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NUCLEAR POWER COSTS

Note by the Director General

1. In its first report to the General Conference under resolution GC(IV)/RES/86, the Board of Governors expressed the opinion that the General Conference would find the latest data available to the Secretariat on the costs of nuclear power a useful complement to the general studies for which it has asked. [1]

2. At the Board's request the Director General has therefore arranged for the preparation of the attached new edition of the review of the subject which it submitted to the General Conference last year [2]. This edition, which contains new data on the smaller reactors and more extensive information on the components of fuel costs, is based on material obtained by the Secretariat up to 31 July 1961.

[1] GC(V)/161, paragraph 6.

[2] GC(IV)/123.

NUCLEAR POWER COSTS

A review by the Secretariat

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A N N E X E S

List of abbreviations

Al	aluminum
aux.	auxiliary
Be	beryllium
BTU	British thermal unit
BWR	boiling-water reactor
¢	cent
D	deuterium
d	day
diam	diameter
ENEA	European Nuclear Energy Agency
GCE	gas-cooled, enriched-uranium reactor
GCN	gas-cooled, natural-uranium reactor
g	gram
hr	hour
HV	high voltage
HWGC	heavy-water, gas-cooled reactor
HWN	heavy-water, natural-uranium reactor
HWE	heavy-water, enriched-uranium reactor
kg	kilogram
kg-yr	kilogram-year
kw	kilowatt
kwe	kilowatt electrical
kwh	kilowatt-hour
kw-yr	kilowatt-year
lb	pound
Mg	magnesium
mills	thousandths of a US dollar
misc.	miscellaneous
Mo	molybdenum
Mwd	megawatt day
Mwd/kg	megawatt day per kilogram
Mwd/t	megawatt day per ton
Mwe	megawatt electrical
n. a.	not available
O	oxygen
OCR	organic-cooled reactor
OCHWN	organic-cooled, heavy-water-moderated, natural-uranium reactor
OEEC	Organisation for European Economic Co-operation
OMR	organic-moderated and organic-cooled reactor

p.	page
Pu	plutonium
PWR	pressurized-water reactor
SS	stainless steel
t	metric ton
U	uranium
UK	United Kingdom
UKAEA	United Kingdom Atomic Energy Authority
US	United States
USAEC	United States Atomic Energy Commission
v.	volume
WPC	World Power Conference
wt%	weight per cent
yr	year
Zr	zirconium
Zr-2	Zircaloy
$	dollar

NOTES

1. All sums of money are expressed in United States currency.
2. The sign " - " in the tables indicates that information is not available.

I. GENERAL OBSERVATIONS ON THE AVAILABLE INFORMATION

1. Since the first review on nuclear power costs was written, new design studies and some additional operating experience of power reactors in several countries have resulted in further data becoming available. These data relate mainly to the fuel cycle and to the smaller reactors, in which there is particular interest, and on which the Agency sponsored a conference in September 1960 [1]. However, for those power reactors at present under commercial construction there is still the reluctance on the part of industrial manufacturers noted in the first review to release detailed information or estimates which may affect their competitive positions [2].

2. Although the uncertainty as to the general applicability of specific information on nuclear power costs has somewhat decreased during the past year, it must still be borne in mind that with the comparatively recent advent of this kind of power, only limited operating experience has so far been gained, and hence much of the technical and economic data at present available represent considerable extrapolation from actual experience. The quantitative values given in this review must therefore be regarded as best estimates, subject to rather substantial reassessment as technology continues to develop.

3. A further point of importance is that the methods of calculating nuclear power costs differ widely from country to country. The treatment of such items as interest rates, amortization periods, research and development costs, indirect construction costs, and allowances for contingencies, escalation and non-equilibrium operation varies considerably; and in many cases it is not possible to ascertain from the published data how they have been handled. The various items that are included in the cost of construction of a nuclear power plant, the costs of the fuel and other charges, and the methods of calculating nuclear power costs are discussed elsewhere [3].

4. A third consideration is that it is not always possible to obtain a valid comparison of construction costs in different countries simply by applying the official rates of exchange for their currencies. One of the main reasons for this is that the ability or inability of a country itself to manufacture all or part of the nuclear and conventional portions of a nuclear power plant may influence the economies of the plant to a considerable extent.

5. From the foregoing considerations it will be evident that in most cases published information on nuclear power costs is specific to one situation only, generally in the country of publication, and is conditioned by local accounting procedures. Hence, before any direct comparison can be made between different schemes for installing nuclear power, all the data must be reduced to a common basis. In view of the difficulty inherent in thus preparing cost information which would be directly applicable to all Member States, an attempt has been made in section III of this review to indicate how the cost data that follow can be evaluated to suit specific local conditions and accounting practices. It should be noted in that connection that the data are mostly for reactor designs based on reactors that have already been built; and further that the correct extrapolation of data from one situation to another is a matter for experts with a knowledge of the local conditions in both situations.

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[1] The proceedings of the conference are being published in two volumes: Small and Medium Power Reactors, IAEA, Vienna (1961) (STI/PUB/30).

[2] GC(IV)/123, paragraph 10.

[3] Introduction to Methods of Estimating Nuclear Power Generating Costs: STI/PUB/44 (in preparation).

II. EVALUATION OF COST DATA FOR SPECIFIC SITUATIONS

A. General

6. Since the cost of nuclear power depends on the conditions of financing and the degree of utilization of the plant, to express that cost simply in terms of total cost per kilowatt hour is of limited value. The cost components in this review are therefore presented in the manner indicated in paragraph 7 below, so that the information may be more easily used to obtain an extrapolation for any given situation.

7. These cost components are usually grouped into the following three main categories:

(a) Capital cost, consisting of the construction cost of the plant and miscellaneous start-up costs, which are conveniently expressed in dollars per net electrical kilowatt of the rated plant capacity. The part of the generating cost in mills/kwh resulting from the capital cost is readily obtainable from a knowledge of the annual capital charge and the plant utilization factor;

(b) Fuelling cost. In this category are grouped costs connected with the preparation, consumption, reprocessing, transport, inventory and insurance of the nuclear fuel, as well as credits for the value of fuel discharged. All these cost components are conveniently expressed in dollars per kilogram of uranium loaded into the reactor during a fuel cycle. The part of the generating cost in mills/kwh resulting from the fuelling cost is readily obtainable from a knowledge of the heat generated per kilogram and the thermal efficiency of the plant in converting heat into electricity; and

(c) Other operating costs, such as the costs of operation and maintenance, third party insurance for nuclear damage, and all other annual charges not placed in either of the other categories. All these cost components are conveniently expressed in dollars per rated electrical kilowatt per year. The part of the generating cost in mills/kwh resulting from these operating costs is readily obtainable from a knowledge of the annual equivalent full-power hours of operation of the plant.

B. Capital cost

8. The largest item of expenditure on a nuclear power plant is that for design and construction, and when considering this component the first essential step is to ensure that the data in fact include all the items of cost. In this connection the breakdown of capital costs given in document STI/PUB/44 [3] and Figures 1 to 4 in Annex VI should prove useful.

9. When the design and construction component of the cost of a particular nuclear plant is to be extrapolated for a given situation, each item of cost should be examined and extrapolated as necessary, and at the same time an estimate made as to the amounts of domestic and foreign capital which will be required according to whether the item can be obtained locally or must be imported. In addition allowances should be made for the cost of transport of imported items and for any export or import duties which may be payable.

C. Fuelling cost

10. The next largest item of expenditure is the initial fuel loading for the reactor together with the working stock of fuel which must be kept available for normal operation and for emergencies. The size of the reserve fuel stock will need to be carefully estimated, taking into account the degree of availability of further supplies at the manufacturing site and the time taken to transport fuel to the power plant.

11. The actual fuelling cost depends on the price of new fuel, any credit obtainable for spent fuel and the estimated burn-up that can be achieved. The designer of the reactor usually provides burn-up estimates; they may, however, have to be revised in the light of experience and the credit obtainable for spent fuel subsequently recalculated to take account of the adjusted content of fissile material. Further adjustments to the credit obtainable must also be made to cover transport and insurance charges, in view of the relatively high cost of transporting highly radioactive, irradiated fuel. If it is intended to discard spent fuel an allowance must be made for its disposal cost or long-term storage.

D. Other operating costs

12. This category of costs includes all annual charges not included in the capital or fuelling costs, as was indicated in paragraph 7(c) above. The principal component is the cost of operation and maintenance, but other components may be charges for heavy water or other special coolants, third party liability insurance, taxes and other items.

13. The extrapolation of operation and maintenance costs from one situation to another, especially in a less-developed area, must take into account several possible factors, such as:

(a) A need for foreign specialists with high salaries and allowances;

(b) A lack of specialized skills and equipment;

(c) A lack of the specialized repair facilities and services that are readily available at short notice in the more advanced countries; and

(d) The transport and use of special materials such as organic liquids, heavy water or helium and of specialized spares and other operating materials.

E. Considerations of financing

14. Having estimated the total amount of domestic and foreign capital necessary to construct the plant and supply the initial fuel charge and working stock, it is necessary to estimate the annual charges which this borrowed capital would incur. Briefly these may be:

(a) Interest or dividends;

(b) Depreciation (the amount depending on the interest rate, the expected life of the plant and the method of accounting);

(c) Interim replacements - an item which is allied to depreciation but may in some countries be classed as part of the cost of operation;

(d) Normal plant insurance; and

(e) Taxes (e.g. income, enterprise and local taxes).

It must be pointed out that no hard and fast rules can be laid down on this subject; each situation must be examined separately.

15. It is also usual to provide a small amount of working capital, some of which is needed for spares and supplies not included in the capital cost of the power plant and the remainder for its day-to-day operation.

F. Computation of generating cost

16. After the capital, fuelling, and other operating costs have been extrapolated, and the charges on the capital initially required calculated, the electricity generating cost can be computed for the particular situation under study. A simplified method of computation is given in Annex VIII, together with a chart to facilitate estimation of the component generating costs under various economic assumptions for equilibrium conditions, that is,

when the total annual operating costs of the plant are assumed to be constant. In that connection, however, further reference is invited to document STI/PUB/44 [3] which contains a discussion of methods for dealing with the non-equilibrium, initial and final operating periods and with the time-value of money. The chart in Annex VIII should, therefore, only be used to obtain general indications of the trends and ranges of costs relevant to the situation in question.

17. It has been pointed out that the estimates of costs presented in this review are based mostly on reactors that have already been built [4], and hence to the present stage of development of the nuclear technology. These estimates will accordingly require review in the light of the new information which is to be expected from the operation of power reactors at present under construction or planned for the near future. Nevertheless, in spite of the review's clear limitations, it is hoped it will prove helpful in the making of preliminary assessments of the economic merit of nuclear power in particular situations. A more detailed and precise assessment for a specific case would require closer analysis of the costing procedure, further examination of the cost figures, study of the effect of integrating the proposed power plant into the relevant electrical grid and examination of the significance of trends in the current movements of nuclear and conventional fuel costs.

III. NUCLEAR POWER COST DATA

A. General

18. The cost data in this review are given for the situation applying in the country in which they were developed. For ease of comparison, however, all costs have been converted into United States currency.

19. The reactor types to which the data relate primarily are those the technology of which is relatively well developed and which have been or are about to be operated on an industrial scale; examples are the pressurized and boiling-water reactors, the gas-cooled, the organic-moderated and the heavy-water reactors. Advanced reactors of the fast breeder or homogeneous types have not been dealt with, nor has any attempt been made to compare the economics of reactors of different types.

20. The use of enriched uranium in a reactor makes possible considerable flexibility in the design, especially in smaller sizes where the smaller cores require correspondingly less capital investment for fuel; enrichment can also be used to achieve increased fuel burn-up and permits a wider choice of materials for the core. Counterbalancing these advantages are the cost of enrichment, the increased cost of fuel fabrication and dependence on the source of enriched fuel. Hence the current interest in reactors which operate on natural uranium such as the gas-cooled, graphite-moderated and the heavy-water reactors, although these types appear to be economically more suitable in larger sizes. In general their capital costs are higher than those of reactors using enriched uranium, but their fuelling costs are lower.

