ON THE COSTS OF NUCLEAR ENERGY

I

General Economic Aspects

1. RADIOISOTOPES

The applications of nuclear energy are at present of two main types - the use of fission as a primary large-scale source of energy and the use of radioisotopes.

It is not my intention here to discuss the cost of radioisotope production or of the various radioisotope techniques. However so as not to pass over the subject in complete silence, I should like to emphasize that the remarkable achievements in this field have amply demonstrated the value of isotopes in all the activities and investigations for which they have been used, viz. medicine, biology, agronomy, hydrology, physical science and industry.

Radioisotopes are used as tracers or as radiation sources. The range of applications is vast and there is a steady increase in their number and variety. Obviously this entails expenditure in connection with research on the feasibility of techniques, investigation and production costs, the purchase of apparatus for isotope utilization, and the payment of salaries to experimental personnel. However all this expenditure is vastly outweighed by the extent and the quality of the practical benefits which are enjoyed in consequence. Think, for example, of the immense value of the cobalt-60 bomb used for the destruction of cancerous tissue and the progress achieved in plant and animal physiology thanks to research with C^{14}-labelled compounds.

In certain instances - in the fields of agriculture and industry - we can compare sets of data enabling us to evaluate the financial benefit, the savings and other advantages obtainable from the use of nuclear techniques and radioisotopes. Here are a few examples which were discussed at a meeting organized in March 1964 by the International Atomic Energy Agency. They refer to the use of isotopes in gauging the thickness of sheets or surfacing materials and the density or composition of materials.

A paper factory in the United Kingdom was able to achieve an annual savings of £60 000 on an investment of £11 000 for a radio-isotope unit and low operational costs. A glass factory, also in the United Kingdom, saved £190 000 by using gauging equipment worth £2650; the annual expenditure was £200. In the United States a potash factory managed to save US $45 000 on manpower and material in addition to increasing productivity by US $25 000 for a sum of less than US $900 spent on the radioisotope control of saline solutions [1].

2. THERMAL AND MECHANICAL ENERGY

Let us now turn to the other applications of nuclear energy based on nuclear fission. This phenomenon, which is produced in chain reactions, is used to obtain heat, produce motive power or generate electricity. Power reactors, used for the controlled release of nuclear energy, can in principle be employed to generate heat, which can be employed to heat water in the environment or to de-salt water by means of distillation. Other reactors can be used for the propulsion of vehicles, especially submarines and surface vessels. Mechanical energy can also be produced in the form of explosions - as is the case with atomic bombs - and used for peaceful purposes. In nuclear power plants, power reactors are used in conjunction with turbo-generators to produce electricity.

The Halden reactor in Norway, which was installed in June 1959, was the first industrial-scale installation (20 MW(th)) designed for the nuclear production of steam (paper-pulp factory). It is a prototype and its main interest is technical rather than economic.

More numerous are the plans for constructing dual-purpose reactors for producing electricity and steam or for generating electricity and de-salting water. A reactor of the first type ("Ågesta") was built in Sweden in Farsta, a suburb of Stockholm, and there are interesting prospects for the establishment of similar mixed plants in Antarctic and Arctic bases. As for the second variety - electricity and desalination - projects exist for installations in Israel, Tunisia and Mexico and other countries with areas short of fresh water.

There are few data on the cost of mechanical energy produced from nuclear sources. On the subject of nuclear propulsion it is known that there are now some 80 atomic submarines in operation, 50 of them belonging to the United States; these include the pioneer vessel "Nautilus" (3200 tons, launched January 1955, able to attain speeds of over 20 knots, travelled under the ice cap of the North Pole). There is also "Lenin", an impressive ice breaker belonging to the USSR (December 1957, 16 000 tons, 44 000 h.p. turbines, able to attain 18 knots in open sea). The United States has built the first merchant ship ("Savannah", a mixed passenger-cargo vessel, 22 000 tons possessing a 69 MW(th) reactor transmitting 22 300 h.p. to the ship's propellers and providing a speed of up to 24 knots - it was launched in July 1959) as well as various naval vessels (aircraft carrier "Enterprise", destroyer "Bainbridge" and cruiser "Long Beach").

