UNITED NATIONS

ECONOMIC
AND
SOCIAL COUNCIL

LIMITED
ST/ECLA/CONF.7/L.A.1
29 November 1960
ORIGINAL: ENGLISH

LATIN AMERICAN ELECTRIC POWER SEMINAR

Held under the joint auspices of the Economic Commission for Latin America, the Bureau of Technical Assistance Operations and the Resources and Transport Economics Branch of the United Nations, with the collaboration of the Government of the United Mexican States

Mexico City, 31 July to 12 August 1961

NUCLEAR POWER COSTS AND THEIR TRENDS WITH SPECIAL REFERENCE TO LESS DEVELOPED COUNTRIES

submitted by the International Atomic Energy Agency

NOTE: This text is subject to editorial revision.

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List of abbreviations

BTU	British thermal unit
BW	boiling-water reactor type
D	deuterium
GCE	gas-cooled, enriched-uranium reactor
GCN	gas-cooled, natural-uranium reactor
HWN	heavy-water, natural-uranium reactor
kwe	kilowatt electrical
kwh	kilowatt-hour
mills	thousandths of a US dollar (= tenths of a cent)
Mwd/t	megawatt days per metric ton
Mwe	megawatt electrical
Pu	plutonium
PW	pressurized-water reactor
SS	stainless steel
U	uranium

/1. Introduction

1. Introduction

The question of nuclear power costs and of their significance for less developed countries has been one of the main concerns of the IAEA since the inception of its activities and many of the steps which the Agency has taken or intends to take in carrying out its program in the development of nuclear power are designed to achieve some progress in this field.

The problem of accurately estimating power costs exists of course in the area of conventional power but the difficulties encountered are enhanced and multiplied in the case of nuclear stations.

Considering that the first power reactors have only started operating in the last five years, that many changes which may have a substantial impact on their fuel and operation costs may occur during their lives as a result of operational experience, that many promising reactor systems are still in the planning stage, that the desire to secure a maximum of technical information has led to the construction of a multiplicity of systems and temporarily prevented a standardization of components with the attending mass production economies, that no free market for fissile materials has as yet been established, one may well wonder what significance could be attached to the frequently quoted nuclear power cost figures and what relevance they may have to the power situation of less developed countries.

The questions arising in the interpretation of available cost figures may be grouped in three categories:

(a) Questions connected with the interpretation of construction and fuel costs in the reactor manufacturing country

This is not as simple a question as it appears at first sight. There are a number of costs connected with the construction of a reactor which may or may not be included in the final investment cost figure. One of these is the research and development behind a specific plant. Sometimes all of it is charged as construction cost, sometimes only part of it is included as an indirect expenditure but it is also possible that none of it be charged to the plant.

/Even if

Even if research and development expenses are clearly excluded there may be additional hidden costs whenever a power reactor is the first of its kind and consequently requires the production of original equipment components.

Again in the case of different elements of fuel costs the figures quoted at present will almost certainly experience wide variations over the life of the reactor to which they refer. This applies equally to the costs of fissionable material, to that of fabrication of fuel elements and to the amounts of energy which will be extracted from these fuel elements before they must be reprocessed. Furthermore, the whole complex of governmental regulations governing the sale or lease of nuclear fuel in some of the most advanced countries is unlikely to remain unchanged over the years.

With regard to fuel costs the conditions of fuel supply to domestic reactor operators are likely to change over the life of the reactor, while the fuel performance for a first plant may be substantially underrated in the original estimate.

(b) Questions connected with the extrapolation of reactor construction and fuel costs from one country to another

Significant adjustments must of course, be made before applying to a less developed country the construction cost figures quoted by a reactor manufacturing country. Civil engineering expenditures will vary substantially in each specific case while the necessity for foreign supervisory personnel will also involve additional expenditures. With regard to fuel costs the conditions of fuel supply to foreign operators will usually differ from those applicable to domestic utilities so that a careful recomputation of equipment, construction and fuel costs will be necessary before any significant figures could be derived by the potential user.

(c) Questions arising from the determination of nuclear power generating costs

While it does not fall within the purpose of this paper to discuss the methods of determining generating costs and of comparing them for alternative power sources, it should be pointed out that the frequent

/practice of

practice of quoting generating cost figures for a nuclear power station under the assumption of a constant load factor which will prevail for twenty or twenty-five years is fraught with simplifications and may be misleading when used for purposes of comparison with the generating cost of a conventional station. If reactors are operated in power systems, system cost analysis becomes unavoidable before any serious comparison of alternative costs can be made. Furthermore, if a country contemplates a nuclear power program rather than the purchase of a single reactor, the whole economic complex which, even in the latter case, is introduced through the channel of the interest rate used for the determination of annual fixed charges has to be taken into account. Without labouring this point any further, it should be clear that global figures expressed in mills per kilowatt hour with the assumption of a given load factor and an often arbitrary way of determining annual capital charges are of limited value for purposes of economic comparison except perhaps as rough indications that the problem should be studied further.

The above considerations govern the presentation of the nuclear power cost data which are outlined in this paper. The three following sections deal with construction costs, fuel costs and operation and maintenance costs for reactors whose technology is relatively well developed and which have been operated or are about to be operated on the industrial scale. The examples are therefore limited to the gas cooled natural uranium reactor, the pressurized and boiling water reactors, the organic moderated and the heavy water reactors. In every case an effort is made to indicate future trends of costs and to suggest reasons for possible decreases in the costs of various items. Attention is drawn, however, to the fact that progress in nuclear technology often arise from difficult compromises between 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 unfavourable impact on another. For this reason one cannot merely add up the possible savings but must exercise critical

/judgment in

judgement in combining them. This advice may be easier to give than to apply but its validity stems from the very factors which have caused the growth of nuclear power: constant experimentation and rapid change.