21. Considerable information has been published on the construction, fuelling and operating costs of nuclear reactors, but in many cases it is not clear what components made up these costs, for how long the estimates would remain valid, what assumptions were made in preparing the cost data and what was the experience on which the costs were based. For these reasons caution has been exercised in selecting the sources of information and in presenting the information itself. The conclusions to be drawn from data from some sources may not be in accord with those derived from information from others. In this respect the Secretariat would welcome further information which would enable it to improve the reliability of the data in a further edition of this review.

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[4] Paragraph 5 above.

22. The three following sub-sections deal respectively with capital costs, fuelling costs and other operating costs. It should be noted that there is incomplete concordance between the cost information obtained from different countries and reproduced in Annexes I to V. Although this can be partially attributed to differences in construction cost indices, a considerable amount can also be due to the different assumptions used in computing the cost data. Some data are based upon actual construction and operating experience of experimental, prototype and industrial plants, and others merely on design studies or projected plant types and estimated fuel costs and performances.

B. Capital cost

23. The United States of America has a number of municipal generating systems or rural co-operative systems which require plants having capacities in the range from 10 to 75 electrical megawatts; and to determine the economics of nuclear power in this range, the United States has recently finished a detailed comparison of nuclear and conventional power costs for small plants. The data in Annex I show the estimated costs of building small and large nuclear power plants in the United States which could be operative by 1964-65. The data are the results of design studies made by contractors of USAEC; they are based on the experience gained from many experimental reactors which are being operated on behalf of USAEC. It will be seen from them that the smaller the capacity of the nuclear plants, the more disadvantageous they become in comparison with conventional steam plants.

24. Among the United States nuclear plants, the organic and direct-cycle boiling reactor with natural circulation appears to have some capital cost advantage, although the fuel cycle cost must of course also be considered in computing the total generating cost. It is to be expected that no one type of reactor plant will prove cheaper than others for all sizes, but rather that certain types and designs will be most suited for particular sizes and applications.

25. The nuclear power program in the United Kingdom of Great Britain and Northern Ireland is based primarily on large plants in which the reactors are of the gas-cooled type, although recently work has been done on those of the pressurized-water, boiling-water, steam-cooled and organic reactor types. The data given in Annex II show the estimated construction costs of large and small nuclear power plants in the United Kingdom. The figures for the gas-cooled reactor plants are based on an averaging of the estimated costs of the latest large commercial power plants under construction at present. It is to be noted that the influence of size on the cost of the United Kingdom reactors is not easy to assess, since both technological improvements and increases in the size of the reactors are simultaneously reducing unit capital costs in succeeding generations of plants.

26. The figures of Annex II for the small power plants using slightly enriched uranium as fuel are from manufacturers in the United Kingdom; in some cases they are based on designs from the United States. The estimates based on the advanced gas-cooled reactor at present being constructed at Windscale indicate that a large power plant of this type could be built in the United Kingdom for a cost of $220 - $250/kwe during the period 1962 to 1966 [5]. At the World Power Conference in 1960 a construction cost of $280/kwe was quoted for a nuclear plant consisting of two 250 Mwe reactors for commissioning in 1965 [6].

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[5] FLETCHER, P.T., "Commercial Prospects of Atomic Energy", Atom, No. 40, UKAEA, London (February 1960), p. 16-23.

[6] VAUGHAN, R.D., Technical and Economic Development of the Gas-Cooled Reactor, paper IV B/11, WPC, Madrid (1960).

27. The nuclear power program in France is based on the use of natural uranium in gas-cooled reactors, with either graphite or heavy water as the moderator. The present program consists of prototype plants of 50 to 100 Mwe output, on which larger plants in the 300 to 500 Mwe range are being planned for the future. Studies have also been made of small reactors fuelled either with slightly enriched uranium, or with natural uranium and moderated with heavy water. Cost estimates for the reactors which have been studied are summarized in Annex III.

28. Annex IV gives estimates of costs based on studies of natural uranium, heavy-water reactors in Canada. Annex V contains data obtained from the Federal Republic of Germany and Japan.

29. To assist in the extrapolation of these construction costs to other situations, the construction cost breakdowns in the raw data obtained by the Agency are shown in Annex VI and diagrammatically in Figures 1 to 3 therein. This presentation should also facilitate a rough estimation of those cost components which could be met in a country's own currency, thus saving foreign exchange. For comparison purposes the components of the estimated cost of a typical conventional power plant constructed in the United States are included in Figure 4 in Annex VI.

30. It will be seen from these four figures that unless comparable steam conditions are achieved, the cost of turbogenerators and auxiliary equipment will be higher for nuclear plants than for conventional plants of similar sizes. Building and civil works with the special concrete shielding and containment structures needed for a nuclear power plant also cost substantially more; the heat transfer system and the reactor part of a nuclear power plant are more expensive than conventional steam generating equipment. It can therefore hardly be expected that the capital cost of a nuclear power plant will fall below that of a conventional plant unless a major technological advance is achieved.

31. In spite of the considerations in the previous paragraph, there is promise in the coming years of some reduction in the cost components referred to. Conservative containment structures which represent a substantial part of the civil works at present considered necessary for a nuclear power plant may become progressively less extensive or be entirely eliminated. Simpler pumps and more conventional piping materials will bring down some of the coolant circuit costs, and the structural materials of the reactor itself should become cheaper through improvements in manufacturing methods. Higher power densities should also bring a significant reduction in the cost of the reactor.

32. In that context, attention is drawn to the fact that progress in nuclear technology often arises from difficult compromises between various efforts to obtain the maximum advantage from numerous, and sometimes conflicting, technical possibilities. In many cases an improvement which would lead to a decrease in one cost factor would have an unfavorable impact on another. For that reason the possible savings cannot merely be added up; critical judgment must be exercised in combining the improvements that will lead to them.

33. No definite answer can be given to the question of whether these possible cost reductions would generally be equally applicable in a less-developed country. The lower wages for unskilled labor would make for lower construction costs, but the higher salaries of the foreign technicians required for construction and start-up would substantially offset this advantage. The possibly lower prices of some of the domestically produced materials would have to be balanced against the transport charges for the main plant components and the cost of the larger stock of spare parts that would be required. The degree of industrialization of the country would condition possible further savings, but the general conclusion to be drawn is that the cost of installing a nuclear power plant in a less-developed country is not likely to be lower than in the country of manufacture - a conclusion that is also valid for a conventional thermal station.

34. Since information on the construction costs of nuclear plants is still so limited and can be obtained only from design studies made for specific situations and conditions, it is becoming necessary to develop techniques for extrapolating the information to other places and to different construction practices. Otherwise the only alternative is to make a complete design study and cost estimate for the desired place and conditions of construction, a procedure which may be too expensive on many occasions to be justified.

35. Extrapolations of construction costs from one country to another can be done in different degrees of detail. Some improvement on the rough and ready method of applying the relevant official rates of exchange to the total costs can be achieved by dividing the total costs into several major components, such as equipment, building materials, labor and overheads, and subsequently extrapolating each of these components by applying suitable cost indices such as those given in Annex IX. The value of the method is however limited by the uncertainties inherent in the use of cost indices.

36. Even better approximations can be obtained if all the cost components of power plant construction are available for both countries. This, of course, involves the preparation of a comprehensive cost estimate in respect of the country to which the extrapolation is to be made. Although this procedure may seem at first sight to be unduly expensive for the preliminary study of the cost of installing the first nuclear power plant in a country, it should not be overlooked that the results may well prove valuable for the development of plans for subsequent nuclear plants.

C. Fuelling cost

37. The five types of reactor at present considered potentially the most suitable for use in less-developed countries use as fuel enriched or natural uranium metal, oxide or carbide, which is clad in stainless steel, beryllium, or an alloy of aluminum, magnesium or zirconium. Uranium metal is used in the form of plates or cast rods sealed in tubes with suitable heat transfer surfaces; uranium oxide and carbide are used in the form of sintered pellets, sealed in thin walled tubes, bundles of which are assembled to form the fuel element.

38. The available fuelling cost data for most of the reactors discussed in paragraphs 23-28 above are presented in Annexes I to V and VII for certain specified conditions of power plant efficiency, reactor size and expected fuel life. For natural uranium fuel obtained from the United Kingdom costs of $40-56/kgU for fabricated fuel elements and credits of $13-17/kgU for spent fuel elements have been quoted. In Annex VII the costs have been sub-divided to indicate fabrication and running costs separately; the balance includes burn-up and reprocessing costs less the credit for plutonium produced, omitting the shipping charge and inventory cost, which would differ in each particular case. The costs shown are indicative of what can be achieved at the present time with present knowledge; for example, according to the Atomic Energy of Canada Limited, and as can be seen from the figure in Annex VIII, if a burn-up of about 10 Mwd/kgU were achieved in the heavy-water natural uranium reactor with a fabricated fuel cost of $60/kgU, the spent fuel being discarded, the fuelling cost would be about 1 mill/kwh. In general the costs do not reflect price reductions which may possibly occur during the economic life of the reactor; neither do they reflect the 0.2 - 0.6 mills/kwh reduction in the cost of the complete fuel cycle due to the revisions of the USAEC price schedule for enriched uranium and of the use-charge rate, which became effective on 1 July 1961.

39. In Annex I the cost of the fuel in the core loading is shown for each type of United States reactor. This cost, expressed as $/net kwe, is equal to the unit cost of the fuel in $/kgU at USAEC's old price, divided by the specific electrical power in kwe/kgU of the particular reactor. Because of the greater neutron leakage from the smaller reactors, a proportionally larger amount of U^{235} is required to achieve criticality and maintain it throughout the whole period that the fuel remains in the reactor. Hence, for a given type of reactor the total cost of fuel for the core is markedly higher in the smaller sizes. The

cost of the fabricated fuel in the core and the fuel component costs expressed in $/kgU are also shown in Annex I. In most cases a reactor operator in the United States would rent rather than buy the fuel, so that the initial investment would be only for the fabrication part of the cost, the cost of the fuel itself being covered by an annual rent.

40. The recent reduction in USAEC's base charge for slightly enriched uranium for water reactors is about 25% (it varies from 20% for a high degree of enrichment to 34% for a 1% enrichment). This reflects a reduction in the cost of natural uranium concentrates from the old price to \$17.60/kgU_3O_8 (\$21/kgU). There has been no change in the cost of separation in the diffusion plant, but the uranium use-charge has been increased from 4 to 4.75% per year. The net effect is to reduce the total fuel use-charge by about 10%, or about 0.1 mills/kwh or less. Further, the burn-up charge has been reduced by up to 20%; or about 0.2 - 0.5 mills/kwh. Hence the revisions of the USAEC price schedule will result in a reduction in the cost of the complete fuel cycle, since the cost of the separative work component remains unchanged, of 0.2 - 0.5 mills/kwh, although for very small reactors it amounts to as much as 0.6 mills/kwh. These cost reductions are based upon an unchanged purchase price for plutonium of $12/g which will remain in effect until 30 June 1963. If the price of plutonium should subsequently be reduced to reflect its energy value relative to U^{235}, the net effect would be a reduction in the plutonium credit equivalent to 0.1 - 0.2 mills/kwh.

41. Economies may be expected in the future in the fabrication of fuel elements, where standardization of design and larger batch production may cause a 30 - 40% reduction in costs. To quote but one example, one type of fuel element for a pressurized-water reactor which had been previously quoted at about $110/kgU has recently been obtained for about one third less. As can be seen from Annex VIII this means a reduction of about 0.4 mills/kwh in the previous estimate of the fuel cost. No less important is the trend toward higher burn-up, which may be expected to lead to reductions of the order of 15% of the present total fuel costs in certain enriched systems. Finally, decreases in the cost of processing irradiated fuel may occur, especially where continuous processing can replace batch treatment.

