I should like to begin by expressing my appreciation to the Directors of the Technical Division for Nuclear Engineering of this Institute for providing me with this opportunity to comment on various aspects of the problem of nuclear electricity costs.

In discussing nuclear power plants and their economic characteristics in relation to thermal and hydroelectric plants, I shall be talking as a specialist in the field and not as Chairman of the Nuclear Energy Commission. Whatever comments I make will reflect my personal opinions only and are not the responsibility of the Commission.

I should also like to stress the close correlation that exists between the subject under discussion and the wider interests of the community. This is an important point and one which gives broader significance to the discussion of what are essentially purely technical questions.

1. AREA OF COMPETITION

To persons interested in nuclear energy questions, and especially administrators in the private or public sector, one of the most important questions is the competitive status of nuclear electricity in relation to electricity supplied from other sources.

In this connection "to compete" means to produce at an equivalent or lower cost. Nuclear plants will be particularly attractive, and even preferable, when they can supply power at costs lower than conventional sources, e.g. water and fossil fuels.

In many European countries and in the United States, the competitiveness of nuclear power is generally considered purely in comparison with thermal plants operating on coal or mineral oil, since such plants are predominant in those countries. This is not the case in Brazil and other countries where the bulk of the electricity produced comes from hydroelectric plants. Table I shows the distribution of installed generating capacities as between the two types of plant in various countries. The data shown are based on information from the Union Internationale des Producteurs et Distributeurs d'Energie Electrique which was published in the periodical Águas e Energia Elétrica No.47 by the Brazilian Council for Water and Electrical Power in March 1964.
Table I
DISTRIBUTION OF INSTALLED CAPACITIES

<table>
<thead>
<tr>
<th>Country</th>
<th>Total power per country in 1961 (MW)</th>
<th>Percentage of total capacity for Thermal (%)</th>
<th>Hydro (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal Republic of Germany</td>
<td>27 254</td>
<td>87.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Australia</td>
<td>6 314</td>
<td>75.7</td>
<td>24.3</td>
</tr>
<tr>
<td>USA</td>
<td>197 923</td>
<td>81.5</td>
<td>19.5</td>
</tr>
<tr>
<td>France</td>
<td>21 272</td>
<td>92.3</td>
<td>7.7</td>
</tr>
<tr>
<td>India</td>
<td>5 580</td>
<td>66.5</td>
<td>33.5</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>36 832</td>
<td>95.5</td>
<td>4.5</td>
</tr>
<tr>
<td>USSR</td>
<td>73 921</td>
<td>77.6</td>
<td>22.4</td>
</tr>
<tr>
<td>Austria</td>
<td>4 269</td>
<td>28.7</td>
<td>71.3</td>
</tr>
<tr>
<td>Brazil</td>
<td>5 172</td>
<td>27.2</td>
<td>72.8</td>
</tr>
<tr>
<td>Canada</td>
<td>23 035</td>
<td>19.0</td>
<td>81.0</td>
</tr>
<tr>
<td>Spain</td>
<td>6 992</td>
<td>31.8</td>
<td>68.2</td>
</tr>
<tr>
<td>Italy</td>
<td>17 086</td>
<td>31.5</td>
<td>68.5</td>
</tr>
<tr>
<td>Japan</td>
<td>23 636</td>
<td>46.4</td>
<td>53.6</td>
</tr>
<tr>
<td>Norway</td>
<td>7 117</td>
<td>2.3</td>
<td>97.7</td>
</tr>
<tr>
<td>Sweden</td>
<td>9 640</td>
<td>22.8</td>
<td>77.2</td>
</tr>
<tr>
<td>Switzerland</td>
<td>5 840</td>
<td>3.5</td>
<td>96.5</td>
</tr>
</tbody>
</table>

The following, more recent data, published in the same periodical (No. 49, 1965), show the position in Brazil on 31 December 1964.

Table II
DISTRIBUTION OF CAPACITY AND PRODUCTION IN BRAZIL

<table>
<thead>
<tr>
<th></th>
<th>Coal</th>
<th>Oil or gas</th>
<th>Hydro</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed power (MW)</td>
<td>342</td>
<td>1,605</td>
<td>4,894</td>
<td>6,840</td>
</tr>
<tr>
<td>Distribution (%)</td>
<td>5</td>
<td>23.5</td>
<td>71.5</td>
<td>100</td>
</tr>
<tr>
<td>Production in 1964 (10^9 kWh)</td>
<td>1,061</td>
<td>6,080</td>
<td>20,728</td>
<td>27,869</td>
</tr>
<tr>
<td>Mean annual load factor</td>
<td>0.354</td>
<td>0.433</td>
<td>0.484</td>
<td>0.466</td>
</tr>
</tbody>
</table>
This country is mainly interested in the comparison of nuclear plants with hydroelectric plants since the latter make up 71.5% of the installed capacity. However, comparisons with conventional thermal plants (coal and oil) are also important since they provide a basis for selecting suitable alternatives in cases where a "thermal complement" is required for a predominantly hydroelectric system.

It must be emphasized that cost is not the only criterion in studies of this kind. Other factors that affect the interests of the community must be considered, e.g. the development of new industries, savings in foreign currency, the utilization of fuel reserves existing in the country (coal, oil-refinery residues, uranium and thorium, etc.), etc.

2. COMPARATIVE INDICES

The two economic indices normally used in comparative assessments of this type are as follows:

1. The unit cost of the generating plant, i.e. the cost of the installed kW;
2. The production cost, i.e. the cost of the kWh actually produced for consumption. We shall follow international practice and express the unit cost in US $/kW and the unit energy cost in mills per kWh (mills = 1/1000 of a dollar). This will avoid the difficulty of discussing economic matters in terms of Brazilian currency, which is still somewhat inflationary.

On the basis of the unit cost it is possible to make a direct comparison between the investments required to set up a power plant in cases where there are various alternatives. It is obvious that in each case the investment required will correspond to the product of the unit cost and the power to be installed.

The capital invested in a power plant has to be paid for and recovered; it earns interest and it has to be reconstituted at the end of the useful lifetime of the facility. The unit cost thus provides a basis for assessing the "fixed annual charge", a determining factor for an important power-cost item. The higher the unit cost, the dearer the power, all other factors being equal.
Another important concept is the mean annual utilization or load factor. This corresponds to the ratio \( f \) between the amount of energy actually produced in a plant in one year and the theoretical value obtained on the basis of the installed power (as given on machine name-plate) if it is assumed that the plant operates continuously throughout the year at full nominal capacity. If \( Q \) is the actual production and \( P \) the installed power, the load factor will be obtained as follows:

\[
f = \frac{Q(\text{kWh})}{P(\text{kW})} \times 8760 \text{(h)}
\]

The 365-d calendar year has 8760 h. Some authors base their calculations on a value of 8766 h, which corresponds more closely to the mean astronomical year, but on the whole it seems preferable to use the above formula as it stands and to introduce a value of 8784 h for leap years.

