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INTERNATIONAL BANK FOR RECONSTRUCTION AND DEVELOPMENT

ECONOMICS OF NUCLEAR POWER

March 14, 1956

Department of Technical Operations
Prepared by: Corbin Allardice

Nuclear cost, achievable
$250 per kw
2 mils per kwh

world average for hydro $320
(a meaningless average)
Pu has 2 isotopes Pu 239
& Pu 241 which are fissile

ECONOMIC NUCLEAR POWER TODAY:
WHERE AND UNDER WHAT CIRCUMSTANCES ?

*****

A Study

by

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March 15, 1956.

Author's Note

This study has been prepared in an attempt to establish benchmarks against which can be assessed the economic feasibility of a 75-100 Mw electric capacity nuclear reactor based on essentially today's technology. Such reference points are necessary in the determination of the Bank's role in nuclear power development and application, and in the evaluation of proposals for financing such an installation.

The need for such a study was pointed out by Mr. S. Aldewereld, and his contributions to its inception and its execution are gratefully acknowledged. Mr. M. Rosen also provided invaluable guidance, as did Dr. W. Rembert, Mr. A. Wenzell, Mr. S. Lipkowitz and Mr. B. Walstedt. Dr. K. Mayer, of the Stanford Research Institute, and Messrs. F. Quackenboss and H. Hollister, of the United States Atomic Energy Commission also provided helpful assistance.

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INTRODUCTION

1. World energy demands are increasing at such a rate as to require the full exploitation of both fossil and hydroelectric energy resources. Even more importantly, world energy demand forecasts for the year 2000 indicate the absolute need for development of nonconventional resources. The non-conventional resource most likely of early practical application is nuclear energy.

2. While world-wide energy needs can be estimated over a relatively long term with considerable reliance, estimation of the short term energy needs of individual countries is a far more difficult task. Nevertheless, various studies that have been made indicate that except in those countries possessed of great untapped hydroelectric resources or plentiful resources of coal or oil, there is a general need for the development of unconventional energy resources to meet rising power needs in the next one or two decades.[1/] This means that nuclear power, assuming it can be produced and sold at prices competitive with other energy sources, will play an important role in the economic development of many nations.

3. Besides the need to develop nuclear power to meet rising energy requirements, other factors operate in some countries to speed nuclear power development and early application. Industrial pressures to develop markets for nuclear fuels and for nuclear power equipment act

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1/ Numerous papers on world energy needs, the energy requirements of individual nations, and the possible role of nuclear and other non-conventional energy sources are contained in Volume I, Proceedings of the International Conference on the Peaceful Uses of Atomic Energy.

as stimuli in the more highly developed nations. Fear of "atomic colonialism" spurs other smaller nations to develop technical competence in the field. To the underdeveloped countries, nuclear power offers unique attraction because of its transportation independence, flowing from its high energy content per unit weight. These and economic, social and political forces tend to place a high premium on nuclear development, even where economic need for a new source of energy is not urgent.

4. The Bank's interest in nuclear energy is primarily in facilities for the generation of electricity or heat from nuclear fuels, and the related production and processing facilities. Important other applications of nuclear energy to research and development, therapy, radioisotope work, food preservation and sterilization, and so forth, in general require small investment with consequent small foreign exchange requirements. While the Bank may become involved in loans for such applications, the individual amounts would be relatively small. In the case of power, process or space heat or propulsion reactors, the capital requirements are large, with varying needs for foreign exchange. The remainder of this paper will deal only with nuclear power plants.1/

5. No means has been found to use the energy of fission to produce electricity directly. As presently conceived, nuclear reactors are simply machines in which the energy contained in the nuclei of atoms of fissile material (U235, U233, and Plutonium) is released to become available in the form of heat which must be removed from the reactor by a coolant in order to

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1/ Process or space heat, propulsion, and small power nuclear reactors are discussed in Appendix I.

make steam for heating or to drive a turbo-generator. The turbo-generator portion can be considered more or less standard. Thus, essentially, nuclear reactors are equivalent to the "fire-boxes" (including in some cases a portion of the "boilers") of modern thermal electric stations.

6. Many different specific nuclear reactor systems have been proposed. Those appearing most promising or presently under advanced development or construction are briefly described in paragraph 13 et seq. As of today no one can say which of the presently conceived reactor systems will prove ultimately to be the "best" system. Indeed, analysis of statements of proponents of the various reactor systems and study of their technical details suggests that no one of them may be so significantly more attractive than the rest as to be the preferred reactor design. As will be seen in later discussion of the reactors being built in various countries, the choice of reactor design is not purely a technical decision. (See Para.14 et seq.)

7. Another point to be considered is that while nuclear power plants are essentially equivalent to conventional thermal stations in that a heat cycle is employed to generate electricity, they are perhaps more closely akin to hydroelectric stations from the point of view of obsolescence. Dr. A. M. Weinberg, Director of the U.S. AEC's Oak Ridge National Laboratory, has pointed this out and his words are well worth bearing in mind:

> "Will one or two reactors emerge as unique choices? I think every worker in reactor design must have wondered whether, in the long run, any one reactor type will emerge as so distinctly superior to the others that it will render the rest obsolete. The history of hydrocarbon-burning devices suggests that the technology will develop a succession of "most desirable" types: the reciprocating steam engine was followed by the steam turbine - which may ultimately be replaced by the gas turbine. Within each class - say the steam turbine - there has been a tremendous development and corresponding high rate of obsolescence; for example, the heat rate on the most modern turbines is less than half the heat rate of turbines only 20 years old.

"But the main reason for obsolescence of conventional power generating devices - low thermal efficiency - will hardly operate to render nuclear power plants obsolete. Rather, nuclear plants ought to be much more like hydroelectric plants: if they have sufficiently low overall operating costs, and this is a sum of costs determined by thermo-dynamic efficiency, material efficiency, maintenance, etc., then it is at least not obvious why they should become obsolete any more than dams become obsolete."1/

Plan of Study

8. Mr. Eugene R. Black, in a statement made in August 1955, pointed out that the development of commercial applications of atomic energy had important implications for economic development and for the International Bank. He said that at that time ".....no one can say where or under what circumstances these applications may become practicable.....". The purpose of this study is to analyse the present status of nuclear development as concerns commercial nuclear power plants, to establish reasonably conservative costs for such facilities built on essentially today's technology, and to arrive at operating and maintaining costs and at costs of fuel for such a plant. It will then be necessary to consider how the nuclear plant should be depreciated, and at what average plant factor it is likely to be operated over its lifetime. The total cost of nuclear power can then be calculated at various percentage returns on investment. The costs thus established for electricity generated in a nuclear plant can then be compared with those for electricity generated in a conventional thermal plant, at various costs for fossil fuel. Analysis of these comparisons will provide the desired benchmarks to appraise "where and under what circumstances" nuclear power may become practicable. A further policy consideration,

1/ From P/862 by A.M.Weinberg; Proceedings of the International Conference on Peaceful Uses of Atomic Energy, Vol.III, P.24.

which is not discussed in this paper, is the degree of Bank interest and participation in the technical development (research and development contra economic application) of nuclear energy as a useable energy resource.

Nuclear Energy Resources

9. The primary raw materials for nuclear power are uranium and thorium. A survey of available estimates of economically recoverable uranium and thorium indicates supplies equivalent to many times the energy content of the reserves of oil, gas and coal. Perhaps the most definitive statements are contained in a survey paper by Jesse Johnson, Director of the U. S. Atomic Energy Commission's Raw Materials Division, given at the Geneva Conference. Pertinent paragraphs are quoted below:

"In 1948 the uranium supply of the Western Nations was almost entirely the product of two mines, one in the Belgian Congo and the other in Northern Canada. In the past, there had been little general interest in uranium and throughout most of the world there had been no serious search for it. Even now, vast areas promising from a geological standpoint are relatively unexplored.

"Today there are major uranium operations in the Belgian Congo, Canada, South Africa, and the United States. Australia, France and Portugal also are producing uranium with favourable prospects for substantially increased production.

"On the basis of present developments and geological evidence, resources of the producing nations of the West are estimated to be between one and two million tons of uranium. This uranium can be produced at moderate cost at an average of about $10 a pound for U_3O_8 ..../uranium oxide/.... in a high grade concentrate......

".....Reserves of commercial phosphate rock in the U.S. alone are estimated at 5 billion tons and the uranium content at 600,000 tons. The U.S. also has an estimated 85 billion tons of marine shale averaging slightly more than 1/10th of a pound of uranium per ton. This represents a reserve of 5-6 million tons of uranium.

