Report No. 556-a

Nuclear Power: Its Significance for the Developing World

July 10, 1975
(Supersedes April 18, 1974 edition)

Public Utilities Department

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Document of the International Bank for Reconstruction and Development
International Development Association

TABLE OF CONTENTS

ANNEXES

1. Chapter 2 of the Bank's Report "Nuclear Power for Small Electricity Systems," TO-674, July 15, 1968, "Nuclear Power Plant Technology"

2. Reactor Technologies: Status and Operating Experience.

3. Estimated Initial Capital Cost, 600 MW Plants for Developing Countries

4. Extract from "Potential Market for Nuclear Plants (1981-1990): Number of Plants vs. Size."

5. Page 1 Estimated World Resources of Uranium
   Page 2 World Uranium Production Capacities

NUCLEAR POWER:
ITS SIGNIFICANCE FOR THE DEVELOPING WORLD *

SUMMARY AND CONCLUSIONS

i. Although at present the proportion of electricity generated in nuclear power facilities is only some 4-5% of all electricity produced, it is increasing at an extremely rapid pace. Projections taking into account nuclear plants now under construction and those for which facilities have been ordered suggest that nuclear power's share of production will be about 20% in 1980, and very possibly exceed 55% by the end of the century. Even before the recent rise in oil prices, it would have been economically attractive for 15 developing member countries to acquire more than a hundred units 500-600 MW or larger for operation during 1980-1989: Argentina, Brazil, China, Egypt, Greece, India, Israel, Korea, Mexico, Pakistan, the Philippines, Romania, Spain, Thailand, and Yugoslavia have or will have power systems sufficiently large to accommodate units of this dimension. (Technical and economic considerations generally require that no single unit should represent more than 10-15% of total system capacity.) At current and foreseen levels of fossil fuel prices and availabilities, nuclear plants of much smaller sizes, down to 200 MW, would be economically attractive in a number of power systems. Were units of this size to be made available, the nuclear power market would expand through 1990 by about another hundred units and include an additional eight developing member countries. However, units smaller than 500-600 MW are unlikely to be offered by manufacturers for some time because their order books are filled with requests for larger ones. Indeed, shortages of skilled manpower, manufacturing capacity and other constraints are likely to limit substantially the nuclear power development programs of the developing world. Moreover, heretofore easy access by developing countries to bilateral and supplier sources for financing nuclear plant may become more difficult in the light of the demands industrialized nations are placing on suppliers.

ii. Compared with conventional oil and coal-fired powerplants, nuclear plants are characterized by markedly higher capital costs (about 1.5 to 2.5 times) and lower fuel costs (about one-half to one-sixth). They also show greater economies of scale. For these reasons nuclear power costs decrease more rapidly than fossil fuel power costs as size of units and plant utilization factors increase. Under the conditions prevailing in recent years nuclear plants of 500-600 MW capacity operating at 70% or higher plant utilization factors had become economically attractive in most industrial countries. Even with the markedly changed competitive position of nuclear power brought about by the recent increases in the price of oil, it continues to be attractive principally for supplying the base load of sizable (larger than 2000 MW) power systems. Thus to meet the continuing problem of supplying smaller systems, and non-base load requirements and the short duration peaks of larger power systems, the world will still require hydroelectric developments, diesel units, gas turbines, pumped storage plants, and fossil-fuelled steam plant.

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* The original paper dated April 18, 1974 has been updated in part to reflect latest developments in regard to safety issues.

iii. Some 15-20 years after the advent of the first industrial sized nuclear power plants, two reactor technologies being offered commercially -- light water reactors, and heavy water CANDU reactors -- have demonstrated reliability in power system operation comparable to conventional plants. Sufficient experience has been acquired in their construction to lend confidence to current cost estimates and completion schedules so that they may be acquired and operated by developing countries without undue risks. Other technologies, such as the high-temperature-gas-cooled reactor, and the advanced-gas-cooled reactor, have been tested in experimental plants. Although a number of large units of these types are under construction, these technologies have still to demonstrate their reliability under industrial operating conditions. At the end of 1973 there were about 130 nuclear reactors in commercial operation throughout the world, with aggregate capacity of about 50 million kw, and another 250 under construction with capacity of over 220 million kw. All told, at the end of 1973 they had produced 807 billion kwh, the equivalent of the total electric production of France, the Federal Republic of Germany, Italy, and the Benelux countries in 1973. About one-half (395 billion kwh) was generated in plants based upon Magnox type reactors, the construction of which has now been discontinued. Virtually all the balance was produced by light water reactors (377 billion kwh) and Canadian heavy water CANDU reactors (29 billion kwh). All other technologies combined have produced only 6 billion kwh or less than 1% of total. As has been true of all new technologies, both light water and CANDU reactors experienced a period of "teething" difficulties which may now be considered successfully overcome. For example, nuclear plants 600 MW and larger operating in the US in 1972 achieved on average performances comparable to that of similar sized conventional fossil-fuelled plants, i.e., availability of 70-75%. The developing world, of course, has had very little construction and operating experience so far. Only seven reactors aggregating about 2000 MW were in operation by December 1973 in three developing countries: India, Pakistan, and Spain. Another 23, aggregating 15,000 MW, were on order or under construction in a total of 10 developing member countries: Argentina, Brazil, China, India, Korea, Mexico, Pakistan, Romania, Spain and Yugoslavia. Construction and operational experiences have varied from case to case and no specific pattern can be detected so far to differentiate between developing and industrial countries.

iv. Nuclear plants are composed of (i) the nuclear steam supply system (NSSS: reactor, primary heat exchangers and associated pumps); (ii) special turbines; (iii) conventional electro-mechanical equipment (generators, transformers, switchgear, controls, etc.); and finally (iv) civil works. The sources of supply for proven NSSSs are at present about 12 companies, in 7 countries, which have great differences in experience among them. Suitable turbines capable of working with the low-quality steam produced by both the light water and CANDU reactors, are available from about 12 manufacturers in 9 countries. All the other elements -- the "balance of plant" -- are available on an even broader scale.

v. Implementation of present forecasts regarding the growth of nuclear power beyond 1990 and its dominant role in the energy sector are critically dependent on either a considerable interim expansion in the amount of proven uranium reserves or on the timely development of the "breeder" type of reactor, which would use fuel 50-70 times more efficiently than present reactors. Current nuclear programs may exhaust presently proven uranium reserves available at less than $10 per pound (the 1973 price was $7-$8) by 1986. And by the year 2000 without new discoveries of reserves, reactors might be using uranium in the $30-$50 per pound price range. (It should be noted that nuclear power costs are relatively insensitive to higher costs of production of uranium ores. Nuclear fuel costs represent only about 20% of the total cost of nuclear generation and, of that fraction, uranium ores account for only one-third, i.e., 6-7% of the total, the balance being largely fuel element fabrication, processing and enrichment.) Moreover, there appears to be considerable room for finding more uranium as past exploration efforts were spurred by the needs of a few countries with nuclear weapons development programs and slowed down considerably when adequate sources to support those programs had been identified. As to breeder reactors, present prospects for commercial operation on a significant scale are in the 1985-1990 range though they have all the uncertainties normally associated with the development and scaling up of a new technology. Medium sized experimental breeder reactors exist in France, the UK, and the USSR. These countries and Germany, Japan, and the US have recently stepped up their programs to develop large 1000 MW commercial breeder reactors.

vi. While the sources of natural uranium are scattered throughout 20 countries around the world, the enriched fuel on which the light water reactor technology depends is presently available from very few sources, dominated by the US. Other countries are entering the market, and it is likely that supplies will be available from 4-5 industrialized countries by the early 1980s when reactors ordered today would commence operation. Developing countries should be fully aware of this situation with respect to fuel supply, and pay particular attention to assuring a dependable long-term supply of fuel when ordering nuclear generating units. The fact that CANDU type reactors utilize natural uranium is a particularly attractive consideration for those countries which have ore, or which may wish to have wider fuel supply options for strategic, security, or political reasons.

vii. The development and operation of nuclear power facilities has taken place in an atmosphere of awareness that the technology had associated with it a host of new safety and environmental hazards. The nuclear industry and the governments of the nuclear powers have drawn up very stringent standards with respect to the design, construction and operation of all the facilities involved, and carried out extensive research into the effects of radiation on man and the earth's biosphere. The release of low-level radiation products associated with the normal operation of reactors would appear to give no general cause for concern. The US Environmental Protection Agency estimates that annual average radiation exposure of the US population in the year 2000 arising from nuclear plants would be less than 1% of the dose from diagnostic x-rays. On the other hand there exists a finite, non-zero, albeit very small probability of a very large reactor accident, involving a core melt-down and subsequent release of large amounts of radioactivity in the environment. Such an accident has never occurred and therefore its probability and consequences can only be derived by theoretical calculations. "The Reactor Safety Study" (known as the Rasmussen Study) released in draft form by the AEC in August of 1974 was the first thorough attempt to quantify the probabilities and consequences of such hypothetical accidents by using a technique known as "event tree" and "fault tree" analysis. The main conclusions of this study show nuclear power risks to be "smaller than many other man-made and natural risks." Criticism has been expressed and a final version of the report will be issued in the Fall of 1975. Although several changes are now being made it is not expected that the overall picture will change substantially. Also, the U.S. Nuclear Regulatory Commission has plans for a number of LWR safety experimental studies, including the large, 1/60 scale Loss-of-Fluid Test (LOFT). Many other experiments are sponsored by the nuclear vendors and the Electric Power Research Institute (the R & D arm of the U.S. electric utilities). Results from these experimental studies will provide a quantitative basis regarding the margins of safety inherent in present reactor designs and calculational methods. There are also hazards involved in processing, storing, transporting and disposing of radioactive wastes, some of which, notably the actinides, have extremely long half lives. Another serious concern is caused by the possibility of theft or diversion of special nuclear materials which provide the raw material for the construction of nuclear explosive devices. The risks generated by a plutonium economy are often cited in this connection by critics of nuclear power.

viii. At national and international levels a regulatory framework has been established to control all nuclear activities and to ensure very high levels of safety and public health protection. These controls have contributed critically to the nuclear industry's excellent safety record. An elaborate system of controls also exists in the safeguards area, to prevent unauthorized use of nuclear materials. However, many weaknesses in the systems (both national and international) have been brought to light and a need for stronger and more effective measures is apparent. Since this report attempts to focus on the economic and technical aspects of nuclear power it does not dwell on the merits of existing or proposed safeguards (e.g. the Non-Proliferation Treaty) which are judged to be matters in the purview of political national and international bodies.

ix. The advent of nuclear power in the developing world, as has been pointed out in its 1968 Report "Nuclear Power for Small Electricity Systems" does not raise any new policy issues for the Bank. Nuclear plants are simply another option to be considered when searching for the least cost solution to the problem of supplying the growing demands for electric power. A review of the technical and economic developments in the nuclear field in recent years suggests that a significant number of developing countries will wish to acquire nuclear plants, and may seek the Bank's assistance in this connection. The Bank could exercise a useful role with its borrowers since the acquisition of nuclear plants will involve a major transfer of technology. The Bank's long association with electric power systems in developing countries would enable it to help borrowers identify in timely fashion the preparatory steps necessary to reach decisions on acquiring the new technology, and to assist in marshalling the resources to meet this need. Although a request for financing a nuclear plant may not be received for some time, the need to provide technical assistance in helping borrowers carry out the planning and other preparatory phases is likely to arise much sooner.

I. INTRODUCTION

1. Although the Bank Group has made loans and credits of more than $6 billion in the aggregate for the development of electric power, it has made only one small one in connection with nuclear power generation. That was in 1959 to Italy. Since that time only ten developing member countries 1/ have made their own commitments to acquire nuclear power generating facilities, and of these only three 2/have plants actually in operation. Except for one informal request in 1968, no one has sought Bank Group financing of either a nuclear installation, or any component. Financing for nuclear installations has been readily available, and generally on attractive terms. Moreover, in the past, nuclear plant and its principal elements have not been available on a basis sufficiently broadly international to make Bank Group financing appropriate.

2. The Executive Directors of the Bank requested in 1967 that they be given a report comprehensively treating the prospects and problems nuclear power might hold for the developing world. This report, "Nuclear Power for Small Electricity Systems" (TO-674) was prepared by the then Projects Department, and issued July 15, 1968. Although 5-1/2 years have intervened since it was published, two statements which appeared in the Foreword of that report are worth repeating in this paper:

> "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.
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> "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."

3. Bank staff have continuously monitored developments on the commercial nuclear front, and mounted a concerted effort in 1970 which involved discussions both with major power systems involved in nuclear developments and a number of the key facilities manufacturers. In particular, this review concluded that

1/ Argentina, Brazil, Republic of China, India, Korea, Mexico, Pakistan, Romania, Spain, and Yugoslavia.
2/ India, Pakistan, Spain.

the barrier of international availability of nuclear plant had been broken, and meaningful competition could be expected for the supply of reactors and turbines of demonstrated capability.