Use is also often made of the number of hours \( h_e \) that would be equivalent to the actual production at full load:

\[
h_e = 8760 f
\]

A value of 7008 "equivalent" hours would thus correspond to a load factor \( f \) of 0.8 or 80%.

As will be seen later on, the utilization factor is of considerable importance in connection with the energy cost since the "fixed annual charge" and other production-independent costs have to be divided by the number of kWh actually produced.

3. INVESTMENT COSTS FOR HYDROELECTRIC PLANTS

There is no direct relationship between the investment required for hydroelectric plants and the installed power. The power available from a waterfall is proportional to two factors:

- the flow \( \dot{\rho} \), which is numerically equal to the volume of water drained per unit time;
- the head \( H \) measured between the free surfaces of water upstream and downstream of the plant.

If the flow is expressed in metres per second and the difference in level in metres, the available power \( P \) in kW is given approximately by the following formula, which assumes a total efficiency of 76.5%:

\[
P = 7.5 \dot{\rho} H
\]
Depending on the head of the water and the width of the passage intercepting the water, there is thus liable to be some variation in the size of the different constructional items, e.g.

- dams
- headraces
- penstocks of different lengths, diameters and wall thicknesses
- channels and regulation dams, etc.

It is also possible to build either run-of-river plants, which are constructed practically without water storage facilities, or else plants including large reservoirs designed to control the water flow over a period of one or more years. Projects of the latter type often involve the flooding of vast areas and the construction of secondary dikes to contain the water. A good example of this category is the Furnas plant on the Rio Grande, which has a reservoir with a volume of $21 \times 10^9$ cubic metres and a useful volume, above the dam crest, equivalent to over 15 thousand million cubic metres; the reservoir covers an area of $1350 \text{ km}^2$ (water surface) and is more or less V-shaped, with arms measuring $170-240 \text{ km}$.

Some idea of the differences in hydroelectric plant costs can be obtained from Table III, which contains data reproduced, in simplified form, from a report issued by CANAMBRA /1/. Some of the original items have been consolidated and all costs have been converted into dollars on the basis of the exchange rate indicated in the report.

The data refer to the plants at Furnas (Rio Grande) and Jupiá (Rio Paraná), both of which are designed to have nominal powers of the same order of magnitude after completion of all the installations (1200 MW in round figures). The average water-drop values are 94.0 and 21.1 m; at full load this is equivalent to flow rates of 1700 and 7600 $\text{m}^3/\text{sec}$, in round figures, respectively.
### Table III
COSTS FOR TWO SELECTED HYDROELECTRIC PLANTS

<table>
<thead>
<tr>
<th></th>
<th>Furnas</th>
<th>Jupiã</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total power (MW)</strong></td>
<td>1152</td>
<td>1209</td>
</tr>
<tr>
<td><strong>Number of units</strong></td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td><strong>Head, normal (m)</strong></td>
<td>94.0</td>
<td>21.1</td>
</tr>
<tr>
<td><strong>Type of turbines</strong></td>
<td>Francis</td>
<td>Kaplan</td>
</tr>
<tr>
<td><strong>Costs (millions of US $) for</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structures and improvements</td>
<td>9.9</td>
<td>26.4</td>
</tr>
<tr>
<td>Reservoir, dams, pipes</td>
<td>60.3</td>
<td>26.5</td>
</tr>
<tr>
<td>Equipment</td>
<td>16.4$^a$</td>
<td>61.2</td>
</tr>
<tr>
<td>Public works</td>
<td>0.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Output substation</td>
<td>4.7$^a$</td>
<td>0.74</td>
</tr>
<tr>
<td>Civil engineering</td>
<td>15.4</td>
<td>7.8</td>
</tr>
<tr>
<td><strong>Total construction costs</strong></td>
<td>106.3</td>
<td>124.0</td>
</tr>
<tr>
<td>Land costs (compulsory purchase)</td>
<td>34.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Other costs</td>
<td>92.9</td>
<td>95.6</td>
</tr>
<tr>
<td><strong>Unit cost (US $/kW)</strong></td>
<td>195</td>
<td>186</td>
</tr>
</tbody>
</table>

$^a$ These figures have been altered to allow for an increase in capacity from the present value of 864 MW (6 units, May 1965) to the final value of 1152 MW (8 units).

In this particular case in spite of the differences in the costs of individual items, the final unit costs are similar. The extent of Brazilian participation is 80% for the Furnas plant and 75% for the Jupiã plant.

The same Canambr report reviews various other projects with unit costs ranging from US $115 to US $354 per installed kW. Some selected examples are quoted $^{22}$ in Table IV.
### Table IV
UNIT INVESTMENT FOR SELECTED HYDRO PLANTS

<table>
<thead>
<tr>
<th>Plants</th>
<th>Normal capacity (MW)</th>
<th>Unit cost (US $/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Under construction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bariri</td>
<td>124</td>
<td>325</td>
</tr>
<tr>
<td>Barra Bonita</td>
<td>123</td>
<td>338</td>
</tr>
<tr>
<td>Chavantes</td>
<td>360</td>
<td>207</td>
</tr>
<tr>
<td>Estreito</td>
<td>800</td>
<td>115</td>
</tr>
<tr>
<td>Fumaça</td>
<td>40</td>
<td>243</td>
</tr>
<tr>
<td>Funil (rio Paraíba)</td>
<td>236</td>
<td>274</td>
</tr>
<tr>
<td>Graminha</td>
<td>76</td>
<td>234</td>
</tr>
<tr>
<td>Ibitinga</td>
<td>117</td>
<td>257</td>
</tr>
<tr>
<td><strong>Under study</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aiuruoca</td>
<td>30</td>
<td>258</td>
</tr>
<tr>
<td>Caraguatatuba</td>
<td>350</td>
<td>216</td>
</tr>
<tr>
<td>Dois Irmãos</td>
<td>144</td>
<td>268</td>
</tr>
<tr>
<td>Funil (rio Grande)</td>
<td>122</td>
<td>156</td>
</tr>
<tr>
<td>Gambá</td>
<td>1044</td>
<td>169</td>
</tr>
<tr>
<td>Igarapava</td>
<td>150</td>
<td>354</td>
</tr>
<tr>
<td>Jaguara</td>
<td>532</td>
<td>134</td>
</tr>
<tr>
<td>Marimbondo</td>
<td>768</td>
<td>205</td>
</tr>
<tr>
<td>Pirajú</td>
<td>83</td>
<td>301</td>
</tr>
<tr>
<td>Rosal</td>
<td>110</td>
<td>147</td>
</tr>
<tr>
<td>São Miguel</td>
<td>56</td>
<td>227</td>
</tr>
</tbody>
</table>

Table V gives estimated costs for projects undertaken between 1953 and 1958, after Robock [3].
Table V
ESTIMATED COSTS FOR PROJECTS UNDERTAKEN BETWEEN 1953 AND 1958