Generally speaking nuclear propulsion at present costs more than propulsion based on the conventional fuels, coal or petrol. On the other hand it does have advantages - nuclear ships can travel longer distances and spend considerable periods of time at sea without refuelling (for example in its first three years of operation the "Lenin" covered more than 50 000 miles without refuelling). Moreover, many of these nuclear ships were built not as economic propositions but as prototypes for research and experiments aimed at future developments. Information on this subject is given in "Nuclear Ship Propulsion", Vienna 1961, the proceedings of a symposium on this subject held by the IAEA in 1960. Recent studies - 45 in all - are listed in the chapter on "Nuclear Propulsion Economics" in Bibliographical Series No. 13 (Nuclear Power Economics), IAEA, December 1964.

In connection with nuclear explosions, little is known of the exact costs of atomic bombs. Estimates suggest that the costs are extremely high; the expenditure is based, like other military investment, on the need to ensure the sovereignty of nations and to defend basic human rights.

On the subject of the peaceful applications of nuclear explosives (called "plowshare" in the United States with reference to the verse in the Bible), I shall comment only very briefly. The power of explosives is almost always expressed in terms of the quantity of TNT which would be capable of releasing an equivalent amount of energy. Thus there are reports of atomic bombs of 50 kilotons (i.e. of TNT) or of so-and-so many megatons (i.e. equivalent to a bomb of so-and-so many millions of tons of TNT). On the basis of United States estimates, the cost of a "mass-produced" 100-kiloton bomb would appear to be around US $1 million. On this basis a mass of nuclear explosive equivalent to 1 ton of TNT would cost US $10. One ton of TNT costs approximately $1000. In other words the cost of a quantity of TNT and the cost of an equivalent quantity of nuclear explosive differ by a factor of 100:

$$\frac{\text{cost of TNT}}{\text{cost of nuclear explosive}} = \frac{\text{US \$1000/ton}}{\text{US \$10/ton}} = \frac{100}{1}$$

In actual fact the economic advantage of nuclear explosions is not so high because the dynamic effects of the two types of explosive, chemical and nuclear, are not fully comparable. In particular, in the case of an atomic bomb exploded above the ground the bulk of the energy released remains in loco in the form of heat; thus the volume of earth displaced is less than in the case of TNT for the same energy power.

Experimental studies have been carried out on the effects of nuclear explosives (in the United States, France and Russia), some of them in connection with underground testing of weapons. It was found that to obtain the same final results in the displacement of alluvial or rocky earth, expenditure with conventional explosives is 4 or 5 times higher than with nuclear explosives (not 100 times as the ratio between the material costs would seem to suggest).

Nuclear explosives are particularly advantageous in cases where 10 kilotons or more are needed to displace enormous masses of earth. This is why nuclear energy is being favourably considered with regard to plans to open up a new canal, without lockgates, permanently linking the Atlantic with the Pacific in some part of Central America. Not only would costs be 4 or 5 times lower than in the case of conventional processes but only one-fifth of the time would be required to complete the project.

3. ENERGY AND DEVELOPMENT

Energy is necessary to ensure development in various forms - namely to provide heat, mechanical energy and electricity. Increased development in turn increases the demand for energy. It is not difficult to list the reasons which give rise to increases in energy requirements in particular countries or geographical regions. There are obvious energy requirements for the maintenance of various utilities, which guarantee an average living standard for a given population. This standard can be equated with the possibilities open to individuals to secure manufactured products, such as clothing, food and personal effects, housing, domestic appurtenances from electric irons to television sets and also electricity (private and public), transport, community services, cultural activities, etc.

All these items require energy (heat, operation of machines, electricity). At the same time energy is needed for all industrial activities - extraction industries, basic industries, manufacturing industries, agriculture, etc. On the basis of the ratio between the sum of the energy needed to obtain these necessary goods, utilities, and services and the number of individuals in a community, it is possible to arrive at the per capita energy consumption index, which is a reflection of the degree of development of the country. This can be expressed in various ways. One can take the annual consumption of energy in its various forms (heat obtained from direct combustion of fuels, electricity used for lighting buildings, public highways and factories, etc.) and reduce the result to a particular unit. This yields the total consumption index, generally expressed in kilograms of coal per capita per year. In other cases one considers the energy produced in the form of electricity fed into the grid system or used on the spot. The corresponding index is generally expressed in two different ways:

kWh per capita per year

kW installed/capita

The first index represents the average consumption of electricity per individual. The second corresponds to the power of the electricity-generating units installed and it is a measure of the available supplies from existing power stations - normally, of course, these available supplies are only used in part. Generating units do not function on a round-the-clock basis on normal power. They are subject to occasional shutdowns for inspection purposes or because electricity requirements drop at particular times. Nor do they always produce electricity at normal power even when they operate.

