual cost itself comprises two terms :-

- The first, the quotient of I and the discounted life, represents the annual fixed charge including the amortization of the invested capital and the financial charges (or interests) on the capital which has not yet been amortized.
- The second is the annual average of the operating costs and the fuel costs.

The calculation of the discounted average cost per kWh can thus be entirely based on annual amounts. These are not quantities which relate to a particular year, but are averages weighted by the discounting factors of the successive years of operation of the station.

None of the foregoing (sections 3.2 and 3.3) implies knowledge of any depreciation rule. Such a rule would appear only when setting out a schedule of yearly capital charges : for example, if one were to suppose these constant and equal to their mean value.

But in practice, the depreciation rule is fixed by financial and fiscal considerations which are not the concern of this report. (cf. Section 1).

4. PRACTICAL WAYS OF APPLYING THE DISCOUNTING METHOD

4.1 Practical Difficulties of Application

The discounting method, which is of great theoretical simplicity, unavoidably gives rise to considerable difficulties when applied in practice.

There are of course the difficulties inherent in long term forecasts of a very uncertain future : one does not know in advance the actual operating lifetime (generally 20 to 30 years), future price changes for various items, the utilisation of the power station within the system, etc. The hypotheses used will sometimes be the result of forecast studies, but they will often be normative and subject to revision as one obtains further information and acquires experience in the construction and operating of power stations.

However, on the economic level, two fundamental difficulties are encountered :-

- The first one is due to the future variations in prices in the economy as a whole, and raises the question as to whether the calculations must be in current money or constant money terms
- The second one is due to the fact that in practice no financial market is perfect and there is no rate a which is identical for every market operator and at which one can borrow or lend unlimited sums.

4.2 Current Money and Constant Money

In every economy, and in particular in all economies of the Western type since the end of the last World War, the prices of goods and services have varied constantly and, very generally, in an upward direction (inflation). The possible transactions allowed by a given monetary mass (purchasing power) therefore diminish in the course of time; this is known as inflation or monetary erosion.

In order to measure the variation in the value of money, it is necessary to define a general price index related to all national transactions in all sectors and at all levels of the economy, or at least in some basic sector (e.g. all retail prices relating to goods and services consumed by households, or the price index of the gross domestic product). Each price is weighted by the quantities of goods or services to which it applies. This index is usually calculated and published by the Government of each country.

Knowledge of this index allows costs to be expressed <u>in constant money</u>, that is to say keeping the unit of money at the value it had on a given date: <u>preferably 1 January of the current year</u>.

In fact, the depreciation of the monetary unit between that date taken as the origin and any date t is measured by the ratio of the general price index for instant t to that of the date of origin (1). A payment made at instant t and in the money for that date is expressed in terms of the money for the date of origin after being divided by this ratio. By correcting in this way all the payments due to the construction and operation of the power station, one obtains constant money costs, expressed in terms of a single and well-defined monetary unit.

4.3 Relative Price Changes

The above considerations only involve the general average of prices, weighted by the quantities to which they apply. However, the prices of any particular commodity or service do not generally vary as this average.

Numerous examples can be given of this :-

- the most important is without doubt that of wages which, in many Western countries and for a number of years now, have been increasing more rapidly than the general price level (increase in purchasing power); the same applies to the wages of power station operating personnel;

- as regards the nuclear fuel cycle, the prices of natural uranium, enrichment and reprocessing have increased much more rapidly than the general price index since 1972 or 1973;

- on the other hand, the price of manufacturing fuel assemblies has generally increased much less rapidly than the general price level, thanks to gradual industrial development, technological progress and mass-production;

- in certain countries, taxes on electricity generating stations are increasing much more rapidly than the general index;

- the price adjustment formulae included in orders for equipment or sub-assemblies may cause the prices to vary at a rate depending on the size of the constant term and of the parts dependent on wages and materials in each formula;

---

(1) Between these two dates, any number of months usually elapse, which do not give a whole number of years. In some countries the general price index is only officially defined year by year. It is therefore necessary to calculate its intermediate values (e.g. month by month), by interpolating in the schedule of annual indices.

- outside the field of electricity generation, one could give any number of examples : the prices which increase least rapidly are generally those in industrial sectors which benefit from extensive mass-production and technological progress (domestic electrical appliances, electronics, car production, etc.); other prices exhibit very irregular variations, particularly those of raw materials.

The relative price change of a given commodity or service is the difference (positive or negative) between the variation of this price and that of the general price index. Calculations using constant money must take these fluctuations into account. In fact, even in a theoretical reference economy in which the monetary unit maintains a constant value from a given date, prices continue to change and these variations are precisely the relative price changes.

In certain cases, these relative price changes are quite stable, because of the correlation between the variation in the price of the commodity or service in question and the increase in the general level of prices.

In particular, the relative change in wages (or increase in purchasing power) has been fairly stable for a number of years now. On the other hand, relative price changes of raw materials such as uranium are difficult to predict.

4.4 Relationships Between Calculations in terms of Current Money, Constant Money and Constant Prices

Let t_o be a reference date and t any date other than t_o. For a given plant item, material or service, one can define three prices :-

- the price $P(t_o)$ at date t_o (in money of the same date)
- the price $P(t)$ at date t (in money of the same date)
- the price $P_o(t)$ at date t, referred to money at date t_o by means of the general price index.

The ratio $\frac{P(t)}{P(t_o)}$ represents the variation in the price in question in terms of current money

The ratio $\frac{P_o(t)}{P(t_o)}$ represents the variation of the same price in terms of constant money, or relative price change.

The ratio $\frac{P(t)}{P_o(t)}$ represents the general price index at t relative to t_o.

One can write:

$$\frac{P(t)}{P(t_o)} = \frac{P_o(t)}{P(t_o)} \times \frac{P(t)}{P_o(t)}$$

The total variation in the current money price between t_o and t is therefore the product of the relative price change and the general price index for t relative to t_o.

A calculation which uses exclusively:-

- prices at date t_o, such as P (t_o), is known as a "constant price" calculation,
- prices at the date of payment, such as P(t), is known as a "current price" or "current money" calculation,
- prices expressed in the monetary unit for date t_o, such as $P_o(t)$, is known as a "constant money" calculation.

4.5 Difficulties in Choice of Discount Rate

The discussion below is not about the discounting method as such. It is intended only to indicate the difficulties encountered when one wishes to define a discount rate, and to explain why it is not possible to give it a precise signification or precise numerical value.

The perfect financial market, mentioned in Section 3.1, does not exist, nor therefore does the single ideal rate a, at which any market operator could borrow or lend unlimited sums of money.

Other methods of approach for the discount rate must therefore be found. There are basically two of these: one using the actual cost of money on the financial market, and the other using a macroeconomic model.

The first consists of estimating the real cost of capital required by the electricity producer, who has at his disposal three sources of financing: he can have recourse to borrowing, equity capital and self-financing.

The cost of borrowed capital is known: it is the nominal rate for the loan, corrected where necessary to take account of the issuing premium, the bonus at maturity, taxation, etc.

The cost of equity capital is more debatable, since it depends on the future long term evolution of dividends, and is usually subject to taxation which is difficult to take account of and varies considerably from country to country, and even from company to company within the same country(1).

---

(1) The cost of equity capital can for example be estimated by the "Gordon-Shapiro" formula:-

$$k = \frac{D}{P} + g$$

where k = cost of equity capital
D = current dividend per share
P = issue price of share, net of costs
g = expected growth rate of dividend

This formula must however be adapted to the taxation regulations applicable to each Company.

The cost of capital obtained by self-financing (depreciation, transfers to reserves, etc.) is not zero, since if this capital were not retained within the Company, it could be placed on the capital market and thus procure an income. On the other hand, if there were no self-financing, the amount of capital required from outside, both equity capital and borrowed capital, would have to be correspondingly increased.

The total cost of the capital for the Company is therefore the average of the costs of the three sources of financing weighted by the quantities of funds required from each of the sources in a given future period. (1).

However, certain countries, particularly the United Kingdom and France where electricity is generated by a public body, use a macroeconomic approach to the discount rate, which is completely different from the above. The value of the rate is then fixed by the governmental authorities and is imposed on the CEGB and EdF, and in theory on all nationalised undertakings.

In the United Kingdom, this rate is fixed in such a way that the profitability of low-risk investments in the public sector should be at least equal to that of similar low-risk investments in the private sector. This can only however be evaluated as an average over a certain number of years. The result is that the value of the discount rate does not undergo frequent changes, that it has not varied in the United Kingdom for over eight years, and that the Treasury does not in practice use this rate to ration capital (there are more direct methods available for this).

In France, the planning bodies consider that the real cost of money on the capital market cannot represent the actual scarcity of capital in the whole of the economy, nor can it ensure the overall balance between saving and investment, because of the imperfections and gaps in the capital market : the sensitivity of the supply and demand of capital to the cost of money is limited, and there are many other means of attracting savings (in particular self-financing as referred to above, and taxes).

According to the French concept, the purpose of the discount rate is therefore to reflect the actual scarcity of capital in the whole of the economy: it is the minimum profitability threshold which must be

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(1) Let i be the cost of the borrowed capital

k be the cost of equity capital

r be the cost of self-financing

φ_e be the volume of loans expected in the next n years

φ_c be the issues of equity capital expected in the next n years

φ_a be the self-financing expected in the next n years.

The total cost of capital will be:-

$$q = \frac{i\varphi_e + k\varphi_c + r\varphi_a}{\varphi_e \quad \varphi_c + \varphi_a}$$

required of investments in order that the total demand for capital shall not exceed the total savings resources available. The rate therefore aims at the collective interest, within the framework of the objectives of the National Plan. It is not tied to the existence of a capital market, and is just as valid in a socialist economy as in a capitalist economy. Its value can be approximated by means of econometric models; it is closely related to the rate of growth of the economy.

The definitions of, and the approaches to, the discount rate are therefore very different between countries and between electricity producers.

4.6 Current Money and Constant Money Discount Rate

The actual cost of capital is established under the actual conditions of the market and hence in terms of current money, whereas the discount rate used by the CEGB and EdF is defined in terms of constant money.

Now the discount rate which represents the price of money is affected, as are other prices, by whether the inflation rate is taken into account or not. Thus the current high rates on the capital markets are the result, at least partially, of the desire of lenders to safeguard themselves against monetary depreciation due to inflation.

One can also point out that, arithmetically, the discounted sum of a schedule of costs is the same either:-

(a) with constant-money costs $[D_o(t)]$ and a rate a, or

(b) with current money costs $[D(t)]$ and a rate a' such that $1+a' = (1+a)(1+\alpha)$ where α is the annual rate of increase of the price index (in practice we have $a' = a+\alpha$).