<table>
<thead>
<tr>
<th>Project</th>
<th>Normal capacity (MW)</th>
<th>Unit cost (US $/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMIG (Cajuru, Camargos, Gafanhoto, Itutinga, Salto Grande)</td>
<td>187</td>
<td>354</td>
</tr>
<tr>
<td>Euclides da Cunha</td>
<td>47</td>
<td>238</td>
</tr>
<tr>
<td>Funil (Bahia)</td>
<td>36</td>
<td>363</td>
</tr>
<tr>
<td>Paredão (Amapá)</td>
<td>70</td>
<td>216</td>
</tr>
<tr>
<td>Paulo Afonso (1st stage)</td>
<td>180</td>
<td>228</td>
</tr>
<tr>
<td>Peixoto (Minas Gerais)</td>
<td>400</td>
<td>323</td>
</tr>
<tr>
<td>Rio Bonito (Espírito Santo)</td>
<td>17</td>
<td>319</td>
</tr>
<tr>
<td>Salto Grande (USELPA)</td>
<td>70</td>
<td>236</td>
</tr>
</tbody>
</table>

The data in the above tables show clearly, as was to be expected, that the unit costs of hydroelectric plants, depending as they do on a large number of individual factors, are subject to a considerable variation.

4. INSTALLED AND FIRM POWER

River flows are not uniform. It is possible to study the variations occurring in the course of a year and to repeat the observations for successive years. Canambra collected data relating to the main rivers of South-Central Brazil (Rio Grande, Tietê, Paranapanema, São Francisco, Paraiá) between 1951 and 1960. The driest cycle was observed in the region in 1954-55, when the mean annual flow rate for these rivers was only 62% of the average figure for the whole period (1931-60). In another dry period in 1934, the average flow rate dropped to 76%.

The "firm power" of a plant is defined as the power which is available for 100% of the time in question and which enables the installations to supply all the power corresponding to certain given conditions (e.g. a given load factor equal to unity or less). In the case of run-of-river plants without reservoirs, the firm power for each day varies from one period to another depending on the fluc-
tuation in the available stream flow. If a period of many years is considered, the firm power corresponds to the minimum flow of the driest period.

The firm power of a hydroelectric plant is generally lower (sometimes considerably lower) than the installed power, which is almost always designed for a higher flow than is observed during a dry period.

There are two ways of making sure that the power available will be higher than the minimum imposed by the low flow rate available during the dry periods:

1. Reservoirs can be provided to store water in basins upstream of the plant. If the impounded volume is high enough above the minimum level required for plant operation, the firm power can correspond to the average stream flow over a number of years. Flow control over several years can then be assured.

2. A thermoelectric plant can be set up to provide the supplementary power necessary in dry periods.

Both solutions cost money and the problem is to decide which one is most suitable in each specific case. When a decision is taken, a firm value is adopted for the power, for example, 80% of the nominal power for which the machinery is designed.

It is obvious that a thermoelectric plant need not be set up specifically to "make firm" the power of a hydroelectric plant or system: it can simply be one of the various sources used to feed a power network.

5. INVESTMENT COSTS FOR CONVENTIONAL THERMAL PLANTS

In the case of thermal plants, the investment required to install a given generating capacity is practically the same at different points in the same region. The unit cost in that region will depend almost exclusively on the power of the units which make up the total capacity of the plant. Canambra has studied estimated costs, for South-Central Brazil, for two-unit 400-MW power plants operating on coal or oil (Canambra report, Vol. 1, p. VI-2). On the basis of these data – due allowance being made for the relative variation which is observed in costs as a function of plant capacity, e.g. in the United States of America (Canambra report, p. VI-1) – the following table of probable estimated values has been drawn up for South-Central Brazil:
Table VI
UNIT COSTS FOR THERMAL PLANTS (US $/kW)

<table>
<thead>
<tr>
<th>Plant capacity (MW)</th>
<th>Coal</th>
<th>Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>241</td>
<td>189</td>
</tr>
<tr>
<td>250</td>
<td>221</td>
<td>170</td>
</tr>
<tr>
<td>300</td>
<td>203</td>
<td>152</td>
</tr>
<tr>
<td>400</td>
<td>190</td>
<td>140</td>
</tr>
<tr>
<td>600</td>
<td>180</td>
<td>136</td>
</tr>
</tbody>
</table>

No consideration has been given to thermal plants of less than 200 MW. The general tendency at the present time is towards the disappearance of small plants in regions where operating stations are being linked with one another on a permanent basis by means of transmission networks, constituting large integrated systems (cf. Canambra report, Vol. 1, p. VI-l).

6. INVESTMENT COSTS FOR NUCLEAR POWER PLANTS

As in the case of conventional thermal plants, the unit costs of nuclear power plants decrease when the power of individual units or reactors is increased (see Appendix).

For the three reactor concepts which have already undergone industrial-scale development abroad, the approximate unit costs for Brazil (uncertainty of 10-20%) are given in Table VII below. The data shown were obtained by interpolation on the basis of recent estimates made by working groups associated with the National Nuclear Energy Commission (CNEN).

Table VII
UNIT COSTS FOR NUCLEAR POWER PLANTS (US $/kW)

<table>
<thead>
<tr>
<th>Capacity of plant (MW)</th>
<th>GCR (Magnox)</th>
<th>HWR (Candu)</th>
<th>BWR or PWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>435</td>
<td>530</td>
<td>335</td>
</tr>
<tr>
<td>200</td>
<td>330</td>
<td>393</td>
<td>252</td>
</tr>
<tr>
<td>300</td>
<td>284</td>
<td>328</td>
<td>215</td>
</tr>
<tr>
<td>400</td>
<td>255</td>
<td>292</td>
<td>197</td>
</tr>
<tr>
<td>500</td>
<td>235</td>
<td>270</td>
<td>188</td>
</tr>
<tr>
<td>Fuel charge (E/P)</td>
<td>35</td>
<td>40</td>
<td>65</td>
</tr>
</tbody>
</table>
It will be seen that there has been a substantial decrease in costs as compared to the 1962 CNEN estimate of US $417/kW for a 300-MW Magnox-type plant for South-Central Brazil. The present figure (US $284/kW) represents a value of 62% of the earlier estimate. Apart from the installation costs proper (which range from land and property to equipment costs), the initial investment also includes the expenditure required for the first set of fuel elements needed to start up the reactor. The cost of this "first fuel charge" is considered to be approximately proportional to the installed power: the proportionality factor for each type of reactor is shown in the bottom line of Table VII (dollars/kW).

7. BREAKDOWN OF PRODUCTION COST

In general the costs of the power produced by any type of plant and transmitted to a consumer area can be considered under four main headings:

(a) the "fixed charges" on the invested capital, i.e. payment and depreciation costs in respect of the capital invested;

(b) maintenance and operation costs, including insurance, replacement of components, etc;

(c) fuel costs (except in the case of hydro plants, where water corresponds to the fuel used by thermal plants);

(d) the cost of conveying electricity along transmission lines.