4. In 1972-1973, the Bank accepted a role as one of the sponsors of a "Market Survey for Nuclear Power in Developing Countries" executed by the International Atomic Energy Agency (IAEA). The Agency's survey of 14 countries and its extrapolation to all developing countries in the world -- with which the Bank is in general agreement -- conclude inter alia that over the next decade the developing world might make commitments for about 100 million kw of new nuclear plants, i.e. of the order of all their presently installed generating capacity. Recent large increases in the price of oil will accelerate this movement. In fact, present indications are that developing countries with electric power systems large enough to operate commercially available nuclear powerplants and which are presently dependent on imported oil will reconsider their options as rapidly as possible, with particular attention to nuclear power, as well as coal. It is thus likely the Bank may be approached in the near future to consider financing nuclear power projects.

5. It seems appropriate at this juncture to reexamine the factors likely to affect the role nuclear-generated electricity may play in the developing world in the next decade. This is the purpose of this paper which reviews:

(i) the growing role of nuclear power in the world's overall energy mix;

(ii) current nuclear powerplant technologies and their sources of supply;

(iii) the shifting economics of nuclear plants vis-a-vis conventional plants, and the nuclear fuel situation;

(iv) environmental and safety aspects of nuclear power;

(v) administrative and institutional aspects of acquiring a nuclear technology; and

(vi) the implications of these factors for the Bank.

6. The paper was prepared by the Public Utilities Department of the Bank. It has benefitted from a review of its contents as to fact carried out by the IAEA, whose contribution is gratefully acknowledged.

II. BACKGROUND AND PERSPECTIVE

7. During the last 20 years oil and natural gas have become the most important components of the world's "energy mix." 1/ In 1950 coal represented about two-thirds of the mix, and petroleum and natural gas together another third. 2/ By 1970 their roles had reversed, the result of a process started earlier in the century in the US following the discovery and development of large oil deposits in the 1920s and 1930s. With the rapid exploitation of Middle East and African oil after World War II, this process extended to Western Europe and Japan. Parallel developments took place in the USSR and other centrally planned economies. By 1950 the US energy mix had "matured" and petroleum consumption, after having increased at a rate twice that of overall energy, began to grow at a rate only slightly above it. By 1970 the mix of energy consumed by Western Europe and Japan had also stabilized, especially with regard to oil consumption. Natural gas recently discovered in Europe's offshore continental shelf is starting to make an impact there. In summary, the past 40 years have witnessed a very rapid growth of petroleum's contribution to the energy mix. This is not likely to continue, however, as the economic and technological factors which caused it have by now spent most of their impact. They are reviewed briefly in what follows.

8. On the supply side, the scientific application of the techniques of geology and geophysics led to the discovery of deep oil and gas deposits. World-wide proven reserves have in the past been kept comfortably ahead of demand and production. In addition, the technology of large pipelines and the development of bigger and automated tankers have kept the cost of transportation of petroleum products down to a fraction of that of coal: about 1/5 to 1/7 for oil, about 1/2 for gas. This has been a critical competitive factor, along with the (then) comparatively low prices of oil.

9. On the demand side, the transport sector accounts for about 15%-25% of total energy consumption. 3/ For technical and/or economic reasons it has become a virtually exclusive province of petroleum. Automobiles and airplanes are a "captive" market with present engine technologies. Railroads and shipping have been converted from coal to petroleum as a result of overall

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1/ The total amount of energy used. Components are compared in terms of equal energy content.

2/ For the limited purposes of this note, discussion of hydroelectricity is avoided. There are several less developed countries with enormous still-untapped water-power resources, and where costs are such that their development will be attractive. Water power provides about 6% of all the world's energy, or about 25% of its electricity.

3/ For instance in the EEC in 1971, primary energy usage was distributed: (i) industry 33%, (ii) transportation 16%, (iii) residential/commercial 24%, (iv) electricity 23%, and (v) other 4%.

system economics: lower capital and operating costs, flexibility of operation, customer preferences (e.g., cleanliness) all have been factors which made oil more attractive in spite of its higher cost vs. coal as measured by heating value alone. 1/

10. Residential and commercial use accounts for about 20% of primary energy consumption in industrialized countries and about 10% in the developing world. Lighting and the electric motors in air-conditioners, refrigerators, and other household appliances represent a "captive" market for electricity. Domestic and industrial space heating which together represent up to 40% of all energy consumption in industrialized countries, present ample opportunity for competition and substitution among energy sources. Heating is presently dominated by gas, having in the past relied in succession on wood, coal and oil. Availability, price, installed cost of appliances, and convenience (cleanliness, automation) are the main factors usually considered in making a choice between fuels. Electricity has also been used for space heating, mainly in the US in connection with commercial buildings where saving in duct space is an important cost factor. In the past this practice has been criticized as wasteful of energy 2/, but it need not be. The more prevalent use of the heat-pump 3/ and other heating devices, together with significantly improved insulation, will encourage more efficient electric heating, which under appropriate circumstances will be both economically attractive and conservative of primary fuel. This will be especially significant as power systems begin to rely on nuclear plants for most of their off-peak generating needs.

11. Industry and electric utilities account for another 25% each of the primary energy market (with the latter growing at nearly twice the rate of the other users). Coal, oil, gas and nuclear power will compete for these markets primarily on the basis of their respective costs per unit of heat delivered at the plant. 4/ The outcome of this competition depends very much on local conditions, especially proximity to coal mines. In the case of the

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1/ In 1925 more than 90% of locomotives and 50% of ships used coal. Today these uses are negligible.

2/ Powerplants convert only one-third to two-fifths of the heat in fuel they burn to electricity, and so direct reconversion of electric power into heat in space heating applications cannot be more than 33-40% efficient in terms of original fuel.

3/ A reverse refrigeration-type machine, electrically-driven, which delivers heat from the environment (e.g. the air) to the space to be heated. An efficient installation will deliver two times the heat value of the electricity required to run it.

4/ Plants burning coal usually have slightly higher capital costs than those burning oil or gas. This can be offset by a fairly small fuel cost differential. Nuclear plants, on the other hand, have much higher capital costs, and become attractive only where substantial differentials exist between nuclear and fossil fuel costs.

utility industry, coal transport costs can be minimized as powerplants can be built near the mines and the electricity transported. For these reasons coal, at least in many regions of the US, the UK, and Western Europe, has maintained a very significant share of the utility market. In the US where coal is relatively cheap, its choice as a boiler fuel is dictated by purely economic considerations. In the UK, Western Europe, and Japan, however, it continues to be used largely because government policies have protected it against the inroads of (then) cheaper imported oil. In the long run, nuclear energy seems destined to become the dominant utility fuel.

12. Table 1 summarizes past developments in the world energy mix since 1925 and includes projections for 1980 and 2000. It shows the changing roles of the various primary energy sources: coal, oil, gas, hydro and nuclear; it also gives the growth of total energy consumption, and the proportion of it which goes through the secondary form of electricity. The rather striking change which is foreseen in the future energy mix due to the introduction of nuclear power is based -- at least for 1980 -- on fairly detailed analysis of the published plans of the major industrial countries. Another notable aspect of this evolution is the growing importance of electricity as a form of energy utilization.

Table 1

World Consumption of Primary Energy: 1925-2000

	Actual			Estimated	
	1925	1950	1970	1980	2000
Total Primary Energy, 10^{15} kcal	12	18	51	83	205
	% Distribution				
Coal	81.7	60.4	33.6	24.6	17.2
Oil	13.1	24.6	39.6	42.4	34.5
Natural Gas	3.1	10.4	19.9	20.3	13.8
Hydro /1	2.1	4.6	6.5	6.0	6.9
Nuclear	-	-	0.4	6.7	27.6
	100.0	100.0	100.0	100.0	100.0
Electricity % of Total	7	14	25	31	50
Nuclear % of Electricity	-	-	2	21	55

/1 Based on 2577 kcal/kwh electricity, the equivalent heat rate in modern steam-electric generating plants.

Source: International Atomic Energy Agency Bulletin, Vol. 15, No. 5, 1973.

13. With the dawning of the "atomic age" after World War II, and the advent of modest (and then subsidized) nuclear power demonstration plants in several industrialized nations, some of the more enthusiastic advocates of nuclear power were predicting not only that it would become the predominant source of electricity in a few years, but that this would be accompanied by a dramatic lowering of costs. Neither of these predictions materialized, primarily for three reasons: (1) the prices of fossil fuels, and particularly that of oil, remained low until very recently; (2) the problems of introducing a new and highly complex technology were probably underestimated; and (3) a growing concern for safety and radiation effects on man and the environment has delayed public acceptance of nuclear power. Although the first commercial-scale nuclear powerplants have been producing electricity for about 18 years, up to the end of 1970 less than 2% of the world's electric power generating capability was nuclear, virtually all of it located in the industrialized world. Recent developments have changed the prospects for nuclear power. The industry has mounted an intensive effort to bring a number of reactor types to maturity, and to prove their reliability. The end of an era of low fossil fuel prices has highlighted a cardinal attribute of nuclear energy: relatively low and stable fuel costs. Finally, increasing needs for electric power and realization that nuclear plants contribute less to pollution than fossil fuel plants are likely to promote more rapid public acceptance. By 1973, installed nuclear capacity had more than doubled in proportion since 1970, to 4.3% of all generating capacity. It is expected to climb to 7% by 1975, and as Table 1 indicates, to 21% by 1980. It is clear that nuclear power has firmly entered the "take-off" zone.

14. Most industrialized countries -- the US, UK, Western Europe and Japan -- contemplate that not less than 50% of their electric requirements in the year 2000 will be met from nuclear sources. In several cases -- France, Japan, and Sweden -- the proportion may be as high as 80-85%. In the less-developed world nuclear power has already made an impressive start, when plants committed and under construction as well as operating facilities are taken into account. India, Pakistan, and Spain have reactors in operation, aggregating a little more than 2000 MW. Other plants under construction or ordered in the developing countries 1/ now total nearly 15,000 MW. Table 2 indicates the extent to which the world has made a commitment to nuclear power, and furthermore shows that the average size of reactors under construction is about 880 MW, compared with about 370 MW for units in operation. In fact, reactors are not now generally commercially available in sizes smaller than 500-600 MW.

1/ Excluding Finland from this classification, and including only Yugoslavia of the centrally-planned economies.

Table 2

Nuclear Power Reactors Throughout the World
(All Types 50,000 kw and larger)
January 1, 1974

Country	In Operation		Under Construction/Ordered		Total	
	No.	1000 kw	No.	1000 kw	No.	1000 kw
Argentina*	-	-	2	940	2	940
Austria	-	-	1	723	1	723
Belgium	1	410	2	1,330	3	1,740
Brazil*	-	-	1	657	1	657
Bulgaria	-	-	4	1,760	4	1,760
Canada	6	2,646	4	3,200	10	5,846
China (Taiwan)*	-	-	4	3,072	4	3,072
Czechoslovakia	1	143	4	2,478	5	2,621
Finland	-	-	3	1,540	3	1,540
France+	9	2,970	19	17,515	28	20,485
Germany (F.R.)	7	2,359	12	11,338	19	13,697
Germany (D.R.)	1	70	2	730	3	800
Hungary	-	-	2	880	2	880
India*	3	600	5	1,110	8	1,710
Italy	3	581	1	822	4	1,403
Japan	6	2,583	20	14,286	26	16,869
Korea*	-	-	2	1,195	2	1,195
Mexico*	-	-	1	600	1	600
Netherlands	2	534	-	-	2	534
Pakistan*	1	137	-	-	1	137
Romania*	-	-	1	440	1	440
Spain*	3	1,120	7	6,520	10	7,640
Sweden	3	1,360	8	6,289	11	7,649
Switzerland	3	1,054	4	3,560	7	4,614
United Kingdom	28	6,117	10	6,634	38	12,751
United States	35	20,790	141	142,353	176	163,143
USSR1/	16	3,444	8	6,500	24	9,944
Yugoslavia*	-	-	1	630	1	630
Total World	128	46,918	269	237,102	397	284,020
Developing Member Countries	7	1,857	24	15,164	31	17,021
Average Unit Size (World)		367		881		715

* Designates developing member countries
\+ Data for France are as of April 1974.
1/ Data possibly incomplete.

Sources: "Power Reactors 1973", Nuclear Engineering International, April 1973.
"Power and Research Reactors in Member States", IAEA, September 1973.
Nucleonics Week, Vol. 15, No. 4, January 24, 1974.
Nuclear News, Vol. 17, No. 3, February 1974.

III. THE TECHNOLOGIES AND THE SUPPLY OF PLANT

15. Nuclear plants differ from conventional fossil-fuel-burning plants principally in the way steam is raised to drive the turbine-generators. The nuclear technology employs a reactor (and associated sub-systems) whereas the conventional plant relies upon a boiler. In both cases, electric power is generated from the heat energy in steam through turbine-generators. It is clear that questions of design and equipment reliability arise in connection with the strictly nuclear elements 1/ of nuclear plants, because they are the products of a new technology. These same questions arise as well in connection with the turbines designed to operate with both the US light water type reactor systems, and the Canadian heavy water (CANDU) reactor systems. These systems produce steam of relatively low temperature and pressure which requires turbines of special thermodynamic design and very large dimensions, unlike the machines employed in association with other reactor technologies which are essentially the same as the equipment successfully used for many years in conventional fossil-fuelled plants.