The higher the energy consumption index the more industrialized a country (or region) and the higher the average standard of living. For this reason the per capita energy consumption tends to go up everywhere from one year to the next. And the rate of growth is such that the total energy consumption in a country or region increases all the time, even in the rare cases where population decreases occur. In the latter cases the rate of decrease in population is always less than the growth rate of per capita energy consumption, and the combination of the two factors gives rise to an increase.

New sources and in particular new electric power plants are needed to meet the growing demand for energy. These new installations must be able to cope with the probable or expected requirements. Otherwise development is impaired and progress becomes impossible. Obviously it is desirable that electricity should be abundant, efficiently distributed and cheap. However, the importance of the cost factor should not be overstressed. Energy costs make up only a small part of the total cost of industrial products; there are exceptions but in the vast majority of cases involving the production of normal articles it amounts to 1-5%. Nor is electricity a high cost factor in connection with the normal facilities found in homes, offices and other places of work or recreation.

In considering the use of nuclear energy as a primary source of electricity the important thing is not that it should be "cheap" in absolute terms but that it should be competitive, that is to say that the cost of nuclear electricity should be produced at a cost comparable with or less than that of electricity generated by conventional sources - hydroelectric plants or thermo-plants based on coal, natural gas or oil. If energy is vital to a country's development one must be prepared to pay what it is worth; the problem is to obtain the energy at the lowest possible cost.

Before discussing the concept of "competitiveness" and analysing the costs involved I shall consider some of the fundamental economic or technical advantages of using atomic energy. My remarks have been suggested in part by a recent book by J. Andriot and J. Gaussens [2].

4. ENERGY DENSITY

The impressive thing about nuclear fuels is their extraordinary energy density. I shall consider the case of uranium-235, which is typical, but my remarks apply equally well - with certain adaptations - to the other fissile elements, plutonium and uranium-233, which can be artificially produced in reactors and used as nuclear fuels.

If one ton of uranium-235 were to undergo fission in all its atoms, it would liberate a quantity of energy equivalent to the energy obtained in the combustion of about 2 480 000 tons of anthracite. In natural uranium this isotopic variety (^{235}U) is present at a concentration of about 0.7%. Thus the maximum energy available corresponding to the fission of all the uranium-235 contained in one ton of natural uranium would be equivalent to 0.7% of the above figure.

Reactors based on the natural uranium-graphite-CO_2 concept can now extract 67% of this maximum theoretical value from nuclear fuel (this includes partial burn-up of the plutonium generated from ^{238}U). Thus in these reactors nuclear fuel behaves as though it had an energy density 12 000 times higher than the energy density of anthracite. In natural-uranium heavy-water reactors (Candu) the energy density of the nuclear fuel is about 2.4 times higher than in graphite reactors. Each ton of uranium in the Candu reactors corresponds to 28 800 tons of anthracite. In breeder reactors - at present existing only in the form of prototypes - the uranium can be used at an energy density equivalent to 400 000 or even 600 000 tons of coal.

5. IMPLICATIONS OF HIGH-ENERGY DENSITY

This extraordinary concentration of energy associated with nuclear fuels has a number of economic advantages:

(i) The transport of fuel becomes less of a problem and power plants can therefore be located at considerable distances from the factories producing the fuel elements;

(ii) Charges of nuclear fuel in the reactor last for relatively long periods of time (advantageous for remote consumer areas, etc.).

This energy concentration makes nuclear fuel economical even with the high fabrication costs involved. In the case of, for example, natural-uranium reactors, the fuel elements cost approximately US $30 500 per ton of natural uranium used, including the cost of the uranium (cost quoted for Magnox-type elements by U.K.A.E.A. engineers in October 1964). Taking into account the energy density mentioned above, one obtains a value of 9.25 cents per million Btu or 0.37 mill per thermie (1000 kilocalories) available in the nuclear fuel.

In the United States anthracite costs 20 - 40 cents per million Btu, or 0.8 to 1.6 mills per thermie. Thus the cost of natural uranium ready for use in a reactor is about one half or one quarter of the cost of coal for the same quantity of heat released in the respective "combustion processes". As I shall explain later on, this does not correspond exactly to the real ratio between the costs of operating power plants. For one thing capital is locked up for longer periods of time in the case of nuclear fuel. Calculations show that the fuel costs correspond approximately to the following percentages:

Power plant with Magnox reactor	17-22%
Coal-powered power plant	37-42%

The above figures correspond very roughly to the results obtained from a comparison of data produced recently by the Reactor Engineering Division of the Atomic Energy Institute (March 1965) for power reactors and published figures for coal-powered plants (TID-8531, USAEC Jan. 1961).