In fact, the discounted cost has a value, in the first case of:-

$$\sum_t \frac{D_o(t)}{(1+a)^t}$$

and in the second case of, footnote (1) on the next page:

$$\sum_t \frac{D(t)}{(1+a')^t} = \sum_t \frac{D_o(t)(1+\alpha)^t}{(1+a)^t(1+\alpha)^t} = \sum_t \frac{D_o(t)}{(1+a)^t}$$

On the other hand, the discounted energy would be equal to:

$$\sum_t \frac{E(t)}{(1+a')^t} \quad \text{instead of} \quad \sum_t \frac{E(t)}{(1+a)^t}$$

It would therefore be reduced, and the discounted average cost per kWh would be increased, as it to be expected.

It is therefore essential to ensure that the data are coherent:

- either one works with current money and adopts a discount rate representing the real cost of money
- or one works with constant money and in this case, the discount rate must be defined as "excluding inflation".

The following examples show the values currently adopted by the electricity producers participating in the working group:-

CEGB	:	10% with constant money (2)
EDF	:	10% with constant money (2)
ENEL	:	10% with current money
Belgian undertakings	:	8.6% with constant money (3)
Badenwerk	:	8% with current money
RWE	:	10% with current money

These values, when rendered homogenous (say by expressing them all in terms of constant money), would allow considerable divergencies.

4.7. Conclusions of the Working Group

Each electricity producer makes, for his own needs, cost calculations according to the method of his choice, whether using current or constant money, with an appropriate interest or discount rate arising from his own management and the actual conditions of the financial market or economy of the country.

In particular, to establish budgetary forecasts and financial needs, each Utility must estimate costs as closely as possible to actual values, and hence in current money terms.

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(1) For the sake of simplification, it is assumed that the annual rate of increase of the general price index is constant in time. The reasoning could easily be generalised. The result obtained in current money with a discount rate augmented for inflation is not surprising since the depreciation of the monetary unit increases the preference for the present.

(2) Discussions have taken place in the United Kingdom and France as to whether it is necessary to alter this value, probably downwards. These discussions have not however been completed at the time of writing.

(3) Value deduced from the real cost of capital in current money.

But for the purpose set by the Nuclear Energy Study Committee, which is to prepare costs to a common and comparable method, the Group of Experts recommend the use of the constant money method.

This at least avoids dangerous hypotheses regarding the future long term evolution of the general price level in the various countries and, if not for the investment cost (Section 5.4), at least for the forecast cost of fuel and operation.

There are at present considerable disparities in the inflation rates (1) of the various countries. However, these disparities will most probably change in the future, but it is not possible to say in which direction. What inflation rate could therefore be adopted for each country in the comparisons of current money costs? And if, being unable to reply to this question, one decided to adopt the same rate for all, this would mean the monetary erosion is no longer taken into account in the comparisons; it is therefore better to make the calculations in terms of constant money.

On the other hand, the relative price changes in constant money terms are relatively more stable than the variations in the general price index, and show less disparities between countries; it is mainly a question of relative changes in wages (see Section 4.3).

Of course, inflation introduces into cost comparisons distortions which vary with time, and which are not taken into account by constant money calculations. However, the comparisons are not made once and for all, and should be updated at fairly regular intervals; in this way the variations due to the inflationary component will appear, just as successive instantaneous views give a good idea of the dynamics of the system under observation, a posteriori.

The same applies to the exchange rates between the currencies of the countries in question: in constant money comparisons, account is taken of the exchange rates in force on the date for which the monetary units are defined. In current money calculations, it would strictly speaking be necessary to imagine a long-term evolution of these exchange rates, as it is related, to a great extent, to that of inflation in the various countries. However, such forecasts would not be on a firm basis. Here again, a succession of comparisons will enable one to see the effect of changes in the relative developments of the national economies.

Once it has been decided to adopt the constant money discounting method, it remains to determine the value or range of values of the discount rate. It is both illusory, in view of the disparities in the definition and choice among the various countries (c.f. Section 4.5 and 4.6), and also useless as regards the practical application of the method, to attach a particular significance to the discount rate at the financial or macroeconomic level.

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(1) "Inflation rate" is here synonymous with the annual variation in the general price index.

Nor is it possible, again because of the disparities between countries, to give it a precisely determined numerical value; it was seen in Section 4.6 that the values in use, in terms of constant money, vary between 10% and an unspecified value, which is however extremely low and fairly close to 0.

Finally, the Group of Experts recommend that the cost comparisons should be established for two values of the discount rate for constant money; 5% and 10%, so as to cover the major part of the range of values actually used, and to test the sensitivity of the comparisons to this basic parameter.

Summarising, in order that the comparisons should be completely valid, it is extremely desirable and essential to unify the following basic data:-

- the date for which the monetary units and exchange rates are defined
- the constant money discount rate (5 and 10%)
- the power station life
- the assumed operating modes of the power station (1) and the discounted total utilisation

On the other hand, the relative price changes in salaries, materials, etc. will remain specific to each country and will reflect the actual situation in each national economy.

Finally, it is desirable to present the costs in such a way as to be able to eliminate easily from the comparisons all the heads of costs which are not specific to conventional or nuclear power stations but which depend exclusively on the general regimes in force in each country (duties, taxes, insurance, possible customs duties, etc.).

All the other data specific to the power station in question must be specified by each electricity producer, according to the definitions and breakdowns detailed in the following sections.

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(1) The comparisons can easily be made for different modes of operation, due to the breakdown of the costs into a fixed part and a part proportional to output (c.f. Section 7).

5. CAPITAL COST

5.1 Technical Description of Power Station

A power station comprises one or more "units", each of which have one or more boilers (nuclear or conventional) and one or more turbo-generator sets (1).

The generating costs may refer to a single unit, or two units constructed together on the same site with a slight difference in time, or even more than two units (e.g. up to four).

Units constructed jointly are usually identical to each other. However, as regards their siting and their overall design, they may be either:-

- independent of each other, or
- twinned 2 by 2, with certain buildings, premises and circuits used in common by a pair of units (machine halls, control room, electrical installations, auxiliary circuits, etc.); the same can hold even in the case of more than two units.

The units are constructed either:

- on a new site, or
- on a site which has already been opened and on which there are units in operation.

In the latter case, the time which elapses from the commissioning of the previous units may or may not affect the cost of the later installations.

The local conditions are generally extremely different depending on whether it is a coastal site or a river site. In particular, the condenser cooling system depends on these local conditions and may comprise either :

- an open circuit, or
- a closed circuit, with natural or forced draught wet cooling towers (or cooling towers of some other type), or
- a mixed circuit comprising the above two systems with alternate operation on one or the other system, or on both simultaneously.

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(1) In some cases the steam circuits can be made common. However, the most frequent case, particularly in the nuclear field, is that in which each unit has a single boiler and a single turbo-generator set.

The net electrical capacity of each unit is the power actually delivered to the system by that unit, all the auxiliary load having been deducted. It must be defined for average cooling conditions. In the case of a mixed circuit, it may vary over a fairly wide range, between operation on open circuit (upper limit) and on closed circuit (lower limit).

Also, it is necessary to distinguish in certain cases (e.g. light water nuclear):

- the rated capacity, guaranteed by the manufacturers
- the design capacity of the plant, which has a margin with respect to the above capacity, but which is not taken into consideration in evaluating future costs as a cautionary measure, as it is not certain that it will be attained.

Finally, the safety and environmental protection constraints which are tending to become increasingly severe in all countries, have an important effect on costs.

In order to identify the content of the generating costs and the causes of deviations in the comparisons, one must therefore have available the following information, which does not however constitute an exhaustive list :-

- the number of units and the number of turbo-generator sets per boiler,
- whether the installation is on a new site, or on an already opened site, stating in the latter case whether costs have already been committed with the first units with a view to subsequent extension,
- in the case of at least two units, their overall design (twinning or independent),
- geographical situation: sea-coast or river, and cooling conditions: open circuit, closed circuit (type of cooling towers), mixed circuit (type of circuit),
- the average technical cooling conditions: temperature of cooling water, condenser pressure, temperature rise in the condenser, temperature of the air and approach to the cooling towers in the case of a closed circuit, etc.,
- the net electrical capacity of each unit under average cooling conditions, indicating the range of variation (particularly in the case of a mixed circuit),
- any margin in capacity with respect to the guaranteed nominal capacity,

- in the case of nuclear stations, the type of reactor (PWR, BWR, GCR, SGHWR, FBR, HTR, etc.), the thermal output of the reactor, the type of containment, the safety constraints (reference accident, safety injection system, emergency supply to the auxiliaries, emergency water reserve, resistance to earthquakes, missiles or aeroplane crashes, protection against sabotage, etc.), and the environmental protection measures (temperature rise in cooling water, standards relating to the radioactivity and chemistry of liquid and gaseous effluents, noise level in the vicinity of the site, conditions for the evacuation of irradiated fuels, etc.),

- in the case of conventional thermal plant, the principal steam characteristics at the admission and exhaust of the turbine(s), the fuel used (coal, lignite, heavy oil, natural gas), the heat rate in thermies G.C.V. or N.C.V. per kWh net, the protection of the environment (number and height of stacks, dust collecting installations, possible flue-gas desulphurization etc.),

- in the case of gas turbines, the main temperature and power characteristics as a function of the ambient conditions, the fuel used (heavy or semi-light fuel oil, natural gas, etc.), protective devices against noise and atmospheric pollution, etc.

5.2 Breakdown of Capital Cost

It is not possible to compare the capital costs for each item of a very detailed breakdown, of the type given in the 1967 Euratom guide. In fact, the division of contracts varies considerably from one producer to another, varying from an extremely fine division up to a turnkey order for the wole power station.

Even the distinction which is often made between direct cost and indirect cost does not always have the same meaning: the costs of design, engineering, supervision and co-ordination of the works, etc., are undertaken either by the owner (e.g. EdF) or by consultancy bureaux or manufacturers (in the case of German producers). The costs incurred by the owner himself vary considerably depending on the case.

On the other hand, it appears possible and desirable to set on one side and eliminate from the comparisons the overheads of the owner, which have no direct relationship with the power station in question (central services, headquarters, etc.) (1).

Finally, the breakdown of the capital cost is limited to 4 items:-

1. Construction cost in terms of constant money, excluding taxes, excluding interest during construction,

(1) These recommendations will also apply to operating costs.

excluding insurance charges, etc., but including the costs incurred by the electricity producer in direct relation to the construction of the power station.

2. Taxes, dues, any customs duties, insurance charges related to the contracts concluded with private companies, etc.

3. Interest during construction.

4. Overheads of the electricity producer (central services, headquarters, etc.).

For the reasons mentioned above and in Section 4.7, the Group of Experts recommend that only items 1 and 3 should be included in the comparison, and these are the subject of the following sections (1).