The Reactor Technologies

16. The prevalent use of the word "reactor" obscures the fact that several differing types of nuclear reactors have in fact been developed, based upon the use of different materials, technologies, and designs. Generally speaking, reactors are classified by: fuel (e.g. natural or enriched uranium); coolant (e.g., gas, water); and moderator, the material needed to slow neutrons and facilitate nuclear fission (e.g., graphite, heavy water, light water). 2/ Most presently developed technologies -- and all those in prototype or commercial operation -- can be classed as "gas-cooled", "light water", or "heavy water". These are summarized in the table below and described briefly in what follows.

1/ Various terms are in common use to describe these. "NSSS" means "nuclear steam supply system." "Nuclear island" is another term meaning about the same thing. This report refers to all the nuclear-associated elements as the "reactor" or "reactor system."

2/ For a simple, concise discussion of the fundamentals of nuclear technology, and the principles upon which the several extant reactor systems are based, see Chapter 2 of the Bank's 1968 report, "Nuclear Power for Small Electricity Systems," appended here as Annex 1.

Table 3

Reactor Types and Designations

Gas-cooled systems	
Magnox	Natural uranium-fuelled graphite-moderated gas-cooled (CO_2) system. It was used in the first stages of the UK and French programs. It takes its name from the material (a magnesium alloy) in which the uranium rods are encased.
AGR	Advanced gas-cooled reactor. A UK development of the Magnox system using slightly enriched fuel in the form of uranium oxide, clad in stainless steel.
HTGR	High-temperature gas-cooled graphite-moderated reactor. A further development of the gas-cooled reactor, using highly enriched uranium and thorium as fuel, and helium as coolant.
Heavy water systems	
PHWR	Pressurized heavy water reactor. This type uses natural uranium as fuel, and is moderated and cooled by heavy water. (The Canadian design is called CANDU.)
HWLWR	Heavy-water-moderated boiling light-water-cooled system. The UK design is called SGHWR: steam-generating heavy water reactor.
HWGCR	Heavy-water-moderated gas-cooled reactor.
Light water systems	
LWR	Light water reactor. Light water is both moderator and coolant. The fuel is enriched uranium. This group includes two basic types, below.
BWR	Boiling water reactor. The coolant boils inside the reactor vessel.
PWR	Pressurized water reactor. The coolant does not boil inside the reactor vessel.
LWGR	Light-water-cooled, graphite-moderated reactor.
Breeder Systems	
LMFBR	Liquid metal fast breeder reactor. This technology is plutonium fuelled, sodium cooled, non-moderated using uranium as a source of additional fissile plutonium fuel.

Reactors of all these technologies (as well as associated turbines) are in operation on an experimental, prototype, or commercial basis. Depth of successful operating experience differs, however, and except for the LMFBR, is discussed below against the background of the need for the developing world to acquire plants of demonstrated reliability only.

17. Complex equipment which incorporates new technology, new design or new materials, or is produced by particular firms for the first time can be acquired only with risk: the risk of production units not working to the standards of prototypes, or inexperienced producers not being able to manufacture to specifications and/or to schedule. These risks can be substantial for electric power utilities acquiring large generating plant, ranging from the economic burden of capital and operating costs exceeding expectations to the risk of not having plant available when needed. The only protection against such risks is to procure equipment of demonstrated technology from manufacturers whose products have achieved sufficient actual operating experience.

18. In order to minimize risks to borrowers, the Bank has been applying a criterion of reliability to all equipment it finances, defined as follows: 1/

> "...when a complex mechanical plant is required (and this covers a broad range from thermal powerplant 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...; 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."
>
> "As all of these considerations are valid *a fortiori* 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."

1/ The Bank's 1968 report "Nuclear Power for Small Electricity Systems," page 4.

This standard is generally accepted by manufactuers and electric power systems as being reasonable.

Operating Experience with Reactors

19. Reactors in commercial operation throughout the world had produced nearly 807 billion kwh through the end of 1973. About half of this total (395 billion kwh) had been generated in plants based upon gas-cooled technologies now considered obsolete largely from a cost viewpoint, and no longer offered commercially. Virtually all the balance of nuclear generation has been either by light water reactors (377 billion kwh) or by Canadian heavy water reactors (29 billion kwh). The aggregate operating experience of all the other technologies listed in Table 3 is only 6 billion kwh. The preponderance of successful commercial operating experience overwhelmingly suggests that in acquiring nuclear plant, the developing world limit its choice to selecting between the Canadian heavy water technology, and the US light water technology. As was true of all new technological advances, each encountered a "breaking-in" period in which difficulties occurred but which have now been overcome. Both have achieved reliability in operation on average equal to or better than those of conventional fossil-fuelled plants. Power systems in the developing world can acquire reactors of either technology within acceptable margins of risk. Table 4 summarizes existing and projected reactor installations by principal technology. Paragraph 20 very briefly describes the status of development or experience of each reactor type, except the LMFBR. More details on all types are presented in Annex 2.

Table 4

Reactors Commercially Operable /1 and Under Construction
December 31, 1973
(Classified by Technology)

	Operable			Under Construction or Planned		
		Net Capacity			Net Capacity	
	No.	MW	%	No.	MW	%
Gas-Cooled						
Magnox	36	8,556	15.9	-	-	-
AGR	1	32	-	10	6,189	3.1
HTGR	1	40	-	7	4,590	2.3
Heavy Water						
CANDU	9	2,640	4.9	11	5,214	2.7
Light Water						
PWR	39	25,539	47.3	119	110,446	56.3
BWR	32	17,206	31.9	73	70,035	35.6
Total	118	54,013	100.0	213	196,474	100.0

/1 Excludes HWGCR, HWLWR and LWGR, and fast-breeder types.

Source: See Table 2.

20. The Magnox reactor has a long record of successful operation, but is no longer offered commercially. Its successor, the AGR, has also been most successful in prototype operation in the UK. The Central Electricity Generating Board has ordered ten 600/625 MW units, but some difficulties have been experienced, and none of them has come into commercial operation yet, although the first is expected to during 1974. The HTGR is the latest development in the gas-cooled technology. One experimental unit and one 40 MW prototype have been in operation for several years. The first large commercial unit (330 MW) is scheduled for service in June 1974 at Fort St. Vrain, Colorado. The HWLWR, SGHWR, and HWGCR prototype plants have been in operation in Canada, France, Germany and the UK but commercial experience is very limited.

Reactor Manufacturing Experience

21. The first light water reactors were manufactured almost exclusively by two US companies, General Electric and Westinghouse. This situation changed somewhat during the second part of the 1960s and will change even more in the next five years. Two other US companies, Babcock and Wilcox and Combustion Engineering, are beginning to acquire a significant portion of the market, while several European and Japanese firms will be manufacturing the major part of their domestic nuclear power facilities. Almost all of the groups outside the US have license agreements with either General Electric or Westinghouse. Most early nuclear plants were bought on a turnkey basis. The present tendency is for utilities to engage architect-engineers and to contract separately for the main parts of the plant, such as the reactor, the heat exchangers, the turbine, and the generator, thereby enlarging the number of firms which can bid. The supplier of the reactor may also sub-contract such important items as the pressure vessel or the heat exchangers. Table 5 shows how the market for light water reactors is being met, and highlights the large differences in experience among manufacturers. 1/

1/ The information in Tables 5 and 6 is from a number of sources, and is probably incomplete. It is presented to illustrate the general scope of supply of nuclear equipment.

Table 5

Suppliers of Light Water Reactors[1/][2/]
(December 31, 1973)

Country (Company)	Reactor Type	Commercially[3/] Operable No.	Commercially Operable MW	On Order No.	On Order MW	Of Which Exports No.	Of Which Exports MW
Belgium							
(ACEC)[4/]	PWR	1	390	2	1,260	-	-
France*							
(Framatome)	PWR	1	266	17	15,575	-	-
(CieGE)	BWR	-	-	2	1,940	-	-
Germany							
(Kraftwerkunion)[5/]	PWR	2	958	7	7,100	2	1,375
(Kraftwerkunion)[5/]	BWR	2	896	6	5,321	1	692
(BBR)	PWR	-	-	1	1,300	-	-
Italy							
(AMN)	BWR	-	-	2	1,822	-	-
(ENI)	PWR	-	-	1	952	-	-
Japan							
(Mitsubishi)	PWR	1	470	4	2,747	-	-
(Hitachi)	BWR	1	439	1	784	-	-
(Toshiba)	BWR	1	460	5	3,408	-	-
Sweden							
(ASEA)	BWR	1	440	7	4,960	1	660
Switzerland							
(GETSCO)	BWR	1	306	2	1,805	-	-
United States							
(GE)	BWR	24	11,341	48	49,010	16	7,329
(Westinghouse)	PWR	18	9,539	59	66,372	12	8,114
(B&W)	PWR	3	1,992	17	16,801	-	-
(C.E.)	PWR	1	710	23	25,133	-	-

1/ Excludes centrally planned economies.
2/ Larger than 30 MW.
3/ Not all are operating because of licensing problems.
4/ In association with others.
5/ Data includes reactors built by Siemens and AEG before formation of KWU.

MAIN SOURCE: Nuclear News, Vol. 17, No. 3: February 1974.
* (Data for France are as of April 1974.)

22. The design and manufacture of PHWRs of the CANDU type have been carried out by the Atomic Energy Company Limited of Canada (AECL), a Crown Company. AECL has already built six units, five in Canada and one in India. Four 745 MW units are under construction in Canada. Another 125 MW CANDU reactor built by CGE has been operating successfully in Pakistan since 1972. A 600 MW unit was sold by AECL in 1973 to Argentina, a country particularly interested in exploiting its own natural uranium, and another to Korea in 1974.

23. The AGRs of the type ordered by the Central Electricity Generating Board of the UK are being built by the successors to the consortia that were responsible for the Magnox program. A recently-consolidated organization is now the only supplier of this type of reactor and its associated heat exchangers. Licensing arrangements with European and Japanese manufacturers are being negotiated. While at the present time a large AGR unit has not yet been completed and placed in commercial operation, by the end of 1974 four reactors are expected to be completed, and another six during 1975-1977.

24. Commercial HTGRs are produced at present only by Gulf-General Atomic (GGA) of the US. As mentioned in paragraph 20, a 40 MW unit has been in operation since 1967, and a 330 MW unit will begin commercial operation in June 1974. GGA has seven more units on order, ranging in size up to 1140 MW.

Turbine Manufacturing Experience

25. As indicated at the beginning of this Chapter, light water and CANDU reactors produce steam which requires physically large turbines of special design, unlike those employed with other reactor systems and conventional fossil-fuelled boilers. There are many experienced and qualified manufacturers of conventional turbines throughout the industrialized countries, and a number of them have also produced the turbines which have operated successfully with light water and CANDU reactors. As is the case with reactors, performance and availability is fully comparable with more conventional machines. Table 6 summarizes manufacturing experience. 1/

26. Several conclusions emerge from analyzing the operating and manufacturing experience discussed in this Chapter:

(i) At present, utilities in developing countries should consider purchasing reactors only of the light water or CANDU technologies. AGRs and HTGRs might also be considered after several plants have been in successful commercial use for a year or more, and have achieved minimum availability of 75%. This is expected to be no sooner than 1975.

1/ See Footnote to paragraph 21.

Table 6

Suppliers of Turbines Suitable for CANDU, PHWRs and Light Water Reactors

Country (Company)	200 MW and Larger: Commercially Operable No.	MW	On Order No.	MW
Canada				
(Howden & Parsons)	4	2,160	4	800
France*				
(Alsthom)	-	-	17	15,575
(Rateau)	1	272	-	-
(CEM)	-	-	2	1,940
Germany				
(KWU)	7	3,293	11	9,693
Italy				
(Tosi)	2 1/	657	1 1/	410
(AMN)	-	-	1	822
Japan				
(Hitachi)	2 2/	940	3	2,164
(Kajima)	-	-	1	1,100
(Mitsubishi)	2	680	7	5,943
(Toshiba) 3/	2	1,117	4	3,259
Sweden				
(STAL-Laval)	1	458	4	2,090 4/
Switzerland				
(Brown Boveri)	4	1,320	4	4,703
United Kingdom				
(English Electric)	1	762 5/	4	4,085
(AEI)	1	220	-	-
United States				
(General Electric)	20	14,760	32	31,668
(Westinghouse)	22	15,779	36	38,239

Notes: Excludes centrally planned economies. Figures cannot be correlated with Table 5 because turbine-generators may be ordered considerably later than reactors.

1/ 2 x 410 MW units in consortium with Belgian manufacturers including "export".
2/ 1 x 460 MW unit with General Electric.
3/ 3 units (2284 MW) with General Electric.
4/ 1 x 600 MW unit with Brown Boveri; 1 x 890 MW unit with ASEA.
5/ Export order.