In the light of current technological progress in the nuclear field it would appear that the fuel costs of the nuclear power plants of the future (particularly those using breeder reactors) will be considerably lower, reaching a value of one per cent of the total costs, or even less according to the most optimistic estimates.

6. FURTHER ADVANTAGES

(a) Systematic use of fissile materials for power plants will result in savings of fossil fuels. This would make it possible for the latter to be reserved for other uses in industry and for vehicle propulsion.

(b) In nuclear reactors the "combustion" process does not rely on oxygen and does not give rise to poisonous fumes or gases - a considerable advantage as compared with conventional fuels. Furthermore, the volume of spent fuel is relatively small. On the other hand, the use of nuclear energy poses problems of a different kind - transport and reprocessing of high-activity radioactive waste.

(c) As already mentioned, nuclear explosives can be used for canal construction and similar large-scale projects involving the removal of large masses of earth.

(d) Nuclear reactors are sources of highly valuable by-products: new nuclear fuels (Pu, ^{233}U), radioisotopes, fission products used as sources of radiation.

(e) Use of nuclear energy entails the development of new materials (special alloys, etc.) and new techniques.

II

Analysis and Comparison of Costs

1. FIRST INDEX OF COMPETITIVE STATUS

The competitiveness of energy costs between various types of power plants must be studied in the context of a particular region. Obviously an atomic power plant can be competitive in one area and not in another. Hydroelectric stations will produce cheaper electricity in areas possessing plentiful hydro resources whilst nuclear plants will be advantageous in areas poor in fossil fuels and water resources. Conventional power plants are less attractive in cases where transmission lines are needed to carry the electricity over long distances; in addition transmission lines can be costly and wasteful of electricity. The cost of imported fuel for a conventional thermal plant is also, of course, affected by transport and customs costs.

In comparing the competitive status of power plants, the electricity generating cost is usually expressed in mills/kWh (basic cost at generating station plus transmission and distributing costs).

2. UNIT COST

Another economic index used in comparative cost studies is the unit cost. This is obtained by dividing the total investment cost by the installed power of a plant and is generally expressed in US $/kW. The value of this index can be illustrated by means of comparison with non-atomic problems, viz. the use of velocity as an index in comparing the advantages and disadvantages of various means of transport.

3. OTHER CRITERIA

The two economic criteria mentioned above are not the only ones to be considered in the assessment of different types of power plant. Other factors to be taken into account include the proximity of consumer areas, the expected lifetime of the plant, construction and amortization periods, interest rates, relevance to technological programmes of country concerned, the availability of specific raw materials in the country, etc. In the case of Brazil the abundant deposits of thorium are a factor of importance in power planning.

Attention should be drawn to the difficulty of allocating exact figures in advance to the two economic indices (unit investment and power production cost). The following points are to be considered:

(a) Reactor technology is progressing at too rapid a rate to enable exact estimates to be made. Only a few reactor types have been developed to the industrial stage and even in the case of proven types there is always the possibility of new technological development and consequent price shifts.

(b) Reactor planning, construction and operation is going on in a variety of countries and many cost items (interest and amortization rates, insurance, fuel and manpower costs) are subject to variation.

(c) No definite data are available on the lifetime of reactor materials (novel problems of radiation damage, etc.) and nuclear power plants. Water turbines and conventional thermal plants are known to have lifetimes of around 50 and 30-35 years respectively but in the case of nuclear plants we have to rely on assumptions. In view of the fact that the reactors initially built for research and development have now been in existence for 10, 15 or more years, the figure of 25 years commonly accepted for the lifetime of a nuclear plant seems a reasonable assumption. It goes without saying that this uncertainty about plant lifetimes also causes uncertainty in amortization-cost estimates.

4. TOTAL INVESTMENT

Investment costs depend on the type of reactor involved and a reactor type is defined in terms of fuel, moderator and coolant. Total investment costs are the sum of various components (fuel elements, structural materials, heat exchangers, etc.) which vary from one reactor system to another. In working out the total cost, it is necessary to take into account not only the installation costs (land, buildings, equipment, interest payments), but also the cost of the first fuel charge.

