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INTERNATIONAL BANK FOR RECONSTRUCTION AND DEVELOPMENT

INTERNATIONAL DEVELOPMENT ASSOCIATION

NUCLEAR POWER FOR SMALL ELECTRICITY SYSTEMS

July 15, 1968

Projects Department

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FOREWORD

i. This report was prepared by the Bank's Projects Department at the request of the Bank's Executive Directors. The study on which it is based consisted of two principal phases. The initial phase involved visits with manufacturers; with the utilities which already have experience of operating nuclear plants; with leading national atomic energy authorities; and discussions and correspondence with the International Atomic Energy Agency. Those principally responsible for this phase were Lord Hinton of Bankside, former Member of the U.K. Atomic Energy Authority and former Chairman of the U.K. Central Electricity Generating Board, and a Special Adviser to the Bank; Mr. Mario Piccagli, Assistant Director of the Projects Department, in charge of Engineering; and Mr. Ugo Finzi. The subsequent phase consisted of the elaboration of the conclusions reached to test them in the light of prevailing economic situations in developing countries and of their power system planning realities; and of the substantial job of report drafting. Those joining the effort in this phase were Mr. Bernard Bell, Deputy Director, Projects Department; Mr. Robert Sadove, Economic Adviser; and Mr. C. Willoughby. The first phase of visits and information collection took place in mid-1967; the final draft of the report was not written until May 1968. In the intervening period there had been technological advance and added experience had been gained in some respects. While some account was taken of this in the report, it should be remembered in reading it that most of the information used reflects the situation as at mid-1967. The report takes into account situations and developments only in countries which are members of the Bank.

ii. In view of the rapid progress and evolution in the field of nuclear power generation and of the possibility that technical advance now unforeseen might significantly alter its economics, it is essential to keep in mind that judgments expressed in a report such as this may prove to be valid only for a short time. The Bank's staff will keep developments in this field under review and periodically re-examine the judgments expressed in the report. Should changes occur which substantially modify these judgments, a supplemental report would be prepared. It should be noted, too, that some of the judgments in the present report are not entirely shared by all the entities and organizations which co-operated with the Bank in this effort. In particular, the International Atomic Energy Agency considers some of the Bank's criteria and conclusions do not make sufficient allowance for the rapid advance of nuclear technology and the effects of this advance on the competitive position of nuclear power. The IAEA further believes that it is not feasible to give clear-cut and authoritative guidance to all the developing countries in the form of a set of general criteria which they should apply in considering the use of nuclear power during the next ten years.

iii. The report indicates that the Bank considers nuclear stations as an additional alternative to hydro, diesel, conventional steam or gas turbines. As with the other alternative forms of power generation, the Bank would expect utilities needing to expand their generating capacity to consider such alternatives and to decide on the basis of a detailed study of their specific problem which alternative offers the most economic solution of the problem.

iv. Wherever the Bank is prepared to make loans for power development and the borrowing utility reaches the conclusion that a nuclear power station meets this test, the Bank will consider the proposed project just as it would consider its alternatives; and if the Bank's appraisal confirms the conclusion reached by the utility about the project's justification, it will be considered suitable for a loan. It should be noted that this has been the Bank's consistent position in regard to nuclear power facilities.

v. In view of the growing interest in desalting of sea water and the possible use of dual-purpose nuclear power and desalting plants, attention is given to this in the report.

vi. The Bank wishes again to express its appreciation and gratitude to all those who extended their co-operation to the staff charged with the preparation of this report.

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SUMMARY AND CONCLUSIONS

i. Nuclear power has made an impressive commercial breakthrough in recent years. However, most of the commercial success is being achieved with units of considerable size, 500 MWe and upwards, which are larger than can be installed on the relatively small and isolated power systems which exist at present in most of the developing countries.

ii. The technology of nuclear power is developing rapidly and consequently the character and the timing of significant change cannot be foreseen with certainty. This report therefore looks ahead for only about ten years and considers the prospects for nuclear power only in terms of plants which could be commissioned by the end of the 1970s. Since for any plant which might be commissioned within the 1970s the investment decision period is only the next 5 to 6 years, this report takes into account only what is known today and can be foreseen in a few years immediately ahead. Even in this short period there may be unforeseen developments which would require modification of the conclusions of the report.

iii. Since the first of the large-scale units are only just beginning to be commissioned, some years must elapse before experience is gained in the construction and operation of nuclear power plants of commercial scale comparable with experience in the operation of modern conventional thermal generating units. The lack of experience will be remedied first on US-built Light Water reactors (BWR and PWR), but there is or will be sufficient experience of the British AGR, the Canadian CANDU and the British SGHW reactors for them to be considered within the period on which this report focuses. By the mid-1970s, the end of the investment decision period with which we are here concerned, operational experience may begin to accumulate with industrial prototypes of power plants using other reactor systems, but not in time to permit consideration during the period under review.

iv. As with conventional thermal plants, the developing countries will be well advised to limit their consideration to proven nuclear plants and to leave to others the risks involved in experimentation with major new concepts; they should postpone ordering any nuclear plant until the results of the first year or two of operating experience on a commercial prototype can prove the validity of design and be incorporated in the unit they would buy. This is particularly important in cases (which will be usual because of the scale economies characteristic of contemporary nuclear technology) where the nuclear plant would constitute a sizeable proportion of total system generating capacity.

v. Considerable uncertainty surrounds the costs at which nuclear generating equipment may be available at any particular time and place. Most of the figures used for illustrative purposes in this report relate to American Light Water plant on which there is relatively greater information. The costs of the other types of reactors which are or may become established (e.g. the AGR, the CANDU or the SGHW) are hard to predict; even more so the prices at which they might be offered. But the proponents of these systems are confident that they could be supplied during the period under review at prices which would enable them to be competitive in kilowatt hour costs with Light Water reactors of comparable size installed at the same time.

vi. Nuclear power technology has evolved to a point where utilities that can make unit additions to generating capacity of at least 500 MW should now consider a nuclear alternative in planning any system expansion. The nuclear alternative will not always be the best course, as for instance in cases where large-scale, low-cost, hydroelectric resources can be exploited or where indigenous fossil fuels are available at exceptionally low cost.

vii. To be capable of absorbing a single generating unit as large as 500 MW without serious sacrifices in the reliability of power supply, a utility would normally need to have a power system with several thousand megawatts of demand by the time the unit would be installed. Most of the power systems in developing countries are at present well below the 1,000 MW level, so that even by the end of the period considered here many of them will likely remain too small to absorb 500 MWe units. Nuclear units of between 50 and 200 MWe capacity would have wide applicability for them. But it is impossible to foresee when, if ever, proven reactors in this range might be available at prices which would make them competitive except under quite unusual circumstances of great difficulty of access, exceptionally high costs for conventional thermal fuel, etc. Consideration of proven reactor systems and of what is known of their costs suggests that attainment and availability of commercially competitive reactors of less than about 300 MWe capacity cannot at the present time be postulated.

viii. While the situation regarding units in the general ranges above 500 MWe and below 300 MWe capacity thus seems to be reasonably clear-cut, it is much harder to make any categorical statement about units of intermediate size, between about 300 and 500 MWe. Yet the whole question of whether nuclear technology can be applicable to the small isolated systems typical of the developing world over the next decade for the generation of electric power may turn on the availability and price of nuclear units of around 300 MWe capacity. These are beneath the standard sizes now drawing the interest of manufacturers and there are strong indications that they represent the limit of economic applicability of the reactor systems likely to be relevant within the period under consideration. One cannot be certain that proven units of this capacity will be offered, but a judgment was reached that the cost of a 300 MW unit would be about twice that of the corresponding conventional thermal unit.

ix. Detailed studies of existing and potential power systems were beyond the scope of this report. However, on the basis of the analysis in Chapter 7 it is possible to say that nuclear units of 300 MWe capacity will have limited relevance for developing countries if they are available at about the $240/kw total capital cost (including interest during construction), which has emerged from the study as a reasonable figure to use for general planning purposes today. Such units would be worth consideration only on systems reaching at least 2500 MW load by the time they were installed, and then only if, first, the characteristics of the system were such that the nuclear plant could be run on base load and if, second, conventional gas or oil fuel cost more than 35¢/M Btu (1.4 mills/kCal) excluding taxes (i.e. fuel costs of about 3.5 mills/kwh). Since oil can be assumed to be available in most parts of the world, at least on the sea coast, at a price between 30-35¢/M Btu (1.2-1.4 mills/kCal) and since this price is expected to trend slightly downward in coming years, it is doubtful whether 300 MWe nuclear units at this $240 price could be competitive with conventional thermal plants.

x. Legislation must be enacted by any country which proposes to install nuclear power plants; this legislation must cover the licensing of installations and operators, periodical inspection of plants and arrangements to cover third-party risks arising from operation of nuclear installations. Although most developing countries will employ consultants to control the design and construction of nuclear power plants, they will need to train a sufficient number of their own engineers to work with the consultants and to operate the plants after completion.

xi. Legislative preparation and staff training should be started ten years before the date when it is expected to commission the first nuclear plant. The expense both in money and manpower of making this preparation is such that it cannot be justified unless it is possible to foresee a continuing need to build nuclear power plants.

xii. The earlier nuclear plants were built under turnkey contracts but some of the established manufacturers are now unwilling to accept such contracts. Consultants or engineer architects can be employed by developing countries but, in the present state of the art, the contractual procedure for nuclear power plants is less tidy and stereotyped than for conventional power plants. It is expected, however, that the position will change rapidly.

xiii. Nuclear power plants may involve "district hazards" i.e. there is a remote possibility of an accident which will cause radioactive contamination of areas around the installation. For this reason "siting criteria" are adopted. The hazard is different for different types of reactor but "siting criteria" are not codified and must, for the present, be fixed on an ad hoc basis.

xiv. In recent years it has been found necessary and justified to install desalting installations in an increasing number of locations as a means of providing needed increases in municipal water supplies. The cost of water from these installations, which are in the range of 1-3 million gallons per day (Mgd) unit capacity (approximately 40-120 liters per second) is around $1/1,000 gal (26.4¢/m^3).

xv. Much attention is being given to the possibility of combining nuclear power generation with desalting with a view to benefiting from substantial savings of scale and achieving important reductions in the cost of desalted water. It is already possible to envisage water costs of between 60-70¢/1,000 gal (16-18¢/m^3) being achieved by the mid-1970s for installations in the order of 100 Mgd (4.4 m^3/sec) and 200 MWe, at fixed capital charges of 10 percent. The limitation on the minimum economic size of nuclear reactor which is explained in Chapter 4 makes it difficult to envisage dual-purpose nuclear desalting plants with an output of less than 100 Mgd (4.4 m^3/sec). If used for domestic and normal industrial purposes this output would meet the total domestic and industrial needs of a metropolitan area with a population of one million people and there are few cities which need such an additional supply of municipal water. It is difficult to see how a cost of 60¢/1,000 gal (16¢/m^3) which may be acceptable for domestic and industrial purposes, could be acceptable for agriculture. Technological innovations and the possible resulting reduction in desalting costs, combined with the development of much higher-yielding varieties and greatly improved skills and management on the agricultural side, might produce a different conclusion in 10 or 15 years. Until then the prospects for dual-purpose nuclear desalting plants appear to be limited.

NUCLEAR POWER FOR SMALL ELECTRICITY SYSTEMS

1. INTRODUCTION

1.01 Towards the end of 1966, the World Bank's Board of Executive Directors requested that a staff study be made of the prospects for nuclear power in the developing countries. The report now produced in response to that request does not deal with the question of nuclear power development in any specific country but attempts to consider in more general terms the extent to which atomic power stations may make economic additions to the electricity supply systems of the developing countries over the next decade.

1.02 It should immediately be pointed out and emphasized that most of the factors which control the economics of nuclear power are connected with system size, with interest rates and with cost of alternative fuels. For reasons which are explained in the report, it is difficult to justify nuclear power plants on small isolated systems and the electricity supply systems in most of the developing countries are small and isolated. The report speaks of electricity supply in developing countries only because it is in these countries that the Bank is active. When system size, rates of interest and cost of fossil fuel are the same the advantages and disadvantages of nuclear power are identical in all countries whatever their stage of economic development.

1.03 The decision to undertake this special study was prompted partly by an impressive series of contract announcements occurring in 1965 and 1966 regarding nuclear power development mainly in the United States and in Europe.

1.04 Utility groups in the United States, France and Britain began, in 1963, to order nuclear power plants which they believed would be economically competitive with fossil-fuel stations, and in three cases analyses of the comparisons were published and widely discussed. Jersey Central Power Company of the U.S.A. was the first of these, when in 1963 it ordered the Oyster Creek plant which was estimated to generate power more cheaply than a competing fossil-fueled station. In 1965 the Central Electricity Generating Board in England placed an order for a nuclear power plant for which the estimated generating cost was about 10 percent below that of the best conventional plant built concurrently in the U.K. and in 1966 the Tennessee Valley Authority ordered a nuclear plant for which the estimated generating cost was about 20 percent below that obtainable from the competing conventional plant on their system.

1.05 Since then very heavy commitments have been made particularly by American utilities. By the beginning of 1965 there was about 1,000 MWe of nuclear generating capacity installed in the United States, much of it in plants of relatively small size built primarily for research purposes, and there was about 2,500 MWe of capacity on order. Orders began to build up in 1965, when contracts were signed for about 5,000 MWe of nuclear capacity, representing about 20 percent of the generating capacity purchased in that year by investor-owned utilities. In 1966 the nuclear industry's share of the orders placed for new generating capacity rose to 55 percent; 24 nuclear plants were ordered with a combined generating capacity of some 20,000 MWe. 1967 saw a further increase in the amount of nuclear capacity ordered, to 31 units with a total capacity of 25,500 MWe, so that by the end of the year American utilities had contracts outstanding for the construction of more than 50,000 MWe of nuclear capacity (Annex 1 gives details).

1.06 The dramatic and unexpected nature of these developments is reflected in the frequent revisions that the U.S. Atomic Energy Commission has had to make in its projections of nuclear generating capacity in the United States. In 1962 the AEC predicted 5,000 MWe by 1970 and 40,000 MWe by 1980. Two years later it raised the 1970 figure to 6,000-7000 MWe and its 1980 prediction to 60,000-90,000 MWe. In 1966 the figures were revised again, to over 10,000 MWe by 1970-71 and between 80,000 and 110,000 MWe by 1980. In 1967 the projections for 1980 were further increased, to between 120,000 and 170,000 MWe. Thus the AEC's minimum expectation of nuclear generating capacity installed by 1980 is now some three times the level predicted only five years ago.

1.07 The World Bank's interest is to consider whether these spectacular developments have any relevance for the expansion of electric power systems in the countries where the Bank is likely to lend which, as a matter of convenience, are referred to in the report as "developing countries". For the purposes of this study, these are taken to include virtually all Bank member countries except Canada, the United States, Western Europe, Japan, Australia and New Zealand. However defined, the category of developing countries covers an extremely wide range of conditions as regards the supply and demand for energy. Many of the countries are very low consumers of energy, from whatever source, and have electricity supply systems of only a few tens of megawatts (MW) installed capacity or even less. Other developing countries such as the Philippines, Turkey, Taiwan, Peru and Pakistan contain integrated public electricity supply systems which are now or will soon be in the million kilowatt range of system capacity. A few countries in the developing world (Argentina, India, Brazil would be examples) have now or will soon have systems which interconnect several million kw of generating capacity. A general impression of the relative size of power systems in different countries of the world can be gained from Annex 2 at the end of this report, but the figures must be treated with care, partly because they are somewhat out of date and partly because they relate to total generating capacity installed in a country rather than interconnected capacity. In most of the developing countries demand for electricity is growing rapidly, frequently doubling in less than the rule-of-thumb ten-year period (equivalent to 7 percent annual growth rate) and in some exceptional situations even exceeding, during short periods, the five-year doubling period (equivalent to about 13 percent annual growth rate).

1.08 Since a large amount of the capital available for investment in these countries has to be devoted to meeting these rapid increases in demand for electricity and since a large proportion of its own loans continues to be devoted to electric power, the Bank has maintained a strong interest in technological developments in the field of electricity supply and has been following the developments in the field of nuclear power ever since the first applications of this new technology began appearing in the mid-1950s. This interest was evidenced, for instance, on the occasion of the Annual Meeting in 1956: the then President of the Bank, Mr. Black, invited some of the leading authorities on nuclear power to join him for a panel discussion on the prospects of the new technology. As Mr. Black stated in opening the panel discussion "....the Bank is not interested in atomic power as an academic exercise. We are not an academic or research institution. We are an international development Bank....but (we know that) a gleam in the eye of a scientist or engineer (today) is tomorrow's investment...." At the time that meeting took place Calder Hall had just been commissioned and the construction of Shippingport was approaching completion. These two plants represented the first attempts to bring the technological concept of power production to a scale beyond the purely experimental.

1.09 The authorities who participated in the 1956 discussion concurred in foreseeing a bright future for nuclear power plants, particularly those of about 200 or 300 MWe, which was the larger end of the size range then being talked about. The consensus seems to have been that units of this size would likely become competitive with conventional plants fired by fossil fuels within ten years in areas with moderately high fossil fuel costs, and earlier in areas with high fuel costs.

1.10 In one sense developments since then have exceeded the most optimistic of the predictions: some of the American plants, as noted, are being built in areas of relatively low fossil fuel costs. However, it should also be appreciated that the American utilities' decisions in favor of nuclear plants have generally involved units of very large size compared with those considered a decade ago; those orders for commercial plants which have been justified on the grounds of economics are for units of 400 MWe or larger, and many of them have been for units in the 800-1,100 MWe range. And there is nothing on the horizon in the really small unit sizes which is likely to be industrially economic.

1.11 The purpose of the present report, like the Bank's 1956 studies, is again to look ahead over the coming years to try to identify the scope that may exist for developing countries to benefit from nuclear technology in the generation of electric power. Despite the advances that have been made in this technology it is relatively new and developing so that it is hard to forecast long-term development. The report therefore focuses mainly on additions to countries' generating systems that might be ready for commissioning before the end of the 1970s. Since it takes at least five years to build a nuclear power plant, this means that the review is limited to plants that may be ordered by 1975 at the very latest.

1.12 The report describes first the main principles of how a nuclear plant works and the principal types of nuclear reactor that are being developed for power generation. Chapter 4 considers the capital costs of nuclear power plants, and attempts to compare them with those of conventional steam electric plants. Chapter 5 deals with nuclear fuels and their costs. The remaining chapters are largely concerned with technical, economic and administrative considerations that should enter into the decision whether or not to install a nuclear power plant. Chapter 8 on Administrative Aspects of Nuclear Power, also considers the preparations that have to be made in a country prior to initiating a nuclear power program. The final chapter discusses the conclusions reached in the review of progress towards large-scale nuclear desalting.