2. Initial investment in a nuclear power station

The data given in tables 1 and 2 show the estimated construction costs of small and large nuclear power stations which could be constructed in the United States of America on the basis of present technology and which could be operative by 1964-65. The data given in table 1 are normalizations, made by a contractor for USAEC, of the results of design studies carried out by five other contractors of USAEC. These results are based on the experience available from many experimental reactors which are being operated on behalf of USAEC. The data given in table 2 represent estimates made by reactor designers and manufacturers in response to a request from USAEC for information on small size power reactors. It will be seen that the estimates for small nuclear power stations are lower than might have been expected from an extrapolation of the estimates for the larger stations and it is difficult to find technical justification for this fact. The data for the small stations were developed from individual studies, all of which were not based on the same criteria and it appears that the estimates for these stations do not include all the cost factors.

The data given in table 3 show the estimated construction costs of large nuclear power stations built or planned in the United Kingdom of Great Britain and Northern Ireland. The figures for the gas-cooled reactor power stations are based on an averaging of the estimated costs of the latest large commercial power stations being constructed at present. It should be added that the estimates based on the design of the advanced gas-cooled reactor at present being constructed for the Atomic Energy Authority at Windscale indicate that a large power station of this type could be built in the United Kingdom for a cost of US $220 to US $250 per Kwe during the period 1962 to 1966.[1]

1/ P.T., Atom (February 1960).

/Table 4

Table 4 gives estimates of construction costs of nuclear power stations received from Belgium, Canada, and the Federal Republic of Germany in reply to a questionnaire sent by the Director General to Member States.

If we consider separately the main components of a nuclear power station it would appear that unless comparable steam conditions are achieved, the cost of turbogenerators and auxiliary power equipment will be higher for nuclear plants than for conventional plants of similar sizes. Building and civil works with special concrete shielding and containment structures cost substantially more for a nuclear power plant; the heat transfer system and the reactor part of a nuclear power plant will cost more than the conventional steam generating equipment. It can therefore hardly be expected that the capital cost of a nuclear power plant could fall below that of a conventional station.

However, there is a promise of a reduction in the costs of the items referred to in the preceding paragraph in the coming years. Conservative containment structures which represent a substantial part of the civil works at present considered necessary may progressively be reduced or entirely eliminated. Simpler pumps and more conventional piping materials will bring down some of the coolant circuit costs, while structural materials in the reactor proper should become cheaper through improvements in manufacturing methods. Higher pwoer densities should also bring a significant reduction in the cost of the reactor's initial fuel charge.

The estimates for large nuclear plants to be built in the next five years indicate that the cost per Kwe installed will exceed that of conventional stations of similar size by a factor of 1.5 or more, but the potential reductions mentioned above may subsequently bring this ratio down to about 1.3.

No general answer can be given to the question of whether these figures would be different for less-developed countries. The lower wages for unskilled labour would make for lower construction costs, but the higher salaries of foreign technicians required for construction and start-up would substantially offset this advantage. The possible lower prices of some of the domestically produced materials would have to be

/balanced against

balanced against the transport charges for the main plantcomponents 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 would seem to be that nuclear power plant construction costs in a less-developed country are not likely to be lower than in the country of manufacture. To a large extent these considerations also apply to conventional thermal stations.

3. Fuel costs

The five types of reactor which are at present considered potentially most suitable for use in less-developed countries utilize the following types of fuel: enriched or natural uranium metal or oxide clad in stainless steel, zirconium alloy, beryllium, aluminium or magnesium alloy. The uranium oxide is used in the form of sintered pellets, sealed in thin walled tubes, bundles of which are then assembled to form the fuel element. The uranium metal is utilized in the form of plates or cast rods sealed in tubes with extended heat transfer surfaces.

Every component of fuel costs offers room for substantial reductions in the near future. With regard to natural uranium, the price of U_3O_8 in concentrates offered by the Agency has now dropped to about US $35/kg. Both figures indicate a trend to lower prices which is unlikely to be reversed in the next few years. A recent study made in the United States of the prices of enriched uranium produced in diffusion plants in that country indicates that they are free of any Government subsidy and suggests that they will not be increased but may conceivably be reduced. Further, the present capacity of diffusion plants in the United States appears sufficient to meet the inventory and burn-up requirements of a nuclear power plant capacity of about 40,000 Mwe.[2/] It is also known that other methods of isotopic enrichment of uranium which may possibly lead to equal or lower production costs are being investigated in various countries.

Even larger economies may be expected in the fabrication of fuel elements where standardization of designs and larger batch production may

2/ Forum Memo (December 1959).

/cause a

cause a 30 - 40 per cent reduction in costs. To quote but one example, the fabrication cost of a certain type of fuel element for a pressurized-water reactor is expected to decrease from US $110 to US $70 per kgU over the next few years.[3]

No less important is the trend towards higher burn-up which may be expected to lead to reductions of more than 0.5 mills per kWh (or about 15 per cent of the present total fuel costs) in certain enriched systems. In this respect outstanding promise is held out by the preliminary estimates for the Canadian heavy water natural uranium reactor Candu, expected to operate by 1964 in which burn-ups of up to 10,000 MWD/ton are expected to be achieved leading to total fuel costs of the order of 1.2 mills/kWh.