42. For a less-developed country that is contemplating the establishment of a nuclear fuel industry the following considerations are of importance. With regard to natural uranium systems, although the mining of ores and the production of concentrates are relatively simple processes, they involve considerable investment. Similarly the production of uranium metal of nuclear purity in small amounts is quite feasible, but the fabrication of fuel elements for use at reactor temperatures, although requiring an investment of only several hundred thousand to a few million dollars, is a much more difficult undertaking. The unit investment cost of a processing plant for irradiated fuel elements increases substantially for smaller throughputs, and a plant of this kind would hardly be economic unless a very substantial nuclear power program were contemplated on a national or regional basis. Finally, the cost of an enrichment plant running into several hundred million dollars clearly rules out this type of development for a less-developed country taking its initial steps towards the utilization of nuclear power.

43. However, as the production of nuclear power increases in a country it is reasonable to expect that some of the operations in the nuclear fuel cycle, such as the mining of uranium ore, the fabrication of fuel elements and possibly the reprocessing of irradiated fuel elements will be performed locally. In the case of a country with a sufficiently large industrial output and a large nuclear power development program, the building of domestic plants to process uranium ores and fabricate fuel elements would appear to be important if expenditure in foreign currency on nuclear power is to be kept to a minimum. On the other hand, the proportion of fixed costs is relatively high for most of the operations in the fuel cycle, so that a fairly large throughput is essential if unit costs are to be kept to reasonable levels. For example, a nuclear plant of 200 Mwe capacity, with an average fuel exposure of 10 Mwd/kgU requires an annual throughput of only 17 tons of fuel, which is much too small to achieve satisfactory unit costs.

44. Information on the unit plant investment cost and the total cost per unit of product for the fuel fabrication steps involved in the natural and slightly enriched uranium cycles is given in Annexes X and XI respectively. [7] Annex XII gives unit costs of shipping irradiated fuel elements, and Annex XIII gives costs of reprocessing irradiated fuel. Annex XIV shows a cost breakdown for the proposed chemical reprocessing plant of Eurochemic, from which the considerable capital investment needed for such a plant can be clearly seen. It follows, therefore, that unless throughputs of several hundred tons a year can be achieved, the unit cost of the reprocessed fuel will be high.

D. Other operating costs

45. The total annual cost of operating and maintaining a conventional thermal power plant, excluding capital and fuel costs, includes the costs of the supervisory, operating and maintenance staff and of the miscellaneous materials and external services required. The same items of cost are involved in operating and maintaining a nuclear power plant, together with the additional costs, which may well be of considerable significance, of such items as third party liability insurance and replacement of losses of expensive coolants such as heavy water. In making cost comparisons it is desirable to show these operating costs in dollars per year per rated kilowatt, to exclude the effect of the plant utilization factor.

46. There is still insufficient information on the operating and maintenance costs of a nuclear power plant used solely for the production of electricity, although estimates have been made by analogy with conventional plants and by inspection of nuclear plant designs. For example it is still uncertain what staff is required. Estimates for water reactors in the United States range from 0.3 - 0.5 employees per Mwe for a 200 - 300 Mwe plant to about 1 to 1.5 employees per Mwe for a 50 - 70 Mwe plant. [8] In the United Kingdom the estimate for a 500 Mwe plant operated by two gas-cooled reactors each of 250 Mwe capacity is about 0.6 employees per Mwe. [9] The figures would be significantly higher for smaller plants, and if the plant were located in an isolated area, they would probably be still higher.

47. Estimates of operating and maintenance costs are presented in Annexes I to V; it should be noted that the annual cost per kilowatt is strongly influenced by the size of the plant. These data indicate that for enriched uranium, water-moderated reactors, normal operating and maintenance costs vary from $20/kwe for a 20 Mwe plant to $4/kwe for a 300 Mwe plant; with an 80% plant utilization factor this corresponds to 3 mills and 0.6 mills/kwe respectively. For the large gas-cooled, natural uranium plants in the United Kingdom operating and maintenance costs are expected to be $5 and $4/kwe respectively for 300 and 500 Mwe plants, which corresponds to 0.7 and 0.6 mills/kwh with an 80% plant factor.

48. Smaller operating staffs, increased automation and lower repair bills are a likely expectation and, together with a greater knowledge of safety requirements, will all contribute to lower operating and maintenance costs. However, since these costs represent less than 10% of the total cost of nuclear power, even a 20% reduction in them would not reduce the total cost by more than 2%.

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[7] ENEA is preparing a report on the cost of the various steps in an enriched uranium fuel cycle.

[8] Power Cost Normalization Studies, report SL-1674, USAEC, Washington, D.C. (January 1960).

[9] Directory of Nuclear Reactors, Vol. I., Power Reactors, STI/PUB/4, IAEA, Vienna (1959), p. 162.

IV. FUTURE TRENDS

49. With nuclear power still at an early stage of development, important reductions in the cost of producing it are envisaged in the future as a result of the technical advances to be expected from the continuous research and development which is now in progress. Present day designs of relatively advanced reactor systems will be further improved to incorporate the experience being gained with the first and second generation plants, and some other reactor concepts now in the experimental stage may prove successful.

50. Reductions in fuel cycle costs will be of great significance; they will result from reductions in fabrication and reprocessing charges, the achievement of higher burn-ups and the lowering of uranium prices. An indication of the reductions in fuel cycle costs which might be achieved is shown in Annex XV for the Canadian cycle, in which the irradiated natural fuel is simply discarded, and for the United States slightly-enriched fuel cycle. It will be seen that nuclear fuel cycle costs in the range of 1 - 2 mills/kwh are predicted, corresponding to about 10 - 20 cents/mill in BTU, which is appreciably below the cost of conventional fuels in most situations.

51. Advanced designs for almost every reactor type also take advantage of various systems of "fuel programing", that is, movement of the fuel to different positions in the reactor. The advantages of this technique are a longer reactivity life for the fuel and a more even distribution of heat production throughout the core, thus permitting a higher average burn-up for a given maximum exposure of the fuel elements. For pressurized-water, organic-cooled and heavy-water-cooled reactors as much as 1 mill/kwh may be saved. If the core power is also increased to take advantage of the resulting improvement in hot-spot regulation, even greater savings in fuel cycle costs are possible.

52. Considerable work is being carried out to develop inexpensive reactor materials with good nuclear properties and capable of withstanding high temperatures; such materials will help to prolong the useful life of nuclear plants. Sizeable savings can be expected from the standardization and improvement of reactor components such as pumps, valves and heat exchangers which represent a large fraction of the total investment. Lack of extensive experience of reactor safety has led to conservative and costly designs for containment shells, control mechanisms and instrumentation; with better understanding of essential safety requirements and the use of improved techniques, the containment and control of reactors will certainly be simplified without sacrificing reliability and safety. Most of the nuclear power plants now under construction are one of a kind; when several plants of essentially the same design are built, the engineering development expenses will be spread out and the cost per unit will decrease.

53. It has been estimated that the cost of generating power with the large gas-cooled reactors in the United Kingdom with a 75% plant utilization factor and an annual capital charge of about 8% will be 7 mills/kwh in 1964, leveling off to 5 mills/kwh after 1974. [10] Conventional fuel is predicted to level off at 49 cents/million BTU, and the cost of generating power by conventional means is expected to decrease from 6.3 - 5.8 mills/kwh in the same period and with the same plant utilization factor. In the United Kingdom, therefore, nuclear power is likely to become competitive with conventional power about 1966.

54. According to a recent USAEC evaluation which assumes a 14% annual capital charge, and 80% plant factor and no changes in USAEC's present schedule of uranium charges or in its purchase price of plutonium, the generating cost of power produced from slightly enriched uranium in a 200 Mwe capacity reactor, which on the basis of present technology would fall between 11 and 14 mills/kwh [8], is expected to decrease later into the

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[10] HINTON, Sir C. et al., The Economics of Nuclear Power in Great Britain, paper IV B/8, WPC, Madrid (1961).

9 - 10 mills/kwh range [11]. Assuming that improvements in the efficiency of conventional thermal power plants are leveling off, power generated under the same conditions in a large nuclear power plant to be constructed toward the end of the next decade would become competitive in cost with conventional thermal power in areas where conventional fuel costs were about 55 cents/million BTU ($2.20/million kilocalories).

55. It is interesting to note, however, that if the annual capital charge is taken as 7 instead of 14%, and the other conditions specified in paragraph 54 above remain unchanged, the generating cost of nuclear power, which on the basis of present technology would fall between 8 and 10 mills/kwh, might come down later into the 6.5 - 7.5 mills/kwh range. At that time and under the same conditions such power would become competitive with conventional thermal power in areas where conventional fuel costs were above 45 cents/ million BTU ($1.80/million kilocalories).

56. The foregoing concluding observations are put forward with the object of drawing the attention of Member States to some of the principal considerations that will in the future determine the conditions under which nuclear power may become competitive. It is also clear that as such factors as types of reactors, sizes of plants, plant utilization factors and rates of annual capital charges change, the limits of competitiveness will correspondingly vary to a substantial degree.

[11] Computations based on data from the course cited in footnote 9, and on the Statement of the United States Atomic Energy Commission to Joint Committee on Atomic Energy, as summarized in Nucleonics, v. 18, No. 4, New York, N.Y. (April 1960), p. 71 ff.

ANNEX I

A N

Nuclear power cost data (Unite

Size range	12.65 Mwe (gross) b/					44 Mwe (gross) b/						
Plant type	Coal d/	PWR	BWR	OCR	HWE	Coal d/	PWR	BWR	OCR	HWE	GCE	C(
Net Mwe	11.83	11.80	12.0	11.39	11.80	41.65	41.6	42.0	40.9	41.3	36.5	5E
Capital cost ($/kwe)	447	1156	892	959	1378 e/	262	575	457	432	732 e/	930	2
Fuel material		UO_2	UO_2	U-10%Mo	UO_2		UO_2	UO_2	U-10%Mo	UO_2	UO_2	
Fuel cladding		SS	SS	Al	Zr-2		SS	SS	Al	Zr-2	SS	
Fuel enrichment (wt% U^{235})		4.45	2.8	2.28	1.5		3.95	2.5	2.53	1.1	2.08	
Average exposure level (10^3 Mwd/t)		13	6.3	8	13		13	9	8	13	9	
Over-all thermal efficiency (%)		25.7	27.6	26.1	25.9		27.7	31.6	30.3	27	30.5	
Core fuel cost ($/net kwe) (USAEC price list) f/		176	95	75	30		141	75	64	24	101	
Fabricated fuel in core ($/net kwe) f/		207	120	104	63		170	98	79	65	146	
Fuel cycle cost ($/kgU)												
Fabrication		106	91	101	159		106	89	70	151	102	
Shipping		16	16	16	16		16	16	16	16	16	
Depletion		220	103	124	137		201	134	133	84	124	
Reprocessing		56	60	50	75		54	48	46	52	47	
USAEC use charge (4%) f/		73	24	19	8		63	26	20	6	31	
Pu credit ($12/g)		(59)	(39)	(42)	(89)		(66)	(53)	(40)	(96)	(54)	
Total ($/kgU) f/		412	255	268	306		374	260	245	213	266	
Fuel cycle cost (mills/kwh) f/		5.2	6.1	5.3	3.8		4.3	3.8	4.2	2.5	4	
Operation and maintenance ($/rated kw-yr)		37	35	43	50		12	11	16	20	18	
Nuclear liability insurance ($/rated kw-yr)		11.5	11	11	11.5		5	5	5	5	5.5	

a/ Variations in cost data of this table reflect different designers' estimates and not necessarily actual costs.

b/ Source: Study of Nuclear Power Plants Capital and Power Generating Costs, 44 Mwe and 12.65 Mwe (gross), report KE 60-19, USAEC, Oakland, Calif. (October 31, 1960).

c/ Source: Power Cost Normalization Studies, report SL-1674, USAEC, Washington, D.C. (January 1960); fuel cost interpolated from original design data; interest on fabrication capital included in fabrication cost; OCR fuel cost extrapolated from USAEC report KE 60-19, to reflect latest estimates.