1.13 In approaching the problem of the type of nuclear generating equipment which may be available from time to time, the report will use the connotation of "proven". In this regard the Bank's view is that when complex mechanical plant is required (and this covers a broad range from thermal power plant to locomotives) a developing country should limit its consideration to makes and designs which have already been manufactured and operated successfully in some other country's system. This view is based on two principal foundations, namely:

(a) a developing country requires even greater reliability of operation than a developed country and demands an even greater assurance of the successful outcome of any project investment (these questions will be gone into in greater detail in the report); and

(b) the Bank has been familiar with numerous instances where complex equipment, even though manufactured by well established and generally reliable firms, gave serious and long lasting difficulties in the case of prototypes even when no new principles were involved.

1.14 As all of these considerations are valid <u>a fortiori</u> in the case of nuclear plants, which involve radical new principles and technologies, the Bank would consider it risky for a developing country to install plant having basic design and components which differ materially from what has been in successful utility operation elsewhere. Only installations which meet the criteria outlined above will be referred to as "proven". In this context, a substantial size extrapolation is sufficient reason for the criterion not to be met.

2. NUCLEAR POWER PLANT TECHNOLOGY

2.01 The essential difference between nuclear power plants of current design and conventional power plants is that in the nuclear plants heat is produced by nuclear fission in a reactor whereas in conventional plants it is produced by burning fossil fuels, such as coal, oil or gas, in a boiler. In both cases the heat produced turns water into steam, and in both cases the heat energy of the steam is converted to mechanical energy in a turbine, and the mechanical energy is in turn converted into electricity by a generator. The nuclear steam supply system thus substitutes for the boiler in a conventional plant. All the other equipment in an electricity generating station, such as the turbine condenser and generator remains in principle the same with a nuclear as with a fossil fuel source of heat.

2.02 For an electric utility, the cost of generating electricity accounts for perhaps one-third to one-half of the total cost of supplying that electricity to its customers, the remainder representing costs of transmission and distribution. In turn, between one-third and one-half of the generating cost is typically attributable to the production of steam in a predominantly thermal generating system. Thus, in considering and comparing a nuclear steam supply system and a conventional source of steam we are essentially focusing on elements which constitute from 10-25 percent of the total cost of electricity to consumers in conventional thermal systems. This, of course, does not mean that the comparisons are unimportant; but it does mean that undue risk ought not to be incurred to secure marginal reduction in generating cost.

2.03 Nuclear plants differ markedly from fossil-fueled plants as regards the configuration of their costs. Capital costs and hence capital charges for nuclear plants tend to be appreciably higher than those for conventional plants of equivalent capacity; they may be about twice as high in the lower size ranges, say around 300 MWe capacity. The saving in the case of nuclear plants comes in fuel costs which can typically be half as much as for conventional plant.

2.04 A nuclear reactor is a device in which a process of nuclear fission can be started and sustain itself (chain reaction) and be controlled. Nuclear fission occurs when the central part, or nucleus, of certain heavy atoms is struck by a subatomic particle called a neutron. The heavy atom splits into lighter atoms, called fission products, which are usually highly radioactive. The splitting of the atom is accompanied by the release from within its fissioning nucleus, of further neutrons and of energy. Most of this energy appears as kinetic energy but almost instantaneously becomes heat as the fission fragments fly apart at great speed and collide with surrounding material. Some of the neutrons released from the nucleus strike materials which absorb them unproductively, but some strike other fissionable nuclei and it is this that serves to maintain the chain reaction.

2.05 Thus, the essential characteristic of fuel for a nuclear reactor is that it contain some fissionable material, or material that undergoes nuclear fission when struck by neutrons. The only naturally available fissionable material is uranium-235, an isotope or form of uranium constituting only about 0.7 percent of the element as found in nature. Almost all the rest of natural uranium is uranium-238. When neutrons strike uranium-238 a "synthetic" fissionable material (plutonium-239) is formed, and for this reason uranium-238 is called a fertile material.

2.06 It is possible to achieve a self-sustaining fission reaction with the natural mixture of uranium-235 and uranium-238. But the use of natural uranium as a reactor fuel imposes some limitations on reactor design and operation. To get around these limitations, enriched fuel is often used. By this is meant fuel containing a higher concentration of fissionable atoms than that of uranium-235 in natural uranium. Enriched fuel can be obtained by putting natural uranium through an isotope separation process which removes some of the uranium-238 from the natural mixture or by adding a synthetic fissionable substance (e.g. plutonium) to natural uranium.

2.07 Solid uranium metal fabricated into rods which are sealed into containers was (and is) used in reactors of early design but the fuel used in all the reactors likely to be sold commercially in future is one of the oxides of uranium. This uranium oxide fuel is generally formed into small cylindrical pellets, and packed into long thin tubes and known as fuel elements. The walls of the cans or tubes serve as fuel cladding, which helps lock in the radioactive fission products formed as the fuel undergoes fission. The fuel elements containing the oxide fuel are assembled into bundles or fuel assemblies, for insertion into the reactor. The fuel is disposed in the reactor in rods parallel to one another and set in a carefully designed pattern. The "geometry" of the fuel is important from a reactor physics standpoint; a certain distribution of fuel within the reactor core is required for the system to function properly.

2.08 The reason for this is that each fission of an atom of U_{235} produces (on average) only 2.3 neutrons. Some of these will be lost by useless absorption in the materials of which the core is constructed leaving only about two neutrons available from each fission. If the chain reaction is to be maintained one of these must strike an atom of U_{235} and cause another fission. But in natural uranium there are 140 atoms of U_{238} for every atom of U_{235} and even in the slightly enriched uranium which is used in most of the present day industrial reactors there are about fifty atoms of U_{238} for every atom of U_{235}. The statistical probability therefore is that most of the neutrons will strike atoms of U_{238} and will not cause further fissions so that the chain reaction will die out. To maintain this chain reaction the probability of neutrons causing further fissions must be increased. This is done by reducing their velocity; neutrons travelling at slow speeds are less likely to be absorbed by atoms of U_{238} and more likely to cause fission of atoms of U_{235}. The velocity is reduced by letting the neutrons collide with the molecules of a moderator which surrounds the fuel elements. The velocity of the neutron is reduced to that of the molecules in the moderator, this velocity is determined by the temperature of the moderator and the molecular speed is therefore called the thermal velocity. It is for this reason that reactors which rely on a moderator to maintain the chain reaction are called "thermal reactors". The elements which can be used as moderators are some of those at the bottom of the periodic table; i.e. the light elements, and those which have been most generally used are hydrogen, an isotope of hydrogen known as heavy hydrogen or deuterium and graphite. When hydrogen or heavy hydrogen are employed as moderators it is usual to use them in combination with oxygen; i.e. as ordinary water or heavy water.

2.09 A coolant is used to remove from the core the heat generated by fission, so that this heat can be utilized to generate in turn steam and electricity. The coolant should be a good conductor and absorber of heat but not absorb too many neutrons. Reactors moderated by light water generally also use light water as the coolant. Most reactors moderated with graphite use a gas coolant, such as carbon dioxide or helium. Reactors using heavy water as a moderator generally use either light or heavy water as the coolant.

2.10 In most reactors control of the rate at which fission occurs, and with it heat output, is obtained by regulating the "population" of free neutrons in the core. This is most commonly done by rods which, when inserted into the core, absorb neutrons and so reduce the number that are available to cause further fissions. Withdrawal of the rods, called control rods, increases the rate. Full insertion shuts down the reactor. Control rods are made with material with a high propensity to absorb neutrons, such as boron and cadmium.

2.11 Provisions must be made in a reactor for introducing and removing the fuel elements. The measure of burn-up (the portion of the theoretical energy potential of the fuel which can be practically recovered from it during exposure in the reactor) is usually expressed in terms of MW (thermal) days per metric ton or kilogram of fuel (MWd/ton or kg). Burn-up is limited by the loss of nuclear reactivity that occurs as fissionable atoms are split and fission products accumulate and by dimensional instability which dictates replacement before fuel element structural damage occurs. In commercial reactors of current design fuel elements remain in the core for between one and four years, but during this period they may be shifted in position in order to obtain better effectiveness in their utilization.

2.12 Upon removal from the reactor the irradiated fuel elements are first moved to a shielded storage vault or pool at the site. There they are left for up to several months to allow for some of the radioactivity to die down. Fuel assemblies removed from the reactors contain partially burned uranium and plutonium which should be reclaimed. The procedure by which the nuclear fuel is reclaimed is called reprocessing. Reprocessing is a complex chemical operation performed at specialized plants to which the fuel is shipped in heavy shielded containers. Most of the operations in reprocessing have to be performed by remote control because, in spite of the cooling periods, substantial radioactivity remains. The chemical reprocessing consists mainly of removing the cladding and then eliminating fission products and radioactive poisons through a sequence of wet processes ending up with uranium and the plutonium which has been created by irradiation of some of the U_{238} atoms.

3. REACTOR SYSTEMS

Summary

The review of known reactor systems and of their status of development shows the following ranking in the order of decreasing degree of proven-ness:

- *Magnox is the only system which, in its original unit capacities, could be regarded as fully proven. It is, however, unable to meet the competition of more recently developed nuclear systems.*

- *Next are the boiling and pressurized water reactors, which would meet the proven test in the roughly 200 MW versions of 1960-62 commissioning vintage except that these have largely become obsolete in both size and design. However, the successor versions (of American manufacture) in sizes from 300 MW to 1,000 MW will soon reach the operating stage in sufficient numbers to warrant the expectation that the letter of the "proven" test will be met by say 1969 or 1970.*

- *Next comes the Advanced Gas reactor (AGR), which can be regarded as a logical development of the Magnox system using an improved fuel element. This new fuel element has been tested for six years in the Windscale prototype; the commercial plants ordered for Dungeness B and succeeding stations use a more advanced design of fuel element which cannot be considered as proven before Dungeness has operated for at least one year (i.e. by 1971-72).*

- *Depending on the outcome of the initial years of operation of prototypes in utility service, the CANDU reactor can be added to the number of proven systems by about 1970, in time for consideration within the period under review.*

- *It should similarly be possible within the period of review to add the Steam Generating Heavy Water reactor (SGHW) to the list of proven reactors provided that the 100 MWe prototype at Winfrith continues to give satisfactory experience and provided that the design of commercial reactors of this type is based on the unchanged module tested there and uses the same conditions of fuel element rating and temperature.*

Other types of reactors, notably fast reactors, are not sufficiently advanced in development to warrant expecting their availability in proven form to developing countries for commissioning before 1980.

* * * *

3.01 A great deal of very interesting reactor development work is now being done in numerous countries. This work covers both improvements and refinements of reactor concepts of demonstrated value and the search for a solution of many problems relating to the more advanced reactors of the future. It stands to reason that some of this work will succeed and attractive new developments will occur in future. Nuclear power technology, in relative terms, is still very much in its infancy: it has already accomplished much, but this is dwarfed by its probable forthcoming achievements. It would be difficult to present a comprehensive survey of all the alternative reactor types on which work is being done: it would also be irrelevant from the viewpoint of this study, which deals with the choice of proven equipment before 1975 (in line with the definition given in the Introduction).

3.02 Of the many reactor concepts which are being studied, very few are likely to reach a sufficiently advanced state of development for consideration by operating utilities in developing countries before that time. First, reactor concepts go through a long period of research and development during which design work is refined and partial components are tested. An experimental prototype is then generally built at some research station, of a scale usually much smaller than the eventual utility version (20-50 MWe has been a frequently recurring dimension for experimental prototypes up to now).

3.03 When it is considered that the experience with the experimental prototype warrants it, a commercial-scale prototype plant is designed and built. In current terms this would mean an installation designed specifically as a power station, with a capacity well above 100 MW. At present, the time cycle for building and initially testing a commercial prototype plant must be considered as no less than some six years and probably more like ten.

3.04 The construction period for a proven nuclear plant in a developing country would have to be estimated as about five years from the moment a decision is made. It follows therefore that if only proven plants are to be considered (i.e. plants which have shown completely successful operation of a commercial prototype of about the same size during at least a year or two) for commissioning by 1980, the corresponding commercial prototypes should already be under construction at this time, and be completed without a hitch. In the light of this, the reactor systems covered in the discussion to follow are gas-cooled reactors, light water reactors and heavy water reactors. To give an indication of longer term development trends, fast reactors are also discussed.

3.05 Before entering into the detailed discussion of these various types it may be helpful to focus on a fundamental choice that had to be made by those who developed the systems now established. In view of the cost and complication involved in enriching uranium there is a strong incentive towards building natural uranium reactors. However, the marginal number of fissionable atoms in natural uranium requires such high neutron efficiency for a power reactor to be feasible in practical terms that the obvious, inexpensive and easily manageable moderator and coolant, i.e. water, is ruled out. Therefore, natural uranium as a fuel has, at least so far, dictated the choice of more efficient (in terms of neutron economy) moderators such as heavy water or graphite and coolants such as heavy water or gas. Conversely, if the cost and inconvenience of enrichment is accepted, lower neutron efficiency is readily acceptable and with it the convenience and advantages of the use of ordinary light water for both purposes.

Gas-cooled Reactors

3.06 There is still more nuclear generating capacity in operation at the present time using gas-cooled reactors than any other type of reactor. Apart from one station in Japan and a small experimental plant in the United States, it is all in Europe. At mid-1967, out of a total of about 4,000 MWe installed capacity, about 3,000 MWe is in the United Kingdom. All the existing central station nuclear generating plants in the U.K. use Magnox reactors, based on the Calder Hall prototype. Even before Calder Hall was completed in 1956, the U.K. initiated a sustained program of construction of nuclear power stations using reactors of this type. The reason for this decision had to do with the evaluation of domestic coal mining prospects as well as the repercussions of events like the 1956 Suez crisis. The Magnox reactors use natural uranium metal as fuel, sheathed in cans of magnesium alloy (Magnox) with graphite as a moderator and carbon dioxide as a coolant. While these primary choices are dictated, as was mentioned above, by the use of natural uranium as a fuel, the use of gas coolants also permits desirably high operating temperatures without involving high pressures, an advantage that can be seen in some ways as compensation for rather poor heat transfer capacity and large volumes. The British Magnox program was subsequently expanded and will shortly come to an end with the completion of the ninth station, at Wylfa, which will have two 590 MWe reactors. Operating experience with the Magnox plants, which on the whole has been good, illustrates the point that availability tends to be low during the early years of first-of-a-kind commercial-scale plants. Table 3.1 presents data provided by the British Central Electricity Generating Board. Both Berkeley and Bradwell stations were commissioned late in 1962.

Table 3.1

Availability of U.K. Magnox Plants
(in % of whole year)

	1963/64	1964/65	1965/66
Berkeley (2 x 140 MWe)			
Reactor 1	58.0	87.0	84.9
2	82.6	79.2	91.6
Total Plant	51.0	58.0	88.0
Bradwell (2 x 150 MWe)			
Reactor 1	74.2	71.3	85.8
2	83.2	97.4	83.2
Total Plant	70.0	77.7	84.3

The figures compare well with the 70 percent cited by the CEGB for the average availability in 1965/66 of the large units of advanced design built over the preceding five years in their conventional stations.

3.07 Similar to the British Magnox plants are the French plants using graphite moderator, carbon dioxide coolant and natural uranium fuel in magnesium alloy cans, and totalling about 800 MWe capacity. France is continuing to build Magnox reactors: three, with unit sizes of about 500 MWe, are under construction and it has recently been decided to build a further larger station of the same type, Fessenheim. To date the operation of the French gas/graphite stations has not been without difficulties.

3.08 The use of Magnox fuel elements set an upper limit to the temperature which could be achieved. This limitation was important in leading to the conclusion that while the Magnox system had been developed to give satisfactory operation, its economics could not be expected to make it competitive. For this reason British plans for expansion of nuclear generating capacity are now based mainly on the AGR; the last three nuclear stations ordered by the British Electricity Boards are of the AGR type, and it is understood that they intend to order more. The AGR was developed mainly with a view to achieving higher top temperatures in the heat cycle, with an increase in thermal efficiency from the level of about 30 percent of the Magnox station to about 40 percent. The AGR uses graphite as moderator and carbon dioxide gas as coolant, just like the Magnox, but the fuel elements are made of slightly enriched uranium oxide (1.3 to 2.3 percent U_{235}), enclosed in stainless steel cans, and the reactor is more compact. A 32 MWe experimental prototype AGR (Windscale) has operated satisfactorily since 1962. The first commercial-scale AGR (Dungeness B Station) with two 600 MWe reactors, is not scheduled for completion until 1970. In assessing the reliability of the AGR, the scope of uncertainty is narrowed by the fact that the design is directly derived from the Magnox reactor and differs from it mainly in that it uses an improved fuel element.

3.09 Important experimental work is under way in the United States and Europe on a third generation of gas-cooled reactors, the High Temperature Gas-cooled reactor (HTGR), but it is unlikely that a proven version will become a relevant alternative for equipment decisions by utilities in developing countries during the period under review. The largest experimental prototype of the HTGR system is the 40 MWe Peach Bottom plant in Pennsylvania, now in its initial operating period. The European countries have been co-operating through the European Nuclear Energy Agency in the DRAGON Project, with a small 20 MWe reactor at Winfrith in England which was completed in 1964 and first reached full power in April 1966.

<u>Light Water Reactors</u>

3.10 At mid-1967 there was in operation about 1,300 MWe of nuclear generating capacity using light water reactors but in view of outstanding contracts, capacity based on the light water system will soon greatly exceed that based on reactors of other types.

3.11 While most of the light water reactor generating capacity, existing and under construction, is in the United States, light water reactor technique is also applied outside the United States: Belgium, France, Germany, India, Italy, Japan, Spain, Sweden and Switzerland all have light water reactors in operation or under construction.

3.12 As there has been a juxtaposition of gas-cooled reactors and water reactors as the two principal systems established during the last decade, it is inevitable that there would be, on an international basis, partisan differences of opinion on the two techniques among those professionally interested. Thus, the proponents of gas-cooled stress its features of high steam pressure and temperature in the heat cycle and prestressed concrete containment as advantages. Similarly, proponents of the water systems stress the smaller bulk of their plants, the advantages of water over gas as a coolant, the lower initial cost and lower operating staff requirements.

3.13 It is difficult to make final objective weighings of these claims and counter-claims: probably none of them warrants a decided preference. It is, however, indisputable that light water reactors have been quoted and ordered at lower capital cost per kilowatt installed than any other reactor system. A large-scale industry is growing to supply them and service them on an international basis. Capital, fuel and operating costs are now estimated at levels which make it appear that light water reactors in the sizes which are being standardized (500, 750 and 1,000 MWe) can generate power at lower unit costs than conventional plants even in areas where fossil fuels are comparatively cheap.