"Known deposits of uraniferous phosphate rock and shale in other parts of the world equal or exceed those of the U.S. in grade and tonnage. The phosphate deposits of Morocco estimated at 20 billion tons are uranium-bearing. The Scandinavian Peninsula and other Baltic territories contain very large deposits of uraniferous shale. Uranium-bearing coal and lignite also have been found in a number of countries.

"The cost of extracting uranium, as a primary product, from phosphate and shale may be between \$30 and \$50 per pound. If valuable by-products can be recovered the cost may be reduced. Between the commercial uranium deposits of today and the high cost uranium sources for the distant future there are deposits of good supply uranium at a cost of between \$10 and \$30 a pound. The resources in this economic class are not well known but they must be large, perhaps several million tons of uranium..... Experience gained from the present uranium program has demonstrated that higher prices will bring in new sources of production and increase available reserves.

"This general review of production and reserves indicates that uranium no longer can be considered a rare metal. There are extensive deposits throughout the world and there are processes for extracting the uranium economically. <u>Uranium production already developed is sufficient for a major nuclear power program of world-wide extent. Additional production can be obtained when needed. When the vast low-grade resources are required, more efficient use of nuclear fuel through improved conversion or "breeding" may offset the higher uranium cost."</u> (Emphasis added)

10. It is clear that the nuclear power industry will not be limited by lack of availability of fuel. It is important, however, to note that deposits of uranium presently considered economically recoverable exist in only a few countries. Even for countries having such uranium supplies, a large capital investment is required to convert the ores to useable fuels. At present, only Belgium, Canada, France, U.S. and U.K. (apart from USSR) are producing high purity uranium metal on a commercial scale suitable for nuclear power reactor use. Other countries, either not possessing uranium resources or having resources but lacking plants or necessary capital to convert the ores into useable fuels, will have to execute political agreements with nations having nuclear fuels in useable form in order to support a nuclear power industry today or in the immediate future. In this regard, the U.S. has recently announced its willingness to make available 20,000 kilograms of U235 for nuclear power reactor uses outside the U.S. All of the nations listed as presently producing uranium metal have indicated

1 gram U235 gives 24,000 kWh of heat

20,000 " " 48 bn kWh = — say 40 stations of 100,000 kW for [illegible]

US agts with Canada
UK (not covering U235, to which UK has access)
Belg
Discussions with Netherlands, Australia, Italy, Japan

Zerah... p 13

willingness to provide supplies to others for power uses. However, in the case of the U.S., and undoubtedly in all other cases, some sort of political agreement will be required between the buyer and the seller nation.

11. This fact has obvious and important implications to the Bank since without fuel a nuclear plant is useless. In addition to all other factors entering into the evaluation of a project for a power plant, the Bank must assure itself that the necessary intergovernmental agreements for the supply of fuel, the reprocessing of used fuel elements, and the recovery of plutonium, uranium 235 and uranium 233 are made and that there is a reasonable likelihood that the agreements will continue in effect for the full period covered by the loan.

Nuclear Power Facilities

12. While the general concept of producing nuclear power is simple, involving as it does the use of a reactor simply as heat source in lieu of a conventional firebox-boiler, the choice of a specific reactor system involves enormous difficulty because of the number of design choices of comparable attractiveness open to the engineer. He must decide among three fuels, and must determine from nuclear considerations and from operating economics the amount and form of the chosen fuel. He must also determine what fertile material he will employ since, except in special purpose reactors, it is necessary to convert some non-fuel material (fertile material) into fuel material in order to achieve economic nuclear power. He must choose the neutron energy range in which the reactor will operate, since nuclear characteristics of the fuel, the fertile material, and all other materials in the reactor vary with neutron energy and thus effect importantly the performance and economics of the power plant. He must choose a suitable

coolant to remove the heat. His system may be heterogeneous with pieces of fuel embedded in a moderator or otherwise fixed in discrete positions; the system may be homogeneous in which the fuel is a slurry or solution. If his reactor system operates in the slow or intermediate neutron range, he must select a suitable moderating material (moderator) to slow down the fast neutrons released in each fission event. Reflectors, control systems, operating temperature ranges, and a host of other design choices must be made.

Table 1[1/]

Choices to be Made in Reactor Design

Fuel	Fertile Material	Neutron Energy	Coolant	Geometry	Moderator
U233 U235 Pu239	Thorium Uranium	Fast Resonance Slow	Gas Liquid Metal Normal Water Heavy Water etc.	Heterogeneous Homogeneous	Normal Water Heavy Water Beryllium Beryllium Oxide Carbon etc.

13. Table 1 does not list all the possible choices, nor do all the combinations of choices listed above (900 different reactors) make sense. Nevertheless, perhaps as many as 100 of the combinations shown are not obviously unfeasible. The reactor systems presently under advanced development or construction in Canada, France, the United Kingdom and the United States represent the more obvious design choices. Each system has been shown to be workable, but no system has as yet been operated as a full-scale commercial power producer.

14. The more promising systems now under advanced development or con-

1/ From P/862 by A.M.Weinberg; Proceedings of the International Conference on Peaceful Uses of Atomic Energy, Vol.III, P.24.

struction are briefly described below:

(a) Aqueous Homogeneous Reactors -- in which a dilute solution of a salt of highly enriched Uranium 235, Uranium 233, or Plutonium in heavy water is utilized as the fuel. This solution is circulated through a tank surrounded by a larger vessel containing the blanket material, a solution or slurry of fertile material, thorium or uranium, which utilizes the neutrons escaping the core, to produce new fissionable material. (U.S.)

(b) Boiling Water Reactors -- in which heat from the core is transferred by allowing the cooling water (either normal or heavy) to boil within the vessel containing the fuel elements. If normal uranium fuel is used the coolant-moderator is heavy water. (U.S.)

(c) Fast Breeder Reactors -- in which an unmoderated core fuelled with plutonium, U235, or U233 and cooled, for example, with sodium is used. The core is surrounded by a uranium or thorium blanket to utilize the neutrons which escape the core. (U.K. and U.S.)

(d) Gas Cooled Graphite Reactors -- in which normal uranium or uranium enriched with U235, U233, or Plutonium in the form of rods or slugs is contained in a graphite moderator. Carbon dioxide under pressure (or some other suitable gas) is circulated through the reactor to remove the heat. (France and U.K.)

(e) Liquid Metal Fuel Reactors -- in which a liquid fuel composed of a few parts per million of Uranium 235 or Uranium 233 in molten bismuth circulates through a graphite moderator. The heat is removed from the liquid metal fuel solution and used to generate steam. A liquid blanket of uranium - or thorium - bismuth slurry surrounds the reactor, and utilizes neutrons from the core to make fissionable material. (U.S. and U.K.)

(f) <u>Pressurized Water Reactors</u> -- in which high pressure water (or heavy water) is circulated through a vessel containing solid fuel elements of slightly enriched or, in the case of heavy water, normal uranium. The water is then passed through a boiler in which steam is produced to drive a turbo-generator. (Canada and U.S.)

(g) <u>Sodium Graphite Reactors</u> -- in which advantage is taken of the high temperatures and high efficiencies to be gained through the use of sodium as the coolant and graphite as the moderator. Enriched fuel is used. (U.S.)

Table 2[1]

Plans for Power Producing Reactors in Selected Countries

CANADA. Atomic Energy of Canada, Ltd. and Hydro-Electric Power Commission of Ontario to build 20 Mw (electricity) prototype heavy water, natural uranium power reactor; to be in operation 1958. Designing 100 Mw reactor of similar type.

FRANCE. French Five-Year Program.

G-1. Contains 100 tons of natural uranium, elements 26 mm dia, 100 mm long, sheathed, in Mg.1200 tons of graphite. Air cooled at atmospheric pressure. Under construction, to produce about 40 Mw heat and 5 Mw electricity in 1956.

G-2. Graphite-moderated; 100 tons of natural uranium, elements 26 mm dia, 300 mm long sheathed in Mg. CO_2-cooled in a pressurized closed circuit. Under construction, to produce 100 to 150 Mw heat, and 30 Mw electricity.

UNITED KINGDOM. United Kingdom's 10-Year Program.

Type of Reactor	No. of Reactors	Electric Output, Mw	Completion Date
Gas cooled, Calder Hall type	4)	400 to 800	1960-1
Gas cooled, improved	4)		1963
Higher power reactors	4)	1000	1963-4
Liquid-metal-cooled reactors	4)		1965
Production and power generation	6	Addition to above program	

UNITED STATES.