Finally, decreases in processing costs for irradiated fuel may occur, especially where continuous processing can replace batch treatment.

Even if the most promising developments fail to materialize and if allowance is made for a possible decrease in credit for plutonium, reductions of up to 30 per cent in total fuel costs in the next five to ten years could realistically be expected.

This encouraging picture may appear attractive to less-developed countries, but the following factors should be taken into account. With regard to natural-uranium systems, although the mining of ores and production of concentrates are relatively simple processes, thay 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 high temperature ia a very 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 any country taking its initial steps towards the utilization of nuclear power.

3/ Nucleonics (April 1960)

/In spite

In spite of the factors which augur a substantial reduction in fuel costs in the near future, such as abundant supplies of uranium, the economies to be achieved by fabricating larger lots of more standardized fuel elements and the spare capacity in existing processing and enrichment plants, the economic advantages for the less-developed countries of establishing domestic nuclear industries in the immediate future are nevertheless limited. However, in the case of a country with a sufficiently large total industrial output and a large nuclear power development program, planning for domestic fabricating and processing plants would appear to be important if its expenditure in foreign currency on nuclear power is to be kept to a minimum.

4. Operating and maintenance costs

The annual cost of operating and maintaining a conventional power station, excluding depreciation and fuel costs, includes the cost of supervisory, operating and maintenance personnel and the cost of the materials and external services which are required. The same items of cost would be involved in operating and maintaining a nuclear power station. In making cost comparisons it is desirable to show the annual cost of operation only (e.g. as dollars per kilowatt per year) and to exclude the effect of the plant factor.

As yet there is still insufficient information on the operating and maintenance cost of a nuclear power station used solely for the production of electricity, although estimates have been made by analogy with conventional stations or by inspection of nuclear station designs. For example it is still uncertain what staff is required. Estimates for water reactors have been given in the United States ranging from 0.3 to 0.5 employees per Mwe for a 200 - 300 Mwe station to about 1 to 1.5 employees per Mwe for a 50 - 75 Mwe station.[4/] The corresponding figures would be significantly higher for smaller nuclear stations. In the United Kingdom the estimate for a 500 Mwe gas-cooled two-reactor station is about 0.6 employees per Mwe [5/] If the station were operated in an

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4/ USAEC, Power Cost Normalization Studies, SL-1674

5/ IAEA, Directory of Nuclear Reactors: Vol.1. Power Reactors, STI-PUB No.4 (1959), page 162.

/isolated area,

isolated area, all these figures would probably be higher.

Reductions in operating staff, increased automation and lower repair bills are a likely expectation and, together with greater experience in safety requirements, will all contribute to lower operating and maintenance costs. Considering, however, that this item represents less than 10 per cent of the total nuclear power costs, even a 20 per cent saving in operating and maintenance costs would imply only a two per cent overall saving.

In the case of less-developed countries a relatively lower wage and salary bill (provided local operating staff have been trained) would have to be balanced against the cost of the larger stock of spare parts which would necessarily have to be carried for repairs in the initial stages. It can, therefore, hardly be expected that a lower wage and salary bill in such countries would lead to any significant difference in the unit price of the electricity generated.

5. Summary of the report and future trends in nuclear power costs

Nuclear power is still in its early phase of development, and important cost reductions are envisaged as a result of technical advances based upon the continuous research and development which is being carried on. Present day designs of relatively developed 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. Of great significance will be the possible reductions in fuel cycle costs; these will result from reductions in fabrication and reprocessing charges, the achievement of improved higher burn-ups and the lowering of uranium prices. 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 total investment. Lack of extensive experience in reactor safety has led to conservative and costly designs

/for containment

for containment shells, control mechanisms and instrumentation; with better understanding of essential safety requirements and the use of improved techniques, containment and control of reactors will 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.

This is particularly true of small and medium sized reactors whose costing has been somewhat lagging behind that of large units but for which intensive development programs are expected to yield a wealth of results in the immediate future.

With all due reservations about the applicability of generating cost figures to different situations it might nevertheless be desirable to outline a few tentative conclusions about the future trends of nuclear power costs.

It has been estimated that the cost of generating power with the large gas-cooled reactor in the United Kingdom will be 7 mills/kwh in 1964, levelling off to 5 mills/kwh after 1974, at a 75 per cent plant factor and with an annual capital charge of about 8 per cent.[6/] Conventional fuel is predicted to level off at US $0.49/million BTU, and the conventional generating costs are expected to decrease from 6.3 to 5.8 mills/kwh in the same period and for the same plant factor. Nuclear power is, therefore, likely to become competitive with conventional power about 1966 in the U.K.

According to a recent USAEC evaluation which assumes a 14 per cent annual capital charge, an 80 per cent plant factor and no changes in USAEC's present schedule of uranium prices nor 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,[7/] is expected to decrease later into the 9 - 10 mills/kwh range.[8/]

6/ HINTON, Sir C. et al., The Economics of Nuclear Power in Great Britain, WPC, Madrid, Paper IV B/8 (1960).

7/ USAEC, Power Cost Normalization Studies, SL-1674.

8/ Computations based on data in the source cited in footnote 10, and on the Statement of the United States Atomic Energy Commission to Joint Committee on Atomic Energy, as summarized in Nucleonics (April 1960), pages 71 et seq.

/Assuming that

Assuming that improvements in the efficiency of conventional thermal power plants are levelling off and under the considerations specified, the cost of power generated in a large nuclear power plant to be installed in the United States towards the end of the next decade would become competitive with conventional thermal power in areas where conventional fuel costs were above US $0.55 per million BTU (US $2.20 per million kilocalories).