5.3 Make-up of the Construction Cost

The construction cost (in terms of current money or constant money) covers:-

- all the payments made by the producer to his suppliers, manufacturers, contractors, design or engineering consultants, industrial architect, etc., to which is generally added a reserve to cover any random charges and contingencies arising during the construction,

- the principal spares (e.g. primary pump in PWR reactors),

- all the costs incurred by the producer, covering all his personnel expenses throughout the duration of the design, the administrative procedures and construction of the power station (personnel involved in the design, negotiation of contracts, administration, accounting, supervision of manufacture and works, training of operating personnel, etc.), as well as all costs other than labour (miscellaneous plant, materials consumed during the tests preceding commissioning, etc.).

At the technical level, the construction cost covers all the design and works, including the preparation and layout of the site and access routes, all the temporary site installations, etc.

The limit of the plant covered by the contract is the high voltage terminals of the station transformers, excluding the lines and substation forming the interconnection with the system. The emergency auxiliary supply transformers are also included.

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(1) These recommendations will also apply to operating costs.

The circuit-breakers on the outgoing power lines, situated on the power station site, are not in principle included in the construction cost.

5.4 Determination of the Construction Cost in Terms of Constant Money

The constant money cost is the sum of all the payments, which have first been adjusted to the monetary unit at the date of reference according to the principle described in Sections 4.2 and 4.4.

However, the practical application is fairly complex and each electricity producer no doubt has his own method. The developments given below are not intended to propose a single method, but to indicate the concrete difficulties and a possible method of dealing with them, on a purely indicative basis.

One can consider any type of item supplied, ranging from a small item of plant up to a large component (boiler, generator set) or even a virtually complete power station.

The following are known or can be estimated:-

- the basic price of the item on a given date (t_1), which often differs from the reference date of the monetary unit (t_o),
- the date of payment of this price if it is paid as a lump sum, or the schedule of payments if it is spread over a period of time,
- a revision formula which is applied to the basic price or to each term of payment, generally of the type:-

$$a + b\frac{S}{S_1} + c\frac{M}{M_1}$$

where: a,b, c are coefficients, the sum of which is equal to 1.

S_1 is the specific index of wages on the date which defines the base price (t_1)

M_1 is the specific index for a typical material (e.g. steel) on the date t_1

S,M are the wages and material indices on the date of payment of all or part of the basic price (1).

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(1) In fact, the price revision formulae are often more complex: there are several terms for wages, as well as for materials, the sum of the coefficients remaining equal to 1. The same contract may include also several revision formulae, which apply respectively to design, construction at the works, transport, erection on site etc. The simplification made for the convenience of the description does not limit the general nature of the problem.

An item of payment which becomes due on date t may be expressed in three ways:-

- $P(t_1)$, in terms of the money corresponding to date t_1 of the basic price
- $P(t)$, in terms of the money corresponding to the date of payment t
- $P_o(t)$, in terms of the money corresponding to the reference date t_o for the monetary unit.

The transfer from $P(t_1)$ to $P_o(t)$ is made in two main steps;-

- first of all from $P(t_1)$ to $P(t)$, by estimating the wages and materials indices for date t and applying the revision formula:-

$$P(t) = P(t_1) \times \left[a + b\frac{S(t)}{S_1} + c\frac{M(t)}{M_1} \right]$$

- then one converts back from $P(t)$ to $P_o(t)$ by estimating the variation in the general price index between t_o and t, i.e. $(1+\alpha)$:-

$$P_o(t) = \frac{P(t)}{1+\alpha}$$

Thus the method of comparing costs in terms of constant money does not allow the electricity producer to dispense with taking into account forecast changes in salaries, materials and inflation for his own country.

This is justified, since all the financial clauses of a contract are a whole, and the basic price cannot be isolated from the revision formulae which accompany it. A supplier may agree a lower basic price if the revision formula is more favourable to him (very low fixed term, larger wages element, etc.), and conversely. The price revision formulae must therefore be included, and their inflationary effect taken into account.

In terms of constant money, these formulae give rise to calculable relative price changes.

For example, suppose that the price P(t) has previously been expressed in money at date t_o, either by applying the price revision formulae between t_o and t_1 if t_1 is earlier than t_o, or in the other case by dividing by the variation in the general price index between t_o and t_1.

Then in the report:-

$$\frac{P_o(t)}{P(t_1)} = \frac{a + b\frac{S}{S_1} + c\frac{M}{M_1}}{1+\alpha}$$

the factor $\frac{S/S_1}{1+\alpha}$ is simply the relative price change in salaries and $\frac{M/M_1}{1+\alpha}$ that in materials (see Section 4.4).

The term $\frac{a}{1+\alpha}$ is a special relative price, arising from the presence of a fixed term in the price revision formula. Since this term remains constant in terms of current money, in relative price terms it decreases as fast as inflation increases.

Finally, in working out the investment cost in constant money, the introduction of the rate of inflation, as well as the relative price changes in salaries and materials, is made necessary:-

- by the existence of a fixed term in the price revision formulae

- by the conversion of costs in original prices to prices at the monetary unit reference date

- for stations under construction, by the conversion to these price levels of costs incurred before the reference date.

The cost of construction in constant money would therefore be usefully supplemented with the following information:-

- the price revision formulae associated with construction costs

- the expected change in the particular price indices used in the formulae over the period covered by the evaluation of those costs

- the expected change in the general price index over the period of construction.

5.5 Interest during Construction

In the financial clauses of each Contract, the schedule of payments is just as closely connected with the base price as are the revision formulae. Here again, in fact, a supplier may agree a lower base price if he is paid more quickly after the signature of the Contract, as this increases his funds and may procure him financial benefits. On the other hand, the more delayed the payments are, the higher will be the supplier's basic price.

The sum of the costs discounted to the date 0 and at the rate a, is:-

$$\sum_t (1 + a)^t P_o(t)$$

The amount of the interest during construction is then:-

$$\sum_t (1+a)^t P_o(t) - \sum_t P_o(t)$$

This is often expressed as a percentage of the construction cost in terms of constant money:-

$$\left[\frac{\sum_t (1+a)^t P_o(t)}{\sum_t P_o(t)} - 1 \right] \times 100\%$$

The schedule of payments, i.e. the $P_o(t)$ schedule, can be defined in the greatest detail on the basis of the time schedules given in the Contracts. The items of payment may however also be grouped, in order to simplify the schedule, without thereby altering the interest during construction; for example, a payment at the start or in the middle of each year (these are not calendar years, but periods of 12 months based on the date 0).

This detailed or simplified schedule must include the expenses incurred by the owner, which consist largely of wages and are distributed uniformly in time; they can therefore be concentrated at the middle of each year.

In the discounting method described in Section 3.1, the schedule of payments during construction is taken automatically into account in the discounting of all the costs, to a date on which the average discounted cost per kWh does not depend (cf. Section 3.2, Footnote). It is not therefore necessary either to define this date precisely or to indicate explicitly the interest during construction.

However, comparisons between the costs of generating electricity must be able to be made, not only in relation to the average discounted cost per kWh, but also in relation to the capital cost per net installed kW. It is then necessary to take the time-schedules explicitly into account, and in order to do this, to discount the costs to date which it is logical to relate to the end of the construction period.

The date adopted for this purpose by the Group of Experts is the <u>date of commissioning or beginning of commercial operation</u>; on this date, the performance guaranteed by the Manufacturers should have been achieved under the conditions laid down in the Contracts, and the electricity producer may take complete charge of the operation of the power station.

Apart from its contractual character, this date also has an economic and financial significance: up to then, the capital invested in the power station has been unproductive, and the electricity producer bears completely the corresponding financial charges. However, from the beginning of commercial operation, the revenue received from the supply of power allows the producer to pay back the borrowed capital.

This date is defined unambiguously in the case of a single unit or if, in the case of several units, the schedule of payments relating to each of them is known.

On the other hand, when the schedule of payments is common to two jointly constructed units, without it being possible to separate them from each other financially, the discounting date is placed rather arbitrarily at an equal point between the commissioning of the successive units.

The schedule of payments does not generally stop at the date thus defined. The subsequent payments are then divided (instead of multiplied) by $(1+a)^t$.

Similarly, energy production does not commence at the start of commercial operation, but a few months before (bringing up to power, semi-commercial operation); the discounting of the energy to that date must of course take this into account.

Finally, one can calculate the centre of gravity of the capital costs i.e. the date on which all the costs could be concentrated without changing the interest during construction. The interval of time x between this centre of gravity and the date of the start of commercial operation is given by the equation:-

$$(1+a)^x \sum_t P_o(t) = \sum_t (1+a)^t P_o(t)$$

However, x is a function of a, and a knowledge of a single point of this function does not enable one to calculate the interest during construction for any value of the rate a.

<u>The figures for the interest during construction</u> (Item 3 of Section 5.2) <u>must therefore be complemented by the schedule of costs including at least one term of payment per year</u> in order to be able to repeat the calculation with the chosen discount rate in order to compare the capital cost per kWe and the average discounted cost per kWh, in particular for the two values recommended by the Working Group: 5% and10%.

5.6 <u>Cost of Dismantling</u>

The capital cost which has been defined and analysed above does not include any provision for the dismantling of the power station, after final cessation of operation.

It is recommended that a separate heading should be provided for this cost, which will then be discounted to the date of origin, in the same way as all the other costs, and will make its contribution to the average discounted cost of the kWh.

This heading will appear "for information" if it is not possible to evaluate this cost; especially in the case of nuclear power stations it is in fact still extremely inaccurately known, although certain studies can give approximate estimates. It may vary considerably depending on whether the dismantling is total or partial, the time lapse between the final shutdown of the power station and the commencement of dismantling, etc.

In any case, this operation takes place at a date far removed from the commissioning and its effect on the average discounted cost per kWh is extremely small, because of the discounting process.

6. OPERATING COSTS (EXCLUDING FUEL COSTS)

6.1 Definition and Breakdown

As in the case of capital costs, the technical description of the power station in Section 5.1 is essential if we are to place the operating costs correctly in their context.

These costs are generally given for one year of operation (here counted not as a calendar year but as periods of twelve months starting from the date the station goes into commercial operation). These costs vary from year to year because of changes in relative prices but they can be given a discounted average value over the whole life of the station (see Section 6.2). The total discounted cost of operation is then equal to the product of that annual average value and the number of discounted years (see 3.3). As the operating expenditure is distributed uniformly over time, in order to discount it, they can be assumed to be concentrated in the middle of each year of operation (see Appendix 1).

The operating costs include:-

- a fixed portion, independent of the utilisation (load factor) of the station, expressed in MU per kWe net per annum
- a portion proportional to the energy generated, expressed in MU per kWh.

As in the case of capital costs, there is no need to give a very detailed breakdown of operating costs. The following limited breakdown is sufficiently in line with the treatment adopted for capital costs (see Section 5.2).

Fixed Part in MU per kWe net per annum

1. Direct operating costs, excluding taxes, comprising: all labour costs on site, materials, stores and supplies, repairs and maintenance, (1) etc.
2. Taxes, dues, fees and insurance charges relating to contracts concluded with outside bodies etc.
3. General costs (regional and headquarters overheads).