MAIN SOURCE: Nuclear Energy International, April 1973.
* (Data for France are as of April 1974.)

(ii) Utilities can now procure light water reactors from about 12 companies in 7 countries, and CANDU reactors from Canada. The number and experience of manufacturers of light water reactors has been increasing. The changing situation should be reviewed in connection with each solicitation of offers, which should take place only after careful prequalification.

(iii) The special turbines required by both light water and CANDU reactors can be purchased on an international basis. As in the case of reactors, offers should be solicited only from prequalified manufacturers.

(iv) Both conventional and nuclear power generating technologies are dynamic. The appropriateness of particular proposals for procurement of nuclear plant will have to be evaluated in the light of the technological and manufacturing situation at the time.

(v) Although nuclear plants have in the past been available from some manufacturers on a "turnkey" basis, this is no longer generally the case. In any event, it will very likely always be necessary and advantageous for power systems in the developing world to retain the services of qualified and experienced architect-engineers to provide assistance in all the complex phases of locating, designing, purchasing, constructing, and operating nuclear powerplants.

IV. THE EVOLVING COST PICTURE

27. The choice between conventional fossil-fuelled generating facilities and nuclear ones involves considering, inter alia, the classical trade-offs between (1) lower operating costs and higher initial capital cost (the nuclear case), and (2) lower initial capital cost and higher operating costs (the conventional case). It will be apparent that the choice will have to be made under conditions of considerable uncertainty particularly as regards operating costs of fossil-fuelled plants because this involves peering far into the future and trying to forecast the behavior of the prices of these fuels. (Nuclear fuel is discussed in some detail later in this Chapter.) Moreover, all indications are that the modes of operation of nuclear plants and fossil-fuelled plants are likely to be different insofar as their lifetime contribution to the production of electricity is concerned on the power system where they have been constructed. Nuclear plants seem particularly suited to nearly continuous operation over their anticipated lifetimes. Conventional plants on the other hand have historically been relegated to fewer and fewer hours of operation as they age, not so much because they lose efficiency but because newer designs tend to overtake them as time elapses. Thus the objective analysis of all the factors impinging upon the choice is indeed complex.

28. In evaluating the economic attractiveness of nuclear power vs. the alternatives, developing countries will have to take into account these uncertainties. Because relatively few nuclear plants have been constructed in developing countries -- thus the cost data base is sparse -- and because considerations such as concern for the environment have changing impacts on plant costs, no hard and fast rules based upon meaningful cost data can be set forth as a guide. Each situation will have to be considered on its own merits. Some benchmarks can nevertheless be roughly estimated, and this is done in the next several paragraphs. The approach used here is simple: a relationship is developed to show at what cost nuclear powerplants would be just competitive with fossil-fuelled plants for different prices of oil and coal. Gas and lignite are not considered for the following reasons. Gas is not widely traded, and except where it is being flared, it is generally more valuable in applications other than as boiler fuel. Lignite is not traded internationally either, and so its exploitation tends to be restricted to mouth-of-mine plants specially designed for local circumstances. Finally, the analysis which follows should be viewed against not only the above background, but also with the following additional caveat in mind. Most economic investigations have been restricted to consideration of relatively large generating units, because nuclear plants have generally not been available in sizes smaller than 500-600 MW. Estimates in this paper for smaller size units are based upon analytic work only, and do not reflect actual commercial procurement experience.

Capital or First Costs

29. The technology of conventional plants in the immediate post-war era was based upon building larger and larger units, and pushing forward the thermodynamic frontier by adopting higher and higher steam temperatures and pressures. The manufacturers and electric utilities were very successful in this endeavor, and unit capacity costs had been constantly driven downward. However, since 1967 wages for construction labor, much higher money costs, longer construction times, and in particular much increased concern for the environment which has required new and costly appurtenances such as cooling towers and exhaust gas cleaning equipment, all have contributed to increasing costs by 80-90%.

30. The prices of nuclear plants have been rising in parallel. In 1967 the US Atomic Energy Commission (USAEC) estimated the cost for a 1 million kw nuclear unit for 1973 service at $135 per kw. 1/ This level of price quickly proved to be transitory. For reasons noted in paragraph 29, and in addition increased public concerns for safety, licensing delays, design improvements and size extrapolations, and fabrication and construction problems -- "teething troubles" — prices of nuclear plants under construction and ordered since the late 1960s have also increased sharply, by about 150%. The last seven years witnessed a very rapid growth in the construction of nuclear plants, and considerable experience has been gained in identifying and solving the problems of managing their manufacture and construction. Current cost estimates are thus likely to be more reliable than was the case in the past, a view supported by contracts presently being executed.

Capital Costs for Plants in Developing Countries

31. In connection with its "Market Survey for Nuclear Power in Developing Countries" (paragraph 4) the IAEA made detailed estimates of the capital costs of both nuclear and fossil-fuelled generating units. These estimates reflect experience in an industrialized country adjusted to conditions anticipated in the developing countries which were investigated in connection with the Market Survey. Such adjustments attempted to take into account, for example, lower costs for labor and local materials in developing countries 2/ as well as the likelihood any given plant design would not have to meet the air-pollution, waste-heat discharge, low-level radiation etc., standards presently being imposed on both conventional and nuclear plants in industrialized countries. The Survey concentrated on the market potential for nuclear units of about 500-600 MW capacity, the lower limit of those being commonly

---

1/ The 640 MW Oyster Creek units were sold for about $115 per kw in 1966, or about the same price as comparable conventional units at that time.

2/ The costs of nuclear and electro-mechanical equipment, for example, were assumed to be about the same for construction in developing countries as in industrialized ones. Labor, on the other hand, was assumed to be only about 40%.

offered on a commercial basis. To indicate only the order of magnitude of the costs of fossil-fuelled and nuclear plants, Table 7 shows average data for 600 MW units, without special environmental features such as sulfur removal facilities or cooling towers. The cost of such features might add as much as 25-30% to the cost of conventional plants, and 3-5% to nuclear plants. The data in Table 7 are presented in more detail in Annex 3.

Table 7

Estimated Capital Costs of 600 MW Units for Developing Countries
(No Special Environmental Features)
(US $ per kw)

	Type of Plant		
	Nuclear	Coal	Oil
Land and Structures	40.1	21.5	19.3
Reactor or Boiler Plant	80.2	53.3	43.7
Turbine Plant	64.8	46.2	45.8
Electrical & Miscellaneous Plant	31.0	21.5	18.0
	216.1	142.5	126.8
Contingency Allowance	14.7	9.8	8.8
DIRECT COSTS	230.8	152.3	135.6
Construction Equipment, and Engineering & Construction Management	65.0	35.2	33.2
Other Costs /1	10.2	6.0	5.7
Interest During Construction /2	63.3	28.3	22.0
INDIRECT COSTS	138.5	69.5	60.9
TOTAL COSTS	369	222	196

/1 Includes taxes, insurance, training, start-up, owner's administration
/2 Nuclear: 5-1/2 yrs.; Coal: 4 yrs.; Oil: 3-1/2 yrs.

Source: IAEA 1973 Market Survey

32. Larger electric power generating units enjoy substantial economies of scale, and this is particularly true of nuclear units. This of course is why nuclear units have so far found general acceptance only in very large sizes. Because of the need to provide reserve generating capacity against emergency and scheduled equipment outages, large units are suitable for operation only on large systems. These reserve and other technical considerations have led power system managers to adopt as a general planning criterion the rule that a system's largest unit be about 10% of total demand, but not

larger than 15%. With this in mind, the IAEA Market Survey developed on an analytical basis estimated costs for generating units in sizes smaller than (as well as larger than) 500-600 MW, which would be suitable for operation on the systems in developing countries. These data have been reviewed and revised to present (January 1974) conditions by the Bank and are used in the analysis which follows:

Table 8

Estimated January 1974 Capital Costs of Generating Units for Developing Countries (No Special Environmental Features)

US $ per kw

Unit Size MW	Type of Plant: Nuclear /1	Coal	Oil
100	1048	440	371
150	865	368	321
200	698	338	286
300	563	296	247
400	493	272	227
600	414	234	201
800	367	215	184
1000	323	206	167

/1 Light water type.

Operating Costs for Plants in Developing Countries

33. Experience with nuclear plants in commercial service has shown that the costs associated with their routine operation and planned maintenance are higher than similar costs for fossil-fuelled plants: about 50% on average, but less than that in larger sizes, and more than that in smaller. Because the largest element of such costs is attributable to labor, it is reasonable to anticipate that while a comparable cost relationship between nuclear and conventional plant operating costs will prevail in the developing world, the actual levels will be lower than in industrialized countries. This is the assumption made in these analyses. The results are not at all critical to this assumption: operation and maintenance expenses are only some 7-9% of annual capital costs for 600 MW units.

Plant Availability

34. "Availability" is a measure of the reliability of a given facility, and in power supply terms is usually stated as a proportion of time, e.g., 0.80, or so many hours in a year, e.g., 7000 hours. Experience with both nuclear and conventional plants has indicated that while availability tends to decrease somewhat with increasing size of individual unit, this effect is about equal for nuclear, coal-fired, and oil-fired units. Units in the 600 MW range have all had comparable availabilities of 0.79-0.81. Plants will usually be operated fewer hours than they are ordinarily available (about 90%), and thus total hours of operation are less than the availability fraction: in this study about 72% actual plant factors have been taken.

Fuel Prices

35. The price of fuel oil burned in powerplants will depend first on the FOB export price prevailing, and secondly on both ocean and inland freight. It is not possible to predict future FOB prices with a great degree of confidence. For purposes of illustration, prices of \$6, \$8, and \$10 per barrel as burned has been taken for heavy fuel oil. 1/ This may be thought of as equivalent to crude at about \$5-9 per barrel FOB Persian Gulf.

36. Coal has historically been an important powerplant boiler fuel in countries where large reserves could be developed reasonably near the markets for power. This has been the case in Western Europe, the UK, and the US for example. Good quality steam coal has been available as low as \$10 per ton recently in Australia and the US, for example, where mining conditions are favorable, and powerplants are located near mines. Those developing countries with economically recoverable coal reserves will of course wish to exploit them. Those that do not, may consider imported coal, on an ad hoc basis as prices are likely to cover a much broader range than oil. Prices for imported coal vary widely with quantity, location of market, and of course the quality of the coal itself, and have been as high as \$30 per ton. 2/

37. The cost of nuclear fuel depends only in a secondary way on the price of uranium. About one-third of the total cost of nuclear fuel is represented by the ore: the balance is the expense of milling and processing, and the fabrication of fuel elements. The total cost of fuel in nuclear generation is small, as is illustrated in the next paragraphs, and thus the effect of changes in ore price is very small.

1/ Historically the price for this heavy fuel oil has followed closely the price of crude of equivalent sulfur content. In recent years, fuel oil has been slightly below crude.

2/ For comparison with oil, this price is equivalent in heating value to fuel oil at about \$6 per barrel. The coal is assumed to be of "standard" heat value, 7000 kcal per kg.

Estimated Power Generation Costs

38. Estimated costs to generate one kwh in 600 MW nuclear, coal-fired, and oil-fired plants constructed in the developing world are presented in Table 9. The underlying assumptions about costs and other factors are those discussed in paragraphs 31-36.

Table 9

Estimated Generation Cost
600 MW Plant in Developing Country

	US Cents per kwh						
	Nuclear	Coal			Oil		
Fuel Price /1	$8	$10	$20	$30	$6	$8	$10
Capital	0.86	0.49	0.49	0.49	0.41	0.41	0.41
Operation & Maintenance	0.06	0.04	0.04	0.04	0.04	0.04	0.04
Fuel	0.17	0.33	0.65	0.98	0.92	1.22	1.53
Total	1.09	0.86	1 18	1.51	1.37	1.67	1.98

/1 Fuel Prices:

Uranium oxide U_3O_8	$8 per pound, $36 per SWU*
Coal	$10-$30 per ton
Oil	$6-$10 per barrel

* SWU = Separative Work Unit: see paragraph 49.

39. This table illustrates clearly the capital cost vs. fuel expense trade-off relationship between nuclear and conventional plants. It also indicates that nuclear generation costs are about twice as sensitive to capital cost assumptions as is true of conventional plants, but that conventional costs are many times more sensitive to assumptions as to fuel prices. For example: in the cases given, the capital cost of the nuclear plant would have to increase by 67% before costs became equal to those of the conventional plant burning $8 oil. Put the other way round, the cost of oil would have to fall to about $4 per barrel before the conventional oil-burning plant became as attractive as the nuclear one.

40. All of the foregoing suggests two things: first, and obviously, present fuel oil and imported coal price levels make consideration of the nuclear alternative very attractive, at least for large plant sizes; and second, the threshold of unit size at which nuclear powerplants have been attractive — heretofore 500-600 MW — may be lower for those countries

dependent upon imported fossil fuels. In view of the uncertainties in fossil fuel prices, the following two tables present "breakeven" fossil fuel prices for different size nuclear plants. Table 10 gives fossil fuel prices in common terms for both fuel oil and coal plants: US cents per million kcal heat content. Table 11 translates these figures into US$ per ton of standard coal (7000 kcal per kg) and US$ per barrel of typical fuel oil (10,150 kcal per kg). In each instance the comparison is made both against nuclear plant unit generation costs based upon Table 8, and against these costs increased by 25%. It is clear from Table 11 that nuclear power may be quite attractive vis-a-vis fossil fuels, even in relatively small size units.