How is each of those items worked out? It might be imagined that complicated calculations are necessary. As will be shown below, the problem is not so very difficult.

8. INVESTMENT CHARGES

This involves two items, interest and depreciation, which are generally considered for each year of plant operation.

According to the Canambría report (Vol. 1, pp. IV-1 a 8), an annual interest of 9% would be a typical rate for capital raised in Brazil, allowance being made for the inflationary correction required. Since imported materials and outside capital may be involved, it is necessary to reckon with an annual interest rate of 6%, plus guarantee
costs, in respect of foreign capital.

If C represents the capital invested, the annual interest rate will obviously be \( A_1 = Cj \), \( j \) being the interest rate expressed as a decimal fraction (for example, \( j = 0.09 \) for 9\% per annum). The capital C corresponds to the total installation cost of the plant, plus the interim interest due during construction. The actual investment (C) should therefore refer to the date on which the plant is brought into operation for the production of power (see Appendix).

Depreciation costs should not as a rule be confused with amortization of loans contracted with a view to obtaining investment capital. These are in principle two distinct financial operations; they may or may not be identified with one another.

Depreciation corresponds to the reconstitution of the capital up to the end of the useful lifetime of the plant. This is assumed to be done by means of the annual setting aside of a fund represented by equal contributions (\( A_2 \)). Each contribution is imagined to be set aside at the end of the year in question, the interest due being capitalized each year from then on to the end of the useful lifetime of the plant. The sum of these contributions, plus the respective interest, should make up the total of the original investment (C), without the other interest, which is paid annually under the heading of \( A_1 \), considered earlier (see Appendix).

The annual charge relating to the invested capital is the sum of two terms:

\[ A = A_1 + A_2 \]

If one assumes 75\% Brazilian participation at an interest rate of 9\% per annum and 25\% foreign participation involving a 6\% interest rate and various other financial conditions (as indicated in the Appendix), one obtains for a 50-yr useful lifetime (for hydro plants):

\[ A = 8.92\% C \]

Assuming 50\% Brazilian participation, 25 yr of useful lifetime (thermal plants) and all other conditions as above, one obtains:

\[ A = 9.73\% C \]
Finally, it should be noted that each installed kW generates an energy equal to 8760 \( f \) kWh, \( f \) being the mean annual load factor. If the installed power of the plant is designated as \( P \), the kWh cost, relating solely to the investment, will be:

\[
a = \frac{A}{P} (8760 f)
\]

This cost item \( a \) is always inversely proportional to the mean annual load factor; the higher the value of \( f \), the greater the use made of the invested capital and the cheaper the power produced.

Another cost item associated with the investment cost of nuclear power plants is the immobilization of capital corresponding to the first nuclear fuel charge, which is renewed during the operation of the reactor. Some authors consider this item in conjunction with the fuel consumption cost. In the present discussion the first charge is considered as part of the investment so that there is a supplementary cost item, the payment of interest and depreciation on the first charge:

\[
a' = \frac{A'}{P} (8760 f)
\]

Assuming again 50% Brazilian participation in the fabrication of the fuel elements and 25 yr of useful lifetime, one obtains:

\[
A' = 9.73 \% E,
\]

where \( E \) is the cost of the first charge.

Thus, on the basis of the assumptions that have been made:

\[
a' = (9.73) \frac{(E;P)}{8760 f}
\]

The values for the ratio \( E:P \) are shown in the last line of Table VII for various reactor types.

There is a similar cost item for conventional thermal plants, namely the cost for storage of the fuel kept in permanent reserve to ensure an adequate supply for boilers.

9. OPERATION AND MAINTENANCE

Operation and maintenance costs (item b in breakdown of costs as shown in section 7) include plant supervision costs, salaries (engineers, technicians, workmen), social insurance, replacement of components, maintenance of machinery, insurance, taxes, etc. In the case of nuclear plants, allowance has to be made for the partial replacement of moderating materials and coolant fluids, whenever they are expensive (e.g. heavy water, \( \text{CO}_2 \), molten sodium, etc.).
To simplify the calculations, all these operation and maintenance costs are generally considered as also constituting "fixed" annual charges, as in the case of the expenditure relating to the payment for and the reconstitution of invested capital. In actual fact some of this expenditure varies with the rate at which the machinery is utilized, i.e. with the load factor. The variations involved are, however, small as a percentage of total expenditure and they can be ignored in the interests of computational simplicity. A fixed estimated value (B) is adopted for the annual operation and maintenance expenditure; the corresponding cost item is obtained in a similar fashion to the previous item (a) relating to the investment:

\[
b = \frac{B}{f \times 8760}
\]

In the case of conventional plants, a value corresponding to 0.15% of the investment cost of the actual plant (excluding, for example, dams and other civil engineering works in the case of a hydro plant) is adopted as part of the annual charge for the replacement of components. For the other operation and maintenance items an annual expenditure of 1-2% of the same investment cost is adopted.

To give an order of magnitude, \( B = 10-20\% \), so that finally:

\[
b = (0.1 - 0.2)a.
\]

With nuclear power plants the costs are a little higher and have to be estimated on a case-to-case basis, particular attention being paid to the reactor type used.

10. FUEL CONSUMPTION COST

The point has already been made that in hydroelectric plants water plays a similar role to fuel in thermal plants but it costs nothing.

With thermal plants, the fuel cost is obtained by multiplying the quantity burned by the unit cost of the material. The cost is practically proportional to the quantity of energy produced (Q):

\[
C = kQ
\]

The corresponding cost item for the kWh is obtained of course by dividing this value by Q. This yields a constant unit cost for the power plant in question, this value being independent of the production and consequently of the annual load factor:

\[
c = \frac{C}{Q} = k = \text{const}
\]
This constant cost varies with the type of installation, the type of fuel and with the cost of the latter in the area in question, inclusive of transport to the plant and other essential expenditures. If $H$ = the energy power of the fuel (in, say, kWh/kg), $X$ = cost of fuel in the area concerned ($/t$), and $r$ = total plant efficiency in converting the latent energy of the fuel into electricity, then

$$k = \frac{X}{Hr}$$

With the units used, this unit cost will be expressed in mills/kWh.

The following values would apply, for example, to the imported Bunker oil used in the coastal area of South-Central Brazil: $H = 12.2$ kWh/kg (equivalent to a calorific power of 10 500 kcal/kg), $X = US$ $19.4/t$ (Canambra report, Vol. 1, p. 6) and $r = 0.30$. Consequently $k = 5.30$ mills/kWh.

Similar considerations apply to nuclear power plants except that the nuclear fuel cycle must be regarded as a closed one. After a certain period of operation in the reactor core, the active material has to be reprocessed to permit utilization of the unburned fissile element (i.e. which has not been subject to fission) and possibly to separate out the new fissile materials formed (e.g. the plutonium formed from uranium-238 or the uranium-233 formed from thorium). These separation operations entail expenditure that is approximately proportional to the quantity of fuel burned in the reactor from the start of steady-state operation.