It is interesting to note that, if in the above computation the annual rate of capital charge is taken as 7 instead of 14 per cent, the power generating costs from a similar 200 Mwe nuclear reactor (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 these assumptions, such power costs would become competitive with conventional thermal power in areas where conventional fuel costs were above US $0.45 per million BTU (US $1.80 per million kilocalories).

Enough qualifications have been introduced in the introduction to this report to indicate that these figures should be considered only as rough indications of range rather than as data for comparative power cost analysis for which they would be entirely unsuitable. Only careful studies can give an indication as to the competitiveness of nuclear power in a specific country and the IAEA hopes to be of assistance to its members if and when they choose to carry them out.

/Table 1

Table 1

UNITED STATES: INITIAL INVESTMENT COSTS FOR MEDIUM AND LARGE NUCLEAR POWER STATIONS BASED UPON RECENT STUDIES a/

Type of station	Capacity (Net Mwe)	Initial investment (US $/kwe)		
		Plant only	Fuel only b/	Fabricated fuel b/
PW	75	435	115	145
	200	282	95	120
	300	242	95	120
BW	75	470	60	100
	200	311	40	75
	300	263	32	57
OM	75	350	28	130
	200	241	97	130
	300	220	96	120
HWN c/	75	640	14	31
	200	425	5.5	12.4
	300	360	4.3	9.6
GCN	75	675		
	200	452	64	88

a/ United States Atomic Energy Commission (USAEC), Power Cost Normalization Studies, SL-1674, relating only to planned reactors.

b/ In the core.

c/ The costs of the heavy water inventory are included in the figures for this reactor.

/Table 2

Table 2

UNITED STATES: INITIAL INVESTMENT FOR SMALL NUCLEAR POWER STATIONS, BASED UPON ESTIMATES OF REACTOR DESIGNERS AND MANUFACTURERS a/

Identification number	Type of station	Capacity (Net Mwe)	Initial investment (US $/kwe)				Remarks
			USAEC report number	Plant only	Fuel only b/	Fabricated fuel b/	
1	PW	11.7 23.6	TID-8513	660 480	152 135	210 184	
2	PW	23.5	TID-8508	445	76	96	Includes 29 Mw of conventional superheat.
3	PW	10.5	TID-8513	1 030	102	233	Identical in design with and of approximately the same cost as the BR-3 station under construction at Mol, Belgium.
4	BW	23.5	TID-8510	372	28	51	Includes 20 and 27 Mw of conventional superheat for the two stations respectively. Many indirect costs omitted.
5	BW	23.5	TID-8508	465	29	74	Similar to number 4, but includes additional indirect costs such as profits, contingency and interest during construction.
6	BW	19.1	TID-8510	451	45	84	Similar to number 4, but includes nuclear instead of conventional superheat. Many indirect costs omitted.
7	BW	19.1	TID-8510	640	45	84	Based on the same

Table 3

INVESTMENT COST FOR NATURAL URANIUM FUELLED GAS COOLED UNITED KINGDOM REACTORS

Name	Capacity (in MW)	Total construction cost (in dollars per kwe)	Initial fuel cost per kwe a/
Berkeley	275 b/	450	70 - 90
Bradwell	300	450	66 - 86
Hunterston	150	350	65 - 85
Hinkley Point	500	370	65 - 85
Trawsfynydd	500	340	47 - 63
Dungeness	550	310	-
Sizewell	600	280	-
Oldbury	550	265	-

a/ Fuel in the core only.

b/ Two reactors.

/Table 4

Table 4

INITIAL INVESTMENT FOR NUCLEAR POWER STATIONS BASED UPON ESTIMATED RECEIVED FROM BELGIUM? CANADA AND THE FEDERAL REPUBLIC OF GERMANY a/

Country and manufacturer	Type of station	Capacity (Net mwe)	Initial investment (US$/kwe)		
			Plant only	Fuel only	Fabricated fuel
Belgium					
ACEC	PW	200	300	...	24
Canada					
Canadian Atomic Energy Comission Limited	HWN	200	328 b/	7.7	23
Canadian Westinghouse	HWN	132	386 b/	11.4	32
Canadian GEC	OCHWN	55	435 c/	5.9	17
GERMANY, FEDERAL REPUBLIC OF					
Interatom	OM	16	520	82	101
Siemens	HWN	49	400	...	40
AEC/KEA	BW	15	500 - 565	...	60 d/
German Babcock and Wilcox	GCE	35	485	...	13 d/

a/ The figures given are provisional estimates relating only to planned reactors.

b/ Does not include US $60/kwe for D_2O investment.

c/ Includes D_2O investment.

d/ Fabrication costs only, fuel costs not included.

/Annex

Annex

TECHNOLOGICAL STATUS OF POWER REACTORS

1. Introduction

It is a well known fact that the level and rate of expansion of power production, especially of electric power production, characterizes the level and rate of expansion of all other branches of a country's economy, including industry, transport and agriculture. It is also well known that a direct link exists between electric power production and the national income per head of population.

Obviously, therefore, development of power engineering in general, and utilization of nuclear fission for electric power production in particular, are highly important for most countries undertaking an industrial expansion program.

The importance for these countries of investigating the potentialities of nuclear energy is greatly enhanced by the extent and rate of progress in atomic power engineering achieved in some countries during the last five to ten years.