X I

tates, present technology)[a]

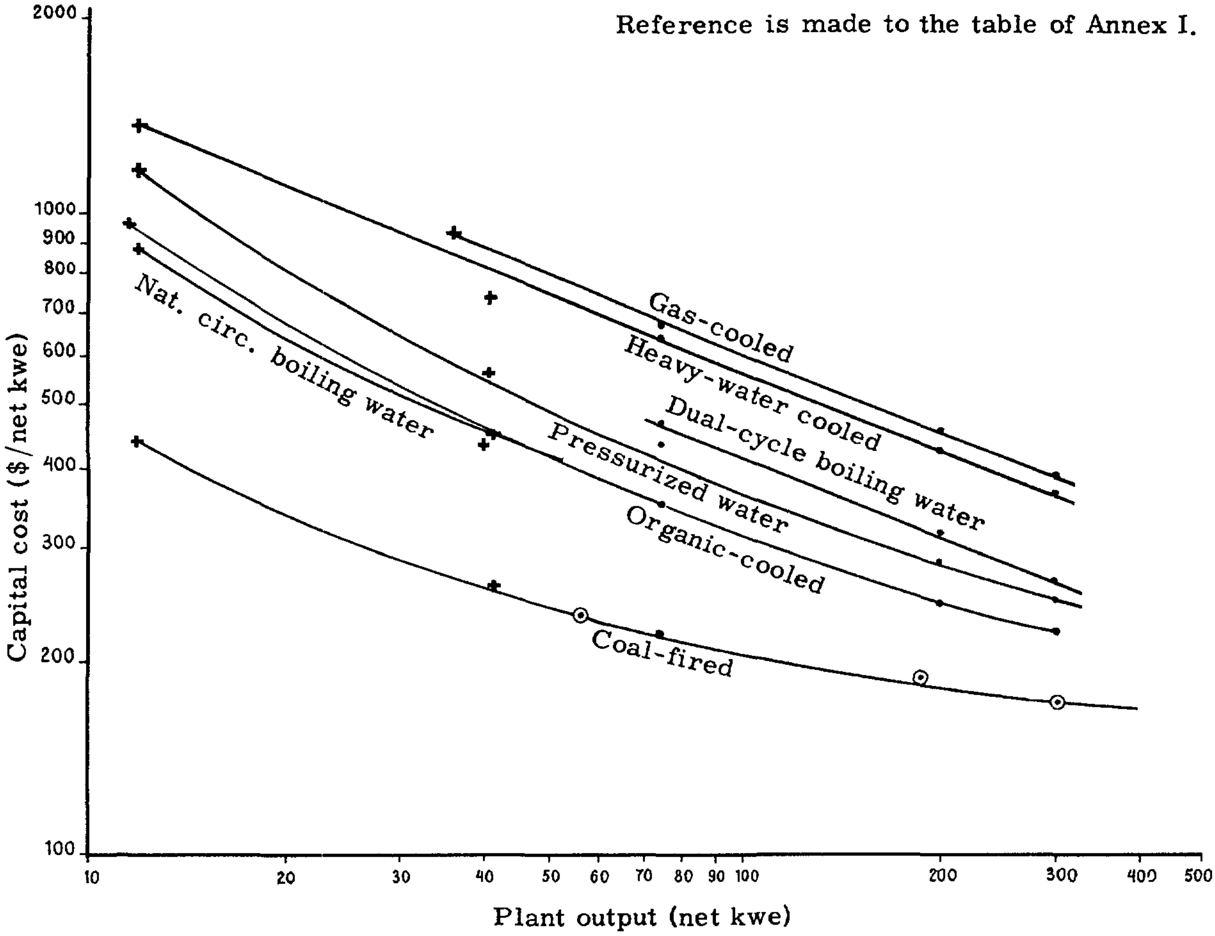
56 - 75 Mwe (net)[c]					180 - 200 Mwe (net)[c]						300 Mwe (net)[c]					
PWR	BWR	OCR	HWN	GCN	Coal	PWR	BWR	OCR	HWN	GCN	Coal	PWR	BWR	OCR	HWN	GCN
75	75	75	75	75	187.7	200	200	200	200	200	303.4	300	300	300	300	300
435	470	350	640[e]	675	186	282	311	241	425[e]	452	171	242	263	220	360[e]	380
UO_2	UO_2	U-10%Mo	U-Zr	U		UO_2	UO_2	U-10%Mo	U-Zr	U		UO_2	UO_2	U-10%Mo	U-Zr	U
SS	Zr-2	Al	Zr-2	Magnox		SS	Zr-2	Al	Zr-2	Magnox		SS	Zr-2	Al	Zr-2	Magnox
3.2	2.1	2.1	0.71	0.71		3.2	1.9	1.9	0.71	0.71		3.2	1.7	1.7	0.71	0.71
13	11	8	3.85	3		13	11	8	3.85	3		13	11	8	3.85	3
4	28.7	28.5	23	-		24.8	29	29.2	23	24.1		25.2	31.2	29.4	23	-
115	60	65	14	-		95	40	60	5.5	64		95	32	58	4.5	-
149	109	80	33	-		123	78	73	13	89		123	60	69	10.5	-
126	160	63	56	-		124	154	60	56	17		126	156	55	55	-
15	15	16	16	-		16	15	15	16	9		16	16	14	15	-
185	136	120	27	-		162	130	110	26	30		165	132	101	26	-
30	38	42	26	-		31	38	38	25	21		31	33	35	25	-
45	30	16	2	-		39	15	14	1	9		40	16	13	1	-
(60)	(61)	(37)	(25)	-		(70)	(61)	(34)	(26)	(25)		(79)	(66)	(31)	(28)	-
341	318	220	102	68		302	291	203	98	61		299	287	187	94	59
4.6	4.2	4.0	4.8	3.9		3.9	3.8	3.6	4.6	3.5		3.8	3.5	3.3	4.4	3.4
9.5	9.5	13	13	10		5.5	5.5	9	8	5.5		4	4	7.5	6.5	4
3.5	3	3	3	3		1.5	1.5	1.5	1.5	1.5		1	1	1	1	1

d/ Hypothetic case.

e/ The capital cost for heavy-water reactors includes the cost of heavy water at $28/lb.

f/ Effective 1 July 1961, the USAEC reduced its base charges for enriched uranium and increased its use charge rate from 4 to 4.75%/year. This results in up to a 20% reduction in the depletion and 10% in use charge, or about 0.2 to 0.6 mill/kwh over-all reduction in the fuel cycle cost.

Reference is made to the table of Annex I.



Capital Cost Estimates for Power Plants in the United States of America (Present Technology)

ANNEX II

Nuclear power cost data (United Kingdom, present design)[a]

Size range	10 - 100 Mwe					30 - 50 Mwe			150 - 550 Mwe			
Plant type	PWR[b]	PWR[b]	PWR[b]	PWR[b]	PWR[b]	GCE[c]	GCN[d]	GCN[e]	GCN[f]	GCN[e]	GCN[f]	GCN[g]
Net Mwe	10	20	30	60	100	30	24	50	150	300	2x250	2x275
Capital cost ($/kwe)	590	450	400	337	289	510	470	700	450	280	320	310-340
Fuel material	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	U	U	U	U	U	U
Fuel cladding	Zr-2	Zr-2	Zr-2	Zr-2	Zr-2	SS	Magnox	Magnox	Magnox	Magnox	Magnox	Magnox
Fuel enrichment (wt% U^{235})	2.75	2.6	2.5	2.3	2.2	2.2	0.71	0.71	0.71	0.71	0.71	0.71
Average exposure level (10^3 Mwd/t)	10[h]	10[h]	10[h]	10[h]	10[h]	10	2.2[h]	3	3	3	3	3
Over-all thermal efficiency (%)	28.5	28.5	28.5	28.5	28.5	30	22.3	-	30	-	30	32
Core fuel cost ($/net kwe)	109	70	66	59	56	43	-	-	-	-	-	-
Fabricated fuel in core ($/net kwe)	154	102	97	90	86	62[i]	126	45-60	46	45-60	46	55
Fuel cycle cost ($/kgU)												
Fabrication	-	-	-	-	-	-	42	-	42	-	42	49
Shipping	-	-	-	-	-	-	-	-	-	-	-	-
Depletion	-	-	-	-	-	-	-	-	-	-	-	-
Reprocessing	-	-	-	-	-	-	-	-	-	-	-	-
Use charge	-	-	-	-	-	-	-	-	-	-	-	-
Pu credit	-	-	-	-	-	-	-	-	-	-	-	-
Total ($/kgU)	390	380	360	340	330	-	28[j]	-	25[k]	-	25[k]	36[l]
Fuel cycle cost (mills/kwh)	5.7[h]	5.5[h]	5.2[h]	5.0[h]	4.8[h]	-	2.4[h]	-	-	-	-	1.6
Operation and maintenance ($/rated kw-yr)	18	13	11	9	8	16	14	-	-	-	-	4
Nuclear liability insurance ($/rated kw-yr)	-	-	-	-	-	-	-	-	-	-	-	-

a/ All figures are design estimates.

b/ Source: WEBB, T.B. and PROSSER, H.S., "Economics of a Range of Small Pressurized Water Power Stations", Small and Medium Power Reactors, v.2, IAEA, Vienna (1961), p. 193; the capital cost estimates are considerably lower than the US figures given in Annex I.

c/ Source: "Small Nuclear Power Stations - By Britain", Engineering, v. 189, London (15 April 1960), p. 517-522.

d/ Source: RUDD, D. and STRICKLAND, R.E., "LPR - a 30 Mw Natural-Uranium Nuclear Power Station", Small and Medium Power Reactors, v. 1, IAEA, Vienna (1961), p. 459.

e/ Source: FLETCHER, P.T., "Commercial Prospects of Atomic Energy", Atom, No. 40, UKAEA, London (February 1960), p. 16-23.

f/ Source: "Magnox Reactor Generating Costs - An Up-to-date Assessment", Nuclear Engineering, v. 5, No. 46, London (March 1960), p. 95.

g/ Source: Private communication for a plant to be completed in 1963-64.

h/ No fuel shuffling; with shuffling the exposure of the fuel discharged could be doubled. (At an assumed additional cost of $100/kg for net fuel consumption the fuel cost would be reduced by 1.5 to 2.0 mills/kwh).

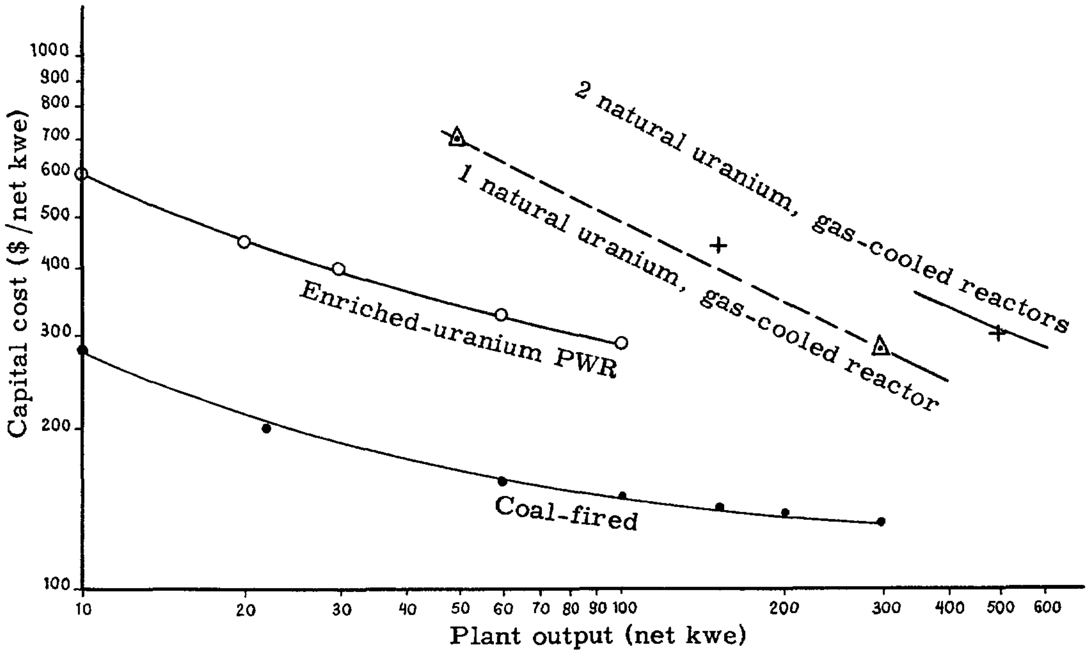
i/ Assuming $110/kgU for fabrication.

j/ Net spent fuel credit of $14/kgU, no shipping charges.

k/ Net spent fuel credit of $17/kgU, no shipping charges.

l/ Net spent fuel credit of $13/kgU, no shipping charges.