It would be beyond the scope of the present paper to discuss the methods used for estimating the fabrication cost of the fuel elements, plus reprocessing costs and minus the value of the plutonium or uranium-233 formed. It is, however, possible to quote a fuel cost (or at least give an estimate) for each type of fuel (e.g. metallic natural uranium, uranium oxide, enriched uranium, etc.) for a particular country; this is generally expressed in terms of cost per kg of fissile material contained in the complete fuel element. The unit values of the items that have to be calculated (reprocessing and plutonium or uranium-233 credit) are also available.
If reprocessing costs and credit on recovered fissile materials are ignored, it is not difficult to work out the fuel consumption cost using an adaptation of the formula considered earlier. Thus, $X$ would denote the cost at the plant site of the "fuel elements", i.e. the elements containing the nuclear fuel which are introduced into the reactor core ($X$ is generally expressed in dollars per kg of material - e.g. uranium - contained in the element); this price includes the whole industrial fabrication process plus the cost of the fuel itself. $H$ would correspond to the burn-up, i.e. the rate at which the energy is extracted from the fuel in the reactor when it is utilized; $r$ would represent the overall efficiency of the installation in converting the energy in the fuel into electricity (the value lies between 0.28 and 0.32 in modern nuclear power plants). Since the burn-up is generally expressed in MWd/t, the equation is normally written as follows:

$$k = \frac{X}{24Br}$$

In the above equation, $B$ is the burn-up (in MWd/t) and 24 is the number of hours per day. If $X$ is expressed in dollars per kg, the unit cost $k$ will be expressed in mills per kWh.

In the above formula, it is assumed that the cost of the first fuel charge is assessed as part of the investment cost of the plant. It is also assumed that there is a steady-state fuel cycle, i.e. that the fuel elements are replaced by new elements as they are burned up (at the rate $B$ mentioned above).

There are other computational methods that are perhaps more precise in certain respects but they are also more complicated. They will not be discussed in the present paper.

To give a concrete example, if in a Magnox reactor $X = \text{US }$35/kg, $B = 3500$ MWd/t and $r = 0.29$, the resultant cost would be $k = 1.44$ mill/kWh.

11. TRANSMISSION COSTS

Thermal power plants can be located very near consumer areas so that the electricity transmission costs are almost insignificant. The kWh cost may be increased by the cost of transporting the fuel to the plant and, for the purposes under discussion, this would be included in the calculation of the unit cost of the actual fuel. From this
point of view nuclear plants show a clear advantage over conventional ones since nuclear fuel has a high concentration of energy and can be transported much more cheaply than fossil fuels. Table VIII gives examples of energy densities (approximate mean values) in relation to the total latent energy contained in the materials listed.

Table VIII

ENERGY DENSITIES

<table>
<thead>
<tr>
<th>Fuels</th>
<th>kWh/kg</th>
<th>kWh/dm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>1.43</td>
<td>1.14 thousandths</td>
</tr>
<tr>
<td>Coal (anthracite)</td>
<td>8.0</td>
<td>12.8</td>
</tr>
<tr>
<td>Bunker oil</td>
<td>12.2</td>
<td>9.8</td>
</tr>
<tr>
<td>Natural uranium (only $^{235}\text{U}$)</td>
<td>19.9 million</td>
<td>372 million</td>
</tr>
<tr>
<td>2% enriched uranium (only $^{235}\text{U}$)</td>
<td>57.0 million</td>
<td>1066 million</td>
</tr>
</tbody>
</table>

For natural and enriched uranium, the figures in the table refer only to the energy from the fission of the $^{235}\text{U}$ isotope.

In the case of conventional thermal plants the question is liable to arise as to whether it is cheaper to transport fuel to the consumer area, where the plant could be situated, or to transmit the electricity produced in a plant situated near the coal mines, oil refinery or fuel-entry port. With nuclear power stations there is no problem. Fuel transport is so cheap that the nuclear electricity stations can be located either near the consumer centre or else at the most suitable grid insertion point.

The location of hydro plants is of course dictated by the natural conditions of the river or basin whose hydraulic potential it is planned to utilize. The station often has to be situated a long way from the consumer area and the question of costs for the transmission of electricity inevitably arises.

Transmission costs are made up of two items:
(1) interest and depreciation of the investment made in the construction of the line (land, masts, towers, wires, insulating units, etc.).
(2) expenditure produced by line losses (heating of wires, "corona" effect, insulator leakages, etc.). This can be expressed as $d(\text{investment}) + d'(\text{losses})$.

Strictly speaking, account should also be taken of the cost of checking and maintaining transmission lines. However, this is an extremely unimportant item in comparison with the two already mentioned and it can be ignored in estimates of this sort.

The fixed charge for the capital invested in the line is calculated in a similar way to the charge due on the investment of a power plant. Assuming a useful operational life of 50 years and a rate of interest of 9%, one obtains the following expression for the kWh transmission cost (excluding losses):

\[ d = 9.129 \frac{T}{P} \times 8760 f, \]

where $T$ represents the total investment in the line (in dollars or mills) and $P$ the power transmitted (in kW).

Costs attributable to line losses have to be estimated in each individual case, allowance being made for the physical characteristics of the line and the electricity transmission conditions. This item ($d'$) can be calculated directly once the percentage of the line losses is known. For losses of 10%, the costs will increase by about 10%, for losses of 5% they will go up about 5%, etc. If $p$ represents the fraction lost, then a more accurate calculation of $d'$ is given by the following equation:

\[ d' = p(a + b + c + d)/(1 - p) \]

As for the investment cost ($T$), it is known that qualitatively this increases with the distance of the line and the quantity of power transmitted. The line characteristics will be established for each project mainly as a function of these two parameters (distance and power). One of the quantities to be established is the voltage; this is worked out for example by means of the Still formula. I shall not discuss any details of this problem here. I shall merely point out that for the lines so far built or planned in Brazil the investment costs correspond to "unit" values which generally lie within the following range:

\[ Y = \text{US} \ 65-95/(\text{km MW}) \]
This value includes the cost of the stabilizer-compensators used for controlling the reactive power; this is generally done by means of groups of capacitors (in series on the line).

Under special conditions costs can be higher or sometimes lower than these extreme values, which nevertheless are applicable to the vast majority of normal cases: distances of 100-700 km, powers of 200-1200 MW, voltages (effective value in 3-phase lines) of 120-500 kV.