3.14 Development of the light water reactors for central station power plants has taken place largely in the United States. It began in earnest in the early 1950s. The circumstances which favored this line of development were the existence of large diffusion enrichment capacity no longer fully required for military purposes and of a considerable body of applicable technology thanks to the development of reactors for submarine propulsion.

3.15 Development of the light water reactor, i.e. a reactor in which ordinary water is used as both moderator and coolant, has branched along two different lines over the past fifteen years. In the Boiling Water reactor (BWR) the coolant water is allowed to evaporate in the reactor and the resulting steam turns the turbine, whereas in the Pressurized Water reactor (PWR) the water is maintained under sufficient pressure to keep it from evaporating and it is circulated to heat exchangers where steam is raised, thus maintaining separate water cycles in the reactor and in the turbine. In the USA, the BWR is presently offered by one manufacturer and the PWR by three others. For each system there are already a number of licensed manufacturers in other countries. As of the end of 1967, there was about 600 MWe of BWR capacity operating in central station power plants, 200 MWe of it in the United States, and nearly 23,000 MWe under construction or on order. At the same date there was about 1,900 MWe of PWR capacity in operation, 1,400 MWe of it in the United States, and over 30,000 MWe under construction or on order.

3.16 Fuel technology in water reactors is now fairly firmly established with enrichment levels of from 2 to 4 percent, and zircaloy canning almost exclusively adopted after attempts at using stainless steel. Steam conditions are modest, i.e. saturated steam at pressures between 800 and 1,000 psi, with resulting steam cycle efficiencies in the order of 30 percent. The technology of water reactors is undergoing continued refinement in the industrial development and manufacture of standardized components of plant, which will need to prove themselves as more of the large number of units under construction reach the commissioning stage in the next year or so. While it can be expected that difficulties will arise with the first few units of the new design and size to reach the operating stage, it is also reasonable to expect that these difficulties will be overcome, the resulting changes in design and manufacturing detail introduced in subsequent units, and a proven standard of manufacture and performance reached in two or three years' time.

3.17 The longest record of operating experience for light water reactors of industrial scale is associated with two well known water reactor installations. The first sizeable BWR was built by General Electric at Dresden near Chicago, Illinois; it has a capacity of 200 MWe and produced its first electricity on April 15, 1960. The first PWR of more than 100 MWe capacity, Yankee, was built by Westinghouse at Rowe in Massachusetts; it has a capacity of 175 MWe and produced its first electricity on November 10, 1960. Table 3.2 summarizes available information about operating experience on these two plants.

Table 3.2

Availability Record of Light Water Reactors
(in % of whole year)

	Scheduled Outage		Forced	Reactor	Plant	Capacity
	Refuelling	Other	Outage	Availability	Availability	Factor
Dresden						
1961	--	20.0	41.9	40.1	38.1	33.0
1962	14.9	5.9	1.0	80.6	78.2	74.3
1963	18.8	4.4	1.2	80.7	75.6	53.8
1964	15.7	1.6	1.8	82.9	80.9	56.2
1965	17.0	0.7	4.0	82.9	78.3	55.4
1966	--	4.4	1.5	97.2	94.1	80.2
Yankee Rowe						
1961	--	8.4	9.3	87.0	82.3	76.0
1962	34.6	0.2	1.2	65.4	64.0	55.0
1963	19.7	0.8	1.5	78.9	78.0	69.0
1964	9.6	0.3	0.6	90.4	89.5	79.8
1965				75.7	72.5	64.6
1966				89.5	89.5	85.8

These figures indicate a pattern somewhat similar to that shown by Table 3.1 as regards the improvement in availability after the first two years.

Heavy Water Reactors

3.18 There is considerable interest in the heavy water concept and experimental prototypes are in operation or under construction in a number of countries. The main potential advantage of this reactor type is its ability to use natural uranium fuel more efficiently than any other designed to date. The combination of natural uranium fuel and greater efficiency in its use should make it possible for it to have the lowest fuel cost among reactor systems so far developed. The developers of this system expect that this low fuel cost will compensate for the high capital cost which is due partly to the features of the design and partly to the investment in heavy water ($12-15 million for a 300 MW installation). The use of heavy water makes operation and maintenance more demanding, as any leaks are expensive.

3.19 Canada has been the leading country in the development of heavy water reactors. Work on research reactors using heavy water as moderator and light water as coolant was started there in the 1940s. In the late 1950s, the Canadians decided to move into the field of nuclear power and to concentrate their effort on heavy water reactor technology. They had no enrichment plants but they did have large indigenous reserves of natural uranium and experience with the problems of handling heavy water in reactor systems. A 20 MWe pilot plant has been in operation since 1962. Construction of the 200 MWe Douglas Point CANDU commercial prototype plant was completed in 1967 and the commissioning program, in the course of which some difficulties were encountered, has not yet been completed. 1/ Further capacity is under construction: two 500 MWe units at Pickering, Ontario; two 200 MWe units in Rajasthan, India; and one 132 MWe unit near Karachi, Pakistan. In all these reactors heavy water is used for the coolant as well as for the moderator.

3.20 Experimental heavy water-moderated and cooled reactors have also been built elsewhere. For instance, Sweden, which also has extensive indigenous reserves of uranium, built a small heavy water reactor of its own design near Stockholm which was commissioned in 1963 and is used to generate power and to provide a district heating service. And in Germany, Siemens has built a 50 MWe prototype heavy water reactor known as MZFR at Karlsruhe.

3.21 As already pointed out, the CANDU reactor uses heavy water as a coolant and this increases both capital cost and difficulty of operation. To remove these objections while still using heavy water as a moderator, both the Canadians and the British have developed modified reactors which use heavy water as a moderator and boiling light water as a coolant. The Canadian prototype (known as the Boiling Light Water (BLW) reactor) is being built at Gentilly, Quebec; it has a capacity of 250 MWe, is scheduled for completion in 1971 and uses natural uranium as fuel. The British prototype (SGHW) reactor has been built at Winfrith with a capacity of 100 MWe. Unlike the BLW, it uses a slightly enriched fuel and by accepting this disadvantage, avoids some of the design difficulties which have to be met if natural uranium is used. The SGHW was commissioned at the end of 1967 and has operated satisfactorily from the outset. As the fuel elements are contained and steam is raised in pipes which can be considered as modules, larger SGHW reactors can be built without fundamental change of design by increasing the number of modules

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1/ Operation at full capacity is reported to have been achieved in April 1968.

in the core. Insofar as reactor performance is concerned, it follows that, provided the module design is not changed, it should be safe to scale up to larger commercial versions after another year or two of satisfactory experience with the prototype.

3.22 Other lines of development in coolants for heavy water-moderated reactors include boiling heavy water, organics and gas. The use of boiling heavy water has been tested on a pilot scale in the small experimental Halden reactor in Norway, sponsored by the European Nuclear Energy Agency. The Canadians are planning to convert their 20 MWe experimental CANDU-Pressurized Heavy Water (PHW) plant to test a CANDU-Boiling Heavy Water (BHW) design this year. In Sweden there is under construction a plant which would use boiling heavy water in a direct-cycle heat transfer circuit similar to the light water BWR. The plant, Marviken, is designed to achieve 200 MWe with internal superheating. Studies indicate that losses of the expensive heavy water from the turbine and condenser in this rather adventurous system can be kept to an acceptably low level but operational experience to support this claim is not yet available. Organic coolants, which can be heated to fairly high temperatures without requiring pressurization to prevent boiling, are being tested in a number of experimental reactors sponsored by the U.S.AEC, its Canadian equivalent (Atomic Energy of Canada Ltd.) and Euratom. Work on gas coolants for heavy water-moderated reactors is also going on, particularly in Europe. A 70 MWe prototype, EL-4, was completed by France at Brennilis (Monts d'Arrée) in 1966 and went critical in 1967, but has recently had to be shut down owing to failure of heat exchangers. A 100 MWe prototype, also using carbon dioxide gas coolant, is being built in Germany at Niedaraichbach, Bavaria, and is scheduled for operation in 1969. It is envisaged that both these reactors would use natural uranium fuel after the first core has been irradiated.

Fast Reactors

3.23 It has already been pointed out that, if natural or slightly enriched uranium is used as a fuel, the neutrons in the core must be slowed down to thermal velocities to maintain the chain reaction. If a pure or nearly pure fissile material is used as the fuel there is no need to do this because the non-fissile atoms are no longer there to absorb the neutrons. The chain reaction can be continued by allowing fast (unslowed) neutrons to strike atoms of the fissile material in the core. Such reactors are therefore called fast reactors. The core of such a reactor can be surrounded by a blanket of fertile material such as U_{238} and the neutrons that are not needed to maintain the chain reaction at the desired level are allowed to escape into this fertile material and so produce plutonium. Because, in such a fast reactor, there is no moderator which inevitably and uselessly absorbs some neutrons, more are available for the production of new fissile material in the fertile blanket and fast reactors can be designed in such a way that the number of new fissile atoms produced in the blanket is greater than the number of fissile atoms destroyed in the core. For this reason they are sometimes called breeder reactors. Thorium can be used as an alternative to U_{238} in the blanket; if this is done the new fissile material created will not be plutonium but a third isotope of uranium (U_{233}) which, like plutonium, can be used as a fuel in other fast reactors.

3.24 The first experimental fast reactor operated was the American EBR-I at the National Reactor Testing Station and this plant, completed in 1951, demonstrated the feasibility of breeding with its first core. The 14 MWe Dounreay Fast reactor in Scotland, cooled by sodium potassium alloy and using enriched uranium fuel, produced its first power in 1962 and has successfully met its research objectives. Further work on breeder reactors in the USA has resulted in the installation at the National Reactor Testing Station in Idaho of the 20 MWe EBR-II which first produced power in 1965; and in the construction by a group of electric utilities of the 67 MWe Fermi power station near Detroit, Michigan which until the present has operated only intermittently and for short periods. France has recently built a small (20 MWe) fast reactor, Rapsodie, at Cadarache which is reported as having reached its rated power output in 1967.

3.25 As to large size prototypes, the British Prototype Fast reactor (PFR), which is under construction at Dounreay, is scheduled to be operational by 1971. France plans to start construction of a 250 MWe demonstration fast reactor, Phenix, at Marcoule in 1969. The U.S.AEC does not plan to make any commitments for a commercial-scale prototype plant until 1969, but intensive studies of alternative designs are under way, and it seems probable that a number of demonstration plants, each of 300 MWe or more capacity, may be built during the 1970s. Germany is also planning construction of an industrial-scale fast reactor prototype during the 1970s.

3.26 It is unlikely that any fast reactors will reach the stage of being proven before 1980, and it is possible that there will be further delay in reaching this threshold. In any event, fast reactors will not be relevant within the period considered in this report as an alternative for installation on small power systems but they may be relevant insofar as they are likely to become commercially viable well within the life of power plants constructed in the next few years and could thus affect the long-term economics of nuclear plants installed before 1980.

4. CAPITAL COSTS OF NUCLEAR PLANT

Summary

The capital cost of a nuclear power plant can only be determined by getting bids. Past experience gives only limited help in forecasting the prices which are likely to be quoted. Construction experience of Magnox reactors established a trend of capital costs for them but this is not relevant because Magnox reactors are now uncompetitive. Only three domestic orders have been placed for AGR's and a price trend cannot be established from this limited experience. The number of heavy water-moderated reactors

which have been built is similarly limited. Only light water reactors have been ordered in sufficient numbers for a price pattern to be discerned and this pattern shows many irregularities and inconsistencies. The American manufacturers of reactors of this type believe that the 300-350 MWe unit size represents the limit of economic applicability of the system and does not warrant being established as a standard size. Consequently, light water reactors of this size may not be available at all and there is great uncertainty about the price at which they may be offered, if available. A reasonable guess at the cost for a 300 MW unit would be $240/kw, or double the cost of a conventional thermal unit of comparable size. The availability of reactors of this size and/or the availability of lower prices may occur as a result of the advent to the market of new reactor suppliers, though they could only offer proven units in the last years of the period under review.

It appears probable that the other reactor types (AGR, CANDU, SGHW) which can be considered for use in developing countries within the period of review are likely to have capital costs higher than those of the light water reactors. It should be remembered however that capital charges form only part of total generating costs and that fuel and operating charges have to be considered: after these have been taken into account the proponents of these systems expect them to be competitive.

No indications were found which would warrant optimism about the possibility of any type of reactor of substantially smaller size than 300 MWe becoming available during the period under consideration at prices which would make them competitive for normal utility service.

* * * *

4.01 The previous chapter dealt with the reactor systems which may be or become proven in time for investment decisions by developing countries during the period under review. This chapter proposes to deal with the questions, perhaps more important for countries with small power systems, of the sizes, or unit capacities, in which such reactors are likely to be available, and their prices.

4.02 The significant development in this respect has been the constant increase in unit capacities to a point where recent utility orders have been for units of half a million kw capacity or (most frequently) more.

4.03 The principal American manufacturers, for instance, are standardizing on light water reactors having capacities of 500 MWe, 750 MWe and 1,050 MWe, each flexible within roughly a 5 percent range, depending on the detailed design arrangement of components and the specific steam conditions in each case. These firms say that they would be prepared to consider quoting for a 300-350 MWe reactor provided they felt there was a reasonable possibility of business resulting from the bid and provided that no important departures from existing detailed designs were demanded. Their view is that the 300-350 MWe unit size is on the margin of economic applicability of the light water reactor system. As another example, the U.K. Atomic Energy Authority considers its AGR to come into its own at 500 or 600 MWe and would not recommend it for sizes under 350 MWe but expects the SGHW to compete in the smaller range.

Trends in the Prices of Light Water Reactors

4.04 Since by far the largest number of orders has been placed in the U.S. for nuclear power plants using light water reactors and the manufacturing development of these reactor systems has been carried further than that of other systems, it is useful to review the trends in the prices at which they have been available. Three successive phases in the development of nuclear power in the U.S. over the last decade can be seen: 1956 to 1963, 1963 to mid-1966, and after mid-1966.

4.05 The first plant constructed for the purpose of proving the feasibility of a central station nuclear plant, was the Shippingport PWR, which started operation in 1957. While Shippingport was being completed orders were placed for the first commercial nuclear power plants, designed and constructed to be operated on a utility system principally for the purpose of proving economic and technical aspects of future plants of the same general type. Dresden (200 MW, BWR), Yankee Rowe (175 MW, PWR) and Indian Point-1 (270 MW, PWR) were ordered in 1956-57 and started operations between 1959 and 1962. Because of the many unknowns, all of these facilities and a number of those that followed them were built as turnkey jobs under the complete responsibility of the principal manufacturer involved. Published figures indicate that Dresden cost about \$304 per kilowatt, Indian Point-1 about \$445 per kilowatt and Yankee about \$220 per kilowatt. The first two figures are substantially above those originally estimated for the costs of the respective plants, but it is not certain whether any of these figures properly represent the costs involved. Therefore, they cannot be considered very meaningful for the purpose of determining price trends.

4.06 In the latter part of 1963 a substantial sequence of new orders for nuclear plants began; the well-known order which opened up this phase was that of Oyster Creek, a nuclear power installation with a capacity of 515 MW, ordered by Jersey Central Power & Light Co., on a turnkey basis; the estimated total cost was about \$125/kw. It gave rise to a controversy stemming mainly from two questions: (1) that it was felt by many that the price was an artificially low promotional one, and (2) that an even lower unit cost (about \$105/kw) was claimed to be achievable if a stretch capacity[1/] of 620 MW was taken into account. Whatever the merit of these questions, the Oyster Creek price and guarantees indicated a dramatically low level of cost at which utilities could purchase large nuclear units. One of the most important implications of these developments was that nuclear plants could compete with conventional thermal units even outside the few areas of (by U.S. standards) high fuel cost where nuclear power had been expected to be economical at an early date. With this demonstration of competitiveness there followed a rapid succession of orders for nuclear power units at prices well below the pre-Oyster Creek level. The phase which had begun with the Oyster Creek contract culminated with the announcement in mid-1966 that the Tennessee Valley Authority (TVA) was placing an order for two BWR units, each with a capacity of 1,065 MWe to be installed at Brown's Ferry, Alabama. TVA's statements showed that the nuclear plant, at a cost of $116/kw including land and interest during construction, would have a slightly lower capital cost than a coal-fired plant of equivalent capacity. In the TVA contract, General Electric gave firm prices not only for the major part of the capital cost of the projects but also for fuel costs for the first twelve years of operation.

4.07 The Oyster Creek-Brown's Ferry phase, which corresponded roughly to the period from mid-1963 to mid-1966 can thus be seen as the time when leading U.S. manufacturers, having evaluated the experience obtained through the prototypes and established manufacturing capacity for nuclear power units, decided to offer installations whose design and main features they judged likely to be economically viable over the long term, at prices sufficiently attractive to cause a large number of utilities who had been considering nuclear power to commit themselves in this field. If this was their intent, it did achieve its purpose in that one witnessed, from 1965 onwards, a rapidly accelerating sequence of orders from American utilities for units in the size range 450 MWe and above.

4.08 In the latter part of 1966 certain developments occurred which can be viewed as opening a distinctly new phase; the most important of these developments were the announcements of the leading U.S. manufacturers that:

1/ 515 MWe was the capacity which the manufacturer, General Electric, guaranteed for the Oyster Creek plant. It represented the capacity attainable by observing very conservative design factors whose acceptance by regulating authorities was a practical certainty. Stretch capacity was the capacity which was expected to be attainable with operation nearer to design limits. More experience, fuller theoretical analysis and more experimental study of the heat flows in the core would be necessary to ensure the feasibility of this and the issuance of licenses to operate at such greater capacity. Jersey Central felt sufficiently convinced of the attainability of stretch capacity by the time Oyster Creek would be completed to order a 620 MW turbine.

(a) As a general policy they would no longer accept turnkey contracts.

(b) They had standardized unit capacities for nuclear power plants and they would in future only supply such standard size units.

(c) They were going to publish price lists for nuclear steam supply systems (i.e. the nuclear boiler) corresponding to the standard sizes they had chosen.