Reference is made to the table of Annex II.



Capital Cost Estimates for Power Plants in the United Kingdom (Present Design)

ANNEX III

Nuclear power cost data (France, present design)[a/][b/]

Size range	30 - 80 Mwe				100 - 200 Mwe		
Plant type	HWGC	GCE	GCN	HWGC	GCE	GCN	GCN
Net Mwe	30	50	60	80	100	100	200
Capital cost ($/kwe)	-	500	485	-	350	380	270
Fuel material	U-Mo rod	U tube	U rod	UO_2	U tube	U rod	U tube
Fuel cladding	Mg-Zr	Magnox	Magnox	Be	Magnox	Magnox	Magnox
Fuel enrichment (wt% U^{235})	0.71	0.8	0.71	0.71	0.75	0.71	0.71
Average exposure level (10^3Mwd/t)	5	3	3	10	3	3	3
Over-all thermal efficiency (%)	30	30	30	32	30	30	30
Core fuel cost ($/net kwe)[c/]	20	62	68	9	48	61	45
Fabricated fuel in core ($/net kwe)	34	85	85	-	68	79	63
Fuel cycle cost ($/kgU)							
Fabrication	-	-	-	-	-	-	-
Shipping	-	-	-	-	-	-	-
Depletion	-	-	-	-	-	-	-
Reprocessing	-	-	-	-	-	-	-
Use charge	-	-	-	-	-	-	-
Pu credit	-	-	-	-	-	-	-
Total ($/kgU)	54	57	41	154	52	41	48
Fuel cycle cost (mills/kwh)	1.5	2.7	1.9	2.0	2.4	1.9	2.2
Operation and maintenance ($/rated kw-yr)	-	-	-	-	-	-	-
Nuclear liability insurance ($/rated kw-yr)	-	-	-	-	-	-	-

a/ All figures are design estimates.

b/ Source: BUSSAC, J., "Développement du programme français de réacteurs à gaz et applications aux centrales de moyenne puissance", Small and Medium Power Reactors, v. 1, IAEA, Vienna (1961), p. 371.

c/ Based on a price of $40.5/kgU.

ANNEX IV

Nuclear power cost data (Canada, present design)[a/]

Plant type	OCHWN[b/]	HWN[c/]	HWN[d/]	HWN[e/]	HWN[e/]
Net Mwe	55	68	132	200	2x200
Capital cost ($/kwe)[f/]	435	507	445	347-407	265-300
Fuel material	UO_2	UO_2	UO_2	UO_2	UO_2
Fuel cladding	Zr-2	Zr-2	Zr-2	Zr-2	Zr-2
Fuel enrichment (wt% U^{235})	0.71	0.71	0.71	0.71	0.71
Average exposure level (10^3 Mwd/t)	6	5.4	7.8	9.8	9.8
Over-all thermal efficiency (%)	28	28.7	25	29	29
Core fuel cost ($/net kwe)	6	8[g/]	11	7-8[g/]	7-8[g/]
Fabricated fuel in core ($/net kwe)	16	16	32	13-16	13-16
Fuel cycle cost ($/kgU)					
Fabrication plus fuel	79	68	128	93	93
Shipping	-	-	-	-	-
Depletion	-	-	-	-	-
Reprocessing	0	0	0	0	0
Use charge	7	3	-	-	-
Pu credit	0	0	0	0	0
Total ($/kgU)	86	71	128	93	93
Fuel cycle cost (mills/kwh)	2.2	1.9	2.7	1.4	1.4
Operation and maintenance[h/] ($/rated kw-yr)	11	11	9	7	5
Heavy water make-up ($/rated kw-yr)	-	1	1	-	-
Nuclear liability insurance ($/rated kw-yr)	-	-	-	1	1

a/ All figures of this table are design estimates.

b/ Source: Communication of Canadian General Electric Company Ltd., Toronto.

c/ Source: Communication of the Atomic Energy of Canada Limited, Chalk River, Ont.

d/ Source: Communication of Canadian Westinghouse International Company Ltd., Hamilton, Ont.

e/ Source: LEWIS, W.B., "Competitive Nuclear Power for Canada"; MOORADIAN, A.J. and ROBERTSON, J.A.L., "CANDU Fueling Costs", Nucleonics, v.18, No. 10, New York, N.Y. (October 1960), p.54 and 60 respectively; see also Annex XV.

f/ Includes D_2O investment.

g/ Based on a price of $35/kgU.

h/ Includes D_2O make-up.

ANNEX V

Nuclear power cost data (Germany, Japan, present design)[a]

Country	Germany					Japan				
Plant type	BWR[b]	BWR[b]	OMR[c]	HWN[d]	GCE[e]	BWR[f]	BWR[g]	PWR[h]	GCN[i]	BWR[h]
Net Mwe	15	30	16	49	35	10	12	134	166	180
Capital cost ($/kwe)	540	360-400	520	400	400-485	670	850	436	528	410
Fuel material	UO_2	-	U-Mo	-	UO_2	-	-	UO_2	U	UO_2
Fuel cladding	Zr-2	-	Al	-	-	-	-	SS	Magnox	Zr-2
Fuel enrichment (wt% U^{235})	2.3	-	1.8	0.71	4	2.2	2.6	2.6	0.71	1.4
Average exposure level (10^3 Mwd/t)	8.8-11	-	4	4	8.8	10	10	-	-	11
Over-all thermal efficiency (%)	27.2	-	26.7	24.5	27	26.3	25	-	-	28.8
Core fuel cost ($/net kwe)	98	-	82	-	75	82	114	57	-	38
Fabricated fuel in core ($/net kwe)	158	-	102	40	88	-	-	-	70[j]	91
Fuel cycle cost ($/kgU)										
Fabrication	159	-	46	-	92	-	-	-	-	184
Shipping	-	-	3	-	-	-	-	-	-	18
Depletion	-	-	66	-	103	-	-	-	-	105
Reprocessing	-	-	42	-	-	-	-	-	-	35
Use charge	-	-	20	-	22	-	-	-	-	29
Pu credit	-	-	(28)	-	-	-	-	-	-	(55)
Total ($/kgU)	-	-	149	-	217	-	-	-	-	316
Fuel cycle cost (mills/kwh)	7	-	5.8	-	3.8	-	-	-	-	4.2
Operation and maintenance ($/rated kw-yr)	17	-	22[k]	10	3	14	-	8	7	8
Nuclear liability insurance ($/rated kw-yr)	-	-	-	-	-	-	-	-	2.5	-

a/ All figures are design estimates.

b/ Source: BRÜCHNER, H.-J., "The 15 Mwe Nuclear Power Station With Boiling-Water Reactor at Kahl/Main - Its Construction and Its Potential Utilization in Developing Areas", Small and Medium Power Reactors, v. 1, IAEA, Vienna (1961), p. 37; and communication by Allgemeine Elektricitäts Gesellschaft, Frankfurt/Main.

c/ Source: Communication by INTERATOM, Internationale Atomreaktorbau G.m.b.H., Bensberg/Köln.

d/ Source: Communication by Siemens-Schuckert Werke AG., Erlangen.

e/ Source: Communication by the Deutsche Babcock und Wilcox-Dampfkesselwerke AG., Oberhausen-Rheinland.

f/ Source: Communication by Hitachi, Ltd., Tokyo.

g/ Source: Communication by Nippon Atomic Industry Group Co. Ltd., Tokyo.

h/ Source: Communication by The Kansai Electric Power Co., Inc., Osaka.

i/ Source: Communication by the Japan Atomic Power Company, Ltd., Tokyo.

j/ Based on a price of $58/kgU.

k/ Includes $5 for organic coolant make-up.

ANNEX VI

Breakdown of the costs of power stations[a]

Identification number and item of cost	PWR 44 Mwe $/kw	PWR 44 Mwe %	PWR 300 Mwe $/kw	PWR 300 Mwe %	BWR 44 Mwe $/kw	BWR 44 Mwe %	BWR 300 Mwe $/kw	BWR 300 Mwe %	GCN 300 Mwe %	HWN 132 Mwe $/kw	HWN 132 Mwe %	HWN 200 Mwe $/kw	HWN 200 Mwe %	CONVENTIONAL 235 Mwe $/kw	CONVENTIONAL 235 Mwe %
I. Buildings and civil works															
Site preparations and improvements	20	4	5	2	20	4	5	2	-	-	-	7	2	-	-
Containment and civil works	47	8	12	5	42	9	29	11	-	-	-	26	8	-	-
Other structures and civil works	31	5	9	4	26	6	11	4	-	-	-	35	11	-	-
Sub-total	98	17	26	11	88	19	45	17	25	77	20	68	21	32	18
II. Reactor and auxiliary equipment															
Reactor equipment	138	24	27	11	89	19	29	11	21	39[b]	10[b]	54[b]	16[b]		
Fuel handling	10	2	5	2	4	1	5	2	1	11	3	8	3		
Waste disposal	8	1	2	1	7	2	3	1	1	15	4	4	1		
Instrumentation	36	6	5	2	26	6	8	3	1	8	2	22	7		
Sub-total	192	33	38	16	126	28	45	17	24	73[b]	19[b]	88[b]	27[b]	Boiler equipment	
III. Heat transfer and steam generation equipment															
Primary coolant equipment	-	-	41	17	7	1	29	11	12	54	14	17	5		
Water supply and treatment	-	-	5	2	21	5	5	2	4	8	2	8	2		
Steam generation equipment	-	-	29	12	30	7	34	13	14	39	10	15	5		
Sub-total	107	19	75	31	58	13	68	26	30	101	26	40	12	63	36
IV. Turbo-generator and accessory power equipment															
Turbo-generator and auxiliaries	82	14	55	23	98	21	58	22	19	66	17	42	13	63	36
Condenser and water system	24	4	15	6	24	5	13	6	1	19	5	15	4	-	-
Auxiliary and miscellaneous power plant equipment to high voltage line	32	6	15	6	31	7	16	5	1	23	6	29	9	6	3
Sub-total	138	24	85	35	153	33	87	33	21	108	28	86	26	69	39
V. Interest during construction	40	7	18	7	32	7	18	7	-	27	7	46	14	12	7
TOTAL	575	100	242	100	457	100	263	100	100	386[b]	100[b]	328[b]	100[b]	176	100

a/ The figures given for nuclear plants are provisional estimates relating only to planned reactors. All indirect costs such as those for engineering, contingencies and start-up have been proportionately shared between the various items of cost shown in the above table.

b/ The cost of the D_2O moderator is not included in this figure.