AEC Program	Heat Output, Mw	Electric Output, Mw	Completion Date	Notes
Pressurized Water Reactor (PWR)	~ 230	60	1957	-
Experimental Boiling Water Reactor (EBWR)	20	5	1956	-
Sodium Graphite Reactor	20	7.5	1955	-
Homogeneous Reactor Experiment No.2 (HRE-2)	10	2	1956	-
Experimental Breeder Reactor No.2 (EBR-2)	62.5	15	1958	-
Industrial Reactor Program				
Yankee Atomic Electric Co.	500	134	1957	Pressurized light-water moderator and coolant.
Nuclear Power Group	692	180	1960	Boiling-water type.
Atomic Power Development Assn.Inc.	300	100	1960	Fast breeder.
Consumer Pub.Pwr.Dist.of Nebraska	250	75	1959	Sodium-graphite reactor
Consolidated Edison	500	236*	1959	Pressurized water, uranium-thorium converter.

(*140 Mw from reactor, 96 Mw from oil-fired superheater)

1/ Based upon the compilation presented in Nuclear Reactor Catalogue, prepared for the United Nations by H.S.Isbin; Proceedings of International Conference on Peaceful Uses of Atomic Energy, Vol.III, P.374, et seq.

15. Table 2 lists presently well-advanced plans for experimental, demonstration or full-scale power reactors in Canada, France, the United Kingdom and the United States. It will be noted that the gas-cooled reactor system has taken priority in development in France and the United Kingdom. This is due to several factors, the most important being the scarcity of heavy water, the scarcity or unavailability of enriched uranium or plutonium, and greater relative experience with air or gas-cooled systems. In the United States, on the other hand, no serious limitation is placed by scarcity of any material, and the systems under development are therefore more diverse. In Canada, the emphasis is on natural uranium, of which Canada has a plentiful supply. Thus, it can be seen that purely technical considerations are not necessarily the influencing factors in choice of reactor systems for early development and construction in any country. Indeed, the U.S. program shows that each of the systems listed above (with the exception of gas-cooled, graphite moderated thermal reactors) has its strong adherents in the U.S. Recalling Dr. Weinberg's statement (see page 3), it is evident that not only is there a difference of opinion as to the best technical system for producing economic electric power, but also work done to date seems to indicate that each of the various approaches is feasible and none obviously impractical.

16. One point should be stressed regarding nuclear power facilities -- their design and manufacture requires a highly skilled technology available only in the more maturely industrialized nations. Thus, particularly in underdeveloped countries, the acquisition of nuclear power plants will involve not only foreign exchange, but also technical assistance and probably the execution of political agreements between the supplier nation and the

purchaser nation. Indeed, present U.S. law allows the export of "utilization facilities" only under and pursuant to an executed "Agreement for Cooperation". Because of security considerations and, perhaps more importantly, trade secret considerations particularly in the field of fuel element technology, it is probable that the export of nuclear power plants will, at least in the early years, involve some sort of intergovernmental agreement.1/

17. In sum, several different technical systems for producing nuclear power are already in an advanced stage of development or construction, and each system has been shown to be feasible, although precise economic information will not become available until a full-scale power reactor has been operated.

Cost of Nuclear Power Facilities

18. Before discussing estimated costs of nuclear facilities, it will be well to consider general aspects of the economics of nuclear power. The actual cost of building and operating an atomic power plant will, of course, determine whether electricity from that plant is competitive with electricity from other sources. It is clear that the capital cost of a nuclear power plant today is higher than the capital cost of an equivalent thermal power plant. The costs of nuclear power plants now being considered for

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1/ In response to a question as to specifications for fuel elements used in the U.K. gas-cooled reactors, Sir Christopher Hinton said they were of the finned type and enclosed in light metal cans. He added: "I would say quite frankly that I think it reasonable to maintain a measure of what I would call industrial secrecy about fuel element design; this is the sort of thing about which one feels one may perhaps not tell one's competitors in detail". Proceedings of the International Conference on Peaceful Uses of Atomic Energy, Vol.III, P.369.

BC [illegible] $200 [illegible]

commercial development are indicated to range between $230 and $320 per kilowatt of capacity.[1/] This compares with about $120 to $160 per kilowatt for conventional thermal plants. On the other hand, the fuel component of power cost for a nuclear power plant should be lower than that for fossil fuels in most places, and, unlike other fuels, that cost would be relatively the same for the same reactor system no matter where the plant is located. Assuming other operating and maintenance costs not associated with fuel are about the same, the savings on fuel over the life of the plant will, then, represent the total amount available to cover the higher capital cost and the faster depreciation of the atomic power plant.

1/ See para. 24.

Table 3

Early Nuclear Power Plants
Canada - UK - US

Builder	Reactor Type	Elec.Cap. Mw.	Estimated Cap.Cost $/Kw.	Estimated Completion Date
U.K.Atomic Energy Authority	Gas Cooled	X 65 ?50	> 600 1/	Fall 1956
U.S.Atomic Energy Commission	Pressurized Water	> 60 ?50	630	1957
Consumers Public Power Dist.	Sodium Graphite	75	320	1958-1959
Atomic Energy of Canada Ltd.	Pressurized heavy water	20	< 600	1959
Yankee Atomic Elec. Co.	Pressurized Water	134	230	1959-1960
Power Reactor Dev.Co.	Fast Breeder	100	540	1959-1960
Nuclear Power Group	Boiling Water	180	250	1960
Consolidated Edison	Pressurized Water	236	233	1960
U.K.Central Electricity Authority	Gas Cooled	150	280 2/	1960-1961

1/ No official estimate of capital cost has been given publicly; the value quoted is conjectural.

2/ At the Geneva Conference, a cost of $350/Kw was given for this plant. Later estimates place the cost at $280/Kw.

19. Table 3 lists nine nuclear power reactors now under construction or in advanced design stage. No cost information is available on gas-cooled French power reactors, but it can be assumed that their costs would be no less than those for the U.K. gas-cooled reactors. The U.K. AEA gas-cooled reactor will be the first central station power reactor to come into operation. It is a dual-purpose plant, in that it is so designed as to permit the simultaneous production of power and of military grade plutonium having a low

X may be higher

percentage of the Pu-240 isotope. Its successors, however, the gas-cooled U.K. CEA plants, will be designed with major emphasis on the production of power. The estimate of $280/Kw for the second generation gas-cooled reactors appears reasonable.

20. The first large U.S. power reactor is the Pressurized Water Reactor being built for the U.S. AEC by Westinghouse. This reactor, as are the Yankee Atomic Electric Co. and the Consolidated Edison reactors, is an outgrowth of U.S. experience in designing and building the propulsion reactor for the USS Nautilus, and the system has been shown to be satisfactorily operable under the severe conditions encountered in forced submerged operation. The estimates given for the Yankee and ConEd reactors are based upon extensive technical experience gained in building the Nautilus and PWR reactor and appear, therefore, to be reasonable, although they may contain subsidies from the manufacturers, since they were both derived from bids for which there was spirited competition among the leading electrical equipment and boiler manufacturers.1/ The Consumers Public Power District sodium-cooled graphite reactor is based on extensive sodium handling technology derived from North American Aviation's sodium reactor experiment, the AEC's Experimental Breeder Reactor and its Submarine Intermediate Reactor, all of which use liquid sodium or sodium-potassium alloy as coolants. The cost estimate appears reasonable. The Nuclear Power Group boiling water reactor is also based on considerable U.S.AEC experience. In this case, the General Electric Company has bid to build the entire reactor and power generating equipment for $45,000,000. It may be assumed that the General Electric

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1/ The ConEd reactor, for example, is being built for the flat sum of $55,000,000 by Babcock & Wilcox. (including cost of [illegible] — so it must be reduced) i.e. a breeding gain > (as in the UK [illegible])

company believes it reasonable to expect that this or early successor boiling water reactors can be built profitably by a manufacturer for $250/Kw. The other U.S. reactor system listed in Table 3 is the Fast Breeder Reactor, and represents the greatest extension of present technology, which fact is evident in the higher estimated cost per kilowatt. However, this reactor could have essentially zero net fuel costs, and possibly may have negative net fuel costs. (the value of fuel produced may be greater than the cost of the original fuel) Its higher capital cost may therefore be justified economically.