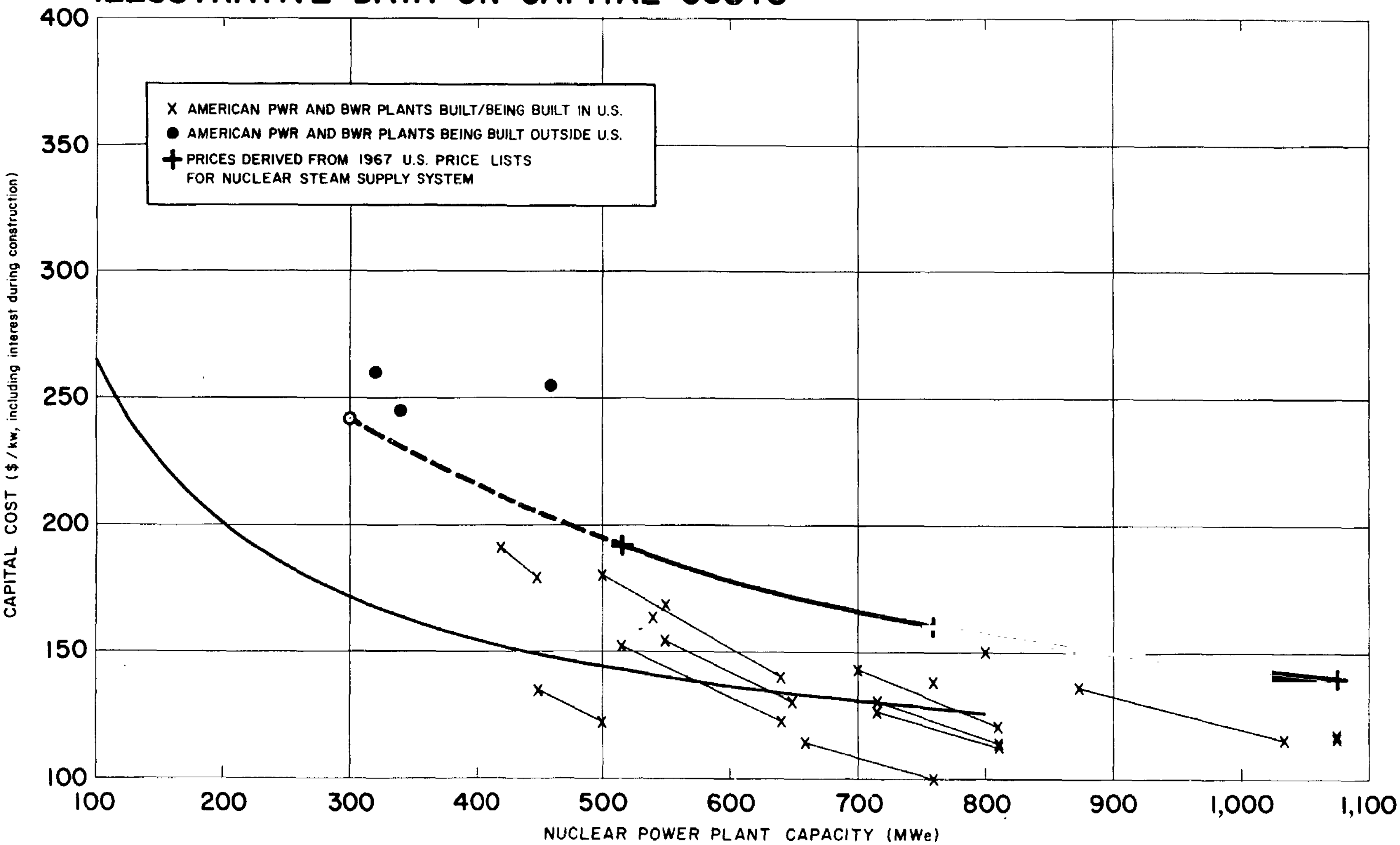
4.09 The price lists for the three standard sizes of 500, 750 and 1,050 MWe, established prices for the nuclear steam supply system substantially above those which had prevailed up to that time. In public discussions within the industry the price increase on the nuclear parts of the installation was acknowledged to be of the order of 30-50 percent, which would be equivalent to an increase of about 10-20 percent in the total cost of a nuclear power plant. In fact the price for the total plant appears to have gone up, by about a third, or even more for the lower unit sizes.

4.10 Figure 4.1 presents available data on the total capital costs to utilities of American light water plants. While there is no assurance on uniformity of basis for these figures, they supposedly include interest during construction and cost of land, but exclude costs of training labor for plant operation and all fuel costs. In addition to doubts about uniformity and comparability of these figures, the limited significance of the use of a cost per kw figure should be kept in mind. Site factors, such as geological and seismological conditions, accessibility and the state of existing transport and transmission facilities, cooling water, and labor conditions may cause a spread of as much as 15-20 percent in the unit cost of power stations that are otherwise identical; this of course applies to conventional thermal stations as well as to nuclear stations. In addition, important variations in the cost of building nuclear power stations might arise if there were sufficient differences in regulatory requirements with regard to plant safety, containment, inspection procedures, etc.

4.11 Whatever these limitations, Figure 4.1 shows the significant upward shift in the list prices and the fact that the single crosses, relating to plants ordered in the later part of 1966, generally fall significantly above the stretch prices indicated for plants of similar size ordered earlier. The Figure also brings out the fact that costs per kilowatt installed tend to fall sharply with an increase in unit size; this is particularly marked in the area up to the 750 MWe size.

4.12 Of particular interest in the context of the present discussion is the left hand side of the figure. The 300-350 MWe unit size, which is not covered in valid price lists as it is not a standard size, is the most interesting one as being the smallest which may be available in a proven version in the foreseeable future. After considering all available information, including drawing some arbitrary analogies with apparent trends during the last five years relating to the larger unit

NUCLEAR POWER PLANTS (LIGHT WATER REACTOR SYSTEM): SOME ILLUSTRATIVE DATA ON CAPITAL COSTS



NOTE: The heavier line connects the points representing estimates of probable total plant cost stemming from 1967 price lists and, for the 300 MW size, the estimate that could be made from available clues. The thinner line represents similar estimates based on the previous (1965) price lists. The crosses and lines refer to plants ordered before the end of 1966 for which information was available and is copied in Table 4.1. The meaning of the two crosses joined by a line relates to stretch capability.

(R)IBRD-3817

FIGURE 4.1

Table 4.1

NUCLEAR POWER PLANT CAPITAL COSTS - SOME ILLUSTRATIVE DATA

Capacity (MWe)		Cost ($/kw)
American PWR and BWR plants built/being built in U.S.		
515-640	Oyster Creek	152-122
500-640	Nine Mile Point	180-140
715-810	Dresden 2 and 3	130-114
550-650	Millstone	170-145
873-1033	Indian Point-2	136-115
420-450	R.E. Ginna	191-179
715-810	Quad Cities 1 & 2	126-112
660-760	H.B. Robinson	128-111
700-810	Palisades	143-120
450-500	Point Beach	150-134
1075	Browns Ferry 1 & 2	116
1075	Peachbottom 2 & 3	117
760	Easton-Niagara Mohawk	138
540	Vermont Yankee	163
800	Surry 1 & 2	160
550	Prairie Island	168
American PWR and BWR plants being built outside U.S.		
320	Tsuruga, Japan	260
460	Fukushima, Japan	255
340	Mihama, Japan	260

Sources: U.S. Congress- AEC Authorizing Legislation Fiscal Year 1968: Hearings before the Joint Committee on Atomic Energy, Ninetieth Congress, First Session, on Reactor Development Program (March 14-15, 1967);
Japan Atomic Industrial Forum: Nuclear Power Cost Study Team, "Problems involved in Cost Evaluation on Nuclear Power Stations in Japan" (October 1967);
Information provided by U.S. Atomic Energy Commission and General Electric (U.S.).

Note: There is no assurance that figures quoted in this Table are indicative of true cost, or that their make-up is uniform and comparable. In some instances it is not even certain whether or not they may include some allowance for initial fuel. (Capital cost discussed in this report for nuclear plant does not include any allocation for initial fuel.)

sizes, a guesstimate of $240 per kw has been made for the total cost of a nuclear plant of this size, hypothetically installed in the U.S. The figure is not inconsistent with information received about the estimate of cost of units of this size being built by U.S. suppliers in Europe and Japan, particularly if one takes into account that it always costs appreciably more to erect such a plant overseas, other things being equal. (Cost of shipment, management and erection personnel, design and supervision complications.) For this reason the $240/kw domestic hypothesis is not really in conflict with the range of estimates ($260-300) encountered in existing overseas contracts.

Construction Costs of Other Reactor Systems

4.13 While the information available on the costs of nuclear plants based on other systems is inadequate to support comparisons between different reactor systems, it may be of some interest to mention the few more meaningful cases.

4.14 The following table presents information provided by the U.K.AEA early in 1967 regarding the construction cost of the Magnox plants.

Table 4.2

Construction Costs of U.K. Magnox Plant

Station	(1) Capacity (MWe)	(2) Year Commissioned	(3) Construction Costs (£/kw)1/	(4) Construction Costs ($/kw) (Col.3 x $2.80)
Magnox				
Berkeley	2 x 140	1962	185	518
Bradwell	2 x 150	1962	175	490
Hunterston	2 x 180	1964	n.a.	-
Hinkley Point A	2 x 250	1965	150	420
Trawsfynydd	2 x 250	1965	142	397
Dungeness A	2 x 270	1965	116	325
Sizewell A	2 x 290	1966	107	300
Oldbury	2 x 300	1967	111	311
Wylfa	2 x 590	(1969)2/	(103)	(288)

1/ In some cases these costs are substantially above those that were originally estimated for the plants in question. Information is not available on original estimates. The U.K.AEA provided information on costs as anticipated four years prior to completion of each plant. For Berkeley and Bradwell, which also took nearly two years longer than originally planned to build, this anticipated cost was about £145/kw compared with the £185/kw and £175/kw now estimated. Over the years there seems to have been considerable improvement in forecasts of construction time and costs. The Sizewell plant, for instance, was completed in 4 years, 11 months compared with the originally estimated 4 years, 8 months, and the total cost of the station, as now estimated is only about 3 percent above that anticipated four years prior to completion.

2/ Figures in brackets represent anticipations in early 1967.

4.15 Cost information on the AGR is limited as only three contracts have so far been let, all for installations in the U.K. Contract prices for these stations (all units are in the 600 MWe range) indicated a total capital cost per kilowatt (without fuel) in the range of £75-80 ($210-225); but escalation has raised the estimate for the first station to about £90 ($250) a couple of years before completion of construction. The U.K.AEA indicated the level they considered reasonable for the cost of AGR installations built overseas under U.K. export conditions. These indications were about £65/kw ($180/kw) for 600 MWe units and £80/kw ($225/kw) for 400 MWe units. It was noted that these hypothetical costs were appreciably lower than the known contract prices for plants now under construction in the U.K.

4.16 As regards the CANDU reactor system, it is generally recognized that its capital cost is substantially higher than that of light water reactors although the considerably lower fuel cost may compensate sufficiently to make it competitive, especially if the applicable interest rate is low. To date construction of CANDU plants in Canada has been undertaken on the basis of a large number of sub-contracts administered and co-ordinated by Atomic Energy of Canada Ltd., in a multiple role of designer-builder and sometimes also equipment developer. Therefore, the progress in the industrialization of the manufacture of this equipment has probably not been sufficient to reach judgments about economic size of units or normal costs. Canadian sources indicated a figure of $390/kw for the cost of the 200 MWe Douglas Point plant and about $270/kw for the first two 500 MWe units under construction at Pickering. Adequate data are not available about the costs of the CANDU plants that are under construction in India and Pakistan. It is naturally impossible to give figures for the SGHW because no industrial orders have as yet been placed.

Capital Costs of Conventional Thermal Stations

4.17 In making comparisons it is important to use realistic and up-to-date figures on capital costs of conventional generating equipment representing those a utility might actually be able to obtain by competitive bids. Recent years have seen some downward trend in the prices of such equipment in real terms. The price at which conventional power stations can be built will, of course, vary with the site factors mentioned above in connection with nuclear plants and with international market conditions. For purposes of this general discussion, some reasonable

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* All price indications quoted in this page were obtained in £ Sterling before the November 1967 devaluation. Dollar equivalents are shown at the pre-devaluation rate of $2.80.

average conventional plant cost figures have been selected on the basis of experience.1/ Table 4.3 presents these figures and compares them with the figures consistent with the 'price list line' in Figure 4.1 for the costs of light water nuclear plants. The nuclear plant cost figures presented here are all slightly below those shown in Figure 4.1 because they exclude interest during construction.

Table 4.3

Indicative Estimates of Comparative Capital Costs of Light Water Nuclear and Conventional Generating Plants

($/kw - excluding interest during construction)a/

Size of plant (MW)	300	400	500	750	1075
Unit Cost of Plant					
Nuclear	216	195	175	148	130
Coal	144	130	120	106	104
Gas/Oil	108	98	90	80	78

a/ Economic costs, as used here, include owner's overheads and land acquisition, but exclude interest during construction, taxes, all fuel and all cost escalation allowances.

4.18 Capital costs of coal-fired plants are taken to be about 25-35 percent above those for oil/gas-fired plants: oil or gas-fired plants are more widely relevant in the developing countries today and the main comparison is, therefore, between the costs shown for them and the nuclear plant costs. The figures indicate that the capital costs of a light water nuclear plant in the 300-400 MW range of plant size may be about twice those of a conventional plant of similar size. At the upper end of the size range presented the differential is considerably less: the nuclear plant may be some 55-60 percent more expensive than the conventional plant.

1/ It should be noted that the figures presented here include no allowance for extra costs involved in plant installation outside the country supplying the basic equipment and services. Shipping costs, the need to bring skilled labor from abroad, and difficulties in local procurement would have to be covered by such an allowance.

4.19 The conventional plant cost figures shown in Table 4.3 are believed to be conservative, in the sense of erring on the high side, if anything, relative to the costs shown for nuclear plants. In a number of cases in the Bank's recent experience, conventional power generating equipment has proved to be available, after international competitive bidding, at prices below those that would be implied by the figures in the table.

4.20 One of the most important factors accounting for the higher capital cost of nuclear power plants is the shielding and containment that has to be provided to satisfy safety and siting regulations.

4.21 The heavy shielding and containment required are also major factors accounting for the sharpness of the decline in costs per kilowatt as the size of nuclear power plants is increased. If the capacity of a reactor is doubled the thickness of the reflector which surrounds the core and of the shielding and containment which enclose the reactor are not materially changed and the cost of the structure is increased by a factor considerably less than two. In fact the absolute cost of containment and shielding for light water reactors increases relatively little with increase in the size of the reactor. The study of cost allocations in some specific instances illustrated this point, as it showed that shielding and containment would account for some $50 per kilowatt in a 300 MWe unit, compared with about $20 per kilowatt in a 760 MWe unit.

4.22 There is no trend apparent which would warrant trying to forecast whether or not price improvements can be expected, although it should be remembered that international competition is likely to have its usual effect. For example, leading American manufacturers have in the last couple of years entered into licensing agreements with a substantial number of manufacturers in Europe and Japan. In view of the large number of orders which had recently practically filled the order books of the American manufacturers, their foreign licensees might in the near future be in a better position to offer reactors of interest to developing countries. Known licensees were canvassed either in writing or on the occasion of visits. It is difficult to generalize the conclusions reached after this canvass, the more so as there was a wide variance in the nature of the replies obtained, from very cautious to obviously over-optimistic. On the whole, the following conclusions can reasonably be drawn:

(1) None of the licensees has up to now built, under his own direct responsibility and without the support of the licensor, a complete installation.

(2) The majority of the licensees do not expect to be ready to do so until two to four years from now.

(3) The majority of the licensees propose to adopt the exact designs developed by their licensors with only such modifications as may

be required by the specific circumstances of any proposed installation; and when developing any modification the majority of the licensees propose to avail themselves of the right they generally have under the license to secure a review by the licensor of the proposed change.

(4) A number of licensees say that they are or will be capable of independently carrying out the detailed design of units of smaller size or, in any event, of sizes not corresponding to those recently chosen as standard. It does not appear likely, however, that such independent designs will be ready very soon and there will remain a question about the extent to which such a unit might be considered proven.

(5) A few amongst the licensees who claim that they are ready to offer units smaller than 300 MW did not offer any convincing evidence that these could be expected to be economical. Other licensees who approached this question more realistically and were trying to satisfy themselves whether smaller units could be economical said that this would take some time and that while they were hopeful for a positive conclusion for a capacity around say 250 MW, they could not be optimistic for smaller sizes.

5. REACTOR FUELS AND THEIR COSTS

Summary

Fuel costs account for a smaller proportion of the total costs of electricity generated in a nuclear power plant than in a conventional thermal plant. Equilibrium fuel costs for a 300 MWe light water nuclear power plant would be about 1.85 mills/kwh, assuming operation at 80 percent capacity factor; at a 60 percent capacity factor they would be about 2.25 mills. There is no clear trend which would permit seeing the probability of either increase or decrease of nuclear fuel costs during the next few years. This conclusion results from the existence of numerous disparate factors which may well be mutually self-cancelling.

Fuel costs for the other types of reactor likely to be relevant to the developing countries over the next decade for use in central station power plants are likely to be lower than fuel costs for light water reactors; those for most types of heavy water reactor will be substantially lower while those for gas-cooled reactors will probably be at an intermediate level.

Nuclear fuel elements are supplied competitively by several firms in several countries and can be obtained under a wide variety of contracts. Under the most comprehensive contracts, the utility pays for its fuel in

terms of an agreed charge per heat unit used. It is very important that the first core or two be purchased from the reactor supplier, and it will generally be advantageous for a utility to purchase fuel under one of the more comprehensive types of contract until there are two or three nuclear plants on the system.

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5.01 It has already been pointed out that fuel costs are normally a much less significant component in the total costs of electricity generation in a nuclear plant than in a conventional thermal plant. This can be illustrated hypothetically by comparison of a 300 MWe nuclear plant using a light water reactor and a 300 MW gas-burning steam plant. Using the capital costs shown in the preceding chapter and assuming total capital charges of 12 percent and operation of both plants at 80 percent capacity factor, the rough comparison shown in Table 5.1 can be made. The figure used for nuclear fuel cost is discussed at greater length in this chapter.

Table 5.1

Costs of Generation: 300 MW Units
(mills per kwh)

	Nuclear	Gas
Capital	4.10	2.05
Operation and Maintenance	0.43	0.21
Fuel	1.85	4.12
	6.38	6.38

5.02 The calculation on which the table is based is set up in such a way as to equalize the costs of energy generated. This implies a gas price of about 46¢/M Btu (1.82 mills/kCal), assuming a heat rate of 9,000 Btu, or 2,265 Cal, per kwh sent out and, as the table shows, the relative importance of capital costs and fuel costs are almost exactly reversed between the two plants. If gas were assumed to be available at a more reasonable price, say half the 46¢, then fuel costs on the conventional plant would be approximately equal to capital costs and the total cost of electricity produced in this plant would be 4.32 mills/kwh. It should also be noted that, since capital charges account for such a relatively high proportion of the total cost of electricity generated in a nuclear plant even at an 80 percent capacity factor, operation at a lower capacity factor would result in an even greater disparity between the costs of electricity production in the two plants. For instance, at a 60 percent capacity factor, total generation costs on the nuclear plant would be about 8.3 mills/kwh including fixed capital charges of 5.5 mills1/, and on the conventional plant, assuming gas at 0.91 mills/kCal, about 5.1 mills, including capital charges of 2.7 mills.