Proportional costs, in MU per kWh (always excluding fuel)

1. Materials used in operation, proportional part of repair and maintenance costs (especially for gas turbines).

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(1) Annual repair and maintenance costs are often expressed as a percentage of the cost of all materials used in repair, calculated as a statistical average.

2. Dues, taxes, fees and insurance etc.

This breakdown of proportional costs is not exhaustive.

As in the case of capital costs, the cost comparisons should be based only on the costs in item 1 (fixed and proportional).

6.2 Effect of Relative Price Changes on Operating Costs

The relative price changes in constant money terms involved in the operating costs are mainly those connected with wages, taxes (generally upwards) and certain materials (in some cases downwards). As operating costs cover a long period of time and include a relatively high portion of wages and also often of taxes, the effect on the relative prices is very considerable.

Consider any item of operating cost which undergoes an annual relative price change α, and let:

t_o be the date of defining the monetary unit

t_1 be the date of commissioning

n be the n-th year of operation

N be the number of operating years.

In constant money at date t_o, the relative cost of the item considered is:-

P_o	at the date t_o
$P_o(1+\alpha)^{1/2}$	for the whole of the year commencing at datat t_o
$P_o(1+\alpha)^{t_1 - t_o}$	at the date t_1
$P_o(1+\alpha)^{1/2 + t_1 - t_o}$ $P_o(1+\alpha)^{t_1 - t_o + 1 - 1/2}$	for the year commencing at t_1 (first year of opeation)
$P_o(1+\alpha)^{t_1 - t_o + n - 1/2}$	for the n-th year of operation (n extending from 1 to N)

The annual cost of this item, on average discounted from the date of commissioning is:-

$$\bar{P} = \frac{\displaystyle\sum_{n=1}^{N} \frac{P_o(1+\alpha)^{t_1-t_o+n-\frac{1}{2}}}{(1+a)^{n-\frac{1}{2}}}}{\displaystyle\sum_{n=1}^{N} \frac{1}{(1+a)^{n-\frac{1}{2}}}}$$

$$\bar{P} = \underbrace{P_o(1+\alpha)^{t_1-t_o}}_{\text{Cost at date } t_1} \times \frac{\displaystyle\sum_{n=1}^{N} \left(\frac{1+\alpha}{1+a}\right)^{n-\frac{1}{2}}}{\displaystyle\sum_{n=1}^{N} \frac{1}{(1+a)^{n-\frac{1}{2}}}}$$

This expression is the product of the costs at date t_1 and a "discounted relative price change" over the whole life of the station. If the relative price change is zero ($\alpha=0$) the expression reduces to P_o.

The calculation should be performed separately for each item which is expected to undergo a relative price change; then all the results obtained in this way are added. From this can be derived an overall relative price change applying to the whole of the fixed costs on the one hand and the proportional costs on the other.

The breakdown necessary for this calculation is not that in the foregoing section, but the following:-

- wages
- taxes, fees, dues
- materials with a non-zero relative price change
- all costs with zero relative price change

The effect of the relative price changes can be considerable. For example the following values are possible:-

+ 4.5% per annum for wages and taxes

- 1% per annum for certain materials

The ratio of $\bar{P}$ (average discounted over the whole life of the station) to P_o (cost at date t_o), can then reach:-

1.25 if $t_1 = t_o$

1.55 if $t_1 = t_o+6$

The overall relative price change is then 3.5% per annum: the costs increase by 3.5% per annum from the first to the last year of operation. The levelised average cost also increases by 3.5% when the commissioning date is postponed by one year.

In order to indicate the effect of relative price changes, the breakdown in Section 6.1 should be supplemented with the following information:-

- the number of people on site
- the portion of wages in items 1 and 3 of the fixed costs
- the relative price changes at constant money, especially in wages (items 1 and 3 of the fixed costs) and taxes (item 2 of the fixed costs and of the proportional costs)
- the overall relative price change when the commissioning date is postponed for one year, in the whole of the fixed costs and on the proportional costs.

This list is not exhaustive. Supplementary information would allow a deeper analysis of repair costs, e.g.:-

- breakdown of manpower into: operation, repair and maintenance, adminstration and site management
- annual repair and maintenance costs as a percentage of the capital cost of the equipment
- etc.......

7. COST OF FUEL

7.1 Brief Reminder of the Cost of Fuel in Conventional Thermal Power Stations

In the case of conventional thermal power stations, the cost of fuel (coal, heavy oil, natural gas, lignite, etc.) is defined very simply: it is the product of the heat rate, in thermies (1000 kcal) per kWe net, and the price of the thermies delivered at the power station (1). This price is expressed, as are all the other costs, in monetary units at the reference date and may or may not show a relative price variation with time.

Environmental protection constraints must be taken into account, precipitation, desulphurisation or mixing of fuel oils, as well as the costs or sales from ash and dust disposal. All fuel expenses arising from investment or operation are taken account of in the preceding chapters.

All fuel expenses, relating to investments (handling or treatment of installations)and to operations (operating and maintenance of the installations) are taken account of in the preceding chapters.

The only costs included here are proportional to energy output and are expressed as a proportional cost per kWh. The total present value fuel cost is then the product of this cost and the total present value energy.

Furthermore, reserve stocks of fuel on site add a fixed cost independent of utilisation. This cost is equal to the initial cost of the stock less recovery value at the end of the station's life, discounted to the commercial commissioning date. In terms of annual cost this is a financial charge equal to the value of the stock and the discount rate.

However, these financial charges remain relatively low and this stock is not physically indispensable for the operation of the power station; this is a basic difference from the case of nuclear fuel.

7.2 Outline of the Nuclear Fuel Cycle

The calculation of the cost of nuclear fuel is much more complex than that for conventional thermal stations: a minimum mass of fuel is necessary in the reactor for the generation of energy to be possible (critical mass); the fuel cycle involves a large number of operations; and the immobilisation period of the fuel during these operations (including irradiation in the reactor) is of the order of 6 years.

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(1) Specifying whether gross or net calorific value is used. It is also necessary to take account of the fact that average efficiency is less than that achieved on full power, because of stoppages, starts, outages, partial running, etc.

The result of this is that the nuclear fuel costs are not purely proportional to the energy produced and they cannot be broken down simply into yearly amounts.

In the methodological framework adopted, the contribution of fuel to the average discounted cost per kWh is the ratio of all the fuel costs, discounted to the date of commercial commissioning, to the total energy discounted to the same date.

In the case of a light water reactor (PWR or BWR) or a fast breeder reactor, the fuel renewals require the shutdown of the reactor and consequently take place at fairly long intervals (often of the order of one year).

The name of fuel batch is applied to a group of assemblies charged simultaneously into the reactor and discharged simultaneously. The assemblies in a batch all have the same characteristics (particularly the same initial enrichment).

All the batches charged prior to commissioning constitute the first charge (or first core). During operation, each renewal consists of discharging one or more batches of irradiated fuel and charging one or more batches of fresh fuel. When the power station is finally shut down, all the fuel contained in the reactor, which constitutes the last charge (or last core), is discharged.

A particularly interesting period is that of the balanced regime, when the renewals take place at regular intervals and when the characteristics of the charged and discharged batches are repeated identically on each renewal.

In PWR reactors, in which the fuel is renewed roughly by thirds of a core, it can be assumed that balance is attained at the third renewal, that all the recharges have, from the first one onwards, balanced characteristics and that only the first and last charges give rise to disturbances in the balanced regime. For BWR reactors recharging is a little more complex, approximately by a quarter of a core, and the equilibrium period is achieved a little more slowly than for PWR's.

The total discounted fuel cost and the average discounted cost of the kWh can be broken down in various ways:-

- either by batch (for example, first charge, recharges and reserve stocks)

- or by operation of the fuel cycle: natural uranium, enrichment, manufacture of assemblies, reprocessing, uranium credit, plutonium credit (Sections 7.3 and 7.4).

- or in terms of a fixed portion (independent of the utilisation of the unit) and a portion proportional to the energy generated (Sections 7.5 and 7.6).

7.3 Operations related to the New Fuel

These operations are the following:-

- extraction and processing of the ore, for delivery in the form of concentrates ("yellow cake")
- conversion of the concentrates into UF6
- enrichment
- manufacture of fuel assemblies, covering all the operations from the enriched UF6 up to the delivery to the site of the finished assemblies, ready for charging into the reactor.

The quantities of fissile materials delivered to the assembly manufacturer are generally slightly greater than strictly necessary, in order to compensate for losses during manufacture. The majority of these losses can be recovered (UO2 pellets vary slightly damaged during handling, or whose dimensions are not within the tolerances, etc.).

From the economic point of view, the factor prices involved are:-

- the price of concentrates in $ per lb of U_3O_8, converted into the currency of each country by the rate of exchange of the $ at the reference date of the monetary unit; the price in MU/lb of U_3O_8 is converted to the price in MU/kg of U contained, by multiplying it by 2.6
- the price of converting the concentrates into UF6, in MU/kg of U contained
- the price of enrichment, in MU/kg-SWU
- the cost of manufacture, in MU per kg of U contained in the finished assemblies.

All these costs include the cost of transport and all the additional costs associated with each operation. They are expressed in constant money at the reference date for the monetary unit. They may be accompanied by a relative price change: that affecting uranium is extremely difficult to predict, but it is to be feared that it will remain in the upward direction. On the other hand, that affecting manufacture should continue to decrease, because of mass-production, economies of scale and technological progress expected in this light industry, which is very repetitive and easily lends itself to automation.

The cost of each operation must be accompanied by a schedule of payments, set out, for example, monthly with respect to the date of loading the assemblies in the reactor (taking into account the period of storage on the site, between delivery and charging).

The discounting of the costs can be carried out in two periods: first of all from the date of payment to the date of charging, and then from the latter to the date of commercial commissioning.

7.4 Operations Related to the Irradiated Fuel

These operations are as follows:-

- transport of the irradiated fuels from the site to the reprocessing plant

- the reprocessing proper, ending with the separation of the fission products and the recovery of the uranium (still slightly enriched with respect to natural uranium) and of the contained plutonium, generally in the form of nitrates

- the treatment of radioactive waste, comprising in particular vitrification, then transportation and final storage

- the transformation of the recovered uranium nitrates into UF6 ready to be sent back to the enrichment plant

The cost of these operations is at present subject to considerable uncertainties and can only be estimated extremely roughly. It is expressed in MU per kg of U, but it must be clearly specified for clarity of definition whether the kg of U is contained in the new assemblies or in the irradiated assemblies (there is a difference of the order of 5%).

The recovery of the uranium which is still enriched (approximately 0.9% of U 235 in the case of PWRs) and of plutonium gives rise to credits, which may be less than or greater than the cost of the whole of the reprocessing (including all the operations described above), depending on the unit prices adopted.

The uranium credit is the saving obtained on the quantities of natural uranium and of kg-SWU intended for the new assemblies, due to the recycling of the recovered uranium: it is calculated on a basis of the unit prices defined in Section 7.3.