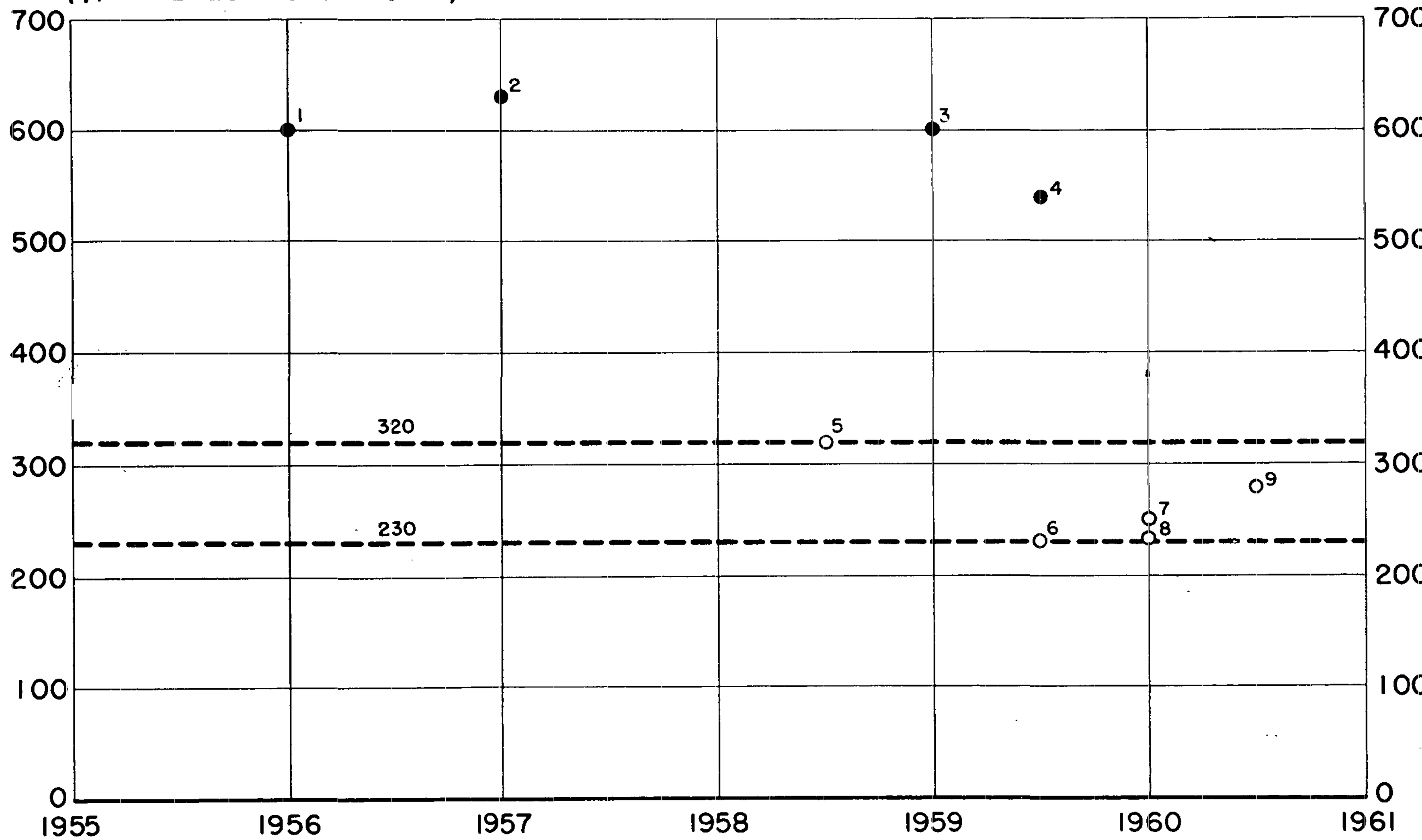
21. The Canadian Nuclear Power Demonstration (NPD) pressurized heavy water reactor is more in the nature of an experimental than power reactor, although it will have a significant electrical output. It is estimated that "second generation" pressurized heavy water reactors of this design will cost about $250/Kw and will have capacities in excess of 100 Mw electric.

22. On Chart 1 are plotted the $/Kw costs of these nine reactors according to the year each is estimated to come into operation. The reactors plotted in black solid dot (•) are those of an advanced type which involve a substantial extension of present technology and those that are the "first" or prototype reactors. Plotted as an open dot (o) are the reactors based on substantially developed technology or upon which firm bids have been obtained from manufacturers. For this latter class, which can be taken to represent the early commercial reactors, the $/Kw costs range between $230 and $320.

23. On Chart 2 are plotted the capital costs of these reactors in relation to their electric capacity in megawatts. As the size of the plants approaches about 100 Mw, the cost per kilowatt tends to become asymptotic, in this case at about $230/Kw. Lane has fitted a curve to a plot of costs for 14 reactors. His plot, in some instances, based on data slightly

ESTIMATED COSTS OF POWER REACTORS

($/KW ELECTRIC CAPACITY)



● 1. UKAEA FIRST PROTOTYPE COMMERCIAL
2. USPWR FIRST PROTOTYPE COMMERCIAL
3. NPD FIRST CANADIAN HEAVY WATER PROTOTYPE COMMERCIAL
4. FBR FIRST COMMERCIAL SCALE BREEDER (US)

○ 5. SGR SCALE-UP TO COMMERCIAL
6. PWR, YANKEE ELEC.; WESTINGHOUSE BID
7. BWR, NUC. PWR. GRP.; GEN. ELEC. BID
8. PWR, CON. ED.; BABCOCK & WILCOX BID
9. UKCEA GAS COOLED POWER STATION