41. It has been clear for some time that nuclear power would be an attractive means of generating electricity in a number of developing countries, and indeed at the end of 1973 in addition to 2,000 MW of nuclear capacity in operation in 7 reactors in India, Pakistan, and Spain, 10 member nations had ordered another 23 units aggregating 15,000 MW in new capacity for delivery in the next 6-8 years. These countries are Argentina, Brazil, China, India, Korea, Mexico, Pakistan, Romania, Spain, and Yugoslavia. Electric power markets in developing countries tend to grow more rapidly than in industrialized countries, and each year will see more power systems reaching the size where presently-available units in the 500-600 MW range will be attractive. Another 5 countries can be expected to join the first group in the later 1980s: Egypt, Greece, Israel, the Philippines, and Thailand. The IAEA has recently re-examined the conclusions of its 1973 Market Survey in the light of the rise in oil prices which took place since the report was published, and now foresees a considerable acceleration in the development of the market. In a report not published but made available to the Bank, 1/ the total market for reactors 600 MW and above in the decade 1981-1990 is now projected at about 180 million kw, nearly half of which lies in Brazil, India, Mexico, Spain and Yugoslavia.

42. The results of the "breakeven" analyses presented in Tables 10 and 11 suggest that nuclear units in smaller sizes might prove to be attractive to countries with smaller power systems. This would likely be true for Bangladesh, Chile, Jamaica, Malaysia, Peru, Singapore, Uruguay, and Viet Nam, as well as for some installations in the countries already referred to in paragraph 41. Three observations need to be made about applications in both this latter potential market -- which aggregates some 25 million kw -- and the one discussed in paragraph 41. First, because increasing demands for nuclear units among the industrialized countries are already creating production "bottlenecks" attributable to scarcities of certain materials but more importantly, skills, those developing countries wishing to shift away from oil-fired plants may find it difficult to obtain firm commitments for delivery of nuclear facilities within the time frame they would like. This argument would apply to nuclear plant in general. Second, as to smaller units -- say 200-400 MW -- as has been observed they are not now generally being commercially offered. Increasing demands for larger units may make their common commercial production unlikely in the immediate future. Third, the prospects for taking advantage of the benefits

1/ An extract appears as Annex 4.

Table 10

Prices of Fossil Fuels
at which Generation Costs
Equal Costs of Nuclear Power
(Fuel Prices in US Cents per Million kcal)

Nuclear Unit Size MW	Breakeven Fuel Prices[1] Coal[2] vs "Base" Nuclear[4]	Coal[2] vs 125% "Base"[5]	Oil[3] vs "Base" Nuclear[4]	Oil[3] vs 125% "Base"[5]
100	608	854	685	932
200	392	562	451	622
300	298	438	351	492
400	264	398	318	453
600	227	341	267	383
800	201	306	239	345
1000	161	257	206	303

1/ At plant utilization of 72%.

2/ "Standard" coal, 7000 kcal per kg

3/ Heavy fuel oil

4/ Capital costs from Table 8

5/ Capital costs and fuel costs increased 25%

Table 11

Prices of Fossil Fuels
at which Generation Costs
Equal Costs of Nuclear Power
Fuel Prices in $ per ton (Coal)
$ per barrel (Oil)

Nuclear Unit Size MW	Breakeven Fuel Prices 1/			
	Coal 2/ vs		Oil 3/ vs	
	"Base" Nuclear 4/	125% "Base" 5/	"Base" Nuclear 4/	125% "Base" 5/
100	42	60	10.20	13.90
200	27	39	6.70	9.30
300	21	31	5.20	7.35
400	18	28	4.75	6.75
600	16	24	4.00	5.70
800	14	21	3.55	5.15
1000	11	18	3.10	4.50

1/ At plant utilization of 72%.

2/ "Standard" coal, 7000 kcal per kg.

3/ Heavy fuel oil.

4/ Capital costs from Table 8.

5/ Capital costs and fuel costs increased 25%.

of nuclear power should be enhanced if power systems consider embarking on nuclear power programs, rather than purchasing single units. This would not only be more attractive to manufacturers but also hold the possibilities of achieving economies through standardization.

Uranium Resources

43. The prices of uranium fuel discussed in this report refer to the basic material produced as a result of simple milling and purifying, usually near the mine itself. The product is uranium oxide — U_3O_8 -- and is known in the trade as "yellow cake." This is the material sold to fuel processors and fuel element fabricators.

44. The magnitude of the world's uranium resources depends on the price consumers are willing to pay to discover and mine such resources. Thus in discussing these resources, it is important to recognize the extent to which the price of uranium is involved in the competitive relation of nuclear vis-a-vis fossil-fuel-fired plants. If current U_3O_8 prices were double -- the level expected to prevail in the mid-1980s -- the unit generating cost of nuclear power would increase less than 1 mill per kwh, 1/ or about 7%. Table 12 summarizes current information on uranium reserves available up to various price levels. Only reasonably assured resources are included; however, estimated additional resources would roughly double the figures given.

Table 12

Reasonably Assured Resources of Uranium Oxide

Price /1 $/lb U_3O_8	1000 Short Tons		
	United States	Rest of World /2	Total
Up to: $10	430	790	1,220
$15	630	1,475	2,105
$30	800	/3	/3
$50	4,800	/3	/3

/1 Each price category includes lower priced uranium.
/2 Excluding centrally planned economies.
/3 No data available.

Source: USAEC Reports "WASH" 1242 and 1243 for US; IAEA/OECD for rest of world.

1/ A mill is one-tenth of a cent.

45. The estimated resources shown in Table 12 may be compared with the projected uranium requirements shown in Table 13.

Table 13

World Requirements for Uranium and Separative Work Units /1

Year	New Generation Millions of kw		U_3O_8 Required /2 1000 Tons		Annual SWU Millions
	Annual	Cumulative	Annual	Cumulative	
1973	19	50	22	-	6
1975	21	93	38	91	13
1980	54	272	81	405	29
1985	75	583	150	1002	58
1990	119	1088	248	2035	100
2000	193	2660	355	5300	159

/1 See para. 49 for definition.
/2 Assumes operation at 80% plant factor.

Source: USAEC Report "WASH" 1139 (revised 1972).

It is seen that the uranium available at $10 per pound may be exhausted by about 1986. By the year 2000, reactors will probably be using uranium in the $30-50 per pound price range.

46. Concern on this account has prompted intensive efforts to develop a commercially attractive "breeder" reactor which would use fuel 50-70 times more efficiently than present reactors. Uranium occurs naturally in two forms, the so-called "fertile" and "fissile" isotopes, 1/U238 and U235. (The earlier gas-cooled and heavy water reactor technologies operate with fuel containing the naturally-occurring proportions of the heavy and light isotopes, about 140:1. On the other hand, the light water and advanced gas-cooled technologies depend upon fuel which contains a higher-than-natural proportion of the fissile U235 isotope.) 2/ It is possible to blanket the core of a reactor with fertile material and operate it in such manner as to induce nuclear reactions within the blanket which result in producing plutonium, an artificial fissile element which can be used as nuclear fuel. Thus, a "breeder" reactor is one which will produce more fissile material than it consumes.

1/ A term to describe forms of an element differing in weight, but having identical chemical properties.

2/ Such fuel is said to be "enriched," and its production requires a separate sub-technology and complex processing industry. This is discussed below in paragraphs 49 et seq.

47. The development of a successful "breeder" would substantially extend the life of the world's known uranium reserves because they would be used much more effectively than is the case with present reactor technologies. Intensive efforts are underway in several countries 1/ to develop breeders and various estimates have been made for the date of initial successful operation: the most optimistic predicts commercial applications beginning in the mid-1980s. Regardless of the time of introduction, the full impact of breeders will not be felt until after the year 2000, and the statements in paragraph 45 are valid under any circumstances of breeder introduction.

48. Uranium is found in more than 20 countries, as shown in Annex 5. Developing countries selecting a technology based on natural uranium (e.g., CANDU) thus would have a broad supply of fuel. This would not be the case for those selecting light water reactors or HTGRs, both of which use enriched fuel.

49. At the present time, the major source of enriched fuel for nuclear powerplants is the US. The US plants were constructed during and after World War II to support the US weapons program and have a capacity of 17 million separative work units (SWU) per year. A SWU is a measure of the capital, power, and plant operating cost to produce a certain amount of enriched uranium fuel. France and the UK have smaller plants, unable to produce enriched uranium at costs competitive with the US. All of these plants are based on a technology called "gaseous diffusion." A number of European countries and Japan, as well as the US, are pursuing the development of an alternative technology, "centrifugal separation", which gives promise of being economic at capacities much smaller than the gaseous diffusion process, and therefore at lower initial cost. Cost data are not available, but it is hoped that sizes as small as 5% of the minimum economic capacity of a gaseous diffusion plant will be feasible. Achievement of this would have tremendous significance for the world supply of enriched uranium fuel. Table 14 summarizes present and foreseen availability of enrichment capacity in the western world. Published figures do not exist for the USSR, but they are probably comparable to those of the US.

1/ Experimental breeder reactors in the 200-300 MW range are already in operation in the USSR, France, and the UK. Other breeders are under construction in these countries, and in Germany, Japan, and the US.

Table 14

Capacity of Enrichment Facilities

	1000 SWU per year	
	Present	Estimated 1983
US	17,000 /1	28,000 /1
UK	400 /1	400 /1
France	200 /1	9,000 /1 /3
URENCO*	50 /2	10,000 /2
Japan	-	5,000 /2
	17,650	52,400

* URENCO is owned by the UK, Germany, and The Netherlands.
/1 Gaseous diffusion.
/2 Centrifugal separation.
/3 Mainly EURODIF, a multinational association (Belgium, France, Italy, and Spain) with facilities located in France.

50. The enrichment picture is far from clear. As evident from Tables 13 and 14 the growth in world needs for enriched fuel will necessitate construction of a new plant by about 1984, and additional capacity of 100 million SWU per year by the year 2000. Construction of the facilities and arranging for the enormous power supply will require long-term planning and tremendous investments. The next few years may see a scramble among non-nuclear nations to secure a share of enrichment capacity by entering into long-term fuel supply contracts. Much attention is being paid to the overall enrichment problem on a broad international basis, and major industrial countries are examining all the possibilities, including associations, to own and operate enrichment facilities. It would seem likely in the light of all the foregoing that future options open to developing countries will not be much broader than at present. In any event, countries ordering nuclear plants must exercise care to assure a long-term supply of fuel. This has not so far presented problems, but it may well become a crucial consideration in "going nuclear," as increasing demands are placed on uranium resources, and in particular, enrichment facilities.

51. An important final aspect of the nuclear fuel field is that a fairly sophisticated process is required to fabricate the enriched uranium into fuel elements useable in the reactors. Moreover, once the fuel elements are spent — i.e., "burned up" in the reactor — they must be reprocessed. This involves recovery of material still-fissile and thus valuable, and at

the same time permits separation of radioactive and other waste material for disposal. Fabrication and reprocessing are presently available through facilities in the US, Europe, and Japan which offer competitive prices.

V. SAFETY AND ENVIRONMENTAL ASPECTS

Opposition to Nuclear Power

52. A serious impediment to nuclear development may be posed by a variety of safety problems which have caused public apprehension and opposition in many countries. In particular, a number of civic and environmental groups in the US have raised critical voices regarding the status of safety in the nuclear industry, the enforcement of safety regulations, and the wisdom of proceeding toward nuclear expansion. Anti-nuclear development groups have appeared also in Sweden, France, West Germany, Japan, Great Britain and other countries. Concerns on which the critics have focussed are: the possibility of catastrophic accidents, in particular a loss-of coolant accident following a disruptive failure of the primary coolant system; the effects on public health of routine amounts of radioactivity that normal operation of the plant releases into the environment; the problems of processing, storing and disposing of radioactive wastes, some of which have very long half-lives; the possibility of theft or diversion of special nuclear materials; the safety hazards involved in the transportation of nuclear fuels and radioactive wastes; the high toxicity of plutonium and other issues. Although technological solutions exist to most of these problems, the debate on nuclear safety often involves value judgements concerning the evaluation of risks, the magnitude of risks society should be taking, and an assessment of social conditions as to the degree in which they affect these risks.