The plutonium credit is determined by applying a unit price to the quantity of plutonium recovered. It must be clearly stated whether this is only fissile Pu (uneven isotopes) or the total Pu.

The value of a gramme of plutonium is still not known accurately, as there is no world market. The only value which can be suggested is the saving in natural uranium and separative work due to the recycling of the plutonium in light water reactors. However, the uncertainties regarding the additional cost of manufacturing, and perhaps reprocessing, the assemblies enriched with Pu (mixed UO2-PuO2 oxide), make the results extremely doubtful. As to the effect of the development of breeder reactors which is expected in certain countries on the value of the Pu, this is even less accurately known and a study of this would be outside the terms of reference of this report.

The cost of reprocessing (in the widest sense of the word) and the U and Pu credits must be accompanied by a schedule of payments set out for example in months from the date of discharging of the fuel batch in question (taking into account the period of storage and cooling in the pond, transportation, etc.).

As with the new fuel, the discounting of costs can be carried out in two phases: firstly from the date of payment (or credit) to the date of discharging, and then from the latter to the date of commercial commissioning.

7.5 Breakdown of Fuel Cost into a Fixed Part and Part Proportional to Output

Contrary to the case of fossil fuel, nuclear fuel costs are not fully proportional to energy output and contain a fixed part, for two reasons already indicated:-

- the reactor must always contain a complete core (critical mass) whereas a fossil fuel stock is not essential to boiler operation and can finally be run down to nothing

- nuclear fuel remains in the reactor for several years, whereas fossil fuel is always burnt quickly and fully.

Consider first the equilibrium regime. At any time, the reactor core has fuel assemblies with all the equilibrium characteristics and with average irradiation characteristics, both in space and time, equal to half the irradiation of discharged fuel; it can be described as "a core in equilibrium at half burn-up".

As regards economics, this core has a value equal to half the sum of its new value (cost of new assemblies) and of its residual value (U and Pu credits less the cost of reprocessing - this value may be negative).

The immobilisation of this mean value in the reactors throughout its life leads to financial charges independent of the unit's utilisation and constituting a fixed component. Furthermore, this value is - theoretically - recoverable at the final shut-down of the reactor, as if it were a stock. The fixed component is thus equal to the difference between the value of an equilibrium half-burnt core and its residual value at end of life, present valued to commissioning date. It is expressed in units of MU/kW.

This fixed part is thus due to the permanent presence of a stock of fuel in the reactor. But this stock is renewed in proportion to energy output and all recharging costs are proportional to energy supplied. These costs, present valued to the date of recharging, are:-

- the cost of the new loaded batch

- the cost of reprocessing the unloaded irradiated batch

- U and Pu credits (negative costs)

The total of these costs divided by the energy produced during one campaign (interval between two consecutive recharges), is the proportional cost, in MU/kWh.

If the unit prices have relative price changes in constant money terms, the proportional cost will vary with time, with recharges, and it is possible to define a discounted average value over the life of the unit.

But this description is very schematic and must be completed. In effect, the initial charge is not "a core in equilibrium at half burn-up" and is composed entirely of new assemblies. The equilibrium regime is attained only after several campaigns (cf. section 7.2).

Although at equilibrium batches stay in the reactor for 3 or 4 campaigns, the first batch discharged only stays in for one campaign: there is a resulting overcost, not so much of the fissile material (since the enrichment can be adjusted accordingly), but rather because of fabrication and reprocessing. It is the same, to a lesser extent, for the second batch only remains for two campaigns, and so on until the time in the reactor reaches the equilibrium value. Similarly, leading up to final shut-down, the last batch only stays for one campaign, etc.

To take account of these perturbations to the equilibrium regime at the beginning and end of the reactor lifetime (together with other much less important ones not mentioned here), it is necessary to add supplementary terms to the fixed component defined above. Some of these terms are not firmly fixed, since they depend on the unit's utilisation during the first few campaigns, by means of the recharging dates and on the fact of discounting. But these terms are relatively very small.

For the proportional cost component, it is possible to keep the above definition, extended over the unit's lifetime and including the transient period prior to equilibrium. It is thus easy to calculate.

To a close approximation, the total present valued fuel cost is a linear function of the total present-valued energy: fixed component + (proportional cost x present valued energy). The mean present valued cost per kWh, in MU/kWh, is equal to:

$$\frac{\text{fixed component}}{\text{present valued energy}} + \text{proportional cost}$$

The fixed part so defined has no reason to equal the cost of the initial charge. For light water reactors, it is not more than 70% of the cost of the initial charge. Consequently, if one spreads the total initial charge cost over the present valued energy and adds the equilibrium proportional cost, one overestimates the total fuel cycle cost.

The initial charge is considered only to establish budgets and financial requirements before the station is commissioned (1).

Appendix 2 gives the mathematical development of the principles described here and a detailed numerical example for reactors with off-load refuelling (in particular PWR and BWR). Reactors with on-load refuelling (gas-graphite, heavy water) need a different presentation but the same general principles apply.

7.6 Effect of Operating Constraints and Random Factors on the Discounted Average Cost per kWh

The results described above give the average discounted cost per kWh as a function of availability and utilisation of the unit (number of hours of equivalent operation at full capacity).

However, these results assume that all the campaigns are continued to their completion, i.e. that all fuel batches are discharged when they have exactly reached their reject irradiation (except in the case of the last 2 batches), for unit nominal performance.

In actual fact, this will not always be the case because the actual utilisation and operation of a power station are subject to a number of random factors, and because of these the operator will have to alter the date planned for the renewal of the fuel, for one of the following reasons:-

- as the result of a defect in the fuel
- in order to make use of a shutdown for other reasons (maintenance, breakdown, etc.)
- in order to obtain a better distribution in time of the shutdowns for recharging and maintenance of each unit, within the framework of the general maintenance programme for all plants
- in order to avoid a shutdown during the period of heaviest system load (in Europe, the hours of full load in winter and particularly in December, January, February)
- etc......

Faced with the various decisions to be made, the operator will usually have the option of choosing between several solutions. This choice will however be limited by a number of constraints:-

- the consequences of the previous history of the reactor and the fuel

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(1) But contrary to the investment cost, the cost of the initial charge need not be spread over the whole life of the unit: a part of this cost is in fact proportional and is spread over the energy produced in the first few campaigns.

- the limits on fuel utilisation imposed by technological and safety criteria

- the availability and limits of exposure to radiation of the personnel in charge of maintenance and fuel recharging, etc....

For example, when it is a matter of adapting the operation of the units to system requirements and avoiding the winter period, the operator will generally have a choice, within the limit of the constraints referred to above, between two possibilities:-

- either extending the campaign beyond the date corresponding to a zero reserve of reactivity in the reactor for normal operating conditions, which necessitates a gradual reduction of power ("stretch out" operation);

- or bringing forward the renewal date, thus losing on the reject irradiation of the fuel.

The economic effect of these decisions is the result of a balance between two terms, discounted from the date of implementing the decision up to the end of the life of the reactor:-

- the additional cost due to the changed in the refuelling programme and the reject irradiation of the fuel, with respect to the method which theoretically minimises the average discounted cost per kWh

- the increase in value to the system of the nuclear power and energy, due to postponing the shutdown. (saving in fossil fuel and investment in peak plant).

Some studies indicate that the first term is relatively very small compared with the discounted average cost per kWh (less than 1%) and that, in the case of a system whose load curve varies considerably with the seasons, the second term is much more important than the first. It is therefore probable that the system requirements will have priority over the actual savings in the fuel cycle of each reactor considered in isolation.

Furthermore, when nuclear stations come off base load, the increasing number of start-ups, shutdowns and hours of operation on part load will involve a slight reduction in the average net efficiency of the units and a slight increase in the discounted average cost per kWh, which is inversely proportional to efficiency. Here again, however, this effect is of secondary importance.

Finally the fuel costs should include cost of fuel assemblies (or fissile material) held as reserve stock during the station lifetime.

8. SYNTHESIS OF RESULTS, CONVENTIONAL-NUCLEAR COMPARISONS, AND CONCLUSION

All the fixed costs, independent of the electricity produced and expressed in MU per kWe net, comprise:-

- capital cost (Section 5)
- total fixed operating costs, discounted over the whole life of the station (Section 6)
- the fixed part of the cost of nuclear fuel (Section 7 and Appendix 2)

The cost proportional to output in MU per kWh, comprises:-

- proportional operating costs (Section 6)
- proportional fuel costs (Section 7).

If we call the fixed part A, the proportional cost b and the discounted total utilisation U, the discounted average cost per kWh is expressed (either for each of the items: capital, operation, fuel, or for the whole three) as:-

$$\frac{A}{U} + b$$

Knowledge of the quantities A and b therefore enable us to calculate the cost of the kWh for a given utilisation without which the costs of the different sources would not be comparable with each other for a given type of plant (nuclear, conventional thermal, gas turbine.....)

By virtue of the knowledge of the relative price changes at constant money, it is also possible to give a list of annual generation cost figures (see Section 3.3), comprising:-

- fixed charges taken as equal annual payments (interest and depreciation, arising from the capital costs and the fixed portion of the fuel cost)
- the operating costs for the year considered
- the proportional cost of operation and of fuel

Let A(t), b(t) and H (t) be the fixed costs, the proportional cost and the utilisation in year t respectively. The cost per kWh is then:-

$$\frac{A(t)}{H(t)} + b(t)$$

and the total cost of generation for that year (per kWe net):-

$$A(t) + b(t)H(t)$$

The discounted average cost per kWh is given by calculating the average of the annual costs, weighted by the number of hours and by the discount factors for successive years, according to the expression:-

$$\frac{\displaystyle\sum_{t=1}^{T} \frac{A(t)+b(t)H(t)}{(1+a)^{t-\frac{1}{2}}}}{\displaystyle\sum_{t=1}^{T} \frac{H(t)}{(1+a)^{t-\frac{1}{2}}}}$$

The discounted average cost per kWh is the most aggregated presentation of the information and it breaks down into three main components:-

- capital investment
- operation (excluding fuel consumption)
- fuel (including the initial charge for nuclear stations).

The structure of the discounted average cost per kWh can differ considerably for different methods of generation. If we compare, for instance, nuclear and conventional thermal, the capital investment portion is heavier, and the fuel portion much smaller, for the first than for the second.

Simply as an indication, the approximate percentages could be as follows, for light water units of at least 900 MW, oil fired units of 600 to 700 MW, both on base load:-

	Nuclear	Conventional Thermal
Capital Investment	50%	18%
Operation	20%	12%
Fuel	30%	70%
Total	100%	100%

But the total cost of the conventional thermal station would be higher by over 50% than the nuclear, for base load operation.