If this "unit" cost is introduced into the above formula, we finally obtain:

\[ d = \left(\frac{9.12}{8760}\right)Y \frac{L}{f} \]

In this formula \( L \) represents the line length (in km) and \( Y \) its unit cost (in dollars per km and MW); the cost is thus expressed in mills/kWh. For example, if \( L = 410 \) km, \( Y = \$91/(\text{km MW}) \) and \( f = 0.80 \), then \( d = 0.49 \) mill/kWh. If one assumes a line-loss value of 10% and a total cost (with the exception of the losses) of 2.50 mill/kWh, for the same \( f = 0.80 \), then \( d' \) will be equal to 0.25 mill/kWh and the transmission cost will be

\[ 0.49 + 0.25 = 0.74 \text{ mill/kWh} \]

12. BASIC COMPARISONS

The total cost of the energy produced is the sum of the various items considered above:

\[ e = a + a' + b + c + d + d' \]

At this point it is possible to compare the costs for a number of different power plants. Although in actual fact power plants operate at different mean annual load factors, it is necessary for the purposes of this first comparison to assume that all the plants operate at the same \( f \), e.g. 0.80. Later on we shall discuss the influence of this load factor.

In the examples of Table IX all the plants are assumed to be of the same capacity, i.e. 500 MW(e). The specific assumptions made for these examples are presented below.
Hydroelectric plants

Let us consider three typical cases:

Case 1. A plant with a specific cost of US $141/kW, i.e. the estimated average cost assumed by Canambra for all the new hydro plants to be built by 1970 in South-Central Brazil. The energy cost relates to the plant site.

Case 2. The same plant but with power transmission over a distance of 300 km along a line costing US $80/(km MW); line losses, 10%.

Case 3. A plant with a unit cost of US $250/kW with transmission as for case 2.

The results are shown in Table IX in mills/kWh.

Table IX

<table>
<thead>
<tr>
<th>Items of breakdown</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit cost (US $/kW)</td>
<td>(141)</td>
<td>(141)</td>
<td>(250)</td>
</tr>
<tr>
<td>a Investment</td>
<td>1.96</td>
<td>1.96</td>
<td>3.47</td>
</tr>
<tr>
<td>b Operation and maintenance</td>
<td>0.30</td>
<td>0.30</td>
<td>0.52</td>
</tr>
<tr>
<td>c Fuel</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>d Transmission (300 km)</td>
<td>-</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>d' Line losses (10%)</td>
<td>-</td>
<td>0.28</td>
<td>0.48</td>
</tr>
<tr>
<td>Total (mills/kWh)</td>
<td>2.26</td>
<td>2.85</td>
<td>4.78</td>
</tr>
</tbody>
</table>

Conventional thermoelectric plants

Let us consider three other cases:

Calorific power: 10 500 kcal/kg = 12.2 kWh/kg.
Cost of heat: 46.7 cents/million Btu = 1.85 mills/thermal unit (thermie).
Unit cost of plant: US $138/kW (nominal electric). It is assumed that the auxiliary installations at the actual thermoelectric plant will consume 5% of the nominal power.
Over-all efficiency: 0.30, i.e. 3.98 kWh (net)/kg of oil or, expressed differently, 342 grams of oil per horsepower hour.

Case 5. A 500-MW plant, situated in Tubarão, Santa Catarina.
Fuel: Brazilian "steam coal".
Calorific power: 5650 kcal/kg = 6.57 kWh/kg.
Cost of heat: 42 cents/million Btu = 1.67 mills/thermie.
Unit cost of plant: US $185/kW (nominal electric), assuming a consumption of 6% of nominal power for plant auxiliary installations.
Over-all efficiency: 0.296, i.e. 2.07 kWh (net)/kg of coal, equivalent to 658 grams of coal per horsepower hour.

It is assumed that the electricity is transmitted to São Paulo along a 700-km line (operating at 400 kV), costing US $86/(km MW) and operating with line losses of 10%.

Case 6. The same plant as above (No. 5) but built at São Paulo or Rio de Janeiro, where the same coal, including transport from Tubarão, would cost US $18.34/t (Canambra report, loc. cit.), i.e. 82 cents/million Btu = 3.25 mills/thermal unit. Table X sums up the results, expressed in mills per kWh, with a probable approximation of 10%.

Table X
CONVENTIONAL THERMAL PLANTS
500 MW, ANNUAL LOAD FACTOR = 0.8%

<table>
<thead>
<tr>
<th>Items of breakdown</th>
<th>Case 4 (oil)</th>
<th>Case 5 (coal)</th>
<th>Case 6 (coal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a Investment</td>
<td>2.02</td>
<td>2.74</td>
<td>2.74</td>
</tr>
<tr>
<td>b Operation and maintenance</td>
<td>0.37</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>c Fuel (consumption)</td>
<td>5.30*</td>
<td>4.69</td>
<td>9.45</td>
</tr>
<tr>
<td>d Transmission (700 km)</td>
<td>-</td>
<td>0.78</td>
<td>-</td>
</tr>
<tr>
<td>d' Line losses (10%)</td>
<td>-</td>
<td>0.96</td>
<td>-</td>
</tr>
<tr>
<td>Electricity cost (mills/kWh)</td>
<td>7.69*</td>
<td>9.62</td>
<td>12.64</td>
</tr>
</tbody>
</table>
If use were made of Brazilian Bunker oil costing 2/3 the price of imported oil, item c would drop to 3.53 and the total cost would decrease to 5.92 mills/kWh.

Nuclear plants

Let us consider three cases of plants all situated near a consumer area and having an installed power of 500 MW(e):

Case 7. GCR plant (natural uranium, graphite, CO₂).
Case 8. HWR plant (natural uranium, heavy water).
Case 9. BWR or PWR plant (slightly enriched uranium, ordinary water).

The estimated costs are summed up in Table XI. It is assumed that the Brazilian participation in the investment amounts to 50% and that the interest rate is 9% per year.

Table XI
NUCLEAR PLANTS
500 MW, LOAD FACTOR = 0.80

<table>
<thead>
<tr>
<th>Items of breakdown</th>
<th>Case 7 (GCR)</th>
<th>Case 8 (HWR)</th>
<th>Case 9 (EWR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a Investment</td>
<td>3.19</td>
<td>3.36</td>
<td>2.61</td>
</tr>
<tr>
<td>a' First charge</td>
<td>0.49</td>
<td>0.55</td>
<td>0.76</td>
</tr>
<tr>
<td>b Operation and maintenance</td>
<td>0.71</td>
<td>0.61</td>
<td>0.47</td>
</tr>
<tr>
<td>c Fuel (consumption)</td>
<td>1.40</td>
<td>1.01</td>
<td>1.56</td>
</tr>
<tr>
<td>Total (mills/kWh)</td>
<td>5.79</td>
<td>5.53</td>
<td>5.40</td>
</tr>
</tbody>
</table>

It is important to bear in mind that there is no single cost for nuclear energy. The cost is a function of the reactor type adopted for the power plant. Moreover, in view of the uncertainties with regard to the basic cost of nuclear equipment in Brazil (reactor components, fuel elements and nuclear materials, etc.), it is impossible to consider the estimated power costs in the above table as entirely reliable. The margin of error is about 10 or 15%. Within this range the final costs are perfectly comparable and it is impossible to say at the present stage which of the three general concepts (GCR, HWR, BWR or PWR) would be most advantageous for Brazil from the point of view of production costs. There are a number of other relevant factors to be taken into
consideration: the size of the investment, savings in foreign currency, the immediate or future utilization of Brazilian uranium and thorium, the possibility of building up reserves of fissile materials for the development of new technologies, etc.