At the first Geneva Conference on the Peaceful Uses of Atomic Energy, held in 1955, information which could be obtained on the industrial uses of nuclear energy was scarce. In fact, apart from small experimental units operated in research centres in the United States, the only nuclear power plant delivering a sizeable quantity of electricity by that time was the Soviet power plant at Obninsk. By contrast, at the second Geneva Conference, held in 1958, a large number of such reports on actual generation of electricity by various types of nuclear power reactors were submitted by scientists from the USSR, United States, The United Kingdom and France. And plans for such nuclear power stations were presented also by a number of other countries.

Today the harnessing of atomic energy has become a reality in a number of countries through the inclusion of atomic power stations in electricity supply systems. However, the transition to the practical utilization of atomic energy has some peculiar features. Representing, as it does, one of the latest achievements of technology, nuclear power

/engineering has

engineering has raised a number of scientific and technical problems differing basically from those previously encountered, and sometimes even quite unknown in the ordinary practice of modern power engineering with conventional fuels.

The demands of these problems frequently conflict and call for compromise solutions. Attempts to find these have led to a considerable proliferation of types of power reactor and atomic power stations, in each of which certain advantages and disadvantages are inherent.

In view of the proliferation fo types of atomic power plant, each with its own particular technical and economic features, it may be of assistance to give a short general description of the types at present in existence or in the planning stage. When considering each type, the level of technical development which it has attained at the present time must be established and account must be taken of the experience gained in constructing and operating it.

It should be noted at the outset that there are sharp variations in the degree of technical development which the various reactor types have attained, both with respect to the amount of theoretical research done on them and to the labour and effort expended on their technical development. Some types, such as pressurized water (boiling and non-boiling) and gas-cooled graphite-moderated reactors, have been extensively developed for a considerable time in a number of countries and are technically the most perfect and tested. The extensive development of other types, for example organic moderated and cooled and heavy water power reactors, has been started comparatively recently and is still in an intermediate stage.

Lastly, numerous types of power reactors which may in future offer prospects of power production on an industrial scale are at a preliminary experimental stage of development and will require much scientific and technological work before their prospects can be assessed. Most of these reactors have a complicated technology which has not yet been completely mastered.

In this connexion, all nuclear power reactors at present operating in construction or under development can be divided into the following groups:

/Group 1.

Group 1. Power reactors sufficiently developed for industrial use

This group contains, first, heterogeneous pressurized water reactors (boiling and non-boiling), and heterogeneous gas-cooled uranium-graphite reactors. A number of industrial nuclear power stations using reactors of these types are operating in countries with advanced nuclear energy industries and are being built or planned in many other countries. Their technology incorporates the wide experience in the use of water and gases as coolants accumulated in conventional power engineering practice. Their technical equipment is produced on an industrial scale. They are less complex to service and maintain than reactors of other types.

Group 2. Technically promising power reactors, experience on the industrial use of which will be available shortly

This group contains organic moderated and cooled, and heavy water power reactors. These reactors are technically and economically promising for industrial use. However, work on them is at a semi-experimental, semi-industrial stage and has not yet been taken far enough to yield concrete conclusions regarding prospects for their use in less developed countries. No experience on their industrial use is yet available. However, a number of nuclear power stations embodying reactors of these types are under construction, and the necessary technical and operational experience will therefore be obtained shortly.

In their general technical and economic features, the reactors in this group closely resemble those in group 1; therefore, in an investigation of the technical prospects of utilization of power reactors in the less developed countries, this group should be given as careful consideration as group 1.

Group 3

This group contains reactor types which cannot, either now or in the immediate future, be recommended for industrial use in less developed countries, owing either to their technological complexity or to lack of data on their operation. They include aqueous homogeneous, liquid-fuel, liquid-metal coolant, pebble-bed and fast neutron reactors.

/Fast reactors

Fast reactors occupy a special position owing to the excellent prospects they offer in the long-term planning of atomic power development. However, owing to inadequate operational experience, technical difficulties, and the high cost of their fuel charge, they must be excluded from the list of types which can be used during the initial stage of atomic power engineering in less developed areas. They become attractive when enough plutonium has been accumulated in thermal reactors to make possible a large-scale regeneration of nuclear fuel and fuller utilization of natural supplies of nuclear raw materials.

Before their technical and economic superiority over the reactors in group 1 and 2 can be proved, much money and effort will have to be spent on experimental and technological testing of the reactors in this group.

In view of the interest which a number of countries have in the application of nuclear energy in the immediate future, and of the consequent need to select the most suitable types of equipment for the initial stage of reactor programs, further technical discussion in this report will be limited to power reactors in group 1 and 2. In the coming sections these will be analysed in turn with regard to the state of their technology.

2. Pressurized water reactors

Pressurized water reactors are extensively developed in the USA and USSR. In the USA this system is at present the most technologically advanced as a result of the experience which has been gained in design and operation of naval propulsion reactors, the Shippingport reactor and the SM-1 reactor in Fort Belvoir; in the design and construction of such units as the nuclear ship "Savannah", the Yankee Atomic Electric Company Reactor, the SELNI project and other large power reactors and in design studies on the small power and process heat reactors.