Given these two costs of generation in the form A + bU, it is easy to calculate the utilisation U_0 for which the choice of a kW of nuclear or conventional thermal is equal:-

$$A_n + b_n U_o = A_t + b_t U_o \qquad (n = \text{nuclear}, \; t = \text{thermal})$$

$$U_o = \frac{A_n - A_t}{b_n - b_t}$$

If the generating plant mix is such that the utilisation U of a new kW exceeds U_o then nuclear is more economic than conventional thermal, and vice versa

If existing conventional plant is scrapped and substituted by nuclear, only the fixed operating costs should be included in A_t **(reduction of the costs of displacement and retraining of labour when scrapping).** The utilisation U_o for equal economic merit between these alternatives is then considerably higher than in the case of new conventional plant. (1)

It would still be necessary to take account, in these comparisons, of differences in station lifetime, availability at peak periods, and later outage times for maintenance and recharging, etc. But the method presented in this report does not enable the comparison between nuclear and conventional thermal to be taken further.

Calculation of the optimal mix, in a given production system between different types of generation (nuclear, conventional thermal, whether being constructed or scrapped, gas turbines, etc.) require a knowledge of all the elements of the generation-demand system; in particular the detailed generating plant constitution, load curve characteristics, the lifetime for each equipment item, required reserve power margins, etc. (cf. section 1: mandate of the Group of Experts).

In conclusion, the complete set of information and results, given by the definitions and schedules set out above and in the summary, provides, on a consistent base:-

- costs of investment, operation and fuel
- total fixed costs per kWe net
- proportional cost per kWh
- average discounted cost per kWh, dependent on station utilisation.

It is thus possible to compare costs, and explain the reasons for difference, for generating means of a given type: nuclear, conventional thermal, gas turbines.

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(1) In a plant mix with new nuclear and gas turbines being added, and a fixed tranche of existing conventional thermal plant, U_o is given to a good approximation by making A_t equal to the gas turbine fixed charge, if the gas turbine utilisation is sufficiently low.

In parallel with the method proposed in this report, each electricity producer will of course use other methods directed to his own needs. In particular, establishing budgets and financial needs means working in current money terms, with an interest rate depending on the particular situation of each producer and each country.

Finally, comparisons between different means of generation in a given tranche of plant can use the above elements, but taking into account also more complex considerations particular to each country.

APPENDIX 1

PRACTICAL APPLICATION OF THE DISCOUNTING METHOD

1. EXPENDITURE OCCURRING AT DISCRETE POINTS IN TIME

We saw in para. 3.1 that an expense D(t) committed at the instant t has a discounted value at an instant taken as the time origin:-

$$\frac{D(t)}{(1+a)^t}$$

where a is the annual discount rate.

The time t is expressed in years, but is not necessarily a whole number. The payment timetables are often defined in months. We then have $t = \frac{m}{12}$, m being the number of months between the instant of origin and the date of the payment.

2. EXPENDITURE UNIFORMLY SPREAD OVER TIME

When it is a question of a continuous flow of expenditure uniformly spread over a period of time (this is for example the case with operating costs), it is necessary to employ the continuous discounting technique. We then define D(t), the expenditure per unit time, the discounted value of which is always:-

$$D(t) \times (1+a)^{-t}$$

The discounted total cost over a period extending from 0 to T is:-

$$\int_0^T D(t)(1+a)^{-t}dt$$

and D(t) is constant and equal to D (expenditure uniformly spread over time):-

$$D \int_0^T (1+a)^{-t}dt$$

We put: k = log (1+a), which we call the continuous discounting rate. The above integral becomes:-

$$D \int_0^T e^{-kt}dt = D \frac{1-e^{-kT}}{k} = DT \frac{1-e^{-kT}}{kT}$$

But it amounts practically to the same thing to discount the total expenditure as if it had been concentrated at the middle of the period considered, i.e. at the instant T/2, which yields:-

$$DT(1+a)^{-\frac{T}{2}} = DTe^{-k\frac{T}{2}}$$

The expansions of the two expressions are:-

$$\frac{1-e^{-kT}}{kT} = 1-\frac{kT}{2} + \frac{(kT)^2}{6} - \frac{(kT)^3}{24} + \dots\dots\dots$$

$$e^{\frac{-kT}{2}} = 1-\frac{kT}{2} + \frac{(kT)^2}{8} - \frac{(kT)^3}{48} + \dots\dots\dots$$

The difference between the two functions is thus of the order of:-

$$(kT)^2\left(\frac{1}{6} - \frac{1}{8}\right) = \frac{(kT)^2}{24}$$

For a period of time of one year and a rate k of 10% at most, the difference is less than $5 \cdot 10^{-4}$. The two expressions can therefore be taken as equivalent.

To summarise, it is sufficient to divide the time into years, to assume that the annual expenditure is concentrated at the middle of each year and then to discount by the conventional method. Here, it is a question not of calendar years but periods of twelve months starting from the date of commissioning of the station.

For example, let D_n be the expenditure in year n, all referred to the middle of the year. Its discounted value is:-

$$\frac{Dn}{(1+a)^{n-½}}$$

and the discounted total cost is:-

$$\sum_{n=1}^{N} \frac{D_n}{(1+a)^{n-½}} \quad (N = \text{life of the station})$$

The same applies to the energy or the number of hours operation equivalent to full power (see para. 3.2): if E_n is the electrical energy produced in the year n, the discounted energy is equal to:-

$$\sum_{n=1}^{N} \frac{E_n}{(1+a)^{n-½}}$$

and the number of hours:-

$$\sum_{n=1}^{N} \frac{H_n}{(1+a)^{n-½}}$$

As an example, for a = 10%, N = 20 years, and

H = 3000 hours in the 1st year
5000 hours in the 2nd year
6600 hours from the 3rd to the 20th year,

we find

$$\sum_{n=1}^{N} \frac{H_n}{(1+a)^{n-1/2}} = 54100 \text{ hours}$$

The number of discounted years (see para. 3.3) equals:-

$$\sum_{n=1}^{N} \frac{1}{(1+a)^{n-1/2}} = 8.93$$

NOTE Section 3 used the notation t and T in place of n and N respectively.

APPENDIX 2

ANALYSIS OF THE COST OF NUCLEAR FUEL FOR REACTORS WITH OFF-LOAD REFUELLING - BREAKDOWN INTO FIXED PART AND PART PROPORTIONAL TO THE ENERGY

1. COST PER CAMPAIGN AT EQUILIBRIUM

The cost of the fuel attributed to a campaign at equilibrium and discounted to the commencement of that campaign, is:-

$$X + Yr^{-T}$$

with X = cost of the fuel charged at the beginning of the campaign, discounted to the date it is charged into the reactor

Y = cost of the fuel discharged at the end of the campaign, discounted to the date it is discharged

T = duration of the campaign

r = 1+a (a: discount rate)

This expression can be written: $\frac{X-Y}{2}(1-r^{-T})+(X+Y)\frac{1+r^{-T}}{2}$

Let: j = log r (continuous discounting rate)

We have: $\frac{1+r^{-T}}{2} \sim 1-\frac{jT}{2} + \frac{j^2T^2}{4} - \frac{j^3T^3}{12} + \ldots\ldots\ldots$

$$1-r^{-T} \sim jT \left[1-\frac{jT}{2} + \frac{j^2T^2}{6} - \frac{j^3T^3}{24} + \ldots\ldots \right]$$

Consequently, the difference between $\frac{1+r^{-T}}{2}$ and $\frac{1-r^{-T}}{jT}$ is in the order of:-

$$j^2T^2\left(\frac{1}{4}-\frac{1}{6}\right) = \frac{j^2T^2}{12}$$

This difference is negligible, because j equals at most 0.10, T is about one year and this term is less than 10^{-3}.

The fuel cost per campaign can therefore legitimately be written:-

$$\frac{X-Y}{2}(1-r^{-T}) + (X+Y)\frac{1-r^{-T}}{jT}$$

We now introduce the energy E produced in the course of the campaign by putting:-

$$(X+Y)\frac{1-r^{-T}}{jT} = \frac{X+Y}{E} \times E\frac{1-r^{-T}}{jT}$$

thus bringing out the energy discounted to the beginning of the campaign. In fact, by putting the utilisation of the station equal to U (energy produced per unit of time), we have $UT = E$ and the energy discounted to the commencement of the campaign is:-

$$E^* = \int_0^T Ue^{-jt} \, dt = U\frac{1-e^{-jT}}{j} = E\,\frac{1-r^{-T}}{jT}$$

From which we obtain the final expression of the fuel cost per campaign at equilibrium:-

$$\boxed{\frac{X-Y}{2}\,(1-r^{-T}) + \frac{X+Y}{E}\,E^*}$$

The first term represents the financial charges on a stock of fuel immobilised in the reactor and recovered at the end of the campaign.

The second term is the cost proportional to the discounted energy produced during the campaign.

The proportionality factor $\frac{X+Y}{E}$ which is expressed per kWh, is itself often termed "proportional cost". We can consider it as a "marginal cost", i.e. as the cost of an additional kWh generated in the course of the campaign.

2. DISCOUNTED TOTAL COST OF AN IDEAL CYCLE AT EQUILIBRIUM OVER THE WHOLE LIFE OF THE REACTOR

In the course of such a hypothetical cycle, all the campaigns repeat identically over the whole life of the reactor. It is then sufficient to discount the foregoing expression at the date the reactor is commissioned, then to summate over the total number N of the campaigns. By putting t_i as the date of the i-th renewal and putting $t_o = 0$, we get:-

$$\frac{X-Y}{2}\sum_{i=1}^{N}(1-r^{-T})\;r^{-t_{i-1}} + \frac{X+Y}{E}\sum_{i=1}^{N} E^* r^{-t_{i-1}}$$

But as $t_{i-1} = (i-1)T$, all the terms of the first sum cancel out except the first and the last, and the second sum is nothing more than the total energy discounted over the whole life of the reactor. This expression is therefore written simply as:-

$$\frac{X-Y}{2}\,(1-r^{-t_N}) + \frac{X+Y}{E}\,E^*_{tot}$$

But it is not complete because the cost of the first charge is not equal to X and that of the last charge is not equal to Y.

It is assumed in what follows that fuel is systematically renewed in core fractions of $^1/L$; for PWR's of Westinghouse type, effectively L=3 and for BWR's of General Electric type, L=4. At equilibrium, each fuel batch remains in the reactor for L campaigns.

It is assumed also that all prices are constant in constant money terms (no relative price changes).

So that the equilibrium regime can be established after commissioning, it is necessary to make the first core up of L batches irradiated respectively to a fraction $\ell/1$ of the reject irradiation level at equilibrium, ℓ going from 0 (new batch) to L-1.