13. INFLUENCE OF LOAD FACTOR

Given the approximations used so far in the present discussion, the following remarks can be made:

(i) The cost of hydro power is always inversely proportional to the load factor. The fact that there is no expenditure on fuel means that the cost of the power is very sensitive to variations in the load factor: the cost would be, say, 2.50 mills/kWh in the ideal case of $f = 1$, 5.00 mills/kWh for $f = 0.5$. This general observation holds true not only for the case of hydro power produced in the vicinity of a consumer area but also for cases where transmission lines link the power plant to the consumer area, since all the cost items ($a$, $b$, $d$ and $d'$) include the factor $f$ as divisor.

(ii) The cost of thermal power is less sensitive to variations in the load factor. Item $c$ (also designated as $k$ in some of our formulae) is constant, i.e. it is independent of the plant production. The other items are inversely proportional to $f$. It is interesting to note that the more expensive the fuel the less sensitive the cost of the power to variations in the load factor. This point is illustrated in Table XII, which shows the values corresponding to the various examples mentioned above. To facilitate the comparison, a reference value of 1 or 100% is assumed for the ideal case of $f = 1$. The Fig. 1, which is based on these figures, illustrates the point more clearly and provides a direct visual synopsis of the problem.
Consideration of the influence of the mean annual load factor is important in any discussion of the way in which power plants should be fitted into a network, i.e. in deciding whether a plant should operate as a base-load or a peak-load station.

In a system in which hydro plants are predominant, account has to be taken not only of the savings in fuels but also of the economy of the water available in rivers and reservoirs. Any discussion of the balance between various sources of power - either installed or planned -
Fig. 1

VARIATION OF THE RELATIVE PRICE OF ELECTRICAL ENERGY WITH YEARLY LOAD FACTOR
must relate to specific systems. In many cases it will be necessary to have recourse to supplementary thermal energy with a view to "making firm" the available hydro power and establishing a balance between the reserves available during dry years and those available in years when water is plentiful. As a general rule the power cost and its relative variation with the load factor are fundamental factors.

Bearing in mind these two factors (absolute cost and its variation with load factor), we are now in a position to discuss briefly the main problem at issue.

14. IS NUCLEAR ENERGY COMPETITIVE?

On the basis of the data in Table X and Table XI, it will be seen that from the point of view of industrial electricity production, nuclear fuel can already compete with fossil fuels, especially with coal in South-Central Brazil.

At the present time the kWh cost for any type of nuclear plant is thought to be about 5.6 mill for power plants installed in South-Central Brazil. Moreover, it is probable that costs will drop during the coming decades as a result of further technical progress and standardization of components. An increase in Brazilian participation would also tend to favour a reduction. Further improvements can also be expected from the large capacities (several hundred MW) of future nuclear power plants. Optimistic estimates put costs for these new plants at 80% of present costs. In the case of conventional plants the decrease in costs will not be so marked since almost all the important technological advances in connection with such plants have already been achieved.

The kWh cost applicable to home-produced Bunker oil (5.9 mill in Case 4 of Table X) is at present of the same order of magnitude as the nuclear kWh (estimated at between 5.4 and 5.8 mill, with a probable error of less than 10%). However, the supply of such oil, obtained as a by-product of Brazilian refineries, will be insufficient to meet requirements. If imported Bunker oil has to be used, the cost of electricity will be appreciably higher (7.7 mill).

As will be seen from Table X and a comparison of the relevant data, coal is at a positive disadvantage in South-Central Brazil because the "steam coal" at present available has to be obtained from Santa Catarina,
or even further away. Even in the case of plants situated near mines and supplying electricity to nearby areas, the cost of the kilowatt hour (made up of items a, b and c of Case 5) amounts to about 7.9 mill. Thus, even under such favourable conditions costs would be 35 or 50% higher than in the case of nuclear power. As things stand at the present time, however, it is still worth while using "steam coal" from Santa Catarina, even though it costs more than nuclear energy, since use of the coal provides a means of utilizing fuel obtained from the production of metallurgical coke.

Coal will only really be able to compete with nuclear fuel if it can be obtained at half the present cost, i.e. US $4.60/t (equivalent to 21 cents/million Btu = 1.33 mill/thermal unit). On this basis electricity in the area of the power plant would cost about 5.6 mill/kWh.

15. COMPARISON WITH HYDRO POWER

Finally, nuclear plants have to be compared with hydro plants. One point in favour of the latter is that the transmission of electricity via transmission lines is not very expensive for distances up to a few hundred kilometres. Cases 2 and 3 in Table IX show that the total increase in costs from transmission (investment plus losses) is of the order of 20% for a distance of 300 km. The expenditure involved could be much higher for distances of many hundreds of kilometres and in cases where very valuable land had to be acquired by compulsory purchase. The main drawback of transmission lines is the possibility of sudden interruptions in the power supply as a result of breakdowns in the circuit or the wires. While this latter eventuality is not very likely, it always has to be reckoned with, particularly in cases where reprisals have to be feared.

Let us assume a cost of 0.31 mill/kWh for item d relating to investment (for a transmission line of about 300 km) and a value of 10% for transmission losses. What maximum unit value must be assigned to a hydro plant to ensure a kWh cost of less than 5.6 mill (estimated average value of the nuclear kWh)? On the basis of a mean annual load factor of 0.80, this value can be calculated as US $296/kW installed (see Appendix).
This value of 300 km can be considered typical for the average length of transmission lines in an integrated system in South-Central Brazil.

On the whole, however, hydro plants operate at load factors of less than 0.80. Canambra assumes a value of 0.59 for the present-day and future hydro plants in the southern central region. If this is the case and if the nuclear plants to be incorporated into existing systems operate at a load factor of 0.80, then the competitive level for hydro plants (operating at a load factor of 0.59) will be about US $213/kW installed (see Appendix).

Thus, given the approximations and assumptions adopted for the present study, this unit cost (US $213/kW installed) constitutes the limit below which hydro plants will continue to be competitive with nuclear plants.

A numerical value of this sort is obviously subject to a certain margin of uncertainty (10 or 20%). On the other hand it is based on reasonable hypotheses and the order of magnitude ought to be realistic. The important point to be borne in mind is that there is a definite competitive limit.