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CHART I

ESTIMATED COSTS OF POWER REACTORS

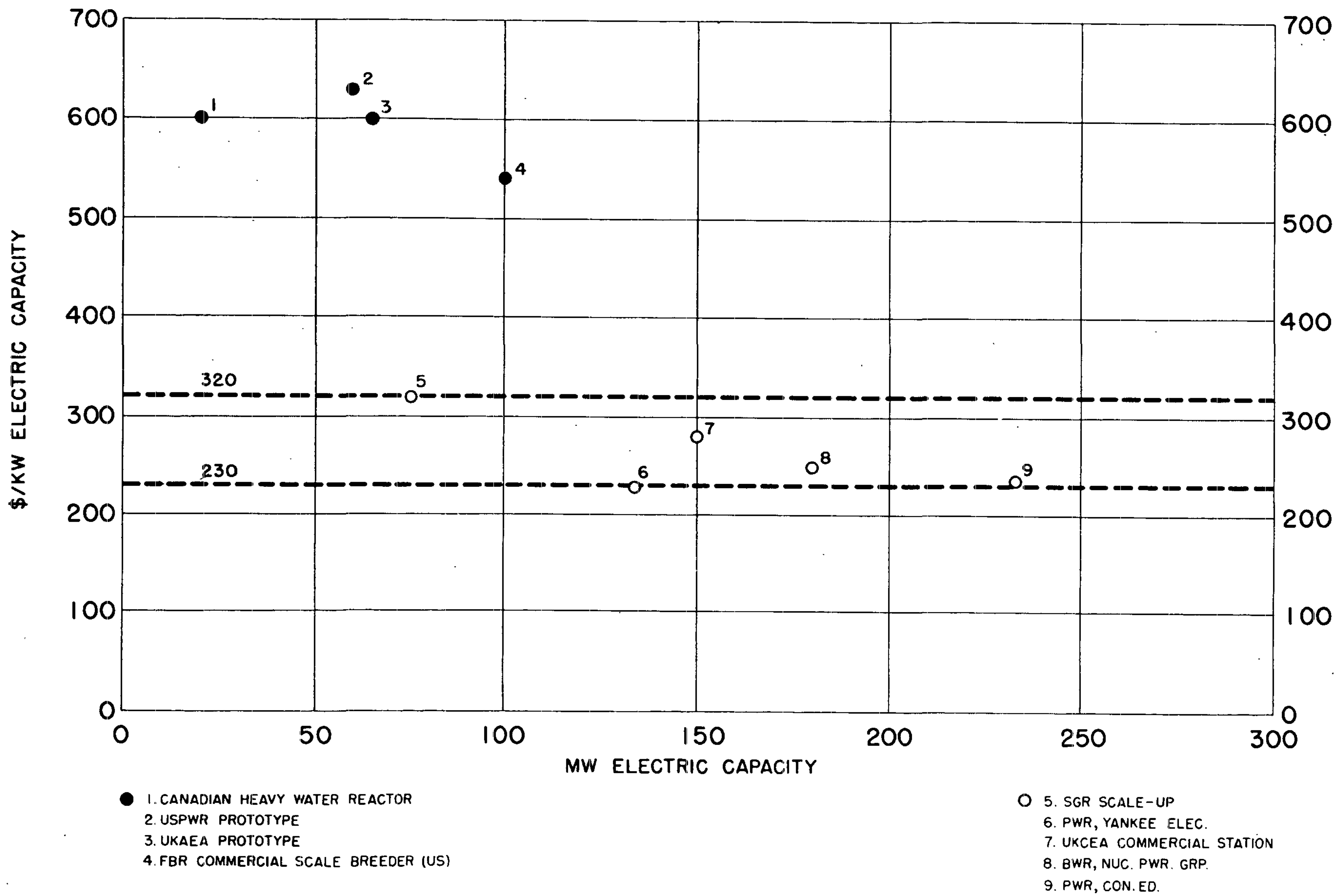

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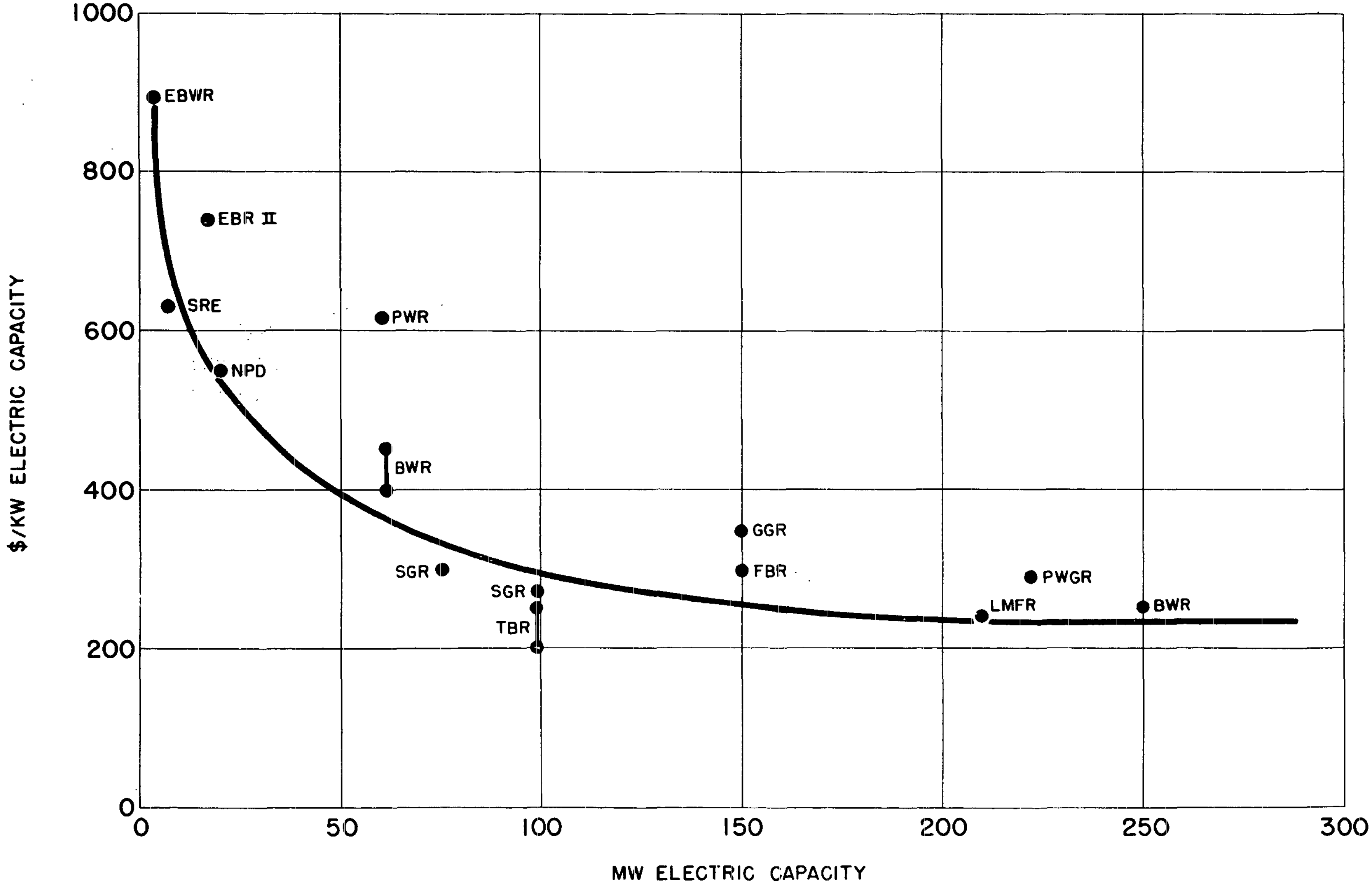
CHART 2

CHART 3

CAPITAL COSTS OF NUCLEAR POWER PLANTS



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different from the more recent values given in Table 3, and including costs for some reactors not presently under construction or authorized, and for some earlier experimental reactors, appears on Chart 3.[1/] It can be noted that the curve fitted by Lane also appears asymptotic at about $230/Kw for reactor sizes of from about 100 Mw upward.

24. In sum, the cost of nuclear power plants of about 100 Mw electric capacity and upwards can be reasonably taken as between $230/Kw and $320/Kw. In the computations of cost of nuclear power which appear later in this paper, the capital cost will be set at $250/Kw. It should be noted that the reactors upon which this range of estimated costs is based are being built in Canada, the United Kingdom and the United States. This estimate is conservative and actual capital costs may well be less.[2/] Whether the same costs would obtain elsewhere would depend on local conditions. At least a portion of the added capital costs for export reactors (transportation, imported expert labor, etc.) might be partly balanced in some cases by lower general labor costs reflected in somewhat lower costs of standard construction such as buildings, excavation, and perhaps lower costs for turbine generators or other standard equipment obtainable locally. ?

The Estimated Cost of Nuclear Power

25. Having determined on a conservative basis a reasonable capital cost

1/ Chart prepared by James A. Lane, Oak Ridge National Laboratory, and included in a paper presented before the National Industrial Conference Board, New York, N.Y., October 1955.

2/ In recent testimony before the U.S.Joint Committee on Atomic Energy, Mr. Philip Sporn, President of American Gas and Electric, stated that the NPG boiling water reactor, which was estimated to produce 180,000 Kw at a capital cost of $250/Kw, would actually have a larger electric capacity and thus its capital cost would be less than $250/Kw.

for a 100 Mw nuclear power plant built on essentially today's technology, it is now necessary to establish costs for operation and maintenance, fuel, depreciation, and return on investment. Since the plant factor substantially affects the mills/Kwh charges attributable to depreciation, we must establish the average plant factor at which the nuclear plant might be expected to operate over its lifetime.

Operating and Maintenance Costs

26. Since no commercial nuclear power reactors have been as yet operated, there is no firm experience upon which to base estimates of operating and maintenance costs per Kwh produced. Most studies on the economics of nuclear power reactors, however, indicate that such costs should be close to those for normal thermal stations. It is to be expected that for the first year or two of operation of early nuclear power plants, operating and maintenance cost may be higher, perhaps double those for standard plants; the basic simplicity of operation of a reactor, however, would seem to permit these costs to be lower in later years. Second or third generation plants should experience operating and maintenance costs lower than for a conventional thermal station. In any event, this component of cost of electricity is not very large -- for large central station plants in the United States it adds about 0.5 to 1.0 mill/Kwh.

27. There is no reason to expect that the labor force required for a nuclear power station will be substantially different in respect of cost than for a conventional station. Early plants can be expected to have somewhat higher than normal costs in first years of operation; but later plants should have lower costs.

28. Most studies on nuclear power economics assume little or no

variation from standard maintenance costs. This point of view is reasonable if one examines the components of a nuclear power plant. The turbo-generator side is standard, and the only increase in maintenance would be due to low level radiation from the primary steam or from contamination of the secondary coolant. The coolant and steam systems will be required to be built to very close specifications, which is reflected in the higher capital cost, but should also be reflected in low maintenance charges. In the reactor itself, there are problems of radiation damage, and of corrosion, both of which are given primary consideration in the design and should therefore not cause large maintenance problems.

29. The average of the estimated costs reported in 16 studies of the economics of nuclear power at Geneva for the combined operating and maintenance cost for a large nuclear power station is 2.02 mills/Kwhr. This value, which is between 2 and 4 times the cost derived from U.S. experience with large conventional thermal stations, is certainly reasonable, and probably higher than will be actually experienced. Its use in this paper is therefore considered as conservative.

30. Insurance costs for a nuclear plant will undoubtedly be higher than for a conventional thermal plant. However, the cost of insurance for a conventional plant is such a small percentage of the total operating costs that even a substantial increase in insurance cost would not materially affect the total cost of power generated. It may be well, however, to indicate the nature of the insurance problem presented by a nuclear power station. The problem falls into two areas: insurance against loss of the plant itself and insurance against third party liability in the event of a major nuclear catastrophe, admittedly an event of extremely remote probability, but which

might cause grave injury to many persons as a result of radioactivity that may be released. These risks can be minimized by completely enclosing the reactor in a containment vessel, by locating the plant in a less densely populated area, and by design of additional safety features in the plant itself. If the plant is government-owned, it is "self insured". If the plant is privately owned, insurance will undoubtedly have to be obtained. In the United States insurance companies have indicated willingness to underwrite $60,000,000 in coverage for each reactor. There is a strong possibility that a larger amount of coverage will become available as the insurance companies investigate the problem further. However, it appears that insurance against a major catastrophe, involving claims of perhaps a hundred million dollars or more, may require some form of government re-insurance in the United States. Solution of the insurance problem will undoubtedly vary in different countries, and should be examined in each particular case. It is expected that the cost of insurance will nevertheless still represent a small proportion of the cost of power. The 2 mills/Kwh operation and maintenance cost used in this paper is considered sufficiently liberal to cover the cost of insurance.