5.03 Fuel costs differ considerably between different reactor systems, and of the main alternative systems discussed, the light water reactors actually have relatively high fuel costs. In general, fuel costs for plants based on heavy water reactors are considerably lower, while those for plants using gas-cooled reactors tend to be intermediate between the two. These differences arise from a variety of factors. One of the main ones is the degree of enrichment required of the fuel. The Magnox and most heavy water systems use natural uranium fuel, while the AGR and some heavy water systems use slightly enriched fuel. Use of reactor systems with high neutron economy may eliminate not only the actual enrichment costs but also costs of reprocessing if, as in some heavy water systems, the burn-up is so high as to make it uneconomic, at least at current price levels, to reprocess the spent fuel. Clearly this would involve quite a different pattern of fuel costs from those involved in a fuel cycle using enriched uranium; and this is important because, as will be seen below, carrying charges for money tied up in fuel inventory account for a significant proportion of the fuel component of nuclear generation costs. The amount of carrying charges will also be affected by the refuelling pattern adopted, which is another factor accounting for differences between the fuel costs in different reactor systems. Finally, the costs of fuel fabrication vary among reactor systems, depending, for example, on the fuel cladding required.

Fuel Costs of Light Water Reactor

5.04 In this chapter the fuel costs and fuel management for light water reactors are discussed as an example of what is involved. The problems with other types of reactors differ to a greater or lesser degree but the same principles apply.

5.05 The BWR and PWR are now designed for periodic fractional refuelling with feed material of uniform enrichment; about one-third or one-quarter of the fuel elements (constituting a so-called fuel region) are replaced each year with fuel elements that are all of the same enrichment. At each refuelling shutdown the central region is removed and replaced by partially irradiated fuel elements from the outer zones of the core, and the new fuel is inserted in the outer zones; thus each

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1/ And fuel costs of about 2.25 mills/kwh, higher than the fuel costs with 80 percent load factor because of the capital charges involved in financing the fuel inventory. See following.

fuel element moves over the course of its in-core life from the outer zones of the core to the center. This procedure has been adopted as being the simplest and most efficient means so far discovered for maintaining uniform flux distribution in the core. One implication of it is that the fuel regions removed from the core in its early years of operation will have short in-core lives compared to the regions that replace them. Various techniques have been adopted to minimize the effect on fuel costs of removal of the first regions after such short in-core lives, but fuel costs in the first two or three years of operation remain at present above 'equilibrium' fuel costs. Here we will speak in terms of equilibrium fuel costs, and so it must be remembered that fuel costs in the first few years of operation will be somewhat above the figures shown.

5.06 Table 5.2 gives an illustrative breakdown of fuel costs for an 800 MWe PWR, based on the equilibrium fuel cycle and current prices in the United States. The table is based on information released by a PWR manufacturer and concerns the use of fuel enriched to a 3.28 percent content of fissionable U_{235} and a burn-up of 31,500 MWd/ton of U. The allowances for fuel shipment are about double those normally assumed in American studies, in order to make at least a token allowance for the greater distances that fuel elements for reactors in developing countries will probably have to be carried. The table brings out the fact that the main components of fuel costs for a PWR are natural uranium (U_3O_8), enrichment, fuel fabrication, capital charges on fuel inventory and the credits included at the bottom of the table for recovery of uranium and plutonium from the spent fuel. These are also the main elements in BWR fuel costs which would differ somewhat in detail but add to about the same figure in mills/kwh.

5.07 Light water reactors of smaller size than 800 MWe would have somewhat higher fuel costs. A rough estimate would put the total fuel cost for a 300 MWe reactor something of the order of 10 percent above that shown in Table 5.2. A small part of this increase is due to the slightly lower plant efficiency of a plant of smaller size, but the main factors are: (1) fuel for a 300 MWe unit needs to be of a somewhat higher enrichment than that for a larger one of similar design because wasteful absorption of neutrons (i.e. their loss from the chain reaction) is governed by the surface/volume ratio of the core and this is higher in a smaller reactor and, (2) fuel fabrication costs per kg of U are about 5 percent higher for the smaller unit.

Table 5.2

Equilibrium Nuclear Fuel Costs at Current Prices (800 MWe PWR)

		Approximate Current Unit Cost	Mills/kwh
(1)	Mining and preparing U_3O_8	\$ 6/lb	0.403
(2)	Conversion to UF_6	\$ 2.30/kg U	0.060
(3)	Enriching UF_6	\$ 26/kg-unit	0.546
(4)	Conversion to UO_2)		
(5)	Pelletizing UO_2)		
(6)	Making fuel cladding) Fuel Fabrication	\$100/kg U	0.427
(7)	Cladding the fuel)		
(8)	Bundling clad fuel)		
(9)	Shipment to reactor	\$ 3/kg U	0.013
(10)	Shipping out spent fuel	\$ 10/kg U	0.041
(11)	Chemical reprocessing of spent fuel	\$ 31/kg U	0.127
(12)	Reconversion to UF_6	\$ 5.60/kg U	0.023
(13)	Value of reconstituted UF_6		-0.129
(14)	Value of plutonium recovered	\$ 9/gm Pu	-0.247
(15)	Sub-total		1.264
(16)	Capital charges, say 33% 1/		.417
(17)	Total		1.681

1/ At 10 percent cost of capital.

Assumptions: 800 MWe PWR, with 31 percent plant efficiency, and run at 80 percent capacity factor. Burn-up of 31,500 MWd/m ton U from Zirconium-clad fuel of 3.28 percent enrichment at loading and 0.96 percent enrichment at discharge. Uranium discharge assumed to be 95.8 percent of initial U load, and plutonium production assumed to be 6.7 grams fissile Pu/kg of U discharged. Calculations were based on these assumptions and the current U.S.AEC table of enrichment services.

Fuel Management

5.08 When considering the fuel cost breakdown given for illustration in Table 5.2 it is important to remember that these factors can all be adjusted, within limits, to suit the use that the utility wishes to make of the nuclear plant during any period in its life. This means that nuclear fuel management is a complicated process, involving consideration of factors specific to the power system on which the nuclear plant is installed, such as the shape of the annual load curve and variations over time in the availability of other generating equipment on the system.

The Principal Components of Nuclear Fuel Costs

5.09 For purposes of fuel cost analysis, natural uranium is generally considered in the form of U_3O_8, which is about 85 percent pure uranium. U_3O_8 is presently obtainable in the United States from the AEC at $8/lb; but it can also be purchased in the free market at prices which have recently been in the range of $6/lb. After the war there was extensive prospecting for uranium to meet the requirement of large defense programs. When the needs for defense had been met there was excess capacity, prices fell and prospecting virtually stopped. Large orders have recently been placed for nuclear power plants and construction of nuclear plants is likely to continue at a high level. This had led to anxiety over uranium reserves and many studies of probable reserves and cost have been made. In all of these there is necessarily a certain amount of guesswork. Two things should be remembered about uranium supplies. The first is that it seems probable that industrial fast reactors will be ordered before 1980. These will use by-product plutonium from thermal reactors as fuel and will breed more fuel than they consume. With expanding nuclear programs this breeding is not likely to meet the need for additional nuclear fuel but it will reduce the requirement of uranium. The second thing to be remembered is that there is no fear that uranium supplies will run out. Supplies will always be available at a price. Most authorities estimate that in order to encourage enough prospecting and mine development the price will have to rise from its present level of around $6/lb to between $7-10/lb. While realizing the amount of guessing involved in such estimates, the Bank sees no reason to disagree with them or to fear that, in the foreseeable future, natural uranium prices will rise to an extent that materially alters the relative economics of nuclear power; a rise in price of $1/lb of U_3O_8 (yellow cake) increases the cost of electricity only by about 0.1 mills/kwh.

5.10 Enrichment is the largest single item in the illustrative fuel costs shown in Table 5.2, accounting for nearly one-third of the total. The enrichment process is one of the most complex stages in the production of nuclear fuel and, with present technology, it requires plants of very considerable scale and cost, using vast quantities of electricity. In uranium enrichment a partial separation of the uranium isotopes is accomplished. The separation process normally used today is gaseous diffusion and it makes use of the fact that there is a very slight difference in mass (235 vs 238) of the two uranium isotopes. Diffusion plants exist in France, the U.K. and the U.S.A. and are still classified installations. It is understood that the full capacity of the recently completed French plant will be needed, at least in the early years, for defense purposes. The U.K. plant is being expanded to meet the requirements of the British domestic nuclear program and the U.K.AEA is apparently prepared to supply enriched fuel elements for reactors of British design built abroad. There are no technical reasons why this British plant cannot be extended to meet overseas requirements but it is difficult to see how it could compete with present U.S. enrichment charges. About half the cost of enrichment is in the cost of electric power used in the diffusion process and British power prices are appreciably higher than the prices at which power is available for the U.S. diffusion plants.

5.11 There has been available large enrichment capacity in the U.S.A. and the U.S.AEC has been and is prepared to enter into contracts for the supply of enriched fuel over the life of a reactor and within a guaranteed ceiling price, subject only to escalation for electricity and labor. It will also enrich uranium bought on the open market by a reactor owner; this is known as toll enrichment and standard prices are quoted for it by the AEC. Contracts for supply of fuel or enrichment services by entities in foreign countries can also be made through the International Atomic Energy Agency in Vienna (IAEA).

5.12 Prices for enrichment services are quoted in terms of dollars per unit of separative work required for each kg of uranium. The definition of a unit of separative work is very complex, but the higher the enrichment desired, the more units of separative work are required. The AEC reduced its charges from $30 to $26/kg unit of separative work in November 1967. There is considerable debate and study going on in the United States whether the enrichment process should be turned over to the private sector; additional enrichment capacity is expected to be necessary around 1975 and it is possible that this might be provided by the private sector. How the price of enrichment services might be affected by these possible developments is uncertain but there is no reason for the time being to justify other than the assumption that the charge for separative work will remain at about the present levels.

5.13 Before leaving the subject of enrichment it is worth noting that in most, if not all, of the reactors likely to be available for commercial use in the next few years it should be possible to use plutonium enriched fuel instead of enriched uranium. This has not been done as yet but it appears that the required development work is being done. The technique should not involve too great difficulties. This may be another reason (in addition to the possibility of obtaining supplies of enriched material from the IAEA) why the aversion in principle to enriched uranium systems is not justified.

5.14 The third major component of nuclear fuel costs is fabrication of fuel elements. Fuel elements are manufactured on a competitive basis by some of the leading suppliers of nuclear reactors and by firms working in close collaboration with them. Design and fabrication of fuel elements are in fact very intimately related to reactor design. Reactor performance and heat output are direct functions of element design which is, therefore, reflected in reactor warranties. Accordingly, the purchaser of a nuclear plant, at least during the foreseeable future, should buy at least the first core loading from the reactor supplier; this procedure avoids the serious difficulties that may arise when responsibility for reactor performance is split between two firms, one of which has supplied the reactor and the other the fuel.

5.15 Fuel management (i.e. the decision as to when and how fuel elements are to be replaced or rearranged) is a complex business done by scientists with the aid of computers. Most suppliers of fuel elements are willing to provide a fuel management service for fuel elements that they have supplied. In developing countries it is essential that any contract placed for fuel element supply should stipulate that this service be provided.

5.16 Fuel element fabrication costs are high and at least in theory would appear to offer good opportunity for sizeable reductions. It is to be expected that fuel element fabrication costs will fall as a result of growing experience, mass production and increasing competition. Some responsible manufacturers believe that this reduction will at least cancel out the rise in cost of yellow cake which must be expected.

5.17 After irradiation in the reactor, as discussed in Chapter 2, fuel elements contain plutonium and fission products in addition to what is left of their original uranium; the plutonium and uranium are potentially valuable and therefore they are usually recovered by chemical separation, giving rise to the reprocessing costs and also the credits shown at the bottom of Table 5.2. Chemical separation facilities exist in Britain and continental Europe, as well as in the United States, and additional plants are being planned, including one in Japan. An industry-owned plant has recently been established in the U.S.A. It has a capacity of one ton/day and cost about $30 million (the one ton/day capacity is generally considered to be the threshold of economic operation); a much smaller plant, of about 125 kg/day capacity, recently completed in West Germany, cost about $15 million. Clearly there are substantial economies of scale involved and it is thought that they extend up to larger sizes, although larger plants are not expected to be reached for a considerable period, even in the United States.

5.18 A market to support one minimum-size reprocessing plant without undue economic penalty should consist of several million kw of nuclear plant. It is therefore desirable that the tendency to build a great many semi-idle reprocessing facilities will be contained. This aspect of nuclear development takes on greater importance when it is considered in the light of the fact that the reprocessing plant is the point in the nuclear flow chart where the success or failure of efforts to establish and maintain safeguards and ensure the peaceful use of nuclear material will be decided. The IAEA greatly emphasize the need to limit and control the establishment of reprocessing plants; and their efforts deserve endorsement and support for economic, in addition to political, reasons.

5.19 Competitive tenders for chemical separation can be obtained and most of the processors of irradiated fuel are prepared to arrange for transport of irradiated fuel elements from the reactor to the separation plant. Such transport is expensive because the fuel elements must be carried in heavily shielded containers. Containers currently in use that can take two tons of spent fuel weigh nearly 70 tons, empty. Conditions for safe transport are prescribed by the IAEA. At present there remain at least formal difficulties about the transport of irradiated fuel, for example, through inter-ocean canals. As the world nuclear power industry expands, however, transport difficulties are likely to be reduced.

5.20 What plutonium has been produced to date in nuclear reactors must be assumed to have gone into weapons, laboratories or stockpiles, but in the future it is likely to be used as fuel in fast reactors or for enrichment of fuel in thermal reactors. In the United States, the AEC has agreed to buy plutonium at a price of $10 per gram of fissile isotopes, which was revised downward to $9.28 recently in connection with the reduction in enrichment charges.

5.21 The last major element in nuclear fuel cycle cost is the cost of capital tied up in the fuel inventory.[1/] Besides fuel in the reactor, the fuel inventory for a reactor at any point in time includes new fuel which is being enriched or fabricated into fuel elements or is awaiting loading into the reactor and spent fuel undergoing cooling at the reactor site or awaiting reprocessing. Detailed calculations of the amount of money required to finance this inventory are complex. They involve computation of a cost stream representing the cumulative total of progress payments for natural uranium, enrichment, processing, fabrication, shipment and reprocessing of spent fuel and of an income stream representing the cumulative total of receipts from sale of plutonium and depleted uranium. For the 800 MWe PWR mentioned earlier, the fuel inventory investment required under U.S. conditions would average about $24 million, when the equilibrium fuel cycle was reached, fluctuating above and below that figure over the course of a year. Then if the cost of money for financing the fuel cycle is assumed to be 10 percent per annum[2/], annual capital charges for fuel inventory will be about $2.4 million. This is about one-third of total annual fuel costs excluding capital charges, assuming

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1/ An inventory of fuel is, of course, often maintained at conventional thermal plants, usually some three to six months of fuel supply for a coal-fired plant, and often several weeks of gas or oil supply for plants using gas or oil or capable of burning either. But the costs of financing fuel inventories are generally much less significant components of fuel costs for conventional thermal plants than they are for nuclear plants.

2/ A fairly common practice in the U.S.A. for working capital requirements.

80 percent capacity factor; hence, the 33 percent allowance for capital charges in Table 5.2. Actual investment required in fuel inventory for a particular plant will clearly vary depending on many specific factors, including location of plant relative to fuel suppliers and fuel reprocessors and contractual arrangements made regarding fuel supply; but the indicative allowance made here serves to illustrate the fact that capital charges on fuel inventory are a major item in nuclear fuel costs.

5.22 It should be emphasized that the account which has been given of the way in which fuel is managed, priced and costed in light water reactors is illustrative. Similar problems arise in the other reactor systems which can be considered by developing countries within the period of review but they differ as between reactor types. For instance, CANDU reactors use unenriched fuel and achieve high burn-ups; fuel costs in these reactors is therefore low because enrichment and reprocessing charges are avoided. AGR, SGHW and CANDU reactors are generally designed for on-load fuel element change and this makes the problem of fuel management completely different from that of the light water reactors which are designed for off-load fuel element change. There are alternative ways of dealing with fuel inventory charges. For instance, the cost of the initial fuel charge can be included in capital and an offsetting capital credit equal to the present worth of the fuel remaining in the reactor at the end of its useful life can be given. Replacement fuel charged into the reactor can then be treated as a simple operating cost.

5.23 It is also important to bear in mind that utilities need not concern themselves with any one of the several steps in the fuel cycle, be it the purchase of uranium, or the reprocessing, or indeed the financing of core loadings. There have been several cases in which manufacturers and suppliers have offered alternative contractual arrangements under which they would in effect provide all fuel services. The utility can, therefore, if it wishes, receive the fuel at the plant, be given precise instruction on when and how to load or reshuffle, and have the spent fuel taken away from the plant for a guaranteed charge per Btu or calorie used. Indeed it appears, in view of the expertise required in carrying out effectively all fuel cycle work, that a utility would need to have substantial nuclear capacity on its system before it is justified in reaching self-sufficiency in this respect. As a matter of order-of-magnitude reference, complete nuclear fuel service contracts known to have been offered for light water reactors in the U.S. recently, would have resulted in the utility paying in the order of 15¢/M Btu (0.6 mills/kCal).

6. NUCLEAR POWER AND SYSTEM PLANNING

Summary

Simplified plant-to-plant comparisons are inadequate to determine the justification of choosing nuclear plant for system capacity additions. Detailed long-term analysis of the power system and alternative expansion plans need to be considered, some including and some excluding nuclear plants. Possibilities of expanding the system by interconnection with neighboring utilities need to be investigated. Hydroelectric resources need to be considered from the point of view of how they might best be employed, with nuclear plants on the system and without them. With nuclear plants carrying base load, hydroelectric storage capability may warrant being used to a much greater extent for peaking purposes than would otherwise be the case, and nuclear energy, because of its low marginal cost, may create special opportunities for use of pumped storage if good potential sites exist. Important system-planning parameters in an economic assessment of nuclear power are the life attributed to nuclear plants, the unit sizes which it is appropriate to consider and the capacity factor which the plant may attain. Where proven systems are being considered, it is reasonable to assume the same life for a nuclear plant as for a conventional plant. As regards acceptable size of unit and the capacity factor at which nuclear plants will be operated, it is impossible to lay down any general rules having much validity. Because of the marked economies of scale which characterize nuclear plants, there will be strong incentives to install large units. But to make them too large may involve dangers of system collapse if they are operated at the high load factors which must be achieved to make them economic.