As the examples in Table IV show, the hydro reserves in South-Central Brazil are fortunately large enough to enable plants to be built at unit costs below this limit. If use is made only of those examples listed in the table whose costs are less than US $213/kW, it will be possible to double the present installed power in this region (around 4800 MW). It is of course desirable that many other favourable cases should be discovered and studied. Nevertheless it will be noted that Table IV also includes projects whose unit costs lie above the limit indicated. These plants will produce electricity at a more expensive rate than nuclear stations. It is essential therefore to make an objective study of the role which atomic energy should play in plans for future power plants in the southern central region or in Brazil as a whole. Our conclusions on this point, which are valid for the whole country, are set out below.
1. In cases where supplementary thermal power is needed, nuclear plants are advantageous and even more economical than many conventional plants.

2. Nuclear kWh costs are competitive with hydro costs for some of the projects at present being studied with a view to the possible construction of a plant in the near future.

3. For these reasons alone nuclear power plants would deserve close study at the present stage of development in Brazil. Moreover, the construction of such plants would contribute to the progress of our country in a variety of ways, e.g. through the use of mineral reserves, the development of industries, international prestige.

For all these reasons no time must be lost in embarking on work on the first nuclear power plants in Brazil.
6. COST OF NUCLEAR POWER PLANTS

The following rough empirical rule can be applied to the cost of nuclear power plants. If \( P \) and \( P' \) are the installed powers in two power plants and \( C \) and \( C' \) represent the values of the respective investments for reactors of the same type (both GCR, HWR, BWR, PWR) and other reactors which have been developed to the industrial stage, then:

\[
\frac{C}{C'} = \left(\frac{P}{P'}\right)^{0.7}
\]

From this it is possible to obtain the following equation for the unit costs of the plants (\( U = C/P \) and \( U' = C'/P' \)):

\[
\frac{U}{U'} = \left(\frac{P'}{P}\right)^{0.3}
\]

These rules are applicable to plants with powers ranging from about 100 MW to probably 1000 MW. The following approximate ratios can be quoted as being illustrative of a specific case:

<table>
<thead>
<tr>
<th>Powers</th>
<th>( P : P' = 1:2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific costs</td>
<td>( U : U' = 1:0.8 )</td>
</tr>
<tr>
<td>Investments</td>
<td>( C : C' = 1:1.6 )</td>
</tr>
</tbody>
</table>

8. INVESTMENT CHARGES

(i) Interest during construction

Let \( C_0 \) represent the investment capital as it would be if it were applied altogether on one occasion. The capital actually invested on the date on which the power plant is ready to be brought into operation is given by:

\[
C = C_0(1 + t)
\]

In this formula the term \( t \) represents the increase due to the interest earned during construction of the plant, since the investment \( C_0 \) will be made at intervals over a period of 3 - 5 years and possibly longer. Depending on the duration of the work, the time schedule of purchases of materials or equipment and the rate of interest, the increase \( t \) can

*Section numbers in the Appendix refer to the corresponding sections of the main text.
vary from 5 to 30%. If, for example, the interest rate is 9% a year and the total investment \( C_0 \) is applied in monthly instalments over a period of four years, then \( t = 20.7\% \). If there are 48 equal three-monthly instalments and the interest rate is the same (9\%), then \( t = 21.5\% \).

If the rate of interest is 6% a year and there are (equal) monthly instalments over a construction period of four years, then \( t = 13.3\% \).

In cases where investments are made simultaneously at different rates of interest, say 9\% (Brazilian capital) and 6\% (foreign capital), the values have to be combined in the same proportion as the investments. If these same rates of interest apply over a four-year construction period and the investments are made progressively in equal monthly instalments over four years, one would obtain:

- for 75\% Brazilian capital, \( t = 18.85\% \)
- for 50\% Brazilian capital, \( t = 17.00\% \)

For hydro plants the Cansamba report (Vol. 1, p. V-8) suggests an interest rate of 10\% on the cruzeiro cost and 6\% on the dollar cost during one half of the construction period. On this basis, \( t = 9.98\% \) for a four-year construction period, 12.55\% for a five-year construction period and 13.43\% for a six-year period. In all cases it is assumed that Brazilian participation amounts to 75\%.

(ii) Interest and depreciation

The annual charge corresponding to depreciation is calculated by the formula:

\[
A_2 = C_j / \int (1 + j)^n - 1
\]

where small \( n \) represents the useful life of the plant in years. It is generally assumed that \( n = 50 \) years for hydro plants and 25 years for thermal plants (conventional or nuclear).

The total charge \( A = A_1 + A_2 \), so that:

\[
A/C = j \int 1 + \frac{1}{(1 + j)^n - 1}
\]
Tables or direct calculations indicate the following values for the second term of the above equation for an interest rate of 9% per year:

\[ n = 50 \text{ years (hydro)} \quad A/C = 9.12\% \text{ (hydro)} \]
\[ n = 25 \text{ years (thermal)} \quad A/C = 10.18\% \text{ (thermal)} \]

The above figures apply to investments based entirely on Brazilian capital. In the case of contributions of foreign capital the calculations have to be modified. Assuming, for example, a rate of interest of 6% for the foreign capital, with payment in 20 years after a waiting period of 5 years, and various additional guarantee costs (e.g. 2% on sight, a six-monthly discount of 0.5% in the first 5 years and 0.25% in the remaining 20 years), we obtain:

\[ A/C = 8.33\% \]

Given the above conditions and 75% Brazilian capital, the annual charge for hydro plants (50 years depreciation) will be:

\[ A/C = 0.75 \times 9.12\% + 0.25 \times 8.33\% = 8.92\% \]

If the Brazilian contribution is 50% for thermal plants, including nuclear plants (25 years depreciation), we obtain:

\[ A/C = 0.50 \times 10.18\% + 0.50 \times 9.28\% = 9.73\% \]

Introducing into the general formula the value \( P \) representing the installed power, we obtain an annual charge per kilowatt as follows:

\[ A/P = (C/P)j \left[ \sqrt{1 + \frac{1}{(1 + j)^n - 1}} \right] \]

15. COMPETITION WITH HYDRO POWER

The competitive value can be worked out by means of the following calculation:

\[ \text{kWh cost} \quad 5.60 \text{ mill} \]
\[ \text{d' losses (10%)} \quad 0.56 \text{ mill} \]
\[ \text{d line investment costs (f = 0.80)} \quad 0.31 \text{ mill} \]

Subtracting (d + d') we obtain

for items (a + b) \quad 4.73 \text{ mill}
Assuming, as in the examples given in Table IX, that the sum of the annual fixed charges \((A + B)\) constitutes 11.2% of the capital invested, we obtain for the unit cost of the power plant (load factor 0.80):

\[
U = \frac{8760 \times (a + b)}{11.2\%} = \text{US } \$ 296/\text{kW installed.}
\]

If a value of 0.59 is adopted for the mean annual load factor, the calculation will be similar except that the term \(d\) will be 0.42 mill, yielding 4.62 mill for the sum \((a + b)\). The final result will be:

\[
U = 8760 \times 0.59 \times 4.62/0.112 = \text{US } \$213/\text{kW installed.}
\]

REFERENCES


2. Ibid 1. (1964) V-10 and 12.