Fuel Costs

31. At present all supplies of nuclear fuels are government-controlled and costs of production have not been released. Prices at which the United States will sell or lease certain materials for research reactors were released at Geneva -- $5,000 per kilogram of uranium at a U235 enrichment of 20%, $40 per kilogram for natural uranium in metal form, and $61.50 per kilogram for heavy water. Prices for quantities of these materials for use in commercial power stations have not yet been established, or at least have

not yet been announced. Most studies estimate values for U235 at between \$15 and \$30 per gram, and for natural uranium at about \$40 per kilogram. In this paper a value for U235 of \$25 per gram and a value for natural uranium metal of \$40 per kilogram has been used as a basis for calculation.[1/]

32. The fuel costs of any reactor will depend upon a large number of variables. However, it has been found possible to develop general expressions for nuclear fuel and inventory costs that are at least indicative of the range of costs to be expected for certain reactor systems. Such expressions and sample calculations for various reactor systems are contained, for example, in a report entitled "Nuclear Fuel and Inventory Costs for Power Reactors" (IRL-138) by D. Kallman, R. A. Pierce, and W. S. Scheib, Jr., of the California Research and Development Company, dated June 1954 and prepared under U. S. Atomic Energy Commission Contract No.AT(11-1)-74.

33. Basically, in a reactor some atoms of a fissionable material are fissioned or otherwise destroyed, some are left in the fuel elements, and some new atoms of fissionable material are formed. There are involved, in computing the fuel component of power cost, certain metallurgical, fabrication, separation and waste disposal costs in addition to the values of the fissionable material destroyed or made. Since fissionable material in the reactor fuel cycle represents a large amount of immobilized capital, inventory charges are made against the fissionable material held in the fuel cycle.[2/]

1/ In connection with the announcement of Feb.23, 1956 that the U.S. would make available 20,000 kilograms of U235 for use in power reactors in other countries, Chairman Lewis L. Strauss of the U.S.AEC said the material had a value of \$500,000,000, which confirms the \$25.00 per gram value proposed for use in this paper.

2/ See Para.38.

The following expressions can be written to reflect these charges:

(a) Nuclear Fuel Cost:

For Heterogeneous Thermal Reactors:

Fuel Cost = f.m. destroyed + f.m. undestroyed - Pu recovered + Fabrication + Separations + Waste Disposal.

(b) Inventory Cost for Thermal Reactors:

Inv.Cost = f.m. feed in reactor + f.m. Feed in Separations Cycle + Pu Product in reactor + Pu Product in Separations Cycle.

34. The assumptions used in the calculations contained in IRL-138, referred to above, are not unreasonable, and it is not considered necessary here to describe them fully. Let us now consider the costs for fuel and inventory calculated in IRL-138 for a thermal regenerative reactor using normal uranium as fuel:

Fuel	Quantities in grams per 1000 Kwh.	Unit Costs per grams	Mills/Kwh.
Fissionable material destroyed	0.20	$ 6.20	1.24
Fissionable material undestroyed	0.20	6.20	1.24
Plutonium recovered	0.16	25.00	(4.00)
Fabrication	56.00	0.005	0.28
Separations	56.00	0.015	0.84
Waste Disposal	0.24	0.50	0.12
Inventory Charges			0.65
Total Fuel and Inventory Costs			0.37

It will be noted that the plutonium produced in the reactor is valued at

$25.00 per gram. This figure is about twice as high as that generally assumed in the Geneva papers. If a value of $15.00 is substituted, the resulting overall fuel and inventory cost would be 1.97 mills/Kwh. The fissionable material, destroyed and undestroyed, is valued at $6.20 per gram which represents normal uranium at $44 per kilogram. Since our value for normal uranium is $40 per kilogram, the fissionable material destroyed and undestroyed should be valued at $5.62 per gram. The cost of fissionable material destroyed then becomes 1.13 mills/Kwhr. The other principal item in these calculations subject to serious error is the amount of fissionable material undestroyed. The amount of fissionable material undestroyed is dependent upon the length of time the uranium fuel element can be left in the reactor without being seriously damaged, or without poisoning the chain reaction through buildup of fission products. The cost attributable to fissionable material unburned assumed in the above calculation requires irradiation of about 4,500 megawatt days per ton, which is somewhat higher than has been achieved on any large scale to date. If irradiation of 3,500 MWD/ton, which has been achieved in Canadian and other normal uranium reactors, is assumed, the direct cost of fissionable material unburned at $5.62 per gram would be 1.69 mills/Kwh. Because more material would have to be fabricated and separated, these costs and the inventory charge would also rise, making the total fuel and inventory cost about 2.85 mills/Kwh.

35. Fuel and inventory costs for sixteen reactors (not all thermal, natural uranium systems) were estimated in various Geneva papers. The average of these costs is about 2.85 mills per kilowatt hour. The spread of such fuel costs, depending upon value assigned to plutonium either as a byproduct or as replacement fuel, the irradiation level to which the uranium fuel elements may be subjected, and the fuel cycling chosen, depends upon

the reactor system employed. For breeder reactors the fuel costs could become zero, and even may show as a credit. For thermal reactors in which irradiations of 8-10,000 MWD/ton can be achieved, the fuel and inventory cost can be perhaps as low as 0.5 mill/Kwhr. These latter systems are, however, not achievable with present technology; they may be expected in third or later generation plants.

36. It should be noted that the calculation of 2.85 mills/Kwhr as the fuel component of power costs assumes essentially present technology, and no increase in efficiency of use of nuclear fuel over the whole life of the power plant. It is more reasonable to expect some increase in efficiency, or decrease in unit costs, as experience further is gained.1/ If a modest allowance of 10 to 15 percent of the calculated cost is taken, the fuel cost component would be about 2.50 mills/Kwhr.

37. In summary, a reasonable and conservative value to assign fuel and inventory cost appears to be about 2.5 mills per kilowatt hour, with the possibility that costs of perhaps 1 mill/Kwh might be obtained in later loadings of the early reactors. It is difficult to see why fuel costs should be substantially higher than 2.5 mills/Kwh over the life of the early power plants. It must be emphasized that the reasonable value suggested above is a generalised value. For any specific reactor system, a specific fuel and inventory cost must be calculated using the specific parameters of

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1/ In the foregoing calculations, a thermal efficiency of 20 percent has been used. Mr. Philip Sporn, President of American Gas and Electric, has reported that the NPG Boiling Water Power Reactor is expected to achieve a thermal efficiency of 28 percent.

the specific system.

38. The foregoing estimate of 2.50 mills/Kwh includes approximately 0.9 mills/Kwh to cover inventory charges on the immobilized capital represented by the fissionable and fertile material committed to the nuclear power reactor, including not only all the nuclear material in the reactor, but also that being fabricated into fuel elements, being stored for cooling after irradiation, and being chemically processed. The amount of material so committed will depend upon the specific reactor. According to Dr. W. K. Davis, Director of the U. S. Atomic Energy Commission's Division of Reactor Development, the total value of the inventory of nuclear fuel may be as high as $50 per electrical kilowatt for some reactors, and in typical heterogeneous reactors the value will be in the range of $20 to $40 per kilowatt. In homogeneous reactors the value may be appreciably less.1/ Accepting the higher value, i.e. $50 per kilowatt, a 100 Mw reactor might require something like $5,000,000 worth of nuclear fuel in inventory. The allowance of 0.9 mills/Kwh, which has been included in the fuel and inventory charge of 2.50 mills/Kwh, would, in a 100 Mw plant operated at a 50 percent plant factor, provide about $395,000 per year, an amount which should be ample to cover financial charges on carrying an even greater fuel inventory.

Amount and Pattern of Use

39. Since the capital costs for a nuclear power station are higher than for a comparable thermal station the amounts charged in the selling price to cover return on that capital investment and depreciation are larger than

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1/ P/477 - "Capital Investment Required for Nuclear Energy" by W.K.Davis; Proceedings International Conference on Peaceful Uses of Atomic Energy.

would be required in the case of a thermal plant. In order to bring those charges within reasonable limits, it is necessary to spread them over as large a number of units of production -- kilowatt hours -- as possible. This indicates the need to operate nuclear power plants at as high a plant factor as possible, or, in other words, to use them as base load stations.

40. Since we have also seen that the capital investment would probably be sharply higher for plants of less than 75 to 100 Mw capacity, we must be sure that the system into which the nuclear plant is to be integrated is capable of accepting a 75-100 Mw plant as a base load installation with a high plant factor.