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6.01 Except for very unusual situations (such as the existence of flare gas or very inexpensive hydroelectric resources), the determination of the nature and detailed features of the most desirable system addition can only be made on the basis of system studies consisting of long-term projection of alternative systems reflecting the different plant alternatives which may be considered for any given system addition. In this respect nuclear does not differ from other possible types of plant, in that it also must be introduced as an alternative and its peculiar characteristics will influence the makeup of the system and the detail of its operation during the life of the plant. In general, detailed alternative system models will have to be compared and the computerization of this type of analysis has now become commonplace with competent power engineering groups. The purpose of this chapter is to single out and illustrate qualitatively the more peculiar features of nuclear installations as they affect system planning.

6.02 Nuclear power adds something new to the range of alternatives available for expanding a power system to meet the daily and seasonal pattern of demand for power. Traditionally the choice has been between hydroelectric plants, with their generally high capital costs and extremely low running costs, and thermal plants with lower capital costs per kilowatt of firm capacity but substantial annual costs for fuel and for maintenance. Nuclear plants are in a way intermediate between these two, with capital costs remaining well above those for thermal plants but with substantially lower fuel costs. In many cases therefore the best solution for a utility may be a given combination of each type of plant, for instance run-of-river hydroelectric, where cheap sites exist, for meeting base load; nuclear for the remaining base load; conventional steam for intermediate load; and either gas turbines or peaking hydro for meeting peak loads. This kind of plan makes use of the specific advantages of each type of equipment for meeting different parts of the load, but detailed calculations are required to determine the correct proportions in which the various types of plant should be installed.

6.03 The analysis should be extended over a considerable period, and power system planning inevitably involves a rather long look into the future. The already long lead typical of power generating facilities becomes even longer in the case of the first nuclear plants, which may well involve an eight-year cycle from initial consideration to commissioning in service. Moreover, the economic evaluation of the merits of alternative system expansion plans including and excluding nuclear plants will be significantly affected by judgments regarding factors such as the size and shape of the demand for power and relative fuel price trends over the life of the generating plant which may be taken as long as thirty years. It goes without saying that judgments about developments so far into the future will be surrounded with great uncertainty, probably greater in the rapidly evolving situation characteristic of developing countries.

Nuclear Plant Reliability and System Reserves

6.04 The stipulation was made in the introduction to this report that developing countries should consider only the installation of proven generating equipment (nuclear or conventional); and it may be of interest to mention some of the reasons that justify this position.

6.05 The main portion of generating reserves on a power system are to cover planned and accidental outages of generating equipment, and errors in load forecasting. The main costs of such insurance are in the form of the investment necessary to provide the spare capacity. These costs differ somewhat between countries, depending primarily on the nature of their sources of power. Investment in reserves is quite expensive: assuming a peak load of 1,000 MW, for example, and an average investment in reserve capacity of say $75/kw, the difference in investment costs between maintaining the 15-20 percent reserve level typical of industrialized countries, and the 5-10 percent reserve level which is more typical of the developing countries, is of the order of $10 million. It is therefore important that reserve should not be carried beyond the point where the rate of return earned, in the form of reduced risk of load shedding, is less than the opportunity cost of capital, i.e. the return obtainable in other sectors of the economy. This brings out several reasons why generating reserves in a developing country should be, as they generally are, appreciably lower than in the rest of the world. In the first place, capital is generally scarcer in the developing countries and the benefits that can be derived from it in uses other than provision of generating reserves are generally higher.1/ In the second place, the economic loss caused by shedding of peak load is generally smaller.

6.06 If the reserves are generally lower in developing countries, it is important that reliable equipment be obtained. The savings which can be had by accepting a somewhat less reliable power supply than in the wealthier countries are, so to speak, already being made. Or, putting the same point another way, for it to be worthwhile accepting nuclear plants of untried design they would have to promise savings in system generating costs sufficient to compensate for the additional investment in the standby capacity that would be needed to restore over-all system reliability to the justified level; and it is not foreseeable that nuclear plants of untried design would be offered at sufficiently attractive prices for this situation to occur.

Limitations on Size of Units

6.07 The importance of insisting upon a high standard of reliability in equipment is further underlined by the fact that individual nuclear units will generally represent relatively large proportions of total system capacity in the developing countries. As pointed out above, all the evidence presently available suggests that about 300 MWe is the minimum size at which reactor systems likely to be available over the next decade will be economic. Above the 300 MWe level, too, costs per kilowatt installed fall with increasing size of unit so that there will be strong incentives to install the largest units that can be justified

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1/ This difference between countries in the cost of capital is widely, if implicitly, recognized in power planning, as evidenced for instance by the fact that in the United States it is common practice to plan to a reliability level of only one day of load shedding every ten years, whereas the comparable formula in Europe is often two days in ten years.

on the power system. Though this conflict between cost savings, obtainable by installing larger units, and reliability, obtainable by installing smaller units, is particularly acute in the case of nuclear power because of the importance of the cost savings involved, it does of course apply also to conventional plants, and most of the discussion here would apply to either type of equipment.

6.08 But there is an important difference between nuclear and conventional power plants. It has already been pointed out that in a conventional power plant only about one-third of the cost of the power generated arises from capital charges; nearly two-thirds arises from the cost of fuel burned. It may therefore be economical to operate a conventional plant on a small system at part load during off-peak periods.

6.09 In a nuclear power plant two-thirds of the cost of power produced arises from capital charges and it is improbable that the nuclear plant will be economic unless it can be operated at a lifetime load factor of at least 75 percent. This will not be achieved unless the nuclear plant is operated at full capacity except at times of unavoidable outage. The nuclear plant will not be economic if it is regularly worked at part load during off-peak periods.

6.10 Now let us visualize a small isolated system with a peak load of 2,000 MW on which a 300 MW nuclear power plant is installed. The base load on the system is not likely to be more than 600 MW and the nuclear unit, operated at full load as is necessary to justify its installation, will carry half of this.

6.11 All power plants, even nuclear plants of tried design can trip suddenly. Supposing this happens under the conditions postulated, 300 MW of generating capacity will be suddenly lost from a system carrying a load of 600 MW. In these circumstances it is very doubtful whether the system control engineer can act sufficiently quickly to stop the system from collapsing. Voltage and frequency will fall so far and so fast that the auxiliary plants at the remaining conventional stations will trip and the whole system will go dead. In such circumstances it may take hours to get plant back on the line again and the area covered by the system will be completely without power.

6.12 It is for this reason that it is suggested that small isolated systems should be cautious of installing nuclear power plants having a capacity greater than 10 percent of the peak load which is expected at the time of commissioning the nuclear plant.

6.13 Different reactor systems will have different planned outage requirements depending on whether they have on-load refuelling or not. Systems without on-load refuelling appear to require no more time for annual refuelling than for scheduled maintenance of other parts of the plant. However this may be, in the case of proven plant it should be possible to plan reliably the required refuelling and maintenance outages, which may be of the order of say, four weeks per year and may be capable of fitting within periods when the combination of lower seasonal load and high seasonal capability of other generating plant on the system does not require that the unit be backed up by corresponding reserve capacity while on a planned outage.

Useful Life of Nuclear Plant

6.14 One final important parameter to be used in system analysis which deserves comment here is useful life. Essentially, it becomes worthwhile to replace a plant when it is worn out or when the savings in system operating and fuel costs which result from having a new plant rather than the old one are sufficient to yield a rate of return on the replacement investment (cost of retiring the old plant and purchasing and installing the new one), which is equal to the opportunity cost of capital. To the extent that fuel cost savings obtainable by replacing an old nuclear plant, with their already low fuel costs, with a newer one appear likely to be low compared with the fuel cost savings obtainable by replacing old conventional plants with new ones, or with nuclear units, the life of a nuclear plant might be expected to be longer than that of a conventional plant, especially in a developing country where cost of capital is high. However, the life of a nuclear plant could be sharply curtailed by the occurrence of an accident which contaminated the plant with radioactivity, so that it could not be repaired. Or the materials used in a reactor may deteriorate with age as a result of irradiation. Then there is the question of all the conventional equipment, which would presumably be assigned the same useful life as in a conventional plant.

6.15 Of those who have had to make a choice, some (like the CEGB in England) have chosen short lives of 20 years, while others (like the United States utilities) have chosen longer periods, e.g. 30 years. It seems that the consensus of opinion on this problem for the time being is that there is no reason to assume different periods for the useful lives of nuclear and conventional plants.

7. ECONOMIC COMPARISONS

Summary

The figures developed in this chapter suggest that it is difficult at this time to see atomic plants in the size of 300 MW playing an economic role in the power development of developing countries. They suggest that, while detailed system studies are the only basis on which alternative decisions of this kind can be tested, utilities would do well not to complicate their planning and render it appreciably more expensive by introducing nuclear alternatives unless:

(a) system conditions are such that they can operate the nuclear plant at a high load factor (75 percent or better). Except where support can be given from quick start-up plant such as storage hydro, considerations of system stability make it difficult to achieve a plant factor of 75 percent unless the peak load on the system is upwards of 2,500 MW and the growth rate is reasonably high (e.g. 10 percent).

(b) *the cost of conventional fuel is no less than 35¢/M Btu (1.4 mills/kCal);*

(c) *the real cost of money is not appreciably higher than 8 percent.*

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7.01 It has been emphasized in earlier chapters that the figures presented in this report cannot be regarded as more than rough orders of magnitude. Nevertheless, it is useful to draw them together to help indicate the prospects for nuclear power on small systems.

7.02 As in other chapters, the main focus will be on nuclear plants of the order of 300 MWe unit size. The levels of capital and fuel costs discussed in previous chapters for units 500 MWe and up leave no room for doubt that utilities capable of absorbing units of this size on their systems should give careful consideration to the nuclear alternative. But few utilities in the developing countries will be able to absorb such large units in the coming decade. On the other hand, review in Chapter 4 of the sizes and costs at which nuclear plants may be available suggested that the smallest proven unit which may be offered during the period under review would be of the order of 300 MWe and that it might cost about twice as much as a conventional plant, or about $240/kw 1/. In the calculations that follow, a 300 MWe light water nuclear power plant at a price of $240/kw is used as a nuclear yardstick for purposes of economic comparisons. This is done merely for convenience and does not indicate bias in choice of reactor type. Other competing reactor systems would have different characteristics of capital and operating costs but do not at present give any indication that in average conditions they will compete more strongly with conventional power.

A Plant-to-Plant Comparison

7.03 If nuclear and convential power plants were expected to render constant and identical services to the system in which they operate throughout their useful lives, a simple plant-to-plant comparison of generation costs (including capital charges) would give a correct economic comparison of the two alternatives. But in fact the lifetime service given by the two plants will not be the same. Apart from any difference in availabilities, the difference between nuclear and conventional fuel costs will result in different utilization of the stations that are being compared and consequently the loading of other plants on the system will be altered.

7.04 In studying a specific proposal to adopt a nuclear alternative it is necessary to carry out an economic evaluation based on a system analysis. Such an analysis takes into account the shape of the load

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1/ Plus any greater cost to reflect overseas installation.

curve on the system, the forecast of load growth, the characteristics of the plant already installed on the system and the probable nature of the new plants that will be added during the lifetime of the station which is under consideration.

7.05 It is obvious therefore that such an evaluation based on system analysis must be specific and that this sophisticated approach is of little value in a hypothetical case.

7.06 Experience has shown, however, that simple plant-to-plant analyses give a reasonable indication of the comparative economics of nuclear and conventional alternatives. Indeed it has been found in some cases that the difference between the result achieved by a simple plant-to-plant evaluation and that obtained by the complex and sophisticated system analysis method is less than the error which could arise from the uncertainty of some of the assumptions which have to be made in applying the complex analysis.

7.07 To obtain an indication of the conditions under which a 300 MWe unit might be competitive with a conventional steam unit, calculations were made on a plant-to-plant basis simply comparing a light water plant of this size with a conventional oil- or gas-fired plant of the same size. Both plants were assumed to have lifetime load factors of 75 percent; both were assumed to have lives of 25 years and straight-line depreciation was used. Cost assumptions are listed in Table 7.1.

Table 7.1

Costs Assumed in Comparison of 300 MWe Nuclear Plant with 300 MW Conventional Plant

	Capital Cost 1/ $/kw	O&M Cost 2/ mills/kwh	Fuel Cost/Consumption per kwh sent out
Nuclear	240	0.46	1.97 mills 3/
Conventional	120	0.23	9,000 Btu (2,265 Cal)

1/ Including interest during construction.
2/ Includes insurance.
3/ E.g. fuel cost derived from figures presented in Chapter 5 after allowing for difference in unit capacity and lower capacity factor.

The principal reference variables in the calculations were the cost of money and the cost of fossil fuel, for which mean values of 8 percent and 35¢/M Btu (1.38 mills/kCal) were adopted. The calculations showed that:

(a) For the mean values, the lower generating cost is achieved by the conventional plant: about 5.6 mills/kwh against 6.8 mills/kwh for the nuclear alternative. The conventional alternative would result in a total annual saving of the order of $2.4 million.

(b) Taking the cost of money as the variable and assuming the cost of conventional fuel at 35¢/M Btu (1.38 mills/kCal), the nuclear alternative would have the same generating cost as the conventional if the cost of money were 1.25 percent.

(c) Taking the cost of fuel as the variable and assuming the cost of money at 8 percent, the conventional alternative would have the same generating cost as the nuclear, if the cost of fuel were about 49¢/M Btu (1.94 mills/kCal).

These calculations give an indication of the approximate level of fossil fuel cost at which a 300 MWe nuclear plant might break even with a fossil-fueled plant. The figure of 49¢/M Btu (1.74 mills/kCal) should be compared with the price at which oil or gas is available in the developing countries exclusive of domestic taxes. Since oil or gas is generally available at or near seaports or producing fields at prices no higher than 30-35¢/M Btu (1.2-1.4 mills/kCal), and since this price may trend slightly downward in coming years, the break-even fuel price is clearly high, suggesting that the prospects for 300 MWe nuclear plants at a capital cost of $240/kw installed are not encouraging.

7.08 It should again be emphasized that these calculations are only acceptable to give gross orders of magnitude and that the threshold numbers obtained should not be taken literally. To illustrate, the experience of groups that have done substantial amounts of detailed system analysis work suggests that for most system situations the 49¢/M Btu (1.94 mills/kCal) figure would be more like say 46¢/M Btu (1.82 mills/kCal) after carrying out a detailed system analysis.

8. ADMINISTRATIVE ASPECTS OF NUCLEAR POWER

8.01 A number of very important administrative arrangements have to be made for the introduction of nuclear power into a country; special legislation and procedures for governmental supervision have to be established, scientific and engineering staff trained, safety standards set up, insurance arrangements made and the public prepared for the installation of an atomic power plant. Some of these arrangements will take a long time; preparation of legislation and organization of training programs, for instance, would generally have to commence perhaps ten years before the first nuclear power plant in a country was expected to be completed.

Legislation and Government Control

8.02 All countries have legislation and government machinery for the supervision and control of industry. The problems and potential hazards of nuclear power are such that most nuclear countries have considered it necessary to set up special branches of government departments to deal with them and have enacted legislation for control of nuclear installations.

8.03 The essential legislation must cover:

(a) Third Party Risks. These are the risks arising from an incident at a power plant or connected with the conveyance of radioactive material which cause damage or inconvenience to people other than those who are responsible for the plant or material. Up to the present time the international insurance groups have not been able to underwrite adequate insurance contracts without major support by governments. The legislation should be so written as not to conflict with these peculiar requirements of nuclear power.

(b) Licensing of Installations. It is usual for licenses for nuclear power plants to be granted in two stages. A construction license is first issued which authorizes the utility to build a reactor of a defined type. The second license is issued when construction is complete and authorizes the utility to operate the plant. The first license says, in effect "You may build a reactor of the type proposed on this site and if, when it is finished, the design and construction are satisfactory you can hope to be given an operating license". The second license says "We are satisfied that the design and construction give the safety characteristics that we require and the reactor may be operated at the specified load".

(c) Licensing of Operators. Some, but not all, atomic countries prescribe training courses for reactor operators, examine them and license them for competence. Developing countries would be wise to adopt such a licensing system.

(d) Periodical Inspection of Nuclear Power Plants. There must be compulsory routine inspection to ensure safety.

(e) Safeguards. Although internal legislation is not involved, attention is drawn to the need to conform with safeguards such as those prescribed by IAEA to ensure that nuclear installations are used only for peaceful purposes. Developing countries may find that many of the industrialized countries will not supply nuclear plant or fuel unless the purchasing country conforms with suitable safeguards. The Bank will want to be assured that acceptable safeguards will apply before it considers financing for a nuclear power plant.

8.04 The International Atomic Energy Agency could help developing countries which propose to embark on a nuclear power program by drawing up model legislation which could be adapted to suit the legislative system of individual countries.

Public Relations

8.05 Because atomic energy was initially used destructively and because few people understood the nature of radiation hazards, there was initial fear of nuclear installations in all countries. In the old atomic countries familiarity has virtually destroyed any real fear and, from the point of view of public acceptability and amenity, nuclear power plants are often preferred to fossil fuel plants. But it is likely that fear will still be encountered in developing countries; the lower the standard of education among the people living around a potential nuclear site, the greater is the fear and resistance. Experience has shown that it is desirable that well before a site for a nuclear power plant is chosen a public relations campaign should be started to familiarize people with what is involved.

Nuclear Research Establishment

8.06 Up to the present time all countries which have established a nuclear power program have had a research establishment for some years before ordering their first industrial power plant. The time has come when such a research establishment is not an essential prerequisite for a nuclear power program but it is helpful. It ensures that there are nuclear scientists and technologists in the country who can be consulted and it provides facilities for basic post graduate training of staff. If it is decided that such a research station is justified, it need only be of modest size having perhaps, a swimming pool reactor, facilities for one or two experimental assemblies, a small hot laboratory and a general physics laboratory.

Training of Staff

8.07 A utility in a developing country which proposes to undertake a program for the construction of nuclear power plants should employ consulting engineers for drawing up and evaluating a scheme, for preparation of the enquiry specification, for bid evaluation and for supervision of construction. Even so, the utility which is buying and operating the stations ought to have its own engineers participating in this work both to familiarize themselves with it and to ensure that the owners' requirements are met. Training of engineers to participate in specification drafting and bid evaluation should start 2-3 years before this work is put in hand. The men should be graduate engineers who would be given 6-12 months' theoretical training either in the nuclear research establishment discussed above, or if this does not exist, in an overseas university. They should then be sent overseas for 18-24 months' experience in manufacturers' works and on an operating nuclear power plant. As the choice of reactor type should result from competition between heavy water, light water and graphite-moderated/gas-cooled reactors, it follows that one or more of the men selected should have his overseas experience in a country where he can become familiar with each of these types. A minimum of four and preferably six men should be trained.