Operation of the pressurized water reactor at Shippingport continues to be one of the most important source of information and experience for this concept. A second seed has been installed in the seed and blanket core and the reactor was returned to full power in May 1960. As of August 30, 1960, the blanket achieved the exposure of approximately 2,600 $\frac{\text{mwd}}{\text{ton}}$ of

/UO_2 average

UO_2 average or 12,400 $\frac{mwd}{ton}$ maximum. This is the highest exposure achieved in large batches of uranium oxide fuel. Developments in support of this project have led to plans for core modifications which will result in a second core with an expected capacity of 150,000 KWE equivalent gross (compared with 68,000 KWE gross for the present design), without increasing the diameter of the pressure vessel. PWR-2 will have about $5\frac{1}{2}$ times the PWR-1 design energy output per unit of fuel flow. This is to be achieved with compartmented flat plate uranium oxide fuel clad in zirconium alloy. The Shippingport PWR proved high safety reliability and other operating characteristics of this power reactor type.

The Yankee Atomic Electric Plant (gross electrical - 118 MW) achieved criticality in August 1960. Its operation will greatly accelerate the rate at which valuable operating experience on pressurized water reactors is obtained. Some of its design features, such as stainless steel-clad fuel, are sufficiently different from the Shippingport design to provide valuable comparative information for evaluation purposes.

The experience of utilizations of pressurized water reactors for propulsion of civilian ships will be gained from the operation of three pressurized water reactors installed in nuclear icebreaker "Lenin" now in operation in the Arctic seas of the USSR.

The nuclear power program of the USSR includes also the erection of a large atomic power station with pressurized water reactors which is now under construction in the Voronezh region of the USSR.

Pressurized water reactors have potentialities for simple reduction of capital and fuel costs. The studies indicate that the substitution of primary pumps employing mechanical shaft seals rather than canned rotors, the modification of the vapor containment, the use of bulk boiling and the simplification and improvement of control drive mechanisms would allow a substantial reduction in the total capital cost of the plant. More extensive reductions are indicated in the fuel cycle costs for this system. The fuel exposure for the uranium dioxide fuel can probably be increased from 27,500 $\frac{mwd}{ton}$ maximum which is current design technology to 40,000 $\frac{mwd}{ton}$. The fabrication costs of stainless steel clad uranium dioxide can also be reduced.

/3. Boiling

3. Boiling Water Reactors

This reactor type is today only slightly less advanced technologically than the pressurized water reactor. This is due, in part, to the fact that it is able totake advantage of much of the extensive experience and technology in the pressurized water system. It is also due to the highly successful operating experience of the Experimental Boiling Water Reactor, Vallecitos Boiling Water Reactor and Borax experiments in the USA, and the reactor of the first atomic power plant in the USSR now operating in boiling condition.

Many design variations and improvements indicating high potentialities of boiling water reactors are being explored or are to be explored in projects such as the above mentioned Experimental boiling water reactor which is in the final stages of modification to increase the heat capacity from 20,000 to 100,000 KW thermal; and the Vallecitos boiling water reactor which is the pilot plant for the large 180,000 KWE Dresden plant recently put into operation.

The engineering experience has been gained through design and construction activities of Dresden, Elk River, Norther States and other boiling water reactors in the USA, a number of them in the USSR (Ural), in Italy (SENN) and some in other countries.

On the basis of this engineering and operating experience substantial reductions in capital and fuel costs for forthcoming projects are possible. The capital costs of this system could be reduced by simplification of design to eliminate large risers and heat exchangers, by increasing the power density, by changes in the vapor containment design and by incorporation of conventional or nuclear superheating of the steam.

Nuclear superheat

It is expected that the production of superheated steam in reactors will have some economic advantage in comparison with water cooled reactors which now produce saturated steam.

The experiments with the nuclear superheat in the reactor of the first atomic power plant in the USSR demonstrated the technical feasibility of nuclear superheat in this type of reactor. A large nuclear power plant with reactors based on nuclear superheat is at present under construction in the Ural region of the USSR.

In the United States several projects are directed primarily towards demonstration of the technology of reactors with nuclear superheat. These projects include the Borax-5 to be placed in operation in 1961, the Pathfinder plant with reactor 62,000 KWE scheduled for completion in mid-1962 and the BONUS project of the Puerto Rico Water Resources Authority, a 16,300 plant scheduled for completion in 1963.

It should be mentioned that nuclear superheat may be incorporated in pressurized water reactors, boiling water reactors and also in some other reactor types.

4. Gas Cooled Reactors

Gas cooled reactors have been most effectively introduced in the United Kingdom and France. In other countries it was widely felt that the relatively poor heat transfer properties of gases would limit power density and fuel specific power that these inherent characteristics would restrict the usefulness of the reactors from the economic point of view. Recently there have been many developments in gas cooled reactors technology which have caused an extension of work on gas cooled reactors. Notable among these developments are:

(1) The very successful programs in the United Kingdom and France and the significant advances in performance being made over the first dual purpose (power and plutonium) reactors at Calder Hall, Chapelcross and Marcoule.

(2) The development of the technique for field-erection of large pressure vessels of ever-increasing thickness which makes possible a higher gas pressure and hence better heat transfer.

(3) The use of pre-stressed concrete for pressure vessels introduced by French engineers, has opened attractive possibilities for less developed countries as a result of the elimination of the costly and complex elements involved in the construction of steel pressure vessels.

(4) The development of UO_2 as a fuel material capable of service at high temperatures for long exposures.

/(5) An

(5) An accumulation of experience with experimental ceramic fuel elements of various types.

Together these developments have provided the impetus for interest in gas cooled reactors in the United States, Federal Republic of Germany, Italy, Japan, Czechoslovak Socialist Republic, USSR and Canada.

The family of gas cooled reactors could be divided into the following categories:

Systems operating on natural uranium which includes only the very large graphite and D_2O moderated heterogeneous reactors.