41. Whether the nuclear plant can be operated with a high plant factor is essentially a function of system demand. (We assume that operational shutdowns will be no greater in a nuclear plant than in a thermal plant.) Therefore, in assessing the feasibility of a 75-100 Mw nuclear plant from an economical point of view, it is paramount that we make sure the electrical system, of which it is to be a part, is such as to allow the nuclear plant to be operated at a high plant factor throughout the year.

Depreciation

42. For a conventional thermal plant, the plant life will be taken as 33 1/3 years, and the depreciation rate will be 3% of the capital cost per annum on a straight line basis. For the nuclear plant, about 30% or 40% of the capital cost is represented by conventional equipment which would have the same life as in a conventional plant, i.e., 33 1/3 years. The remaining 60% to 70% of the capital cost comprises non-standard, specialized items for which a plant life of 20 years will be assumed. This would appear to be a

conservative estimate; the early large size nuclear reactors at Hanford, Washington which began operation about twelve years ago, are still performing satisfactorily as is the smaller air cooled reactor at Oak Ridge, which began operation somewhat earlier. The combined overall plant life of the nuclear plant will therefore be taken as 25 years, and the plant will be depreciated at 4% of its capital cost per annum on a straight line basis.

43. The amount of money allocated each year to cover depreciation (four percent of the capital cost) would, if placed in a sinking fund at, say, 4.75 percent interest, actually permit the complete writing off of the plant in 17 years, or about 8 years before the technically determined life of the plant had expired. The use of a 4 percent, straight line depreciation schedule is considered prudent from a banking point of view.

44. The question of obsolescence of a nuclear power plant should be mentioned at this point. In a conventional thermal plant the primary reason for obsolescence is that new plants display a consistently higher thermal efficiency, and since the cost of fuel is the most significant portion of selling price of electric power at the bus bar in conventional thermal plants, the new plants are able to make power cheaper than old ones. It is to be expected that later nuclear plants will undoubtedly be able to produce electricity at lower fuel costs than the earlier plants. However, the older plant will also benefit from advancing technology and in many, if not most, cases will be able to show comparable decreases in fuel costs in later loadings, as new alloys or new methods of fabrication enable a larger burnup of the fissionable material in the core. As was pointed out earlier, the fuel component of cost of electricity generated in a nuclear power station is significantly less than the fuel component of cost of electricity

generated in a conventional thermal station. Thus, as A. M. Weinberg has noted (see Para.7) the problem of obsolescence of a nuclear power plant is more comparable to that of a hydroelectric station than to a conventional thermal station.

45. As was mentioned earlier, the number of hours per year that the nuclear plant will generate power (i.e. the plant factor at which it will operate) has an important bearing on the cost of power generated. A study conducted by the General Electric Company of modern conventional thermal power stations in the United States revealed that over the life of these plants a plant factor of 43% was achieved. The G. E. study suggests that nuclear stations, because of lower fuel costs, should achieve a lifetime plant factor of 50%. However, because the nuclear plant is depreciated faster than the thermal plant, and because the fuel and operating component of cost of the nuclear plant will be lower than such costs in a thermal plant, it is not unreasonable to expect that the nuclear plant, in competition with thermal plants, will be operated in later years of its life at a much higher rate than would a thermal plant of equivalent age (See comments on obsolescenc Para.44). In the opinion of the writer, a nuclear plant "competing" with conventional thermal plants may achieve an overall lifetime plant factor of over 60%. Even in competition with newer nuclear plants, the older nuclear plant may be expected to be operated at a plant factor of about 50%.

Generating Costs for Nuclear Power, excluding Financial Charges

46. Table 5 contains calculations of the cost of generating nuclear power (including depreciation) in a 75-100 Mw nuclear plant costing $250/Kw of electric capacity operated at various plant factors. It represents generation costs in a nuclear plant that might be constructed on essentially

today's technology. The fuel and inventory cost (titled "Nuclear Fuel" in Table 5) is that previously computed as conservative, and may in practice decrease over the life of the plant to about 1.0 mills/Kwh. It is maintained as a constant in Table 5 regardless of plant factor, since the only effect of increasing the plant factor is a slight decrease in the inventory component of the charge. The operation and maintenance cost used in Table 5 is two to four times that experienced in conventional thermal stations in the United States. Over the life of the nuclear plant, it is expected that this cost might decrease to perhaps 1.0 mill/Kwh. Also, this cost will in fact decrease with an increase in plant factor. However, the 2.0 mills/Kwh cost is maintained as a constant in these calculations in order to introduce again a conservative bias. The depreciation costs shown in Table 5 are calculated on a straight line basis at 4 percent per annum, based upon a plant life of 25 years. However, as was pointed out in paragraph 43, if the depreciation allocation each year is invested at, say, 4.75 percent interest, the plant will in fact be completely written off in 17 years. Once again, this gives a conservative bias to the calculations.

Table 5

Cost of Generating Nuclear Power at Various Plant Factors
(Excluding Return on Investment)

Expressed in U.S.Mills per Kilowatt Hour

	Plant Factor				
	50%	60%	70%	80%	90%
Nuclear Fuel	2.5	2.5	2.5	2.5	2.5
Operation and Maintenance	2.0	2.0	2.0	2.0	2.0
Depreciation	2.3	1.9	1.6	1.4	1.3
Generating Cost (excluding Return on Investment)	6.8	6.4	6.1	5.9	5.8

Total Cost Including Return on Investment

47. In view of the larger capital investment required for a nuclear power plant as compared with a conventional thermal station the burden of financial charges is of major importance in evaluating "where and under what circumstances" nuclear power may be economically attractive. As was pointed out earlier, the average lifetime plant factor at which the power plant will be operated also substantially affects the cost of electricity generated. Table 6 shows estimated cost of electricity generated in a nuclear plant at various financial charges and at various plant factors.

Table 6

Total Cost of Generating Nuclear Power at Various Plant Factors and at Various Returns on Investment
(Expressed in U.S. Mills per Kilowatt Hour)

Plant Factor		Return on Investment 3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
50%	Generating Cost	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
	Financial Cost	1.7	2.3	2.9	3.4	4.0	4.6	5.1	5.7	6.3	6.8	7.4	8.0	8.6
	Total	8.5	9.1	9.7	10.2	10.8	11.4	11.9	12.5	13.1	13.6	14.2	14.8	15.4
60%	Generating Cost	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
	Financial Cost	1.4	1.9	2.4	2.9	3.3	3.8	4.3	4.8	5.2	5.7	6.2	6.7	7.1
	Total	7.8	8.3	8.8	9.3	9.7	10.2	10.7	11.2	11.6	12.1	12.6	13.1	13.5
70%	Generating Cost	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
	Financial Cost	1.2	1.6	2.0	2.4	2.9	3.3	3.7	4.1	4.5	4.9	5.3	5.7	6.1
	Total	7.3	7.7	8.1	8.5	9.0	9.4	9.8	10.2	10.6	11.0	11.4	11.8	12.2
80%	Generating Cost	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
	Financial Cost	1.1	1.4	1.8	2.1	2.5	2.9	3.2	3.6	3.9	4.3	4.6	5.0	5.4
	Total	7.0	7.3	7.7	8.0	8.4	8.8	9.1	9.5	9.8	10.2	10.5	10.9	11.3
90%	Generating Cost	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
	Financial Cost	1.0	1.3	1.6	1.9	2.2	2.5	2.9	3.2	3.5	3.8	4.1	4.4	4.8
	Total	6.8	7.1	7.4	7.7	8.0	8.3	8.7	9.0	9.3	9.6	9.9	10.2	10.6

Comparative Costs of Nuclear and Conventional Thermal Power

48. We are now in a position to compare the cost of electricity generated in a nuclear plant with the cost of electricity generated in a conventional thermal station. The conventional thermal station has the advantage of lower operating and maintenance costs -- about 0.8 mills/Kwh on the average in the U. K. and U. S. -- in contrast with the 2.0 mills/Kwh cost used in this paper for the nuclear plant. Since the capital investment for a conventional thermal station has been taken as \$120/Kw[1/] as compared with the \$250/Kw used in this paper for the nuclear plant, and since depreciation has been set at a more rapid rate for the nuclear plant (4 percent per annum, straight line, as contrasted with 3 percent per annum, straight line, for the conventional thermal station), depreciation and financial charges will also be higher for the nuclear plant than for the conventional thermal station. On the other hand, the fuel component of cost of electricity generated in a nuclear power plant will be considerably less than the cost of fuel used in a conventional thermal station, except in extremely low-cost fossil fuel areas.