Environmental Impact During Normal Operations

53. The principal environmental impacts attendant upon operation of nuclear reactors are (1) rejection of waste heat (so-called "thermal pollution"), and (2) low-level radioactive emissions. As to the first, both conventional steam-electric plants and nuclear-fuelled plants produce electric power through the expansion of steam through turbines, imperfect machines that behave according to the immutable laws of thermodynamics, and so inevitably waste some heat which is rejected to the environment. The efficiency of converting heat to power can be increased by employing steam temperatures and pressures as high as possible, and modern equipment is designed to wring out maximum electric power from the heat available. Light water reactors, because they produce steam at pressures and temperatures lower than modern conventional boilers, are inherently less efficient and thus waste somewhat more heat than fossil-fuelled plants of the same electric capability; their efficiencies are of the order of 33%, vs. 40% for conventional plants. 1/

1/ It should be recalled, in considering the degree to which waste heat removal presents a problem with nuclear plants, that it is the difference between their efficiencies and that of the alternative convential plants that is important. HTGRs and the liquid metal fast breeder reactor are expected to perform as well as or better than conventional plants in this respect, i.e., to achieve efficiencies of 40%.

The waste heat must be removed from the plant site and dissipated in such way as to avoid undue concentration. Traditionally, powerplants have been sited when possible on rivers or lakes which acted as reservoirs adequate to receive and distribute the waste heat, and eventually dissipate it through the atmosphere. As plant sizes became larger and larger, the effect on the water systems became more pronounced, and increasing attention was paid to the intensity of the release itself, and to methods for assuring dissipation. At many sites the concentration of heat has (or would have) reached the level of infringing on the aquatic biosystems, and cooling towers have been adopted. These devices allow the rejection of the waste heat directly to the atmosphere, but at an additional cost. Employment of cooling towers may add as much as 5-10% to the initial cost of a nuclear facility. In summary, the effect on the environment of the large amounts of waste heat released by nuclear plants can be mitigated, but the price must be paid.

54. As to the second environmental impact, the normal operation of reactors is accompanied by the continuous leaking of very small amounts of low-level radiation products, some entrained in cooling water system releases, and some directly to the air as gas. The maximum allowable amount of such releases is specified in the reactor's operating license. Almost all concerned with the problem accept the hazards involved as virtually non-existant. Nevertheless, however small, they may be cumulative and suggestions have been made that long-range studies of their effects on the human population be made. It is by no means clear that such studies would yield unequivocal results. In any event, the guidelines issued by the USAEC require releases to be kept so low so as to expose individuals near the plant to not more than 1-2% of the limit deemed acceptable. Stated in terms of probable fatalities due to radiation-induced cancer, those attributable to routine nuclear effluents in the US for the period 1970-2000 have been estimated at 1/20% of those caused by unavoidable natural background radiation. 1/

Nuclear Accidents

55. A reactor cannot explode as a result of an uncontrolled nuclear chain reaction because of built-in negative coefficients of reactivity that tend to shut it down when a power excursion starts. Safety in presently

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1/ Everyone living at sea-level is exposed to about 130 millirems of radiation annually from natural sources such as cosmic rays, ground radioactivity from rocks and building materials, as well as from radioactive potassium-40 which exists naturally in the body. This background radiation increases with altitude, and may be double that at sea-level in cities such as Denver. People living in Kerala in India have been exposed for centuries to radiation levels of several rems per year from the radioactive sands in the region. By comparison, the projected annual exposure of the population in the US from nuclear power plants in the year 2000 is estimated by the US Environmental Protection Agency to be about 0.5 millirem, less than 1% of the present average annual dose from diagnostic medical X-rays.

operating nuclear plants has been excellent compared with other types of powerplants. Indeed, in the nearly 100 reactor-years of experience accumulated to date, the public has suffered no injury as a result of an accident. 1/

56. Much study (and much conjecture) has been addressed to the questions: "What is the probability of a serious accident which would release large amounts of radioactivity to the environment?" and "What would be the consequences of such an accident?" It is generally agreed that the worst accident would involve the loss of coolant 2/ in a light water reactor. Even though the chain reaction would cease instantaneously, the fission products present in the fuel elements would continue to release large amounts of heat, which if not removed, would cause massive melting of the core. This could be followed by reactor vessel melt-through, breach of the containment and large radioactive release to the environment. Despite all care in design, fabrication, construction, inspection and operation of a nuclear power plant, it is recognized that there exists a very small but finite probability that a sudden break in a large pipe or even in the pressure vessel could occur, thus causing a loss-of-coolant accident. Because the risk, however small, exists, all reactors are required to incorporate a system (made of several redundant sub-systems) to provide emergency cooling to the core in the event of loss of the normal operating coolant. The emergency coolant would prevent the core from overheating and no radioactive release would occur, although the plant may suffer serious damage.

The probability for a loss-of-coolant accident and of the emergency core cooling systems failing when needed to function are difficult to obtain since no such accident has yet occurred: there lies the difficulty. On the other hand the sequence of events following a pipe break and the performance of the emergency cooling systems can only be gleened through calculations and mathematical models which incorporate many simplifications and approximations. These problems and a certain lack of adequate experimental data have caused much controversy in recent years.

57. In the period 1971-1973, the U.S. temporarily suspended licensing reactors following failure of tests on emergency core cooling systems, and then studied the problem both through a special Task Force, and public hearings. Much debate ensued. 3/ The USAEC later issued revised criteria for the acceptance of reactors, which were more restrictive. Although they should satisfy many of the criticisms voiced, the new criteria were still characterized by some as "window dressing," but most of the scientists who had expressed earlier disagreement found them acceptably conservative. The nuclear reactor manufacturers on the other hand found the new rule unnecessarily conservative and the financial cost necessary for compliance as being incommensurate to the lowering of an already very small risk.

1/ The single instance where substantial radioactive material was released to the environment occurred at the Windscale site in the UK early in the 1950s, and was caused by a type of open-loop air-cooled reactor system no longer used.

2/ This loss of coolant in a light water system would bring about an almost instantaneous shutdown of the nuclear chain reaction, forestalling any "atomic explosion."

3/ For example, public hearings lasting 126 days were held in 1972, and 23,000 pages of testimony were taken. They reflected the views of the USAEC staff, the manufacturing and utility industries, and in particular the "Union of Concerned Scientists," a Boston area coalition of several hundred scientists, engineers, and other professionals who had previously published reports

58. In considering the problem of severe nuclear accidents, a realistic assessment of probabilities and the associated consequences must be made. Such a study was sponsored by the AEC in 1972 under the direction of Prof. N. Rasmussen of MIT. The Draft of this Reactor Safety Study (designated as WASH-1400) was issued in August 1974 for public comment. The study employed, for probability estimation, the "event tree" and "fault tree" analysis technique which has been used extensively in the U.S. space industry and in the U.K. chemical industry. The study represents a first but massive effort to quantify the risks from nuclear power and to compare them to other non-nuclear risks. The Draft report claims that the chance of a core melt-down per year could reach 1 in 17,000 but would involve no more than one death and $100,000 in property damage beyond the nuclear plant site. As the hypothetical severity of such an accident increases its probability decreases. Thus, a core melt-down, followed by failure of all back-up safety systems, all during the worst possible weather conditions, could lead to some 2300 fatalities, $6 billion in property damage and the permanent contamination of 31 sq. miles of land around the reactor. This accident, however, would have a probability of 1 in 10 million. The study concludes that even with 100 nuclear plants in operation (as would be the U.S. situation in the early 80's) the chance of an accident severe enough to kill 100 persons is far less than the chance of an airplane crash of similar magnitude. The report's main conclusion, stated in general terms, is that potential hazards of nuclear power plants do exist but that they are "smaller than many other man-made and natural risks."

Voluminous criticisms and comments have been written on the Rasmussen study. Most noteworthy among them is the Reactor Safety Study conducted by a group of scientists, unconnected to the nuclear industry, under the auspices of the American Physical Society (APS). It must be noted that their work did not consider the need for nuclear power or its benefits and should not be considered as a net assessment of the risks versus the benefits of nuclear reactors. Their major conclusions were: (a) no reasons were uncovered for substantial short-range concern regarding accident risks; (b) a better quantitative evaluation and improvements can and should be made in the safety situation; (c) the "event-tree" and "fault-tree" approach can have merit in a relative sense but absolute probabilities do not inspire much confidence; (d) there is no reason to doubt that the emergency core cooling systems will function adequately under most circumstances but better quantitative understanding is needed; (e) the long-term cancer mortality was underestimated in the Rasmussen study by a factor of 50. Many changes and refinements are being incorporated in the final version of the Rasmussen study which is due in the Fall of 1975. However, it is not expected that the overall picture of nuclear reactor risks will change substantially. Meanwhile, it becomes increasingly apparent that a similar quantitative risk assessment must be applied to the other parts of the nuclear fuel cycle, notably the fuel reprocessing plant which is, according to many observers, the weak link in the chain.

59. Many of the critics of nuclear power remain unconvinced over the efficacy of the safety devices because a full-scale test has never been performed. Besides the impracticality and enormous cost of such a test, it is doubtful that any useful data could be derived since a very large number of tests would be needed to establish an adequate statistical base. Instead, a number of separate effects, systems effects and integral experiments are being conducted or planned in a number of countries with nuclear manufacturing capability. These experiments are intended to provide an improved engineering base on which analytical methods rest in such areas as heat transfer, thermal hydraulics and metal to water reaction. Two major safety research facilities are the Power Burst Facility (PBF) for the testing of fuel under extreme conditions and the Loss-Of-Fluid Test (LOFT) in Idaho. The former has been completed and is operational. The latter, which is a 1/60 scale model of a PWR, has unfortunately experienced serious delays and is not expected to undergo nuclear test until 1977. The experimental results from LOFT, along with the continuing effort in computer code development, will provide a much improved quantitative basis for assessing the margins of safety in present reactor designs and the degree of conservativism incorporated in the present acceptance criteria. It is anticipated, as the APS study asserted, "that a much better quantitative evaluation and consequent improvements of the safety situation can be achieved over the next decade if certain aspects of the safety research program are substantially improved and the results of the research implemented."

Theft and Diversion of Nuclear Materials

60. The spectre of an organized attempt to steal fissionable material and fabricate weapons is always present, and diversion of material might occur at any point in the fuel cycle: the enrichment plant, fuel manufacturing facility, reactor site, a fuel reprocessing plant, or in transit. However, the construction of a nuclear weapon device requires uranium enriched to a concentration of fissile isotope many times that found in the fuel elements of light water reactors. Thus the most likely target would be one of the few enrichment facilities in the world, which are guarded with utmost care. 1/ Furthermore, construction of an explosive device requires many diverse skills, so a successful attempt by a few "nuclear brigands" is not likely.

1/ When and if breeder reactors come into general use, the problem will be much more serious because they operate on nuclear fuel of weapon quality, plutonium.

61. The problem is attracting increasing attention. The IAEA has a major program dealing with the safeguarding of special nuclear materials. Regulations exist today to cope with these threats. For example, installations handling special nuclear materials must be designed and equipped to withstand an organized armed attack including automatic weapons. Strict security measures are imposed during transportation to avert any attempt at hijacking. At the same time, methods are being developed to account for these materials as they flow from one place to another. On the other hand, critics of the USAEC policies and practices have characterized present nuclear safeguards in the US as weak, inadequate and lacking the priority they deserve. They called for increased physical security for transport and storage and sought open public debate on a problem which should be a matter of public choice, based on a thorough examination of the issues, the alternatives and their consequences.

62. Despite all these measures, it is not difficult to imagine how, in a facility that handles about one-quarter of a ton of plutonium daily, a few grams at a time could be stolen by a determined individual without being detected. Many people have expressed the opinion that social and political conditions throughout the world are far from being stable enough to induce confidence that acts of sabotage, blackmail and other criminal activities, involving special materials, will not happen.

Waste Handling

63. The natural or enriched uranium fuel used in heavy and light water reactors presents no particular problem in shipment and handling, not only because the radiation levels are very low, but also because the material is used in tubular metal fuel elements which contain it. However, after use in reactors the spent material does contain highly radioactive products which are the result of nuclear fission and are extremely dangerous. The spent elements are kept for a time at the powerplant under controlled conditions to allow very short-lived radioactive products to decay, and to allow the generation of heat to abate. They are then shipped in special containers with appropriate safeguards to fuel reprocessing centers where valuable residual fuel (uranium and plutonium) are recovered, and the radioactive wastes are separated. Thus the handling and disposal of large amounts of dangerously radioactive material are problems associated with fuel reprocessing, rather than with nuclear powerplant operation. In contrast with the hundreds or possibly thousands of reactors which would be in operation in the world by the year 2000, fuel reprocessing facilities are likely to be very few and suitably located in isolated areas where radioactive wastes can be stored in various alternative manners described below.

64. Economic and technical evaluation of alternative processes for the safe storage and disposal of these wastes is currently underway. Until now, the very large waste volumes accumulated by the weapons program (for producing plutonium) have been stored in large steel tanks located just beneath the surface of the ground. For the disposal of wastes produced in plants reprocessing

fuel from commercial nuclear powerplants, two main alternatives are being studied: (i) storage for a few years in double walled, permanently monitored, stainless steel tanks and subsequent concentration and fixation of the remaining long lived products in solid (glass or ceramic-like) forms; and (ii) immediate solidification to eliminate interim tank storage. Whatever system is adopted, long lived radioactive products in solid form will need to be guarded in special repositories for centuries.