8.08 When the order is placed and construction starts, the utility should have its own engineers and physicists co-operating with the consultants in examination of design and supervision of construction. These men will need similar training which should start 2-3 years before the date of placing the order. The number of additional graduates required at this stage will be between 15 and 25.

8.09 When the reactor is commissioned, some of these men will be required for managerial duties at headquarters, the remainder will be available as operating staff. Additional operating staff with overseas training will be necessary. Their training should start when or soon after the order is placed; the additional number so required will be between 15 and 25.

8.10 All figures given are dependent on a variety of circumstances and are intended only to give a general idea of the requirements of graduates for a single reactor; no allowance has been made for staff requirements for a continuing program of nuclear construction.

8.11 In addition to these graduate employees of the utility, about ten graduate engineers and physicists will be required in the government department responsible for licensing and inspection and these men will require overseas training.

8.12 Very roughly, therefore, the construction and operation of a single nuclear reactor will involve the employment of say 30-40 graduate engineers and physicists additional to those needed for the corresponding fossil-fueled thermal plant. Overseas nuclear training for say 40-60 graduates is necessary.

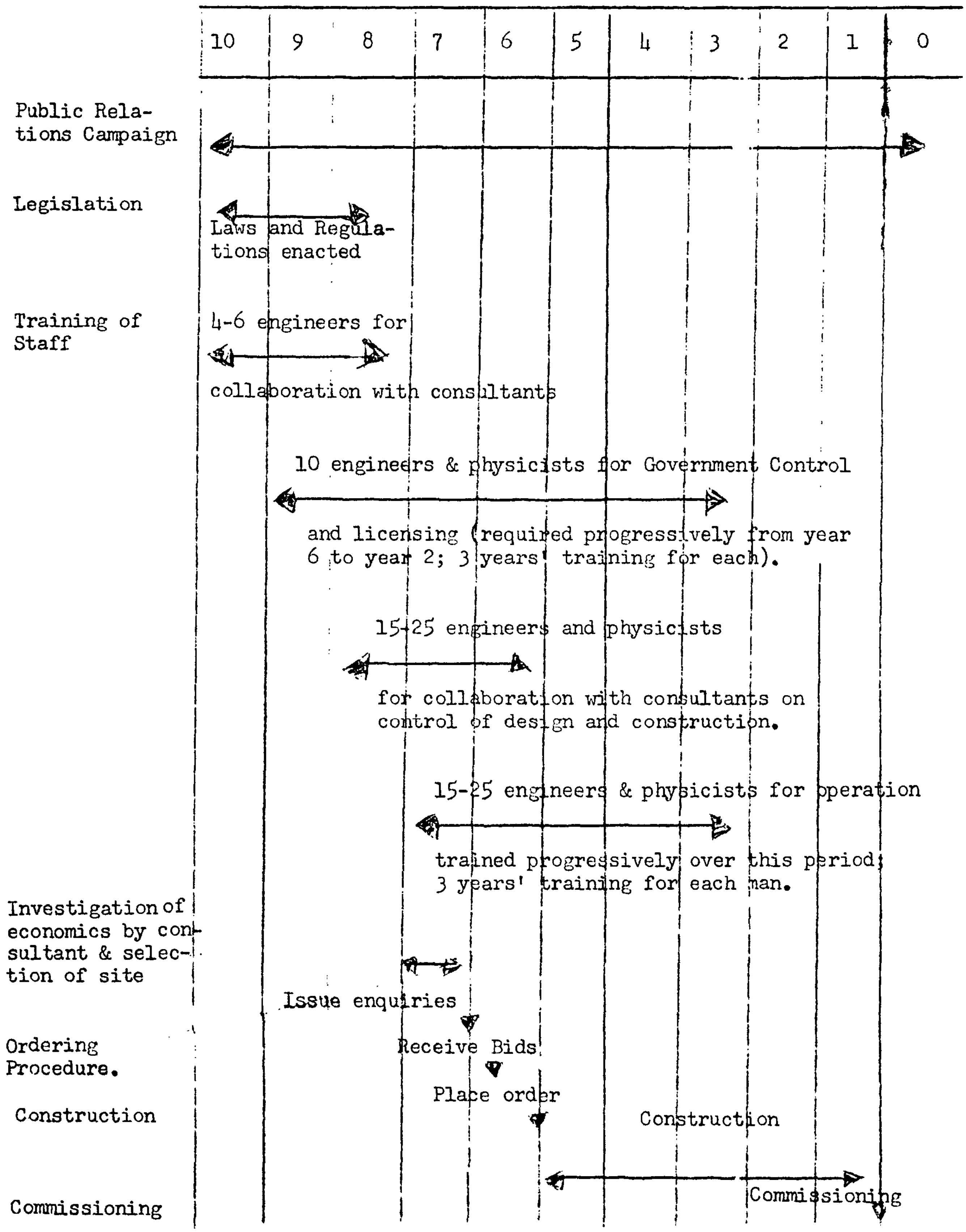
8.13 The additional annual cost of staff for the nuclear power plant is therefore likely to be around $150,000 and the cost of the training program will be of the order of a million dollars. The capital cost of the small research station which has been seen to be desirable but not essential is likely to be around $3,000,000 and the operating cost will be of the order of $500,000/year; some part of these costs should be considered as an overhead on nuclear power, from the point of view of the national economy.

8.14 It is desirable that most, if not all, the engineers selected as trainees for participation in design, construction and operation of nuclear power plants should have had experience on conventional fossil-fueled plants. A utility which has not got some modern fossil-fueled plants in operation on its system will find it difficult to bring a nuclear plant into operation economically. Such utilities should give consideration to the installation of conventional thermal plants to give them experience before ordering a nuclear plant.

8.15 For convenience, this preparatory work is programmed in Figure 8.1. The total time required from the beginning of the preparatory work to commissioning is 10 years. The estimated time between issuing enquiries and commissioning is 7 years: this is lower than the estimate (8 years) of one of the leading nuclear plant manufacturers.

FIGURE 8.1

YEARS FROM DATE OF COMMISSIONING OF FIRST REACTOR



Safety and Siting

8.16 Safety standards for nuclear plants should be established in good time by the responsible authorities in a country planning to introduce nuclear power because they will affect plant design.

8.17 Industrial nuclear reactors are almost unique in that such great technological progress has been made without (as yet) a single disastrous accident. That this is the case is no doubt due largely to the fact that, because of the initial fear of atomic energy and because the effect of serious failure is too great, unusual care has been exercised. But it should be remembered that, at present, operating experience is confined to countries which have strong research and engineering organizations to give support to operating staffs. It is not difficult to envisage an accident which would cause damage to a reactor which (because of radioactive hazards) could not be repaired; the possibility of such incidents is reflected in the comparatively short obsolescence periods that have been adopted in some countries.

8.18 What is discussed in this section is not the sort of accident which may simply put the reactor out of operation but the accident that may give rise to a 'district' hazard; i.e., the danger of a failure which might cause an emission of radioactivity which would make it necessary to evacuate (if only temporarily) a district surrounding the reactor. The evaluation of the risk arising from accident is difficult and can be done only on the basis of calculation because there is, fortunately, no practical experience of major failure against which calculations can be checked. Scientists and engineers in utilities, manufacturers, design organizations and licensing authorities still argue about the extent of the risk and will continue to argue for many years before agreement is reached and siting criteria can be formulated on a definite and rational basis. Different reactor systems have different characteristics in this respect. For instance, the AGR of integral design with pre-stressed reinforced concrete pressure vessel appears to have great integrity and to be unlikely to experience failure which would give rise to a district hazard. Yet the British siting criteria limit the number of residents within certain areas around such a reactor.

8.19 In the case of the American BWR and PWR reactors, a district hazard would arise if an accident caused the discharge into the atmosphere of steam which is radioactive or contains radioactive materials. This hazard is controlled by containing the whole reactor complex in such a way that any steam so released will be condensed and will not be emitted to the atmosphere. Even so, American licensing practice has set limits to the number of people inhabiting areas around the reactor, though these limits are modified to suit the type of containment which is used.

8.20 It seems unlikely, in conclusion, that one can look forward, at least for a time, to the establishment of objective and explicit siting standards. This makes it even more important for any country to decide, in the absence of such standards, how the problem of selecting and approving sites will be dealt with.

Contracting Procedures and Competitive Procurement

8.21 Most nuclear power plants now commissioned have been built under turnkey contracts and this is natural. In the early days neither utilities nor consultants had much knowledge of how to evolve an integrated design for a nuclear plant. It was convenient for the utility to place the whole responsibility with a single contractor who had experience both of reactor design and of the conventional parts of the plant. In the old nuclear countries those conditions no longer hold; there are consultants and engineer/architects with experience in the design and construction of nuclear power plants. Much of the work involved in the construction of nuclear plants is civil engineering and reactor manufacturers would normally quote only for the nuclear boiler and, if invited to do so, for the turbo-alternator and its normal ancillaries. Not all manufacturers are willing firmly to shut the door on turnkey contracts, but the prospects that any will be accepted will be increasingly poor in future. In the U.K., in Continental Europe, and perhaps in Japan, there still appears to be a readiness to undertake turnkey contracts.

8.22 It appears unlikely that in the future turnkey contracts will be accepted with the prime contractor undertaking to supply a plant for a fixed sum with firm guarantees of timing, output and performance. Progress in engineering, manufacturing and construction practices in this field is, however, still far from the point where the planning, design and procurement for nuclear plant could be envisaged in the way that is customary for other power plant work. The position is perhaps best understood if it is realized that nuclear reactor manufacturing still has many similarities with process plant work, where the customer and his consultants can have only limited freedom in determining specific design layout, characteristics and performance.

8.23 Reactors, and particularly established reactors of standardized design which, as we have shown should be those considered, are rather rigid in their size, layout, design and steam conditions. Thus, if the utility wishes to make its choice on the basis of open international competition, it must in essence accept, as far as the reactor is concerned, what the manufacturers offer rather than ask them to bid on its own specifications. This makes it difficult to obtain and properly to evaluate competitive offers of different type reactors, and gives rise to additional problems, such as:

(a) Consulting firms with good experience in this field are not many and they tend to be more familiar with reactor systems developed in their own country; thus they might have difficulty making balanced evaluations of competing reactors of different types;

(b) as was pointed out, the range of steam pressures and temperatures encompassed by competing reactor types is wide. This means that in a fully competitive approach preparing specifications and obtaining competitive bids for the "conventional" end of the plant (turbo-generator and accessories) becomes a laborious and involved process, as several alternatives should be provided for, corresponding to different types of reactors, the more so as

(c) at present and in the near future the longer lead item in some important markets is the turbo-generator (by as much as two years longer than the reactor); this would involve either firming up a reactor order long before it is necessary to do so in view of the plant commissioning date or obtaining turbine bids to suit all reactor types before a reactor is chosen. There are obvious drawbacks to either procedure.

8.24 These problems are outlined here to show that the Bank's normal international bidding procedures are, for the time being, poorly suited to the case of nuclear plants, and their application might cause difficulties. In reality, these difficulties may be tempered on two main grounds:

(a) this situation should evolve rapidly. Over the next few years more consulting firms are going to acquire greater experience with all types of reactors. Manufacturing will become gradually better established and more competitive. New manufacturing facilities are being built and delivery periods should return to more normal levels. It is possible that before the Bank has to process loan proposals for nuclear plants in developing countries as a matter of course, the application of its normal policies will no longer appear difficult. In the meantime, any financing proposal deserving consideration, which may be put to the Bank, could be handled in a flexible, case-by-case manner as regards planning, procurement and construction arrangements.

(b) It appears likely that for the next few years countries not yet established in the nuclear power field may buy their first plants after bilateral negotiations for equipment and finance rather than as a result of open international competition as is customary for projects with World Bank financing. The "bilateral" route need not exclude competition. A competent consulting engineer should be employed to assist in these negotiations and generally to protect the interests of the utility. It is possible that, at the present stage of development of nuclear power, and in view of the desirability of placing as much of the responsibility as possible on an experienced main contractor, such a bilateral approach may be the simplest and most convenient one for a developing country to adopt.

9. NUCLEAR POWER AND DESALTING OF WATER

9.01 In recent years the desalting of water has been linked in imaginative thought with the use of nuclear power plants, it is important that the logic of this link and the limitations of this logic should be understood.

9.02 Desalting plants of modest size are in use in many parts of the world. The system generally used is the distillation of the salt water in multiple effect evaporators; whether this will ultimately prove to be the best system remains to be seen; alternative methods of desalting such as purification by freezing, reverse osmosis or electrodialysis are under research and development and might ultimately prove to be best. Already some of these alternatives appear attractive for desalting brackish, as distinct from sea water. Because the distillation method is the one which is at present most widely used for desalting sea water, it is natural that engineers should seek to meet the demand for large-scale desalting plants by extrapolation of this established technique.

9.03 The heat required in the evaporation process of desalting is usually supplied as low temperature steam; high temperature steam cannot be used because it leads to scale formation on the tubes of the evaporators in the distillation plant and the present limit of temperature is about 250° F (121° C). Such low temperature steam can be most cheaply supplied as back pressure steam from a power plant; that is to say, steam is raised at a conveniently high pressure and temperature, is passed through a turbo-alternator in which its pressure and temperature are reduced, electric power is generated and the steam then leaves the turbine and is taken to the desalting evaporator. Part of the cost of the steam can reasonably be charged to the power plant and included in the cost of the electric power which is produced, and this reduces the price at which steam must be charged to the desalting evaporators. The initial steam may be raised in any sort of boiler using any sort of fuel, fossil or nuclear, and the right fuel to use is the one that gives the cheapest steam, taking into account both capital and operating charges.

9.04 When power generation and desalting are linked together in this way there is room for flexibility in design. The temperature at which the steam is passed from the turbine to the desalting plant can be reduced below 250° F (121° C) in which case more power and less water will be produced from a given quantity of steam. Alternatively, if one assumes a given quantity of back pressure steam at a fixed temperature, the quantity of desalted water produced can be increased or decreased within limits by increasing or decreasing the capital cost of the desalting plant. Another possibility is to use a 'pass-out' steam turbine in which some steam is bled off from the turbine to the desalting plant while the rest passes on through the remaining stages of the turbine to the turbine condenser. In such plants quite small desalting units can be used.

9.05 When such flexibility exists it is impossible, in a report such as this, to deal with every possible combination and in considering the problem we have assumed conditions which are generally considered to optimize the case for dual-purpose desalting and power plants under the conditions which are likely to exist in developing countries.

9.06 If, as appears desirable in this optimized case, the steam is piped away from the turbine to the desalting plant at a pressure of 30 psia (about 2 kg/cm^2) (which corresponds to a temperature of about 250° F or 121° C) the steam rate of the turbine (i.e. the quantity of steam required to generate one kwh of electricity) is greater than it would be if the steam had been allowed to expand to condenser pressure in the turbine. A larger boiler is therefore needed to supply the steam which is required to generate a given quantity of power.

9.07 As has been said earlier in this report, the maximum size of generating unit which can conveniently be installed on any electricity system is determined largely by the maximum demand on that system. But if the turbine exhausts to a desalting plant the steam rate will be higher than if the steam is allowed to expand in the turbine to condenser pressure and a larger boiler will be required to match a turbo-alternator that has an electrical output which is pre-determined by the maximum load on the system.

9.08 The capital and operating costs per kw of all boiler plants (conventional and nuclear) fall with increasing size but the fall is steeper in the case of nuclear-fueled boilers than in the case of conventional boilers. As stated elsewhere in this report it is improbable that nuclear reactors will be economical unless they have an output of about 300 MWe, when used in an ordinary single-purpose power plant. Recent studies have shown that if a reactor of this size were used in conjunction with a dual-purpose power and desalting plant, the output of electricity from the back-pressure turbine would be about 150 MW and it might be possible, from the point of view of the electricity system, to consider such a reactor when the system peak load is only half as large as it would need to be if the whole of the reactor's steam were used to generate power. It follows that nuclear power might be economical on a smaller system if it is used in conjunction with a desalting plant. Alternatively, in a system which has a peak load of 3,000 MW and so would justify the installation of a turbo-alternator of say, 300 MW capacity, if a dual-purpose power/desalting plant is built it would be possible to install a reactor about twice as big as would be needed for a single-purpose power plant of similar capacity and the reactor would therefore have a lower capital cost per kw and a better chance of competing with a fossil fuel-fired boiler.

9.09 It follows therefore that, on small electricity systems, the use of desalting evaporators in conjunction with a nuclear power plant may so raise the size of the reactor which can be justified as to make consideration of nuclear power reasonable when otherwise it would be uneconomic.

9.10 But it is doubtful whether the technology of desalting has yet been advanced to the point at which the very large desalting units which would be needed for such plants can be built with confidence. A desalting plant using the back-pressure steam from a nuclear reactor of the smallest size that we have considered as feasible would produce about 75 Mgd (3.3 m^3/sec). The largest desalting unit at present in operation has a capacity of around 2.5 Mgd (110 l/sec) and about 30 such units would be needed to match the steam output of the smallest nuclear reactor which is likely to be economical. Such a plant with 40 desalting units would be cumbersome and expensive. A great deal of work is being done to develop larger desalting units; the most important project which aims to do this is the Metropolitan Water District Scheme at Los Angeles where a plant with a total output of 150 Mgd (6.6 m^3/sec) from three 50 Mgd desalting units is proposed. The first unit is scheduled for operation in 1973 and full operation is planned for 1976. Prototype modules are being built which are scheduled for testing in 1968. These dates give a measure of the amount of research and development which is involved.

9.11 Research is being done elsewhere on alternative evaporation systems which may prove to be better than the one that it is proposed to use at Los Angeles. About 40 percent of the capital cost of the desalting evaporators that are being used on the Los Angeles scheme is spent on the tubes which are used in the evaporators. If a design could be evolved which would give a higher heat transfer coefficient for the conduction of heat through these tubes the capital cost could be reduced. This is the aim in developing the 'long-tube vertical' evaporator as a competitor to the 'multi-flash' evaporator which is being used at Los Angeles. The date when a large new system of this sort can be established in commercial use is likely to be even more remote than for the large multi-flash units.

9.12 Even if development proceeds in a reasonably trouble-free way there will not be industrial experience of the large desalting evaporators that can be matched with the smallest economic nuclear reactor before the mid-1970s. Desalting plants of this size ordered before that date will be of pioneering design and the estimates of operating cost will not be supported by practical experience.

9.13 Even supposing that it was decided to accept the technological risk of ordering such untried plant within the next five years it is difficult to envisage many places which could find use for the large quantity of desalted water produced at the price which can reasonably be predicted for it.