Reactors of this group are the Calder Hall and Chapelcross reactors, the Marcoule production reactors, the British Electricity Board stations and similar stations in Italy and Japan, the French EDF stations and the heavy water gas cooled reactor in the Czechoslovak Socialist Republic. The heavy-water-moderated gas cooled reactors are being designed also in the United States and in France.

Graphite moderated natural uranium reactors built, under construction or contracted for, will have a combined electrical capacity in excess of 3 million kilowatt, making this in one sense the most important reactor concept in the world today.

The dominant feature of this class of reactors is the use of natural uranium as a fuel which appears desirable to many nations not wishing to become dependant on a foreign source of enriched nuclear fuel. This advantage is, however, coupled with a serious inherent limitation, as the use of natural uranium requires large reactors and involves the use of graphite or D_2O moderators and of gas as coolant.

These limitations could be avoided in gas cooled reactors by using partially enriched fuel with metal cladding of fuel elements. In this group are the Advanced gas cooled reactor now under construction in the United Kingdom and Experimental gas cooled reactor in the USA.

The principal feature of the slightly enriched reactors is that they operate at significantly higher gas temperatures than natural uranium systems and can use fuel which permits much higher burn-up. Performance limits for the slightly enriched systems can hardly be defined at the present time. No reactors of this type have been operated, nor have enough in-pile fuel and cladding tests been made to establish the limiting factors.

/There is

There is a third group of gas cooled reactors including high temperature homogeneous or semi-homogeneous systems constructed entirely of refractory materials. In this group are the British-OEEC-Euratom "Dragon" reactor being built in England, the HTGR-1 and the Sanderson-Porter pebble-bed reactors in the USA, and the Brown-Boveri-Krupp pebble-bed reactor in the Federal Republic of Germany, all of them in the design stage. Many problems will have to be solved before the fuel for these reactors is developed. Apart from the important fuel development problems that remain, greater knowledge and experience will be required to evaluate the problems of controlling and dealing with fission products contamination of the coolant. However, this group appears to constitute a goal towards which gas cooled reactor development is likely to proceed. It is important to note that one of the attractive features of these reactors is that they promise, in addition to competitive power, the ultimate potential for efficient utilization as fuel of the basic raw material, thorium.

5. Organic moderated and cooled reactors

The technical feasibility of this concept was established by the successful operation of the Organic Moderator Reactor Experiment (OMRE) in the USA. However, the OMRE is not a prototype of nuclear power plant but rather a full-scale irradiation facility designed to study the behaviour of the most promising organic compounds under conditions similar to those encountered in power reactor application.

At present, there are no operating nuclear reactors - neither experimental nor on a prototype scale - which are organically cooled. Operating experience with the Organic Moderated Reactor Experiment continues to be the principal source of data on organic material as reactor moderator and coolant.

In order to broaden this experience and increase the rate of development of promising variants of this basic design, construction has been initiated on an experimental organic cooled reactor in the USA to be completed in 1962. Construction is also proceeding on the 11,400 KWE organic moderated and cooled reactor plant at Piqua, USA, scheduled for completion in 1961.

/There is

There is considerable interest in this reactor type in other countries but the developments are in a less advanced stage than above projects.

The experimentally proved main characteristics of organic moderators and coolants make their use not only technically but also economically attractive in power reactors. The lower capital costs for this system in comparison with a water cooled and moderated system is made possible because of its low pressure and non-corrosive behaviour as compared to many reactor materials in organic liquids. On the other hand, the high fuel costs resulting from the low exposure which can be achieved in metal cores of the current technology and the high operating costs which are occasioned by the necessity of replacing the organic material as it is destroyed by reactor irradiation, require extensive research and development work.

The potential of this system lies in the development of a new fuel element and cladding material which can achieve much longer life by increasing power density in the core and by increasing the heat transfer capabilities of the system.

6. Heavy water moderated reactors

Heavy water moderated power reactors as well as graphite moderated gas cooled power reactors are very attractive because of possible use of natural uranium. Moreover, because of its particularly favourable effect on the neutron economy the use of D_2O permits the achievement of rates of burn-up largely exceeding those of graphite moderated natural uranium reactors. The practical technology of heavy water moderator for power producing reactors is not far advanced in any country. However, the basic technology for this system has been developed through research and development programs and much useful engineering technology in this field is available from the design construction and operation of the many research reactors in various countries. A vast amount of basic and engineering information has been generated in Canada where major emphasis was placed on this system.

/To date

To date no heavy water power reactor is being operated either as a prototype or as a full-scale plant and the first power reactors of this type will come into operation in 1961/1962 so that no operation experience with them can be acquired before 1962/1963. However, work on power stations employing this type of reactors is proceeding in a number of countries. Examples are: Nuclear Power Demonstration-2 (NPD-2) now under construction and CANDU in the design stage in Canada; construction of a 17,000 KWE tube-type power reactor of Carolina Virginia Nuclear Power Associates in the USA to be completed in 1962, and construction of a heavy water moderator gas cooled power reactor in the Czechoslovak Socialist Republic. Other countries such as France, United Kingdom and the USSR are also working on power projects with heavy water reactors. The boiling heavy water reactor for district heating with ultimate thermal capacity of 20,000 KW came into operation in Halden, Norway, recently.

A large natural uranium heavy water power reactor will require heavy capital investment and will thus have to produce a large amount of heat in order to be economic. It is, therefore, rather improbable that heavy water power reactors will be economically competitive with other reactor types in the small or medium capacity range. A decrease in the size of the reactor can be made by using enriched uranium but in this case the use of heavy water as a moderator looses one of its main reasons.