But the value of a new batch is X and its residual value at the moment it is discharged at the reject irradiation level is -Y (with the sign convention adopted for Y). It appears logical to assume that the potential value of this batch of fuel varies linearly between 0 and the reject irradiation. The value of a batch irradiated to a fraction ℓ/L is then:-

$$(1-\frac{\ell}{L})X - \frac{\ell Y}{L} = \frac{(L-\ell)X - \ell Y}{L}$$

The total value of the first core thus constituted is therefore:-

$$\frac{1}{L} \sum_{\ell=0}^{L-1} \left[(L-\ell)X - \ell Y \right] = \frac{(L+1)X - (L-1)Y}{2}$$

and represents an additional $\frac{1}{2}$ (L-1) (X -Y) compared with normal renewal, which must be added to the discounted total cost of the fuel.

On the other hand, at the moment the reactor is finally shut down, the last core consists of L charges, irradiated respectively to a fraction ℓ/L of the reject irradiation level at equilibrium, ℓ going from 1 to L.

The recovery value of this core, of which the incompletely irradiated (L-1) charges can be used for charging another reactor being put into service, is then:-

$$\frac{1}{L} \sum_{\ell=1}^{L} \left[(L-\ell)X - \ell Y \right] = \frac{(L-1)X - (L+1)Y}{2}$$

or an addition of $1/2$(L-1) (X - Y) compared with the value of the fuel discharged at a normal recharging (-Y), which it is necessary to discount to the commissioning date and subtract from the total cost.

Finally, it is necessary to add to the total cost:-

$$\frac{1}{2}(L-1)\ (X - Y)(1-r^{-t_N})$$

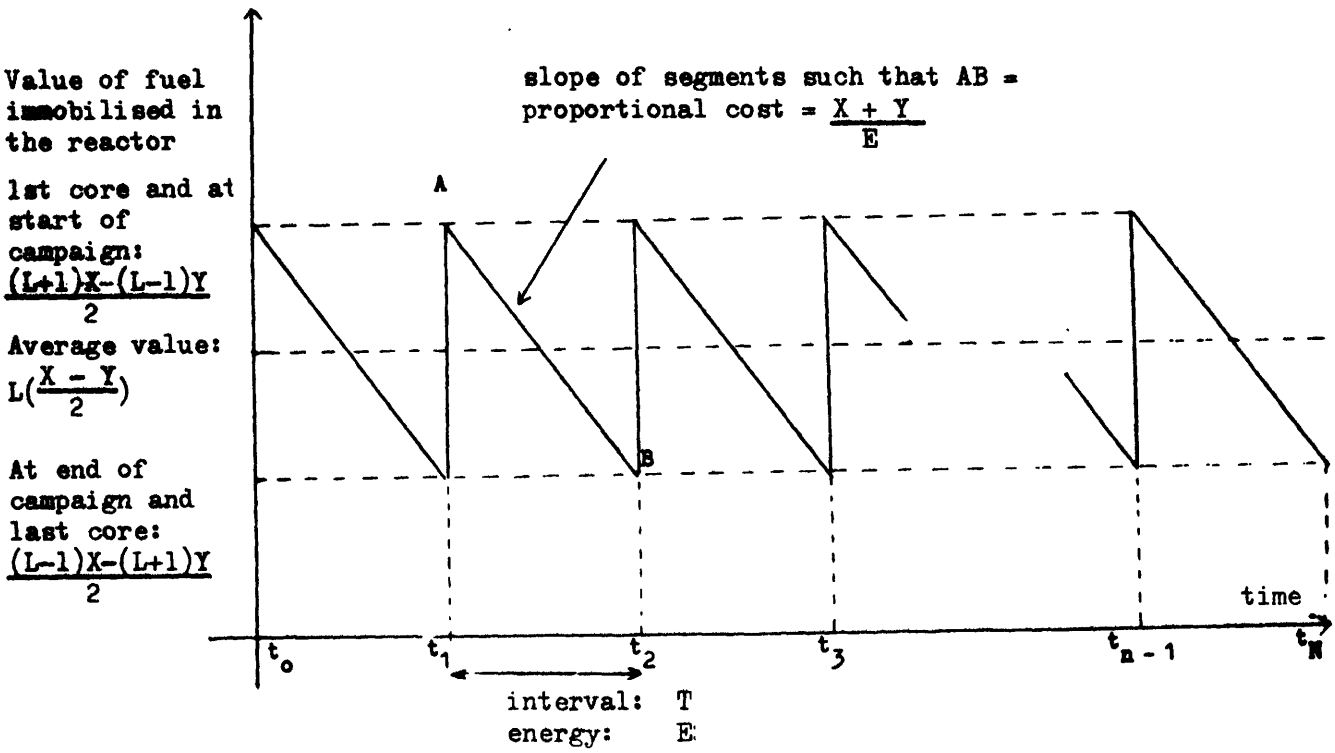
and the discounted total cost becomes:

$$\frac{L}{2}\ (X - Y)\ (1-r^{-t_N}) + \frac{X + Y}{E} E^*_{tot}$$

The first term is the <u>fixed part</u>: it is the mean value of fuel immobilised in the reactor (a core in equilibrium at half burn-up less the same value recovered at end of life and present valued to commissioning date. The second term is the part <u>proportional</u> to the total discounted energy.

It should be noted that this formula is valid irrespective of the distribution in time of the dates for renewing the fuel or the duration of the campaigns. On the other hand, the energy (not discounted) produced per campaign has to be constant, equal to E and uniformly distributed over the duration of each campaign.

The value of the fuel permanently in the reactor varies with time according to a saw-tooth pattern, as shown in the following diagram:-



It can be seen from the diagram that the average value of the fuel immobilised in the reactor is not equal to the cost of the first charge, but is less than it, roughly in the ratio L to (L+1), (Y is generally much smaller than X). The cost of the first core is therefore not the same as the fixed part of the fuel cost, since this takes account of recovery of stock at end of life. Similarly, for symmetrical reasons, the value of the immobilised stock is greater than that of the last charge, in the ratio L to (L-1) approximately (neglecting Y).

3. CORRECTIONS TO BE MADE FOR THE FIRST AND LAST CHARGE

In fact, the initial charge is entirely new but the initial enrichment of the (L-1) batches which remain less than L campaigns in the reactor can be adjusted so as to reduce the expenditure on fissile material as much as possible.

Put, for one charge at equilibrium:-

F : cost of fabrication
U : cost of fissile material

R : reprocessing cost
V : U and Pu credits

We have:-

$$X = F + U$$
$$Y = R - V$$

Suppose that the expenditure on fissile material is proportional to the energy furnished by each batch of the first core. The quantities U and V then play only the role of X and (-Y) at the end of the foregoing paragraph and the cost of the first core is:-

$$LF + \frac{1}{L} \sum_{\ell=0}^{L-1} \left[(L-\ell)U + \ell V \right] = LF + \frac{(L+1)U + (L-1)V}{2}$$

instead of:-

$$\frac{(L+1)X - (L-1)Y}{2} = \frac{(L+1)(F+U) - (L-1)(R-V)}{2}$$

giving a supplement of ½ (L-1)(F+R) relative to the ideal cycle. In effect $\frac{(L-\ell)}{L}(F\ R)$ is lost for each (L-1) batches discharged after ℓ compaigns instead of L, giving altogether:-

$$\sum_{\ell=1}^{L-1} \frac{L-\ell}{L}(F+R) = \frac{L-1}{2}(F+R)$$

Similarly, the residual value of the final charge is:-

$$-LR + \frac{1}{L} \sum_{\ell=1}^{L} \left[(L-\ell)U + \ell V \right] = -LR + \frac{(L-1)U + (L+1)V}{2}$$

instead of:-

$$\frac{(L-1)X - (L+1)Y}{2} = \frac{(L-1)(F+U) - (L+1)(R-V)}{2}$$

giving a reduction of ½(L-1)(F+R) relative to the ideal cycle. It is also a supplementary cost which must be present valued to commissioning date and added to the total discounted cost, giving the following global expression:-

$$\boxed{\frac{(L-1)}{2}(F+R)(1+r^{-t_N}) + \frac{L}{2}(X-Y)(1-r^{-t_N}) + \frac{(X+Y)}{E} E^*_{tot}}$$

In fact, the extra cost arising from the manufacture of the first charge is higher, because of the longer manufacturing time and higher interest during construction than for a normal batch. In addition, there is also an extra cost arising from the fissile materials because of certain constraints imposed by the reactor physics and the non-linearity of the cost of uranium as a function of enrichment.

Nevertheless, the terms due to manufacture and reprocessing remain predominant, as can be seen from the numerical example given in para. 5.

4. CORRECTIONS TO BE MADE IN GOING FROM THE IDEAL CYCLE TO THE REAL CYCLE

The causes of the difference between the real cycle and the ideal equilibrium cycle are:-

- the costs of the first core, the first batches charged and discharged and the residual value of the last charge
- the energy produced during the first campaigns.

Let:-

t_i = the date of the ith batch (with t_o=0)

C_i = the cost of the batches charged at t_i, discounted to that date

D_i = the algebraic sum of the expenditure and credits relating to the fuel discharged at t_i, discounted to t_i (D_i is positive when the expenditure is greater than the credits)

E_i = the energy produced during the ith campaign.

At equilibrium we have:-

$$C_i = X$$

$$D_i = Y$$

$$E_i = E$$

But during the first M campaigns before reaching the equilibrium condition and then at the final shut down of the reactor, it is necessary to add to the cost of the ideal cycle at equilibrium the following corrections:-

- initial charge: $C_o - \frac{(L+1)X - (L-1)Y}{2}$
- subsequent batches: $\sum_{i=1}^{M} (C_i - X) r^{-t_i}$
- irradiated batches discharged: $\sum_{i=1}^{M} (D_i - Y) r^{-t_i}$
- last charge: $\left[D_N + \frac{(L-1)X - (L+1)Y}{2} \right] r^{-t_N}$

On the other hand the proportional part is equal to the product of $\frac{X + Y}{E}$ and the discounted total energy of the ideal cycle, where the energy of each campaign is constant and equal to E.

If we wish to show the real discounted total energy, or E^*_{real}, the proportional cost has to be broken down into two terms:-

- a main term: $\frac{X + Y}{E} E^*_{real}$

- a corrective term $\frac{X + Y}{E} (E^*_{ideal} - E^*_{real})$

  with $E^*_{ideal} = E \sum_{i=1}^{N} \frac{r^{-t_{i-1}} + r^{-t_i}}{2}$

If the energy were in all cases uniformly distributed over the duration of each campaign, we would have:-

$$E^*_{ideal} - E^*_{real} = \sum_{i=1}^{M} (E - E_i) \frac{r^{-t_{i-1}} + r^{-t_i}}{2}$$

But the real energy does not necessarily comply with this uniform distribution (for example, the 1st campaign may last at least two years and the utilisation may be 3000 or 5000 hours in the 1st and 2nd year respectively).