9.14 The estimated cost of water from the Metropolitan Water District scheme at Los Angeles has been stated to be 22¢/1,000 gal (5.8¢/m^3) but it should not be thought that this is a figure that can generally be achieved. The estimated cost is low because the demand for electric power in California is high and justifies the installation of two large reactors and turbo-alternators which will generate 1,600 MWe of power. Because of their large size these reactors have a low capital cost per kw and only part of the steam raised in them goes ultimately to the desalting evaporators. Moreover, in estimating the cost of desalted water, the interest rate charged on the capital cost of the desalting plant is only 3.5 percent, a rate which is usual in municipal water supply schemes but is below normal borrowing rates.

9.15 A more realistic cost of water, 67¢/1,000 gal (17.7¢/m^3 or \$218/ac-ft) has been arrived at in a study of a dual-purpose plant for Israel, carried out by consultants for the U.S. and Israeli Governments. The capital cost of the plant was estimated at \$200 million, and it would have a capacity of 200 MWe and 100 Mgd. In calculating the unit costs of the water produced, annual capital charges were taken to be 10 percent of the capital investment which implied an interest rate of approximately 8 percent.

9.16 A cost of 67¢/1,000 gal (17.7¢/m^3) may not be prohibitive for water used for domestic and special industrial purposes, but it is hard to see how it could become economic to use water at this price for agriculture, which represents the main potential bulk demand in many developing countries. Under dry, hot climates an irrigation delivery of something like 3 ac-ft per cropped acre (9.120 m^3/ha) would be required per growing season. At \$218/ac-ft (17.7¢/m^3) the cost of water per cropped acre would be roughly \$650 (\$1,610/ha); the desalted water might be mixed with water from other sources, such as the groundwater aquifer, but this would make an appreciable difference only in a limited number of cases. It has been estimated that if the water were used to produce wheat and the new high-yielding varieties of wheat were planted, then the yield/ac might be 100 bushels (6.75 m tons/ha). At the c.i.f. price of imported wheat delivered to most developing countries, the gross production value per acre would be in the range \$200-250 (\$495-620/ha), or only about one-third of the cost of the water used. Approximately two-thirds of the 67¢ cost of desalted water represents capital costs and approximately one-third operating costs, including fuel. On this basis it is evident that, even if the capital investment were provided as a gift, the annual operating costs alone would approximate the gross value of the wheat which might be produced. This is without taking account of the cost of conveying the water from the desalting plant to the farms and also without taking account of the cost of all the other inputs required for crop production.

9.17 Wheat is of course not a high-value crop. If it could be assumed that the cropping pattern involved substantial areas of higher-value crops such as citrus and vegetables, then the gross value of production per acre might be several times as high as in the case of wheat. The costs of other purchased inputs would also be higher than in the case of wheat. The Israelis, for example, have calculated that incremental water for use in their agriculture might, by some time in the 1970s, be worth as much as approximately \$90/ac-ft (28¢/1,000 gal or 7.3¢/m^3). This is after assuming high-value and high-yielding crops. This \$90 value of water is still **far** short of the \$218/ac-ft cost which stems from the study mentioned above and also considerably short of the \$130/ac-ft (40¢/1,000 gal or 10.6¢/m^3) which may be a reasonable expectation for desalted water some time in the 1970s or 1980s.

9.18 It seems therefore that the conclusions on nuclear desalting are, on technology, that dual-purpose desalting plants ordered before the mid-1970s would be of untried and uncertain design; and, on economics, that it seems doubtful whether in the foreseeable future desalted water could be used economically in agriculture. On the other hand, the combination of technological advance and consequent reduction in cost on the desalting side, with the development of much higher yielding varieties and greatly improved skills and management on the agricultural side, might produce a different conclusion in 10 or 15 years.

9.19 It is possible that large desalting installations have reached a stage of development similar to that which had been reached in the 1950s when nuclear plants such as Calder Hall and Shippingport were being built. These plants were not economic and many uneconomic nuclear plants were built afterwards before experience brought the cost of nuclear power down to a level which, in suitable conditions, is economic. It may be that, before the cost of large desalting units is brought down to an economic level several uneconomic plants have to be built to provide experience.

9.20 One general point should be noted in connection with large desalting plants, namely that it is difficult to envisage suitable locations for them except on the sea coast. There are two reasons for this. The first is that large quantities of circulating water are needed to cool the condensers in the plant and this water is not usually available in arid areas away from the coast. The second is that there is necessarily an effluent from the plant which contains all the salts that have been extracted from the desalted water which is produced. This effluent must be disposed of and it is difficult to dispose of it except into the sea.

9.21 Nothing which has been said on this subject should be read as discouraging research and development work to develop large desalting units, such work is considered to be of great importance. Nor should it be thought that anything which has been said discourages the installation of smaller desalting plants having capacities up to, say, ten or even twenty million gallons a day.

NUCLEAR POWER PLANTS HAVING UNIT SIZE OVER 100 MW_e 1/
(as at mid-1967)

1. GRAPHITE MODERATED CO_2 COOLED REACTORS

Year Ordered	Name, Owner, Location	Type	Net Capacity Rounded (MW)
	In the U.K. and France		
1956 *	BERKELEY, CEGB, U.K.	Magnox	2 x 140
*	BRADWELL, CEGB, U.K.	Magnox	2 x 150
*	HUNTERSTON, SSEB, U.K.	Magnox	2 x 180
1957 *	HINKLEY POINT A, CEGB, U.K.	Magnox	2 x 250
1958 *	EDF 2-CHINON, EDF, France	French Gas Graphite	2 x 110 2/
1959 *	TRAWSFYNYDD, CEGB, U.K.	Magnox	2 x 250
*	DUNGENESS A, CEGB, U.K.	Magnox	2 x 270
1960 *	SIZEWELL, CEGB, U.K.	Magnox	2 x 290
1961 *	EDF 3-CHINON, EDF, France	French Gas Graphite	2 x 240 2/
1962	OLDBURY, CEGB, U.K.	Magnox	2 x 300
1963	ST. LAURENT 1, EDF, France	French Gas Graphite	2 x 240 2/
1964	WYLFA, CEGB, U.K.	Magnox	2 x 590
1965	DUNGENESS B, CEGB, U.K.	AGR	2 x 600
1966	ST. LAURENT 2, EDF, France	French Gas Graphite	2 x 260 2/
	HINKLEY POINT B, CEGB, U.K.	AGR	2 x 620
	BUGEY, EDF, France	French Gas Graphite	2 x 270 2/
	Outside the U.K. and France		
1959 *	LATINA, ENEL, Italy	Magnox	200
*	TOKAI MURA, JAPC, Japan	Magnox	150
1966	VANDELLOS, FECSA, Spain	French Gas Graphite	2 x 250 2/

* In operation.

Total in operation: 20 units, about 4,100 MW
Total under construction or on order: 16 units, about 6,300 MW
General Total, Graphite/CO_2 **reactors:** 36 units, about 10,400 MW

1/ The list is limited to plants powered by reactors of the types considered in the report and does not include Communist **countries.**

2/ One reactor, two turbogenerators.

2. PRESSURIZED WATER REACTORS

Year Ordered	Name, Owner, Location (State or Country)	Net Capacity Rounded (MW)
	In the U.S.	
1956 *	YANKEE ROWE, Yankee Atomic, Mass.	170
*	INDIAN POINT 1, Consolidated Edison, N.Y.	260
1963	SAN ONOFRE, So.California Edison etc., Calif.	430
	CONNECTICUT YANKEE, Conn. Yankee Atomic, Conn.	460
	MALIBU, L.A. Dept. of Water & Power, Calif.	460
1965	INDIAN POINT 2, Consolidated Edison, N.Y.	870
	TURKEY POINT 3 & 4, Florida Power & Light, Fla.	2 x 720
	R.E. GINNA, Rochester Gas & Electric, N.Y.	420
1966	ROBINSON 2, Carolina Power & Light, S.C.	660
	PALISADES 1, Consumers Power, Mich.	700
	POINT BEACH 1, Wis. Mich. Power, Wis.	450
	OCONEE 1 & 2, Duke Power, S.C.	2 x 870
	BURLINGTON, Philadelphia Electric etc., N.J.	990
	SURRY 1 & 2, Va. Electric & Power, Va.	2 x 780
	FT. CALHOUN, Omaha Public Power D., Nebr.	450
	DIABLO CANYON, Pacific Gas & Electric, Calif.	1060
	THREE MILE ISLAND, Metropolitan Edison, Pa.	830
1967	EDISON PW 1-ZION, Commonwealth Edison, Ill.	1050
(half	PRAIRIE 1, No. States Power, Minn.	550
year)	- Jersey Central Power & Light, N.J.	800
	KEWANNE, Wisconsin Power & Light etc., Wis.	530
	MAINE YANKEE, Maine Yankee At. Power, Maine	800
	CRYSTAL RIVER, Florida Power, Fla.	820
	POINT BEACH 2, Wis. Mich. Power, Wis.	450
	- Middle South Utilities	800
	INDIAN POINT 3, Consolidated Edison, N.Y.	960
	OCONEE 3, Duke Power, S.C.	870
	CALVERT CLIFFS 1 & 2, Baltimore Gas & Electric, Md.	2 x 800
	BURLINGTON, Public Service Electric & Gas, N.J.	990
	PRAIRIE 2, Northern States Power, Minn.	550
	Outside the U.S.	
1959 *	TRINO (FERMI), ENEL, Italy	240
1961	CHOOZ, SENA, France	270
1963	ZORITA, UEM, Spain	150
1965	OBRIGHEIM, KWO, West Germany	280
	BEZNAU, NOK, Switzerland	350
1966	MIHAMA, Kansai Electric Power, Japan	340

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* In Operation.

Total in Operation:	3 units, about 700 MW
Total under construction or on order:	37 units, about 24,700 MW
General total, PWR's (mid-1967):	40 units, about 25,400 MW

3. BOILING WATER REACTORS

Year Ordered	Name, Owner, Location (State or Country)	Net Capacity Rounded (MW)
	In the U.S.	
1956 *	DRESDEN 1, Commonwealth Edison, Ill.	200
1963	OYSTER CREEK, Jersey Central P & L, N.J.	510
	NINE MILE POINT, Niagara Mohawk Power, N.Y.	500
1965	DRESDEN 2, Commonwealth Edison, Ill.	710
	PILGRIM, Boston Edison, Mass.	620
	MILLSTONE POINT, Conn. L. & P. etc., Conn.	550
1966	DRESDEN 3, Commonwealth Edison, Ill.	710
	QUAD CITIES 1 & 2, Commonwealth Edison etc., Ill.	2 x 710
	MONTICELLO, Northern States Power, Minn.	470
	BROWNS FERRY 1 & 2, T.V.A., Ala.	2 x 1060
	VERMONT YANKEE, Vt. Yankee Nuclear Power, Vt.	510
	PEACH BOTTOM 2 & 3, Philadelphia Electric etc., Pa.	2 x 1060
	EASTON, Niagara Mohawk, N.Y.	750
1967	BAILLY, North. Indiana Public Service, Ind.	510
(half	SHOREHAM, Long Island Lighting, N.Y.	540
year)	COOPER, Consumers Public Power District, Neb.	800
	BAYSIDE, Atlantic City Electric, N.J.	1060
	MILLIKEN, N.Y. Gas & Electric, N.Y.	800
	BROWNS FERRY 3, T.V.A., Ala.	1060
	Outside the U.S.	
1959 *	GARIGLIANO, ENEL, Italy	150
1962 *	GUNDREMMINGEN, KRB, West Germany	240
	TARAPUR, Dept. of Atomic Energy, India	380
1964	LINGEN, KWL, West Germany	160 1/
1965	TSURUGA, JAPC, Japan	310
	S. MARIA DE GARONA, Nuclenor, Spain	440
	OSKARSHAMN, OKG, Sweden	400
1966	MUEHLBERG, BKW, Switzerland	310
	FUKUSHIMA, Tokyo Electric Power, Japan	440

* In Operation.

Total in operation:	3 units, about	600 MW
Total under construction or on order:	28 units, about	18,200 MW
General total, BWR's (mid-1967):	31 units, about	18,800 MW

1/ Increased to 240 MW by conventional superheat.

4. CANDU (HEAVY WATER MODERATED AND COOLED REACTORS)

Year Ordered	Name, Owner, Location	Net Capacity Rounded (MW)
	In Canada	
1959 *	DOUGLAS POINT, AECL, Ontario	200
	PICKERING, Ontario Hydro, Ontario	2 x 500
	Outside Canada	
1964	RAJASTAN, Dept. of Atomic Energy, India	2 x 200
1965	KARACHI, PAEC, Pakistan	120

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* In operation.

Total in operation:	1 unit, about	200 MW
Total under construction or on order:	5 units, about	1,500 MW
General total, CANDU's (mid-1967):	6 units, about	1,700 MW

5. SUMMARY

	In Operation		Under Construction or on Order		Total	
	Units	MW	Units	MW	Units	MW
Graphite moderated CO_2 cooled	20	4,100	16	6,300	36	10,400
Pressurized water	3	700	37	24,700	40	25,400
Boiling water	3	600	28	18,200	31	18,800
CANDU (Heavy Water mod.& cooled)	1	200	5	1,500	6	1,700
	27	5,600	86	50,700	113	56,300

Installed Generating Capacity,[1/] by Countries, Dec. 31, 1964
(in MW)

	Hydro	Thermal [2/]	Total
North America			
Canada	20,331	6,768	27,099
Mexico	2,230	3,041	5,271
United States	42,899	197,572	240,471
Central America			
Canal Zone (Panama)	46	43	89
Costa Rica	103	37	140
El Salvador	102	19	121
Guatemala	27	75	102
Honduras	35	35	70
Nicaragua	34	74	108
Panama	4	71	75
West Indies			
Bahamas	-	37	37
Bermuda	-	36	36
Cuba	31	949	980
Dominican Republic	8	160	168
Haiti	3	27	30
Jamaica	21	165	186
Lesser Antilles	-	65	65
Netherlands Antilles	-	243	243
Puerto Rico	107	707	814
Trinidad-Tobago	-	254	254
South America			
Argentina	377	4,071	5,078
Bolivia	87	70	157
Brazil	5,219	1,915	7,134
Chile	718	673	1,391
Colombia	865	794	1,659
Ecuador	67	103	170
Guyana (3 divisions)	-	119	119
Paraguay	-	52	52
Peru	740	430	1,170
Uruguay	224	208	432
Venezuela	387	1,670	2,057

1/ Including public utilities and industrially owned generating capacity.

2/ Including nuclear.

	Hydro	Thermal 1/	Total
Europe			
Albania	100	27	127
Austria	3,719	1,800	5,519
Belgium	52	5,083	5,135
Bulgaria	565	1,165	1,730
Czechoslavakia	1,692	6,173	7,865
Denmark	10	2,325	2,335
Finland	1,951	2,015	3,966
France	12,312	14,234	26,546
Germany (East)	280	9,534	9,814
Germany (West) 2/	3,658	32,409	36,067
Greece	253	620	873
Hungary	19	1,889	1,908
Iceland	127	44	171
Ireland 3/	219	791	1,010
Italy	13,964	9,751	23,715
Luxembourg	929	254	1,183
Netherlands	-	6,727	6,727
Norway	9,033	132	9,165
Poland	382	8,923	9,305
Portugal	1,311	297	1,608
Romania	416	2,450	2,866
Spain	7,019	2,707	9,726
Sweden	9,019	2,496	11,515
Switzerland 4/	7,888	200	8,088
Turkey	490	957	1,447
United Kingdom	1,713	44,186	45,899
U.S.S.R.	22,300	80,800	103,100
Yugoslavia	1,851	1,511	3,362
Islands 5/	-	144	144
Africa			
Algeria	234	357	591
Angola	329	63	392
Cameroon	152	12	164
Central African Republic	6	2	8
Chad	-	5	5
Congo (Brazzaville)	15	12	27
Congo (Leopoldville)	810	90	900
Dahomey	-	7	7
Ethiopia 6/	64	47	111

1/ Including nuclear
2/ Including West Berlin
3/ Situation as of April 1, 1964.
4/ Situation as of September 30, 1964.
5/ Including Cape Verde, Cyprus, Gibraltar, Malta-Gozo.
6/ Situation as of September 10, 1964.

	Hydro	Thermal 1/	Total
Africa (continued)			
Gabon	-	12	12
Gambia	-	5	5
Ghana	-	143	143
Guinea	20	48	68
Ivory Coast	20	48	68
Kenya	28	74	102
Liberia	5	113	118
Libya	-	100	100
Malagasy (Madagascar)	28	46	74
Malawi	1	12	13
Mali	1	8	9
Morocco	292	82	374
Mozambique	65	117	182
Niger	-	8	8
Nigeria 2/	21	252	273
Rhodesia	705	472	1,177
Rwanda	7	2	9
Senegal	-	78	78
Sierra Leone	-	41	41
Somalia	-	9	9
Southwest Africa	-	79	79
Sudan	15	66	81
Tanzania 3/	41	29	70
Togo	1	8	9
Tunisia	28	100	128
Uganda	127	20	147
Union of South Africa	5	6,472	6,477
United Arab Republic	350	1,181	1,531
Upper Volta	-	6	6
Zambia	49	214	263
Asia			
Aden	-	51	51
Afghanistan 4/	47	14	61
Burma	84	168	252
Cambodia	-	39	39
Ceylon 5/	56	100	156
China (Mainland)	2,600	10,300	12,900
China (Taiwan)	628	580	1,208
Hong Kong	-	652	652

1/ Including nuclear.
2/ Situation as of April 1, 1964.
3/ Excluding Zanzibar.
4/ Situation as of March 20, 1965.
5/ Situation as of September 30, 1964.

	Hydro	Thermal 1/	Total
Asia (continued)			
India 2/	3,578	5,415	8,993
Indonesia	188	228	416
Iran 3/	242	603	845
Iraq	-	457	457
Israel	-	645	645
Japan 2/	15,623	22,428	38,051
Jordan	-	41	41
Korea (North)	2,250	80	2,330
Korea (South)	143	611	754
Laos	-	11	11
Lebanon	126	154	280
Malaysia 4/	144	616	760
Nepal	3	8	11
Pakistan	347	785	1,132
Saudi Arabia 5/	-	486	486
Syria	16	204	220
Thailand	140	408	548
Viet Nam (North)	5	170	175
Viet Nam (South)	84	140	224
Oceania			
Australia 6/	2,052	5,906	7,958
New Zealand 2/	1,910	426	2,336
Philippines	291	679	970
Miscellaneous Other 7/	88	407	495
Total			734,000

1/ Including nuclear.
2/ Situation as of April 1, 1964.
3/ Situation as of March 20, 1965.
4/ Including Malaya, Sabah, Sarawak and Singapore.
5/ Including Saudi Arabia, Bahrain and Kuwait.
6/ Situation as of June 30, 1964.
7/ Including Brunei, Fiji Islands, Guam, Mauritius, New Calendonia, Rennion, Ryukyn Islands, Western Samoa.

Source: U.S. Federal Power Commission, World Power Data 1964.