Because this system is at an early stage of development for power generation, its potential improvements are not so evident as with more developed power reactor types. However, the development of a pressure tube reactor instead of the pressure vessel type, achieving an increase in power density and the exposure lifetime of the fuel, may substantially reduce the cost of power in this reactor type.

7. Advanced concepts

Research and development is continuing on a number of reactor concepts which appear to have certain advantages but which are not yet at a point where technical feasibility is assured, or reasonable evaluations can be made. This work includes continued study of aqueous homogeneous reactors

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with the second Homogeneous Reactor Experiment, assembly of a reactor experiment using a molten plutonium alloy as fuel in the USA, and sodium cooled reactors with thermal, intermediate and fast neutrons. Of these the Experimental Breeder Reactor N°1, in the USA, BR-5 in the USSR and Dounrey fast reactor in the United Kingdom, are most important. Many reactor concepts are being evaluated as candidates for new reactor experiments. Notable among these are: (a) the molten salt reactor, based on fused salts of uranium, thorium and beryllium; (b) the beryllium oxide, with high temperature gas cooling; and (c) the pebble-bed reactor, based on small balls of graphite impregnated with uranium carbide loaded into a hopper and cooled with gas - probably helium. Preliminary studies are also being carried out on direct conversion systems involving thermionic, thermoelectric and magneto-hydrodynamic devices. Hopefully, such devices may make it possible in the long run to take better advantage of the unique ability of nuclear fuels to produce high temperatures.

In addition to the specific work that is carried on under individual power reactor projects, the national development programs of several countries include an area of more broadly based nuclear technology development which is generally applicable to nuclear systems. The objectives of these efforts are to provide data on reactor fuels and materials, reactor physics, reactor components and associated equipment, to carry out engineering development of a general and fundamental nature, to investigate the feasibility and potential of new methods for improving reactors, and to provide tools such as test and research reactors and remote handling devices, for use in reactor research and development. Developments in this area help to lower the cost of nuclear power generation through improvements affecting many types of reactors and through reductions in the overall cost of the reactor fuel cycle. This work includes development of fuel reprocessing techniques which will permit reprocessing of advanced fuels not susceptible to existing processes. The work includes environmental investigations and development of practical systems for the safe handling and disposal of the wide variety of radioactive wastes evolved from nuclear energy activities.

/8. Conclusions

8. Conclusions

From the above survey some provisional conclusions may be drawn:

1. There is no doubt that at present the use of power reactors, at least of boiling and non-boiling pressurized water reactors as well as of gas- and of water-cooled uranium graphite reactors, for the generation of electricity on an industrial scale is technically definitely established.

2. During the next five years the technical possibility of generating power on an industrial scale with organic moderated and cooled reactors and with heavy water reactors will become clear.

3. The possible use of power reactors on an industrial scale in less developed countries, as indeed in any country, is restricted not by technical considerations, but by economic factors and by the availability of trained personnel.

4. It is not possible at the present time to select any one type of reactor as the most suitable for use in less developed countries. A separate decision on choice of reactor type must be taken in each particular case, after considering all the technical, economic and other factors.

5. In deciding to construct an atomic power station in any country and in selecting the type of reactor to be used in it, the fact should be remembered that any choice will involve some economic risk owing to present lack of experience of long operation under industrial conditions.

6. No existing reactor type can be considered to have been developed and tested under industrial conditions long enough to be safely recommended for immediate and exclusive use for commercial electric power production unconnected with experimental purposes. There are a number of reasons for this:

(a) All reactors at present in operation, both large and small, are either experimental or semi-industrial plants intended for work no the development of their type, or dual purpose plants for the production of both plutonium and power.

(b) No existing power reactor has been in operation for more than two to five years (in most cases the period is much less), that is, for only a short part of its estimated life.

/(c) All

(c) All estimates of fuel cycles are based on a number of assumptions which have not been tested on an industrial scale. For no type of reactor is there a fully worked-out fuel cycle, and statistical data for the assumptions used in economic calculations regarding the degree of burn-up and the cost of reprocessing depleted fuel elements are even less adequate.

7. On the other hand, nuclear power engineering is developing at such a rate that over the next five to ten years sufficient experience will be accumulated to permit a solution of the basic problems of reliable operation of a number of power reactor types for the economic production of electric power in many parts of the world.

9. References

(1) "Directory of Nuclear Reactors", Vol. 1, Power Reactors, published by the International Atomic Energy Agency, Vienna, 1959.

(2) "A Summary of Nuclear Power Research and Development in the United States" Paper SMPR/46 presented by U.M.Staebler, at the Conference on Small and Medium Power Reactors, Vienna, September 1960.

(3) "Status of Nuclear Power based on the Canadian Program" Paper SMPR/63, by J. Melvin, Conference on Small and Medium Power Reactors, Vienna, September 1960.

(4) "Development of the French Gas Reactor Program" Paper SMPR/25 by J. Bussak et al Conference on Small and Medium Power Reactors, Vienna, September 1960.

(5) "Gas Cooled Reactors" Proceedings of the Symposium sponsored jointly by the Franklin Institute and the American Nuclear Society, February 10 and 11, 1960.

(6) "Power Reactor Potentials" Remarks by F. Pittman at the Atomic Industrial Forum Meeting Washington D.C., November 3, 1959.

(7) "Civilian Power Program, Part 1","Current Status of Reactor Concepts" Report TID-8615, USAEC, 1959.

(8) "Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy", 1958, Vol. 1, 8, 9.