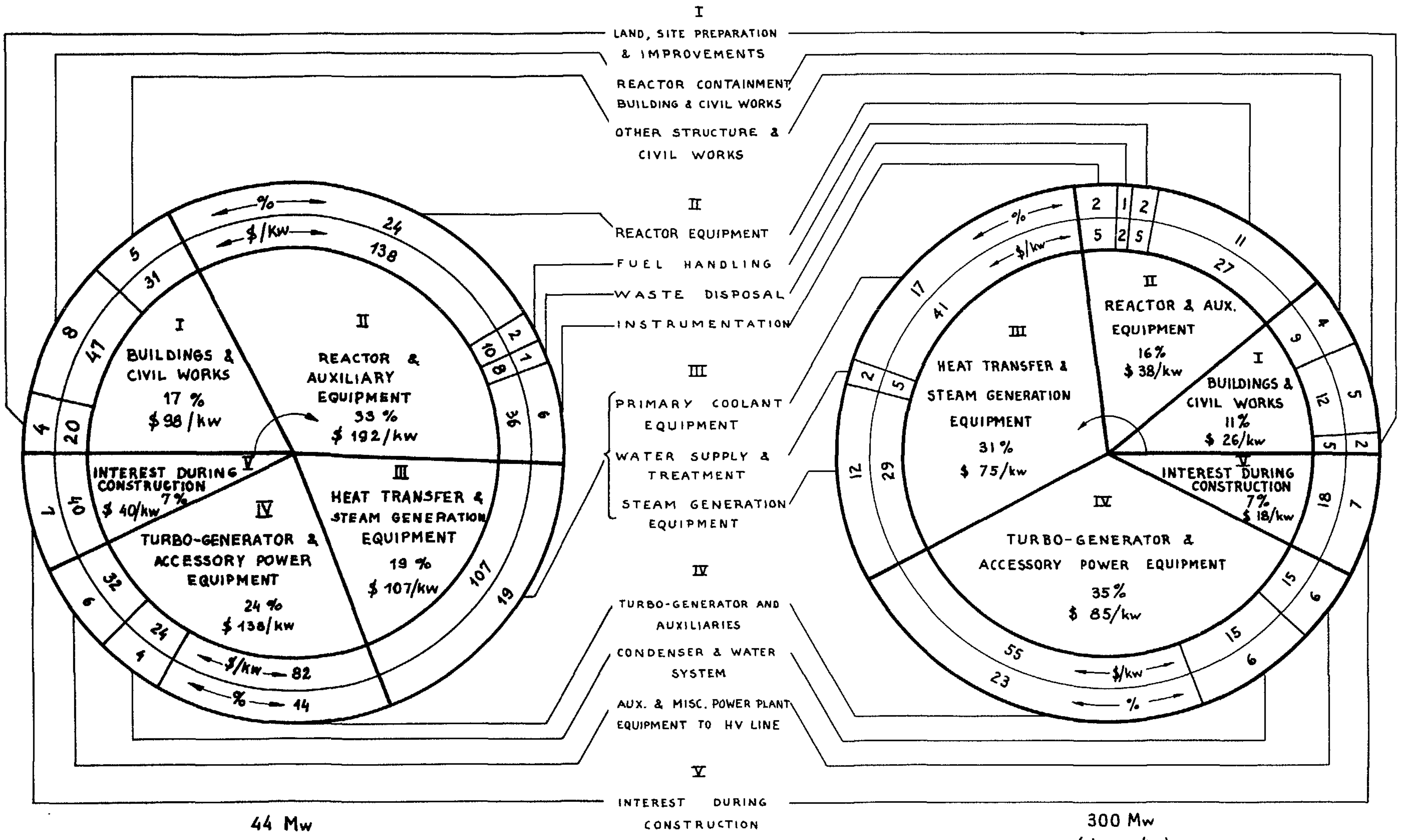


FIGURE I

BREAKDOWN OF NUCLEAR POWER PLANT COSTS FOR PLANNED PRESSURIZED-WATER REACTORS

Note: Percentages adjusted to whole numbers

References: USAEC report KE-60-19
USAEC report SL-1674

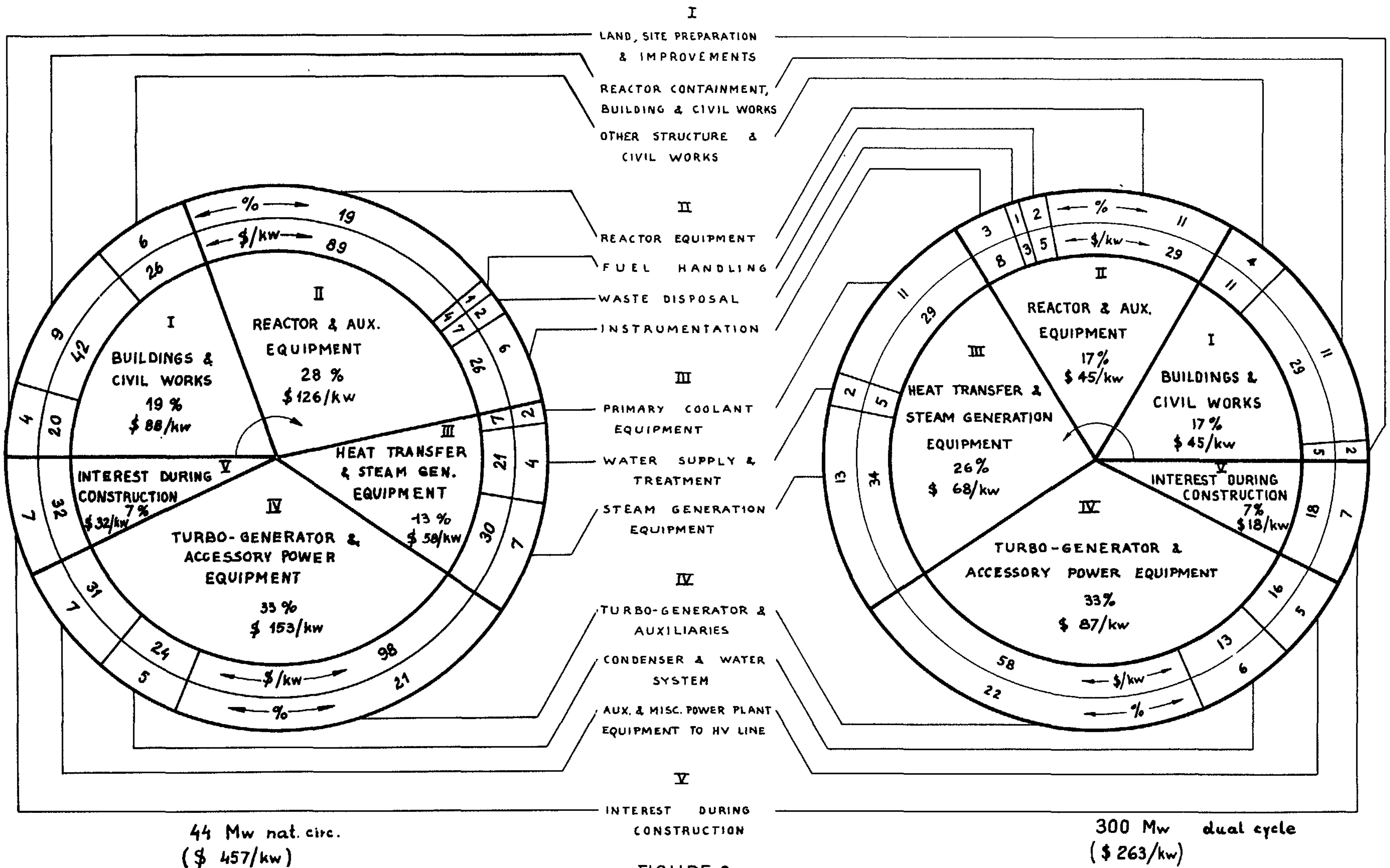
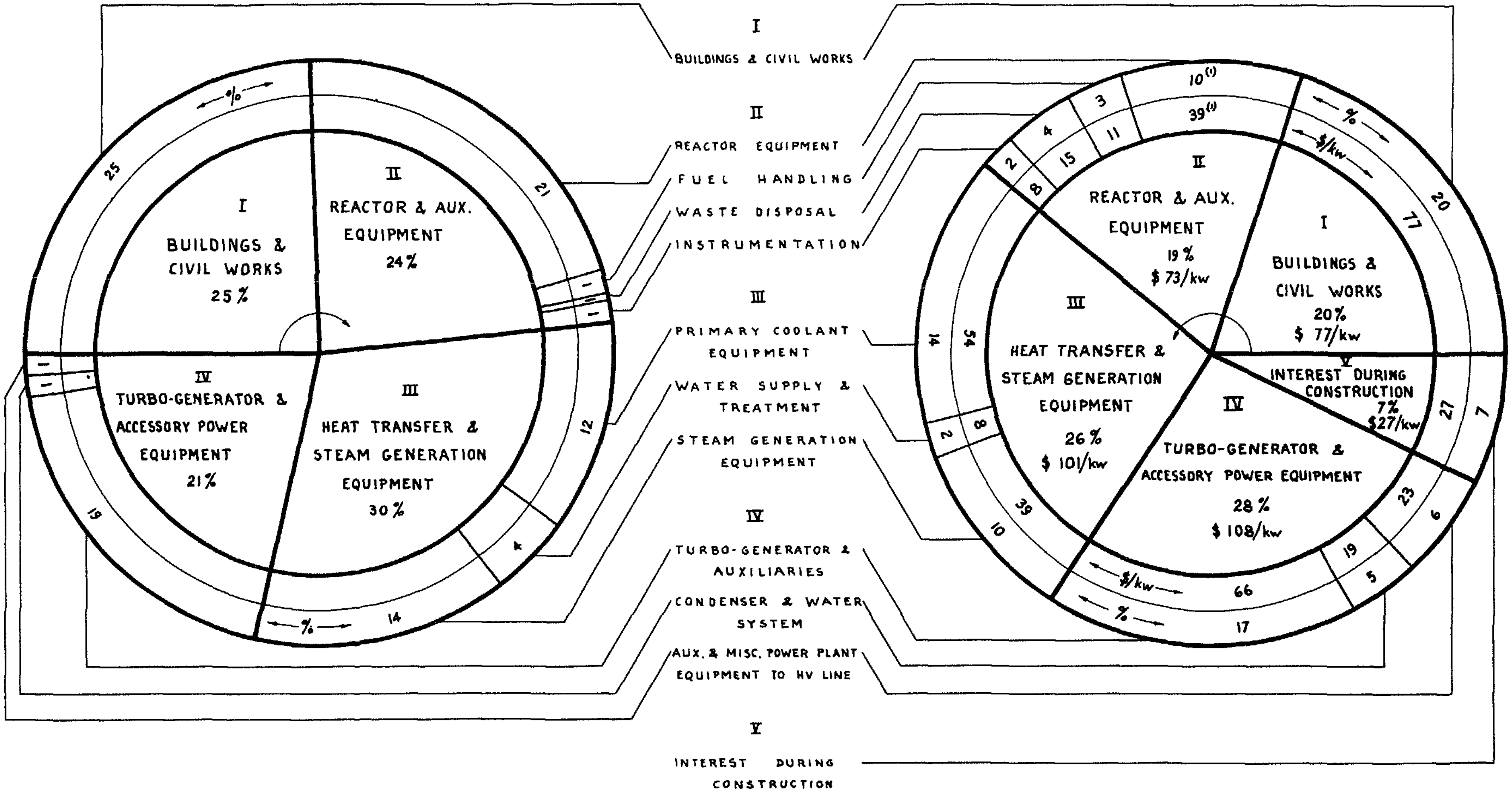


FIGURE 2

BREAKDOWN OF NUCLEAR POWER PLANT COSTS FOR PLANNED BOILING-WATER REACTORS (DUAL CYCLE)

Note-Percentages adjusted to whole numbers

References: USAEC report KE-60-14



PLANNED GAS-COOLED REACTOR
(U K, > 300 Mw)

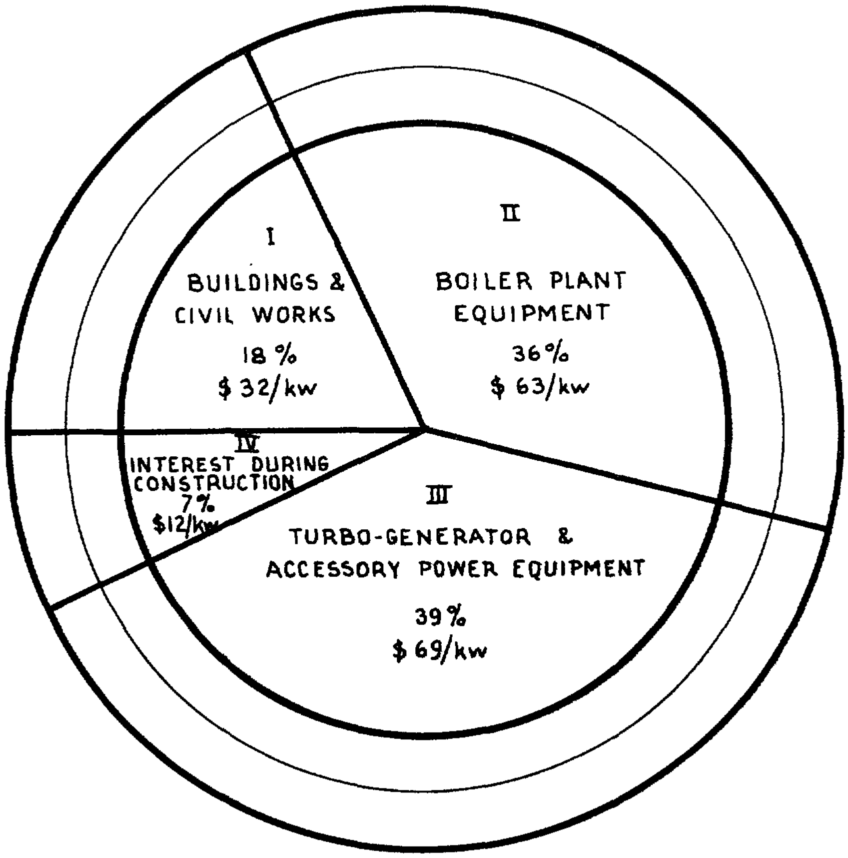
FIGURE 3

PLANNED HEAVY-WATER REACTOR
(CANADA. 132 Mw, $386/kw)