The estimated cost of installing various types of plant in Brazil, obtained by interpolation on the basis of recent non-Brazilian reports, is given in Table I.

TABLE I

ESTIMATES OF UNIT COSTS (US dollars/kW)

Reactor type	Unit cost without fuel				Additional cost for fuel (US $/kW)
	Installed power:	150 MW	300 MW	450 MW	
Magnox (or GCR)		375	284	245	35
Candu(or HWR)		462	328	281	40
BWR and PWR		290	215	185	65

Figures are based on the assumption that the components are purchased outside Brazil - France or the UK for Magnox, Canada for Candu, United States of America for BWR and PWR.

The difference in equipment costs between nuclear and coal-powered plants can be assumed - without fuel - as 35-40% for stations based on BWR or PWR reactors, 45-50% for Magnox-type stations and around 60% for Candu power plants.

Table II - based on information from the book by Andriot and Gaussens referred to above - illustrates the difference in cost breakdown between a nuclear 500-MW(e) plant (current French prices) and conventional stations.

TABLE II

COMPARISON IN COST BREAKDOWN FOR TWO TYPICAL PLANTS

Items	Cost breakdown (%) for plants operating on:	
	Coal	GCR
Land and site improvement	17.1	19.6
Engineering and construction	8.6	9.2
Reactor	-	22.4
Moderator (graphite)	-	12.2
CO_2 circuit	-	27.8
Boilers	33.3	-
Steam circuit	4.2	5.6
Water circuit	5.6	6.4
Control equipment	3.3	6.9
Fuel maintenance installations	6.4	12.5
Turbo-generator	14.0	14.0
Electrical equipment	7.5	8.4
Total	100.0	145.0

5. FIXED ANNUAL CHARGES

The main cost components for the kWh are as follows:

(a) Investment capital

Includes interest and depreciation, may include taxes and insurance. Canambra Engineering Consultants Limited quoted 9% for interest rates in Brazil [3]. The annual fixed charges on depreciable investment (a little over 10%) can be obtained from this value of 9% and the estimated lifetime of a nuclear plant (25 years). Canambra puts the annual rate for thermal plants at 14%. Insurance costs are estimated at 0.8% for nuclear plants as against 0.25% for thermal stations (TID-8531).

(b) Operation and maintenance of plant

Includes engineering, inspections, salaries, social insurance, fuel storage, maintenance of machines, etc. Replacement costs for moderator and coolant must be taken into account (heavy water with Candu reactors).

(c) Nuclear fuel.

6. UTILIZATION (LOAD) FACTOR

The annual load factor or the mean annual utilization factor of a plant is an extremely important item in any assessment of the way in which fixed charges affect electricity costs. The greater the number of hours a plant operates, the higher the utilization factor. The utilization factor will also be higher, the greater the power supplied by the generators during this time.

The fixed annual charges are considered "fixed" precisely because they are considered independent of the number of kilowatt-hours produced by the generators. The corresponding portion of the total electricity costs is obtained by dividing the value of the fixed annual charges by the number of kilowatt-hours generated in the course of the year. Logically, the higher the unit investment (US $/kW), the greater has to be the total number of kilowatt-hours produced if this cost item is not to be excessive.

7. FUEL AND THE TOTAL ENERGY COST

The total investment costs are relatively low in systems based on expensive fuels (e.g. enriched uranium) and vice versa.

Other factors affecting fuel costs are burn-up, reprocessing costs, plutonium and ^{233}U credits, etc. Table III gives a comparative breakdown of costs. Assumptions are the same in all three cases with respect to electricity production (500 MW(e)), interest (9% per annum), plant lifetime (25 years) and load factor (80%). Data are subject to an error of 20% or less, the uncertainty being mainly caused by the variety of sources of information, lack of exact data on burn-up, and unknown extent of national participation.

TABLE III

PRODUCTION COSTS

Items	Breakdown of costs of energy produced in 500 MW(e) plants and load factor of 0.80 (mills/kWh)		
	GCR (Magnox)	HWR (Candu)	PWR or BWR
(a) Investment costs	3.19	3.36	2.61
(a') First load	0.49	0.55	0.76
Sub-total	3.68	3.91	3.37
(b) Operation and maintenance	0.71	0.61	0.47
(c) Fuel consumption	1.40	1.01	1.56
Total cost	5.79	5.53	5.40

Nuclear power costs are much lower in large plants (500 MW (e)) than in smaller ones (50 MW (e)). There is little variation in plants over 500 MW(e)..

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