65. The size of the management problem can be appreciated by noting that in the US it is anticipated all the bulk wastes generated from nuclear facilities through the year 2000 — less in volume than those already produced and managed successfully in connection with the US weapons program — would fill a one-story warehouse covering one acre of land. (An actual storage facility would of course be larger, say 100 acres.)

66. The disposal of solid radioactive wastes, in retrievable form as described above, necessitates adequate surveillance and maintenance practices which cannot be guaranteed for centuries into the future. Consequently the desirability of developing methods of ultimate disposal, free of the burdens of surveillance, and maintenance is recognized. The problem is not an urgent one and many schemes are being examined (deep caverns in bedrock, nuclear transmutation, extraterrestrial shots, underground salt mines, etc). However, there are other schools of thought which believe that permanent repositories accessible to continuous monitoring and vigilance will be the best means of ensuring control, and thus they do not see a need for an "ultimate" disposal system.

67. The discussion above has attempted to present a balanced view of the worst hazards reasonable people expect may have to be encountered. As noted, the probabilities of their occurrence are a matter of conjecture. The developing world will wish to carefully weigh them in connection with adopting nuclear power as a partial solution to its energy dilemma.

VI. PREPARATIONS FOR THE INTRODUCTION OF NUCLEAR POWER IN DEVELOPING COUNTRIES

68. The introduction of a new and sophisticated technology generally requires a substantial amount of special preparation, including in the case of nuclear power, nuclear-related legislation, the establishment of new institutions, training, and mounting public relations programs. Some of these are reviewed below.

Regulatory Aspects

69. In all countries already engaged in nuclear activities of any significance, installations are subject to a system of prior authorization and control. The establishment of such a regulatory framework is essential for countries contemplating a nuclear power program, and it should cover not only the design, construction, and operation of the plants, but also trading in, transporting, processing, disposing of, or otherwise using fissile and/or radioactive materials.

70. Regulations governing nuclear installations as well as administrative procedures vary greatly from country to country but are generally characterized by certain common features. Each nuclear installation has been subjected to a specific in-depth safety evaluation by highly specialized bodies. Authorization is usually granted in two stages: the first for siting and construction; the second for operation. Licensing applications generally include very detailed information concerning the characteristics of the site (geology, meteorology, population density, etc.); the design of the plant; the competence of the operating agency, and the professional qualifications of the staff; provisions for monitoring radiation in effluents; contingency plans for various types of accidents, etc. Procedures for consulting the general public and local population have also begun to be established and the scope of such consultation as well as the role of local, federal or other judiciary, administrative or nuclear regulatory bodies need to be clearly defined to avoid unjustified delays. It will be clear that laying down an appropriate regulatory framework cannot be accomplished casually, or quickly. Countries contemplating the acquisition of nuclear facilities must give early attention to these considerations.

Nuclear Insurance

71. Insuring nuclear facilities against claims which may arise from third parties requires special attention in view of the possible consequences of a major accidental release of radioactive materials. Most West European countries have subscribed to the 1960 Paris Convention which assigns to the operator (and not to the supplier) of a nuclear plant absolute and sole liability for damage to third parties, and originally required a minimum coverage of $15 million. In other countries, national laws usually do not exempt suppliers from liability, but in order to protect the general public from having to engage in litigation, they provide for governmental indemnity to the population, independent of any other damages which may be collected from the operators or suppliers of nuclear plants, or others. Developing countries will need to create adequate insurance coverage and procedures, and in particular agree clearly with foreign equipment and fuel suppliers the extent of the latters' liability in case of accidents.

International Safeguards

72. Under international treaties subscribed to by practically all nations, countries acquiring nuclear facilities and materials have to submit them to the inspection, supervision, and other control procedures of the IAEA. Their purpose is to avoid diversion of any fissile or radioactive materials to non-peaceful uses. It is unlikely industrialized countries would permit export of nuclear power facilities in the absence of an agreement to submit to these safeguards.

Training

73. In addition to the basic measures discussed above, the introduction of nuclear technology to the developing world will require that preparatory steps for training of manpower — which very likely will have to take place

overseas — be planned sufficiently in advance. Establishment of a national nuclear research center has frequently been found to be a very useful preparatory step for initial training in the handling of radioactive materials, radiation protection, operational training in small research reactors or simulators, etc. However, even with such a facility available, countries going nuclear will generally require additional specialized outside help to carry out feasibility studies; assist in the invitation and evaluation of offers to supply equipment; and supervise the design, fabrication, construction testing, and initial operation of nuclear plants. Help can be obtained from a number of experienced private companies. In addition, considerable assistance may be expected and should be required directly from the national atomic energy authorities of the supplier countries or indirectly through the IAEA. 1/

Public Relations

74. A final but not unimportant preliminary step would be carrying out a serious and honest program of education directed at the general public, to improve its understanding of this new technology and how it affects people from an environmental and safety point of view. Experience in industrialized countries has shown that uninformed and sometimes irrational fears can cause serious difficulties to the implementation of nuclear programs, which might have been avoided by thoughtful and timely public relations efforts.

1/ The XVth General Conference of IAEA proposed that a "Manual on the Introduction of Nuclear Power in Developing Countries" be prepared as soon as feasible. Work is currently under way.

VII. IMPLICATIONS FOR THE BANK

75. The advent of nuclear power in the developing world, as has been pointed out in its 1968 Report "Nuclear Power for Small Electricity Systems" (para. 2), does not raise any new policy issues for the Bank. Nuclear plants are simply another option to be considered when searching for the least cost solution to the problem of supplying the growing demands for electric power.

76. A review of the technical and economic evolution which has taken place in the nuclear field in recent years suggests that a significant number of developing countries will wish to acquire nuclear plants, and may seek the Bank's assistance in this connection: nuclear plants are attractive economically (para. 39); the technology has demonstrated reliability in commercial operation (para. 19) and satisfied generally-accepted criteria regarding safety and the protection of the environment (Chapter V); and, nuclear plants can be procured through international competitive bidding, in a market which is broadening (para. 21 et seq).

77. Nuclear plants require much higher initial investments than equivalent conventional plants (para. 30), particularly in foreign exchange. This financing has generally been readily available from bilateral sources, partly because supplier countries wanted to gain an early start in the export markets, and partly because such sales have been modest. However, demand for nuclear facilities, primarily from developed countries, has recently increased very rapidly, placing strains on manufacturing and construction capacity which will likely continue for some time (para. 41).

78. From the institutional viewpoint, the role of the Bank could be important because the acquisition of nuclear plants will require a major transfer of technology. Chapter VI has outlined the complex preparatory work national agencies and utilities in developing countries will need to carry out if they are to make a successful entrance into the nuclear age. Some of these preparations require quite long lead times and substantial expenditures, particularly for feasibility and safety studies, as well as for training. Through its long association with electric power systems in developing countries, the Bank could help marshall the resources needed to carry out these essential steps. Drawing upon its experience with other projects with complex technical and institutional implications, the Bank could help developing countries cope with this new technology by administering technical assistance programs financed by the UNDP; by bringing adequate specialized assistance from the IAEA and the national atomic energy commissions of industrial countries to bear on the problems of creating a regulatory system; by helping in the selection of private engineering companies needed to carry out feasibility and safety studies; and by including the financing of such studies in prior loans for other power facilities. Finally, by financing nuclear projects the Bank could help ensure that they are carried out under the careful supervision of competent architect-engineers, that equipment is supplied by qualified manufacturers, and that provisions are made for adequate training of local staff to ensure successful operation.

This material is Chapter 2 of the Bank's Report "Nuclear Power for Small Electricity Systems," TO-674, July 15, 1968

"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 U235 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 U235 and cause another fission. But in natural uranium there are 140 atoms of U238 for every atom of U235 and even in the slightly enriched uranium which is used in most of the present day industrial reactors there are about fifty atoms of U238 for every atom of U235. The statistical probability therefore is that most of the neutrons will strike atoms of U238 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 U238 and more likely to cause fission of atoms of U235. 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 irradition of some of the U238 atoms."

REACTOR TECHNOLOGIES: STATUS & OPERATING EXERIENCE

1. Each of the reactor types shown in Table 3 is listed below, in the same order, together with a brief description of experience with its operation.

Magnox Reactor

2. Although a large number of early Magnox installations (principally in the UK) have enjoyed a long record of successful commercial operation, and can definitely be considered reliable, the construction of this reactor has been discontinued in the UK and France, where it was developed.

Advanced Gas-Cooled Reactor (AGR)

3. The AGR is the successor of the Magnox gas-cooled graphite-moderated series of reactors. It differs from them mainly in the use of higher temperatures and pressures -- and its much higher thermal efficiency -- and has required research on CO_2-graphite reactions and the use of enriched fuels, resembling the fuels used in light water reactors. The 34 MW prototype at Windscale has been in operation since 1962 to explore these problems in depth. It has been a remarkable success, with availability 1/ increasing from 72% in 1963 to 95% by 1968. On the basis of this experience the UK Central Electricity Generating Board and the South of Scotland Electricity Board in the late 1960s ordered a total of five AGR stations, each to have two reactors of 600-625 MW unit size, for commissioning between 1972-1977. The first AGR scheduled in this program, Dungeness B, experienced severe manufacturing and construction problems which caused a delay of about three years and the partial termination of the contract with the supplier. It will not be in service until 1975. Other plants have experienced less serious delays. The first AGR station to operate is expected to be Hinkley Point B in mid-1974.

High-Temperature Gas-Cooled Reactor (HTGR)

4. Interest in HTGRs exists mainly in Germany, the US, and the UK. The German experiment involves a 13.5 MW reactor which has been operating since 1966 at Juelich, and a 300 MW thorium-fuelled unit planned for 1975. In the US the 40 MW Peach Bottom reactor has been in operation since 1967, and a 330 MW unit is under construction in Plattsville to start operation in June 1974. Several commercial units in the 800 to 1500 MW range are being ordered by US utilities for operation in the 1980-1983 period. Commercial HTGRs follow the Magnox and AGR types as the third generation of the gas-cooled reactor technology. They use a mixture of U 235 and thorium as fuel, graphite as moderator, and helium gas as coolant. They are attractive because of high thermal efficiency, better fuel consumption characteristics, and partial

1/ Proportion of a given period of time that a plant is available for operation.

reliance on thorium instead of scarce uranium. They present more difficult safeguard problems because of the use of highly enriched uranium of weapon quality. It will be a few years before this type of reactor will have achieved significant operating experience on power systems.

Pressurized Heavy Water Reactor (PHWR)

5. The ability of the PHWR type to operate on natural uranium coupled with the fact that it does not require a large pressure vessel should make it attractive to many developing countries, especially those with resources of natural uranium. A 25 MW prototype has been in operation in Canada since 1962, but the first experience with a quasi-commercial CANDU version of the PHWR was gained at the 208 MW Douglas Point plant, which started operation in November 1966. It experienced a variety of problems with components of the heavy water circuit, principally pumps and valve seals; the high-pressure saturated-steam stages of the turbines; tritium and cobalt radiation; and fuel elements which failed. Modifications in design and construction have therefore been made both at Douglas Point and in the newer Canadian PHWR reactors, and it now appears that the earlier problems have been solved. The four 510 MW units which were put into commercial operation at the Pickering station during the period April 1971 to May 1973 have achieved utilization factors from 70% to 93%. Small PHWRs are also in operation in India, Pakistan, and Germany, and larger units are being planned by Argentina and Korea. The source of supply for this type of reactor is at present limited to Canada, but may broaden in response to a growing international demand.

Heavy-Water-Moderated Boiling Light-Water-Cooled Reactor (HWLWR, SGHWR)

6. The SGHWR is a light-water-cooled boiling water reactor designed and operated by the UK Atomic Energy Authority. A 100 MW prototype plant was commissioned in late 1967. It was afflicted at one time by a number of fuel element failures that were traced to malfunctioning of the water purification plant, but these have since been corrected and it has been giving satisfactory service with availability of the order of 90%. Research and development information on this reactor has been exchanged with the Canadian Atomic Energy Authority, which has built a 250 MW HWLWR plant at Gentilly, similar to the British SGHWR. The Canadian plant, which started operation in 1970, is based on experience with heavy water reactors of the CANDU type, and on the UK prototype. A 200 MW reactor of this type is under construction in Japan. Although HWLWRs can operate on natural uranium, their economics improve if slightly enriched fuel is used, and the trend is towards this alternative. Commercial SGHWRs of 450 MW and 600 MW have been designed by UK manufacturers and offered to various countries, but a unit of this size has not yet been ordered. Total operating experience has not yet been sufficient to justify consideration by developing countries, although the two units in operation have achieved very good availability. Features inherent in the design of this type of reactor (pressure tubes rather than pressure vessels)

permit it to be scaled down with less cost penalty than light water and gas-cooled reactors, and this has prompted the UK to consider offering it in the market for small and medium plants.

Heavy-Water-Moderated Gas-Cooled Reactor (HWGCR)

7. Prototype HWGCR have been in operation in France since 1967, and in Czechoslovakia and Germany since 1972. There are at present no plans for construction of additional units.