BREAKDOWN OF NUCLEAR POWER PLANT COSTS

Notes: (1) Excludes D_2O moderator
Percentages adjusted to whole numbers
Cost of land excluded

References: UKAEA
Canada: Private communication

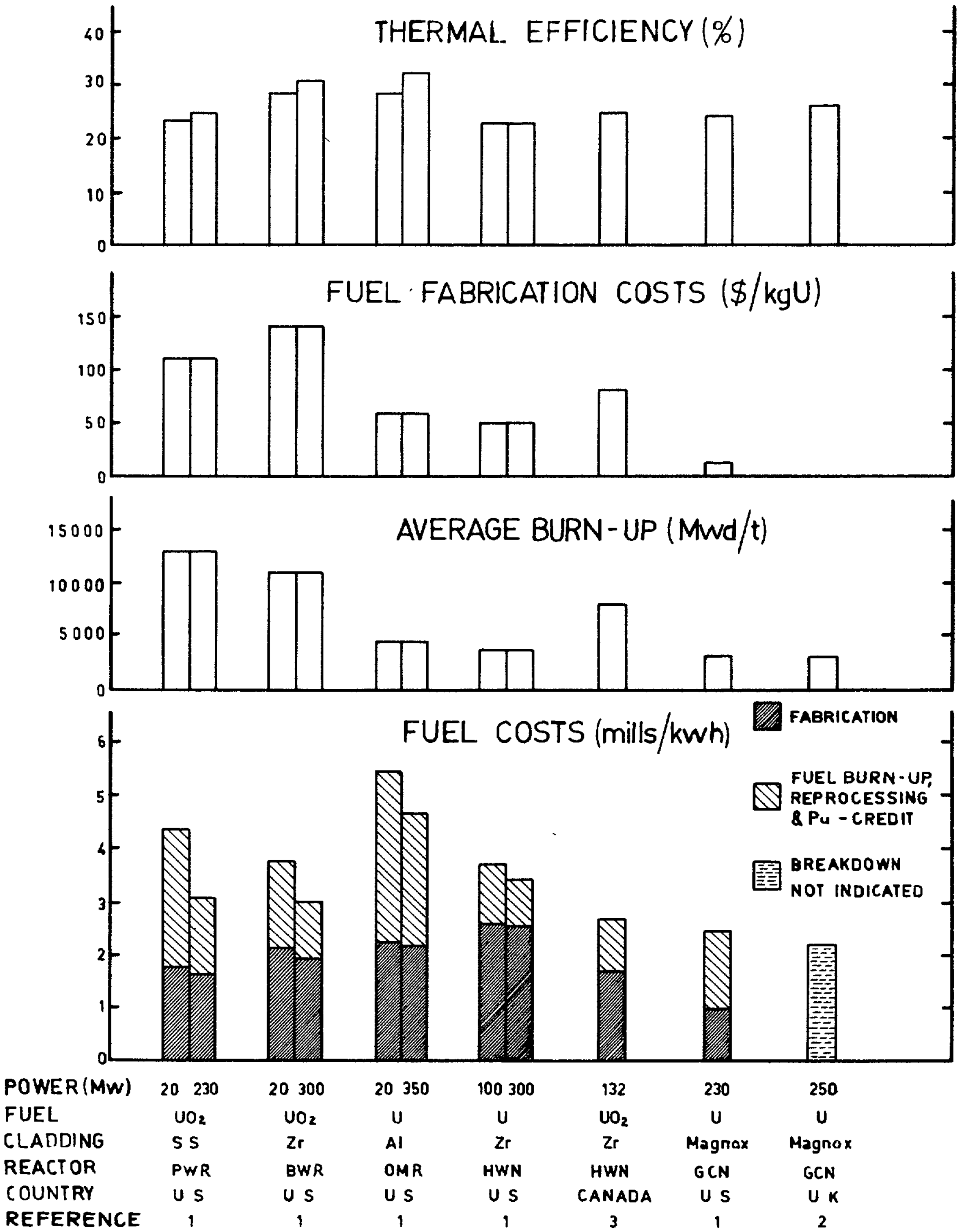


235 Mw
($ 176/kw)

FIGURE 4

BREAKDOWN OF TYPICAL CONVENTIONAL POWER PLANT COSTS IN THE UNITED STATES

Reference: STONE and WEBSTER to USAEC, COMMUNICATION SWI.



ESTIMATED NUCLEAR FUEL COSTS
BASED ON PRESENT-DAY PRICES

Notes: For planned reactors, plant factor 80%
Shipping and inventory costs excluded
References: 1. USAEC, report SL-1674
2. FLETCHER, P.T., Atom (Feb. 1960)
3. Private communication

ANNEX VIII

Examples of calculations of component cost of electric power generation

For the assessment of the various cost components upon the electric generation cost, and to indicate the effect of possible changes, a chart has been prepared as shown in the figure attached hereto. The chart permits an approximate but quick computation for the fuel, capital and other charges, using the data similar to that given in the report and the capital charge rate and plant factor applicable to the specific situation.

Example I. Total generating cost calculation

The fuel, capital and other component costs of the electric power generation are obtained as indicated in the chart by A, B and C respectively.

A. Fuel cost

Given that the net fuel costs in \$/kgU charged to the reactor are \$45 (which includes costs of fuel preparation, fabrication, burn-up, inventory, plutonium credit, processing charges and shipment) and the expected average fuel exposure is 3 Mwd/kgU, the heat cost, as indicated in the chart, is \$15/Mwd (or 18¢ per million BTU). For a plant having a thermal efficiency of 30% (for conversion of heat generated to net electrical kilowatt-hours sent out) the fuel cost in mills/kwh is 2.1 as shown in the chart by A.

B. Capital cost

Given a unit capital cost of \$400 per net kilowatt of electricity sent out by the plant and a total annual charge rate of 8%/year (including interest and repayment of loan), the annual charge per kilowatt as indicated in the chart would be \$32. For a plant operating at an 80% plant factor, the capital cost component in mills/kwh would be 4.6 as indicated in the chart by B.

C. Other costs

This item will include all other annual charges not included in A or B above, such as operation and maintenance costs. Assuming these costs at \$5/kw-yr and a plant factor of 80% as above, this cost in mills/kwh would be 0.7 as indicated in the chart by C.

D. Total generating cost

The total cost of electricity generation is the sum of A + B + C, or, for this example, 2.1 + 4.6 + 0.7 = 7.4 mills/kwh.

Example II. Effect of change in the capital charge rate

Assuming the conditions as in the above example, but the capital charge rate to be 14% per year rather than 8% per year (to reflect charges due to taxes, etc.), the capital cost component obtained from the chart, (B), is 8.0 instead of 4.6 mills/kwh. The total generating cost thus becomes A + B + C = 2.1 + 8.0 + 0.7 = 10.8 mills/kwh.

Example III. Effect of nuclear liability insurance

If the same conditions as in Example II are taken, and additionally about $2/kw-yr is assumed for the nuclear liability insurance, giving a total for other costs of $7/kw-yr, as obtained from the chart, (C), at the 80% plant factor, the cost incurred would be about 1.0 mill/kwh. Thus the total generating cost is then A + B + C = 2.1 + 8.0 + 1.0 = 11.1 mills/kwh.

Example IV. Effect of reduction in capital cost investment due to improvement in design

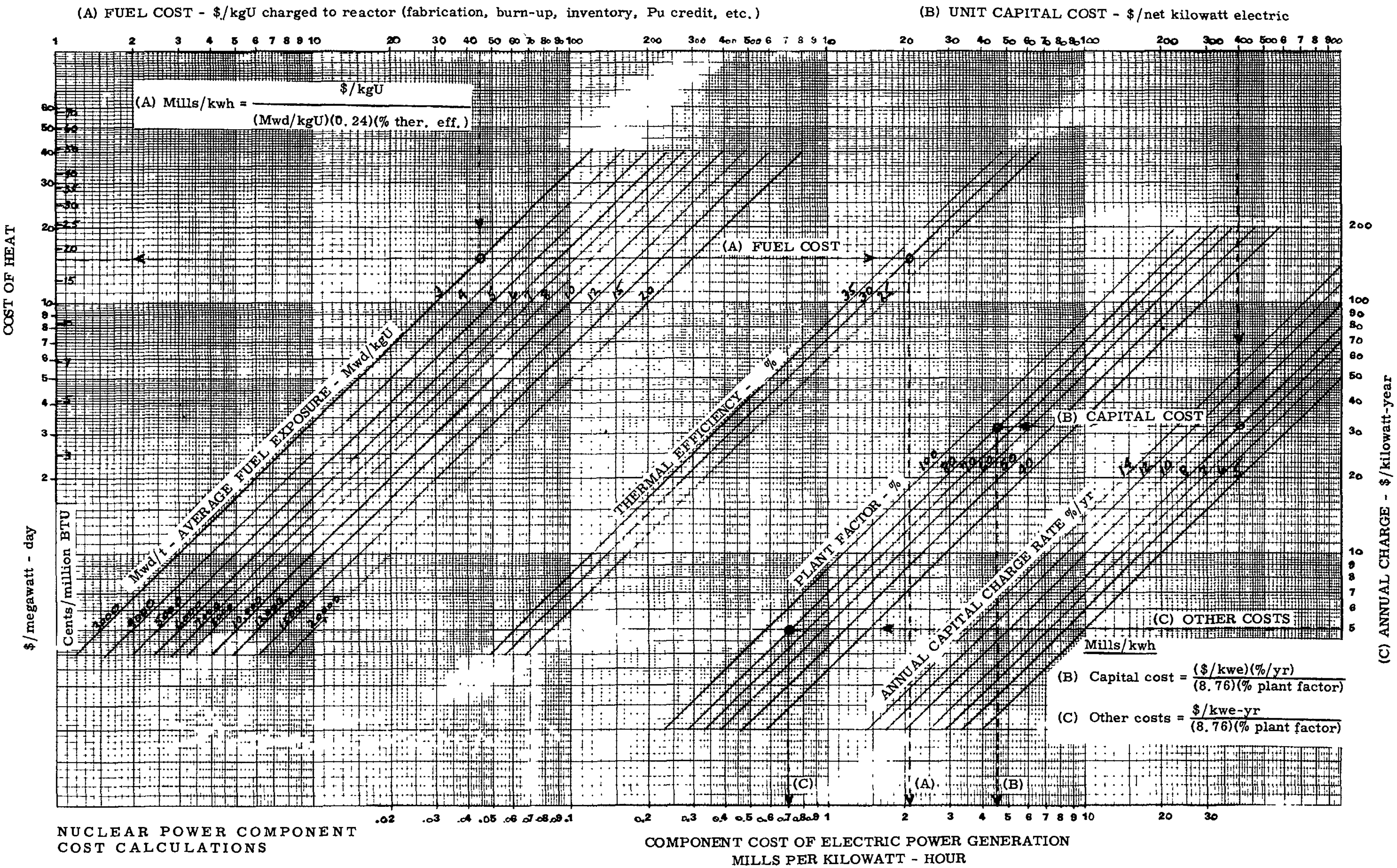
Assuming that a $30/kwe reduction of capital cost can be achieved due to simplification of design and the same reactor parameters are used as in Example I (8% per year capital charge rate and 80% plant factor), the savings in generating cost as obtained from the chart, (B), is about 0.35 mills/kwh.