In summary, the complete breakdown of the discounted total cost of fuel is:-

- fixed part of the ideal cycle: $\frac{L}{2} (X - Y)(1-r^{-t_N})$

- cost difference of the 1st charge: $C_o - \frac{(L+1)X - (L-1)Y}{2}$

- cost difference of the 1st batches charged:

$$\sum_{i=1}^{M} (C_i - X) r^{-t_i}$$

- cost difference of the 1st batches discharged:

$$\sum_{i=1}^{M} (D_i - Y) r^{-t_i}$$

- cost difference of the last charge: $\left[D_N + \frac{(L-1)X - (L+1)Y}{2} \right] r^{-t_N}$

- energy difference:

$$\frac{X + Y}{E} \left[E \sum_{i=1}^{N} \frac{r^{-t_{i-1}} + r^{-t_i}}{2} - E^*_{real} \right]$$

- proportional part (cost proportional at equilibrium extended to the whole life of the reactor and to the real energy): $\frac{X + Y}{E} E^*_{real}$

To consider as fixed the whole of all the terms apart from the last obviously constitutes an approximation. But this is quite acceptable. In fact, the terms where no renewal date is shown are strictly independent of the utilisation of the unit and these are the predominant terms, as is shown by the numerical example in the next paragraph. The cost differences of the first batches charged are practically nil; those of the first batches discharged are very low. The cost difference of the last charge is also very low because of its distant date and the effect of discounting. The energy differences beyond the 1st campaign are also very small. Finally, a variation in the utilisation beyond the Mth campaign affects only the date of definitive shutdown t_N and the terms containing it: their variation is negligible.

From the practical point of view it is not very easy to calculate the fixed cost directly. It is better first to calculate:-

- the average discounted cost per kWh
- the proportional cost (at equilibrium)

and deduce the fixed part, equal to the difference between these two costs multiplied by the total discounted energy.

If the price of fuel is affected by non-zero relative price changes, it is then necessary to calculate the mean discounted value of these prices and the proportional cost over the reactor life.

5. NUMERICAL EXAMPLE

This concerns a Westinghouse PWR reactor with three loops rated at 2775 MWth and 905 MWe. The fuel in the core is replaced by thirds (L=3). The replacement dates, the characteristics of the batches charged and discharged and the costs X and Y discounted to the charging or discharging date are given in the attached table (Batches No.4 and 6 remain in the reactor twice with intermediate storage in the pond).

The operational assumptions, in equivalent hours at full power, are as follows, starting from the start of effective generation (3 months before commercial operation):-

3000 hours in the first year
5000 hours in the second year
6600 hours in the third to the twentieth year (base load).

The discount rate is 10% at constant money. The discounting date in this case is that on which generation of energy began, not the date of entry into commercial operation. We change from the first to the second simply by multiplying all the quantities by $1.1^{3/12}$. The unit prices, expressed in European Units of Account (UA) of January 1976 are:-

- uranium concentrates : 48 UA per kg of U content
- conversion into UF_6 : 3.5UA per kg of U content
- enrichment : 80 UA/kg - separative work units
- manufacture : 115 UA per kg of U content
- all reprocessing operations : 190 UA per kg of U content
- plutonium : 11.5 UA/g fissile

The relative price changes are taken as zero. Well defined payment schedules are given for each operation.

We then obtain the following results:-

- discounted total cost of fuel : 201.8 MUA(1)
- discounted total energy : 49.155 TWh
- discounted average cost per kWh:

$$\frac{201.8 \times 10^8}{49.155 \times 10^9} = 0.41 \text{ cUA/kWh (2)}$$

of which 0.10 cUA/kWh is for the first charge
0.31 cUA/kWh is for recharges

- breakdown of the fuel cycle by operations:-

U concentrate	0.166	cUA/kWh
conversion to UF6	0.012	cUA/kWh
enrichment	0.175	cUA/kWh
fabrication	0.061	cUA/kWh
credit for recovery of manufacturing losses	-0.013	cUA/kWh
reprocessing (in the widest sense)	0.061	cUA/kWh
uranium credit	-0.028	cUA/kWh
plutonium credit	-0.023	cUA/kWh
	0.411	cUA/kWh
rounded to	0.41	cUA/kWh

- proportional cost at equilibrium:

$$\frac{X + Y}{E} = 0.34 \text{ cUA/kWh}$$

with X = 20.9 MUA
Y = 0.8 MUA
E = 905 MW x 6600 hours p.a. x 1.068 years
= 6.38 TWh

- proportional part of the total discounted cost:

$$0.34 \times 10^{-8} \times 49.155 \times 10^9 = 167.2 \text{ MUA}$$

(1) MUA = 10^6 UA
(2) cUC = 10^{-2} UA

- fixed part: 201.8 - 167.2 = 34.6 MUA
- breakdown of the fixed part:
  - fixed part of ideal cycle : $\frac{3}{2}(X - Y)(1-r^{-t_N})$ = 25.85 MUA
  - initial charge : $C_o-(2X - Y)$ = 9.65 MUA
  - first recharge : $(C_1- X)r^{-t_1}$ = -0.12 MUA
  - first batch discharged : $(D_1- Y)r^{-t_1}$ = 0.23 MUA
  - second batch discharged : $(D_2- Y)r^{-t_2}$ = 0.31 MUA
  - third batch discharged : $(D_3- Y)r^{-t_3}$ = 0.19 MUA
  - fourth batch discharged : $(D_4- Y)r^{-t_4}$ = -0.08 MUA
  - final charge : $(D_N+ X - 2Y)r^{-t_N}$ = 1.50 MUA
  - energy difference relative to the ideal cycle:

$$\frac{X + Y}{E}\left[E\sum_{i-1}^{N} \frac{r^{-t_{i-1}} + r^{-t_i}}{2} - E^*_{real}\right]$$

$$= 0.34 \times 10^{-8} \left[6.38x7.57-49.155\right] \times 10^9 \qquad = -2.92 \text{ MUA}$$

Total fixed part = 34.61 MUA

This fixed part, discounted to commercial commissioning date, would be 35.5 MUA or 39.2 UA/kWe.

This example shows that the first two terms (fixed part of the ideal cycle and initial charge) are predominant, which confirms that the approximations made above are well founded. In all the fixed part is appreciably less than the cost of the initial charge (50.8 MUA) and is 68% of it.

Finally, the details of the costs of the first charge, recharges at equilibrium and final charge are as follows:-

first charge C_o = 50.8 MUA (fabrication : F_o = 9.6
(enriched U : U_o^o = 41.2

recharges at equilibrium : X = 20.9 MUA (fabrication: F = 2.9
enriched U : U = 18.0

discharges at equilibrium: Y = 0.8 MUA (reprocessing: R = 4.0
(U,Pu credits: V = 3.2

final charge : D_N= 9.1 MUA (reprocessing: R_N= 12.1
(U,Pu credits: V_N= 21.2

The corrections for first and final charges are:

$$C_o-(2X - Y) + (D_N + X - 2Y)r^{-t_N}$$

which breaks down into:

fabrication : $F_o - 2F + Fr^{-t}N$ = 4.1 MUA

reprocessing : $R + (R_N - 2R)\bar{r}^{t}N$ = 4.6 MUA

rissile materials (enriched U, Pu and U credits)

$U_o - (2U+V) + (U+2V-V_N)\bar{r}^{t}N$ = 2.4 MUA

total correction : 9.6+1.5 = 11.1 MUA

The theoretical correction of section 3 is : $(F+R)\ (1+r^{-t}N)$ = 8.0 MUA

The true correction is bigger because :-

- the cost of fabrication of the initial charge is 9.6 MUA instead of 3x2.9 = 8.7, because of higher interest during construction
- the over-cost arising from fissile materials is 2.4 MUA since U_o is greater than (2U+V) (41.4 MUA instead of 39.3) and V_N is less than (U+2V) (21.2 MUA instead of 24.5).

Nevertheless, the fabrication and reprocessing costs constitute much the greater part of the corrections arising from the initial and final charges (79%).

NUMERICAL EXAMPLE - CHARACTERISTICS OF CHARGED AND DISCHARGED BATCHES

New Fuel Charged					Irradiated Fuel Discharged						
Batch No.	Date of loading in years	Mass of U in kg	Enrichment %	Cost C in MUA	Batch No.	Date of unloading	Mass of U in kg	Enrichment %	Fissile Pu in g per kg of initial U	Irradiation of reject in MWD/t	Cost D in MUA
1	0	23,100	2.1	50.77	1	2.17	22,548	0.88	5.09	16,116	1.07
2		462	2.1		2	3.11	451	0.63	5.63	21.922	1.17
3		24,024	2.6		3		23,156	0.81	6.28	26,253	
4		462	2.1		4	4.16	451	0.63	5.63	20,194	1.04
5		24,024	3.1		5		22,974	0.82	6.65	32,859	
6		462	2.1		6	5.23	451	0.63	5.63	20,841	0.65
7	2.17	24,024	3.25	20.81	7		22,972	0.92	6.63	32,714	
8	3.11	24,178	3.25	20.95	8	6.30	23,090	0.88	6.68	33,735	0.77
9	4.16	24,178	3.25	20.95	9	7.37	23,090	0.88	6.68	33.735	0.77
10	5.23	24,178	3.25	20.95	10	8.44	23,090	0.88	6.68	33,735	0.77
11	6.30	24,178	3.25	20.95	11	9.51	23,090	0.88	6.68	33,735	0.77
12	7.37	24,178	3.25	20.95	12	10.58	23,090	0.88	6.68	33,375	0.77
13	8.84	24,178	3.25	20.95	13	11.64	23,090	0.88	6.68	33,735	0.77
14	9.51	24,178	3.25	20.95	14	12.71	23,090	0.88	6.68	33,735	0.77
15	10.58	24,178	3.25	20.95	15	13.78	23,090	0.88	6.68	33,735	0.77
16	11.64	24,178	3.25	20.95	16	14.85	23,090	0.88	6.68	33,735	0.77
17	12.71	24,178	3.25	20.95	17	15.92	23,090	0.88	6.68	33,735	0.77
18	13.78	24,178	3.25	20.95	18	16.99	23,090	0.88	6.68	33,735	0.77
19	14.85	24,178	3.25	20.95	19	18.06	23,090	0.88	6.68	33,735	0.77
20	15.92	24,178	3.25	20.95	20	19.12	23,090	0.88	6.68	33,735	0.77
21	16.99	24,178	3.25	20.95	21	20.19	23,090	0.88	6.68	33,735	0.77
22	18.06	24,178	3.25	20.95	22		23,450	1.66	6.19	22,587	-9.11
23	19.13	24,178	3.25	20.95	23		23,861	2.56	4.33	9,820	

European Communities — Commission

EUR 5914 — Method for calculating the cost of electricity generation from nuclear and conventional thermal stations

Luxembourg: Office for Official Publications of the European Communities

1982 — 85 pp. — 21.0 × 29.7 cm

Energy series

DE, EN

ISBN 92-825-3176-7

Catalogue number: CD-ND-82-093-EN-C

Price (excluding VAT) in Luxembourg:
ECU 5.55 BFR 250 IRL 3.90 UKL 3.10 USD 5.50