Light Water Reactor (LWR)

8. Operating experience with light water reactors is the greatest of any of the types now being offered commercially. By the end of 1973, light water nuclear plants had generated a total amount of electricity equivalent to the consumption of all developing countries of the world in 1971. Utilities which are operating this type nuclear powerplant have concluded that they are at least as reliable as conventional ones. Although the prototypes were run one to five years before they achieved a high standard of availability, more recent installations have generally required only one or two years, about the same "running in" period as is required for boilers of advanced design in large, conventional plants. Performance has been satisfactory for plants in the 600 MW to 800 MW range representing the majority of those now in operation. Experience to date suggests that performance at 70-75% plant utilization factor, comparable to large conventional fossil-fuelled plants, is a reasonable basis for projecting system planning and economic studies. No major technological changes in materials or in concept have been introduced in the most recent reactors, but very large increases in size have occurred in a very short time, from units of about 200-300 MW in 1962, to 600 MW in 1967, 800 MW in 1971-1972, and 1000 MW in 1973.

Light Water Graphite-Moderated Reactor (LWGR)

9. Reactors of this type have been in operation since the 1950s in the USSR and since the early 1960s in the US. Such reactors are not being offered commercially in the US primarily because of their high cost. In the USSR, however, two plants are under construction, each to have two 1000 MW units for operation in 1975-1976. To date, no LWGRs have been offered for sale on the international market.

Breeder Reactors

10. Several types of breeder reactors have been proposed. Experience and progress toward commercial breeders has concentrated on the liquid metal fast breeder concept. This reactor type uses liquid sodium metal as a coolant, plutonium as fuel (an artifically-created fissile material presently produced by neutron bombardment of U 238 in conventional nuclear plants) and no moderator (thus their name "fast" as against the moderated or "slowed down" neutrons of

conventional nuclear reactors). In the breeder the fissile plutonium core is surrounded by a "blanket" of natural uranium, or "depleted" uranium produced as residue in fuel enrichment plants. This blanket is the "fertile" material in which neutron bombardment produces new "fissile" plutonium. It is because more plutonium is produced in the blanket than is consumed in the core that the reactor is called a "breeder." Breeder reactors allow the "burn-up" of a much higher proportion of uranium, about 50-70 times that of light water reactors. The principal breeders currently in operation are located in France (250 MW, operating since December 1973); UK (250 MW, operating since October 1973) and the USSR (150 MW, operating since June 1972); this latter also produces steam for sea water desalination. Additional breeders are under construction in Germany, Japan, and the US. Commercial breeders would be about 1000 MW in size and are expected to be in operation in the 1980s.

ESTIMATED INITIAL CAPITAL COST
600 MW PLANTS FOR DEVELOPING COUNTRIES

1. The three tables of this Annex are based upon data taken from the IAEA "Market Survey for Nuclear Power in Developing Countries." The cost data are based principally upon experience in an industrialized country, modified in IAEA's country-by-country application in the light of conditions prevailing in the particular developing country. Thus the costs which follow, as well as those discussed in Chapter IV which were taken from this Annex, are meant to be generally illustrative, rather than representative of costs which are likely to prevail in any given situation. The data are as of 1973.

2. Note that none of the tables contains provisions for special environmental protection facilities such as sulfur-dioxide removal equipment (in the case of oil and coal units) or near-zero radiation release systems (in the case of nuclear units). Neither are the costs of cooling towers included. The costs for oil and coal-fired plants do, however, include electrostatic precipitators which add about $8-10 per kw of capacity to the total cost. There are no effective economic facilities in operation anywhere for removal of sulfur-dioxide from the emissions of fossil-fuelled plants. Some estimates of the costs of such systems when developed are as high as $75 per kw, depending upon the application and the sulfur content of the fuel as burned.

3. Cooling towers have been in successful operation for some time in many areas. Depending upon the type employed, their installation where needed might add $8-10 per kw to fossil-fuelled plants, and perhaps 50% more than that to nuclear plants.

4. All of the foregoing suggests that while each situation must be considered separately, concern among developing countries for protecting the environment is likely to increase the cost of fossil-fuelled plants more than nuclear ones.

ESTIMATED INITIAL CAPITAL COST
600 MW PLANT FOR DEVELOPING COUNTRIES

Light Water Nuclear Unit

	US$ Millions[1]			
	Equipment	Material	Labor	Total
Land				0.1
Structures and Site Facilities	1.1	13.3	9.6	24.0
Reactor Plant Equipment	30.3	11.7	6.1	48.1
Turbine Plant Equipment	24.9	8.3	5.7	38.9
Electric Plant Equipment	4.3	6.9	3.5	14.7
Miscellaneous Plant Equipment	1.7	0.2	1.0	2.9
Spare Parts Allowance				1.0
	62.3	40.4	25.9	129.7
Contingency Allowance				8.8
DIRECT COSTS				138.5
Construction Facilities, Equipment, Services				10.9
Engineering & Construction Management				28.1
Other Costs[2]				6.1
Interest During Construction[3]				38.0
INDIRECT COSTS				83.1
TOTAL COST - $ millions				221.6
- $ per kw				369

1/ Rounded
2/ Includes taxes, insurance, training, start-up, owner's administration
3/ 5-1/2 years

SOURCE: IAEA 1973 Market Survey

ESTIMATED INITIAL CAPITAL COST
600 MW PLANT FOR DEVELOPING COUNTRIES

Coal-Fired Conventional Unit

	US$ Millions[1/]			
	Equipment	Material	Labor	Total
Land				0.1
Structures and Site Facilities	0.6	7.6	4.6	12.8
Boiler Plant Equipment	21.0	5.0	6.0	32.0
Turbine Plant Equipment	17.7	5.9	4.1	27.7
Electric Plant Equipment	4.5	2.3	3.0	9.8
Miscellaneous Plant Equipment	0.9	0.7	0.8	2.4
Spare Parts Allowance				0.7
	44.7	21.5	18.5	85.5
Contingency Allowance				5.9
DIRECT COSTS				91.4
Construction Facilities, Equipment, Services				8.0
Engineering & Construction Management				13.1
Other Costs[2/]				3.6
Interest During Construction[3/]				17.0
INDIRECT COSTS				41.7
TOTAL COST - $ millions				133.1
- $ per kw				222

1/ Rounded
2/ Includes taxes, insurance, training, start-up, owner's administration
3/ 4 years

SOURCE: IAEA 1973 Market Survey

ESTIMATED INITIAL CAPITAL COST
600 MW PLANT FOR DEVELOPING COUNTRIES

Oil-Fired Conventional Plant

	US$ Millions[1]			
	Equipment	Material	Labor	Total
Land				0.1
Structures and Site Facilities	0.5	6.8	4.2	11.5
Boiler Plant Equipment	16.7	4.5	5.0	26.2
Turbine Plant Equipment	17.6	5.9	4.0	27.5
Electric Plant Equipment	4.1	1.7	2.1	7.9
Miscellaneous Plant Equipment	0.9	0.7	0.7	2.3
Spare Parts Allowance				0.6
	39.8	19.6	16.0	76.1
Contingency Allowance				5.3
DIRECT COSTS				81.4
Construction Facilities, Equipment, Services				7.6
Engineering and Construction Management				12.3
Other Costs[2]				3.4
Interest During Construction[3]				13.2
INDIRECT COSTS				36.5
TOTAL COST - $ millions				117.9
- $ per kw				196

1/ Rounded
2/ Includes taxes, insurance, training, start-up, owner's administration
3/ 3-1/2 years

SOURCE: IAEA 1973 Market Survey

EXTRACT FROM "POTENTIAL MARKET FOR NUCLEAR PLANTS (1981-1990): NUMBER OF PLANTS VS SIZE"

Country	Market[1/] 1000 MW	Reactor Size MW 200	300	400	600	800 and Larger
Spain	20.0					17
Mexico	19.6					19
Brazil	19.4				1	18
India	14.3			6		12
Yugoslavia	12.4				3	12
Korea	9.4				6	7
Iran	9.4				6	7
Czechoslovakia	7.8				5	6
Taiwan	7.4				7	4
Argentina	7.2				8	3
D.D.R.	7.2					8
Poland	7.0					7
Pakistan	5.9		1	5	6	
Egypt	5.6			6	4	1
Philippines (Luzon)	5.6				8	1
Turkey	5.6			2	8	
Bulgaria	5.4				6	
Venezuela	5.1		1		6	
Greece	5.1			1	6	
Romania	5.1		1		6	
Singapore	4.7		7	5	1	
Colombia	3.9			1	6	
Thailand	3.8		2	5	2	
Bangladesh	3.8		2	5	2	
Hungary	3.6				6	
Hong Kong	3.2			5	2	
Cuba	2.2		2	4		
Israel	2.1			5		
Peru	1.8		2	3		
Chile	1.6			4		
Jamaica	1.5	2	2			
Uruguay	1.0	5				
Malaysia (West)	1.7	1	5			
Indonesia (Java)	1.6	3	3			
Kuwait	1.2	6				
Iraq	0.8	4				
Nigeria	0.6	1				
Rep. Viet Nam	0.6	2				
TOTAL		24	28	57	105	122

1/ Totals do not reconcile in each case because reactors smaller than 200 MW are omitted in this Extract.

SOURCE: IAEA

ESTIMATED WORLD RESOURCES OF URANIUM
(Data Available January 1973)

Types of Resources / Country	Price Range less than $[1]10/lb U_3O_8				Price Range $10-15/lb U_3O_8			
	Reasonably Assured Resources (Reserves)		Estimated Additional Resources		Reasonably Assured Resources		Estimated Additional Resources	
	1000 MT uranium	1000 short tons U_3O_8	1000 MT uranium	1000 short tons U_3O_8	1000 MT uranium	1000 short tons U_3O_8	1000 MT uranium	1000 short tons U_3O_8
Argentina	9.2	12	14	18	7.7	10	23	30
Australia	71	92	78.5	102	29.5	38.3	29	38
Brazil	-	-	2.5[2]	3.3	0.7	0.9	-	-
Canada	185	241	190	247	122	158	219	284
Central African Republic	8	10.5	8	10.5	-	-	-	-
Denmark (Greenland)	5.6	7.0	10	13	-	-	-	-
Finland	-	-	-	-	1.3	1.7	-	-
France	36.6	47.5	24.3	31.5	20	26	25	32.5
Gabon	20	26	5	6.5	-	-	5	6.5
India	-	-	-	-	2.3	3	0.8	1
Italy	1.2	1.6	-	-	-	-	-	-
Japan	2.8	3.6	-	-	4.2	5.4	-	-
Mexico	1.0	1.3	-	-	0.9	1.2	-	-
Niger	40	52	20	26	10	13	10	13
Portugal (Europe)	6.4	9.3	5.9	7.7	1	1.3	10	13
(Angola)	-	-	-	-	-	-	13	17
South Africa	202	263	8	10.4	62	80.6	26	33.8
Spain	8.5	11	-	-	7.7	10	-	-
Sweden	-	-	-	-	270	351	40	52
Turkey	2.2	2.8	-	-	0.5	0.6	-	-
United States	259	337	538[3]	700	141	183	231	300
Yugoslavia	6	7.8	10	13	-	-	-	-
Zaire	1.8	2.3	1.7	2.2	-	-	-	-
TOTAL (rounded)	866	1126	916	1191	680	884	632	821

1/ $ Value of March 1973: 1$=0.829 EMA u/a = 0.829 SDR (Special Drawing Rights). This $ value corresponds to $42.22 per fine ounce of gold.

2/ Plus 70,000 MT U by-product from phosphates.

3/ Plus 70,000 MT U by-product from phosphate and copper production.

SOURCE: "URANIUM: Resources, Production, and Demand" August 1973 OECD.

WORLD URANIUM PRODUCTION CAPACITIES

Countries	Annual Production Capacities					
	1973		Planned for 1975		Attainable for 1978 1/	
	MT U	Short tons U_3O_8	MT U	Short tons U_3O_8	MT U	Short tons U_3O_8
Argentina	46	60	165	210	520	670
Australia	-	-	770	1,000	4,600	6,000
Canada	4,600	6,000	6,500	8,500	10,800	14,000
France	1,800	2,300	1,800	2,300	2,000	2,600
Gabon	600	780	600	780	1,200	1,560
Italy	-	-	92	120	92	120
Japan	30	40	30	40	-	-
Mexico	30	40	225	300	340	450
Niger	750	975	1,500	1,950	1,500	1,950
Portugal	114	148	114	148	170	220
South Africa	4,130	5,370	3,800	5,000		
Spain	115	150	132	171		
Sweden 2/	120	155	120	155	120	155
United States	14,600	19,000	14,600	19,000	26,000 3/	34,000
Yugoslavia	-	-	-	-	230 4/	300
TOTAL (rounded)	27,000	35,000	30,500	40,000	48,000 5/	62,000 5/

1/ Given favorable market situation and adequate lead time.
2/ Production based on resources available at $10 to $15/lb U_3O_8.
3/ 1,000 MT by-product included.
4/ Construction of mine and concentration plant to be completed in 1976.
5/ Estimates for South Africa not included.

Source: See Annex 2, Page 1.