Example V. Effect of cost of shipment of irradiated fuel

Assuming the same parameters as in Example I (3 Mwd/kgU and 30% efficiency), and a fuel cost for shipment of $15/kgU, the cost as obtained from the chart, (A), is about 0.7 mills/kwh.

Example VI. Effect of change in fuel exposure

Assuming that the estimated net fuel cost of a slightly enriched reactor with a thermal efficiency of 25% is $300/kgU, and a fuel exposure of 13 Mwd/kgU is expected, the fuel cost obtained from the chart, (B), is 3.8 mills/kwh. However, if a fuel exposure of only 10 Mwd/kgU is obtained, the depletion cost less plutonium credit would be reduced by about $7 for each Mwd (as indicated in Annex I for a 200 Mwe PWR: $162/kgU minus $70/kgU divided by 13 Mwd/kgU), thus a reduction in the net fuel cost of $21/kgU (difference of 3 Mwd/kgU x $7/Mwd) would result. Then the net fuel cost would be $279/kgU, since the other fuel charges would remain constant and the fuel cost as shown in the chart, (A), would be about 4.7 rather than 3.8 mills/kwh.



NUCLEAR POWER COMPONENT COST CALCULATIONS

ANNEX IX

Examples of component cost indices[a]

Country	Building materials	Process and manufacturing equipment	Construction labor
United States of America	1.0[b]	1.0[b]	1.0[b]
United Kingdom	0.80[c]	0.85[c]	0.70[d]
France	0.70[c]	0.75[c]	0.95[d]
Belgium	0.70[c]	0.65[c]	0.60[d]
Venezuela	1.28[e]	1.28[e]	1.10[d]

a/ Source: Private communication.

b/ Costs for Cleveland, Ohio, USA.

c/ Based on obtaining all material and equipment locally.

d/ All labor figures include a factor for the efficiency and proficiency of local labor, as well as all labor taxes, benefits, social security payments, etc. paid by the employer.

e/ For a project in Venezuela all equipment and most materials must be imported from the United States.

ANNEX X

Indication of component costs for the fabrication of natural uranium fuel[a]

Process step	Plant capacity t/year	Plant investment million $	Unit cost $/kgU	Source
A. Ore concentration				
Ore to U_3O_8 (ore assaying 0.1 to 0.2% U_3O_8)	50 000 ore	3	-	USA[b]
	1 000 000 ore	15	-	USA[b]
	60 000 ore	2	3 - 6	France[b]
B. Refining				
(i) U_3O_8 to metal	2 000 U	8.6	3.50	USA[b]
	4 000 U	12	-	USA[b]
	8 000 U	17	-	USA[b]
	1 000 U	8	6	France[c]
(ii) U_3O_8 to UO_2	-	-	10	Euratom[d]
C. Fabrication				
(i) U-Magnox clad	-	-	13 - 21	Euratom[d]
	-	-	16 - 20[e]	UK[b]
	-	-	10 - 15[f]	UK[b]
	60 - 300 U	-	7 - 12	France[c]
(ii) UO_2- Zircaloy clad				
(a) Pellet preparation	24 U	-	10	France[b]
(UO_3 reduction)	36 - 48 U	-	7 - 8	France[b]
(b) Element fabrication	100 U	0.60 - 0.70	50	France[c]
	800 U	3.00 - 4.00	25 - 40	France[c]
	Small scale	-	29[g]	Canada[b]
	Large scale	-	21[g]	Canada[b]
	-	-	48 - 95[h]	USA[b]

a/ Most figures of this table are estimates.

b/ Private communication.

c/ PIATIER, H., "Le cycle de l'uranium du minerai à la production de plutonium", Small and Medium Power Reactors, v.2, IAEA, Vienna (1961), p.21.

d/ Basic Assumptions for Nuclear Power Estimates in Europe, document 27211, OEEC/ENEA, Paris (1960).

e/ 1958/1959 estimate.

f/ Recent estimate.

g/ 1.9 cm diam pellet.

h/ Lower figure for 1.27 cm diam pellet and higher for 0.94 cm diam pellet.

ANNEX XI

Indication of component costs for the fabrication of slightly enriched uranium fuel (United States)[a]

Process step	Plant capacity tU/yr	Plant investment million $	Unit cost[b] $/kgU	Source
A. Hexafluoride preparation				
U_3O_8 to UF_6			2.6	c/
B. U^{235} enrichment				
Diffusion plant	500	70 - 75	USAEC price scale	d/
C. Metal preparation				e/
UF_6 to U (1.87% U^{235})	30	3		
	300		24	
D. Oxide pellet preparation[f]				
(i) UF_6 to UO_2 pellet (1.87% U^{235})	150		19	e/
(ii) UF_6 to UO_2 powder				g/
1.0% U^{235}			9 - 12	
2.0% U^{235}			11 - 14	
3.0% U^{235}			14 - 16	
(iii) UO_2 powder to pellet				g/
0.3 in. diam			16 - 20	
0.4 in. diam			15 - 18	
0.5 in. diam			14 - 18	
E. Element fabrication[f]				g/
(UO_2 powder to enriched element)				
(i) Stainless steel clad				
0.3 in. diam pellet			82 - 99	
0.4 in. diam pellet			61 - 73	
0.5 in. diam pellet			50 - 60	
(ii) Zircaloy-2 clad				
0.4 in. diam pellet			118 - 142	
0.5 in. diam pellet			94 - 113	
F. Recovery				g/
(i) $UO_2(NO_3)_2$ to UF_6 (up to 5% U^{235})			5.6	
(ii) $Pu(NO_3)_4$ to metal			($1.50/gPu)	

a/ Most figures of this table are estimates.

b/ Ranges reflect spread on data from suppliers.

c/ Private communication.

d/ Joint Action by OEEC Countries in the Field of Nuclear Energy, C(56)164, C(56)168, C(56)188, OEEC, Paris (1956).

e/ MURRAY, J.P. et al., Economics of Uranium Fuel Cycles, paper P/439, Second Geneva Conference (1958).

f/ $2 million investment for plant of 100 tU/yr ($6 million for Pu fuel) for fabrication from UF_6 to finished element. Source: ULLMANN, J.W., "Some Major Fuel Cycle Problems", Small and Medium Power Reactors, v. 2, IAEA, Vienna (1961), p. 57.

g/ Nuclear Power Plants Cost Evaluation Handbook, v.4, USAEC, San Francisco, Calif. (December 31, 1960).

ANNEX XII

Indication of cost of shipping irradiated fuel elements[a]

Shipments	$/kgU	Source
Overseas		
European port to USAEC processing plant and return	20	b/
European reactor site to USAEC processing plant and return	25	c/
European reactor site to USAEC processing plant and return	18	d/
Finland to United Kingdom	10	b/
Japan to United States	10 - 15[e]	b/
Japan to United Kingdom	9	b/
Within the United States (distance of 3000 miles)		f/
Freight to processing plant	1.50 - 2.40[g]	
Freight for return of casks	1.40 - 2.30[g]	
Cask rental	2.00 - 2.90[g]	
Sub-total	4.90 - 7.60[g]	
Insurance	1.50 - 6.00[h]	
Total	6 - 14	

a/ Most figures of this table are estimates.

b/ Private communication.

c/ Basic Assumptions for Nuclear Power Estimates in Europe, document 27211, OEEC/ENEA, Paris (1960).

d/ LÖBL, O., Cost Factors of Nuclear Energy, Part I, Stresa Conference (1959), p.57.

e/ First figure refers to natural U, second one to enriched U.

f/ Costs of Nuclear Power, report TID-8531, USAEC, Washington, D.C. (January 1961).

g/ Variation due to size of cask, 70 and 30 tons, and containing 3.8 and 1 tons of U respectively.

h/ Uncertainty in insurance rates.

ANNEX XIII

Costs of chemical reprocessing plants for irradiated fuel[a]

Country or organization	Capacity t/yr	Investment cost million $	Investment cost $/kg-yr	Production costs ($/kgU) Fixed[b]	Production costs ($/kgU) Operating	Production costs ($/kgU) Total
France[c]	50	12	240	24	24	48
	250	20	80	8	12	20
	500	30	60	6	8	14
	2 000	60	30	3	5	8
US[d]	300	19	63	6	12	18
	3 000	66	22	2	4	6
US[e]	300	20.5	68	7	8[f]	15
OEEC[g]	500	35.5	71	7	7	14

a/ All figures of this table are estimates.

b/ At total capital charge of 10%/year.

c/ Source: PIATIER, H., "Le cycle de l'uranium du minerai à la production de plutonium", Small and Medium Power Reactors, v.2., IAEA, Vienna (1961), p.21.

d/ Source: CULLER, T.L., "General Economics of Chemical Reprocessing for Solvent Extraction Processing", Symposium on the Reprocessing of Irradiated Fuels, report TID-7534, Bk.3, USAEC, Brussels (1957), p.1103.

e/ Source: KRATZER, M.B., "Atomic Energy Commission Charges for Chemical Reprocessing Services", Symposium on the Reprocessing of Irradiated Fuels, report TID-7534, Bk.3, USAEC, Brussels (1957), p.1154.

f/ 27% of operating costs are for waste disposal.

g/ Source: Joint Action by OEEC Countries in the Field of Nuclear Energy, C(56)164, C(56)168, C(56)188, OEEC, Paris (1956).

ANNEX XIV

Estimated breakdown of construction costs for Eurochemic reprocessing plant[a]

Item	Per cent
Process building	5
Process equipment	27
Waste treatment facilities	8
Research facilities	12
Supporting facilities	4
Administration buildings	2
Health physics facilities	1
Utility installations	4
Site and housing estate	12
Purchase of technical know-how	8
Contingencies	17
	100[b]

a/ Source: The European Nuclear Energy Agency and the Eurochemic Co., OEEC, Paris (March 1958).

b/ Cost breakdown in reference a/ was given for a plant of 100 t/year capacity estimated to cost $12 million. This figure was revised to $15 million; see Nuclear Power, v.5, No. 52, London (August 1960), p.62.

ANNEX XV

Examples of possible reduction in fuel cycle costs

I. CANADIAN "THROW-AWAY" CYCLE EMPLOYING NATURAL UO_2[a/]

(Average exposure level - 9750 Mwd/t; efficiency - 29%)

	$kgU Present	Projected (1964)
Price of yellow cake	22.50	15.00
Yellow cake to UO_2 powder	7.50	3.70
Sintering and grinding	10.00	7.50
Sub-total, finished UO_2 pellets	40.00	26.20
Zircaloy components	31.00	19.00
Assembly and inspection	22.50	22.50
Total fabrication cost ($/kgU)	93.50	67.70
Total fabrication cost (mills/kwh)	1.4	1.0

II. US SLIGHTLY ENRICHED CYCLE ($12/g Pu credit)

	Mills/kwh Present[b/]	Projected (1967)[c/]
Fuel preparation and fabrication	2.0	0.6
Fuel burn-up	1.7	1.6
Shipping and reprocessing	0.7	0.1
USAEC use charge (4.75%)	0.2	0.2
Total fuel cost	4.6	2.5
Less plutonium credit	0.8	0.5
Net fuel cost	3.8	2.0

a/ Source: MOORADIAN, A.J., and ROBERTSON, J.A.L., "CANDU Fueling Costs", Nucleonics, v.18, No. 10, New York, N.Y. (October 1960), p.60.

b/ Source: Power Cost Normalization Studies, report SL-1674, USAEC, Washington, D.C. (January 1960); see also Annex I, BWR, 200 Mwe.

c/ Source: STEWART, D.H., US Nuclear Power Generating Costs, paper 137 B3/11, v.4, WPC, Montreal (1958), p.1437.