49. The relative attractiveness of the nuclear plant vis-a-vis the conventional thermal station is largely dependent upon the cost of fuel for the conventional station and upon the rate of financial charges appropriate in the specific location. Charts 4 to 8 compare the cost of electricity generated in a nuclear power plant of 75-100 Mw electric capacity built on essentially today's technology, with the cost of electricity generated in a conventional thermal station of similar capacity, at various fuel costs for a conventional plant. Chart 4 (at a 50% plant factor) shows that wherever

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1/ Conventional thermal stations of 75-100 Mw are estimated to range from \$120/Kw to \$160/Kw. The \$120/Kw figure used in these calculations favors the conventional thermal stations.

COMPARATIVE COST OF ELECTRICITY

NUCLEAR AND CONVENTIONAL THERMAL AT VARYING COSTS OF FOSSIL FUEL

(50% PLANT FACTOR)

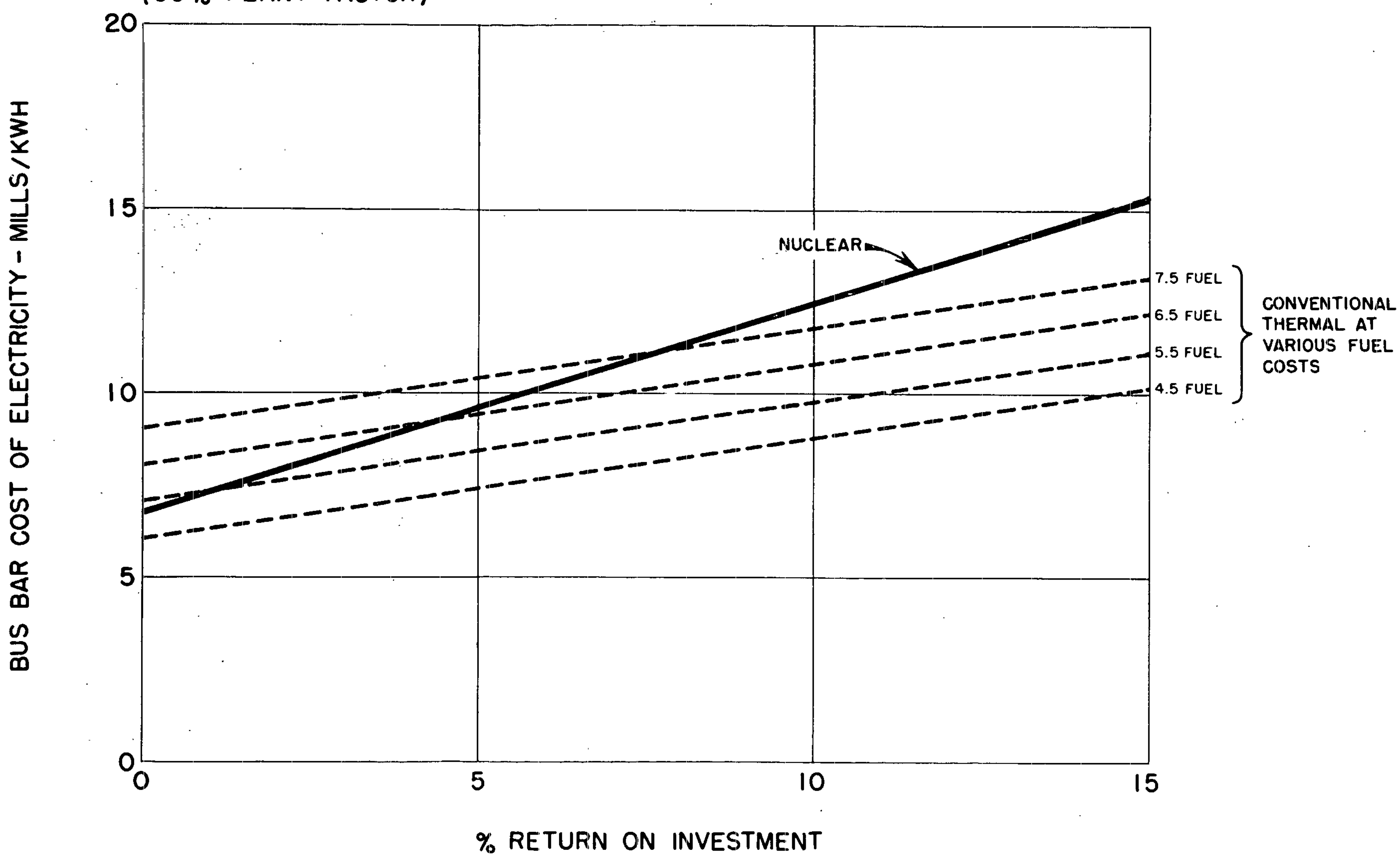

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CHART 4

COMPARATIVE COST OF ELECTRICITY

NUCLEAR AND CONVENTIONAL THERMAL AT VARYING COSTS OF FOSSIL FUEL

(60% PLANT FACTOR)

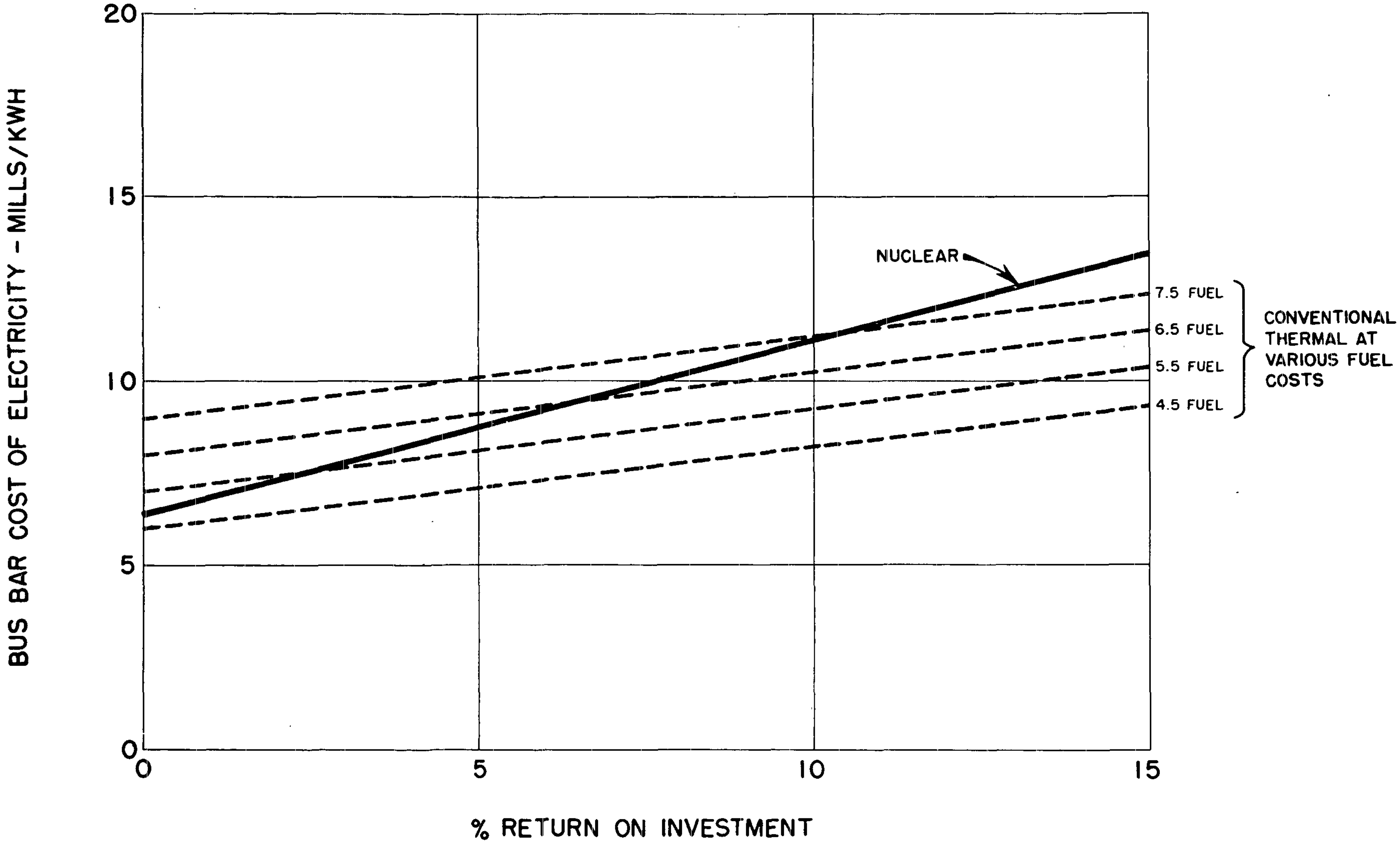

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CHART 5

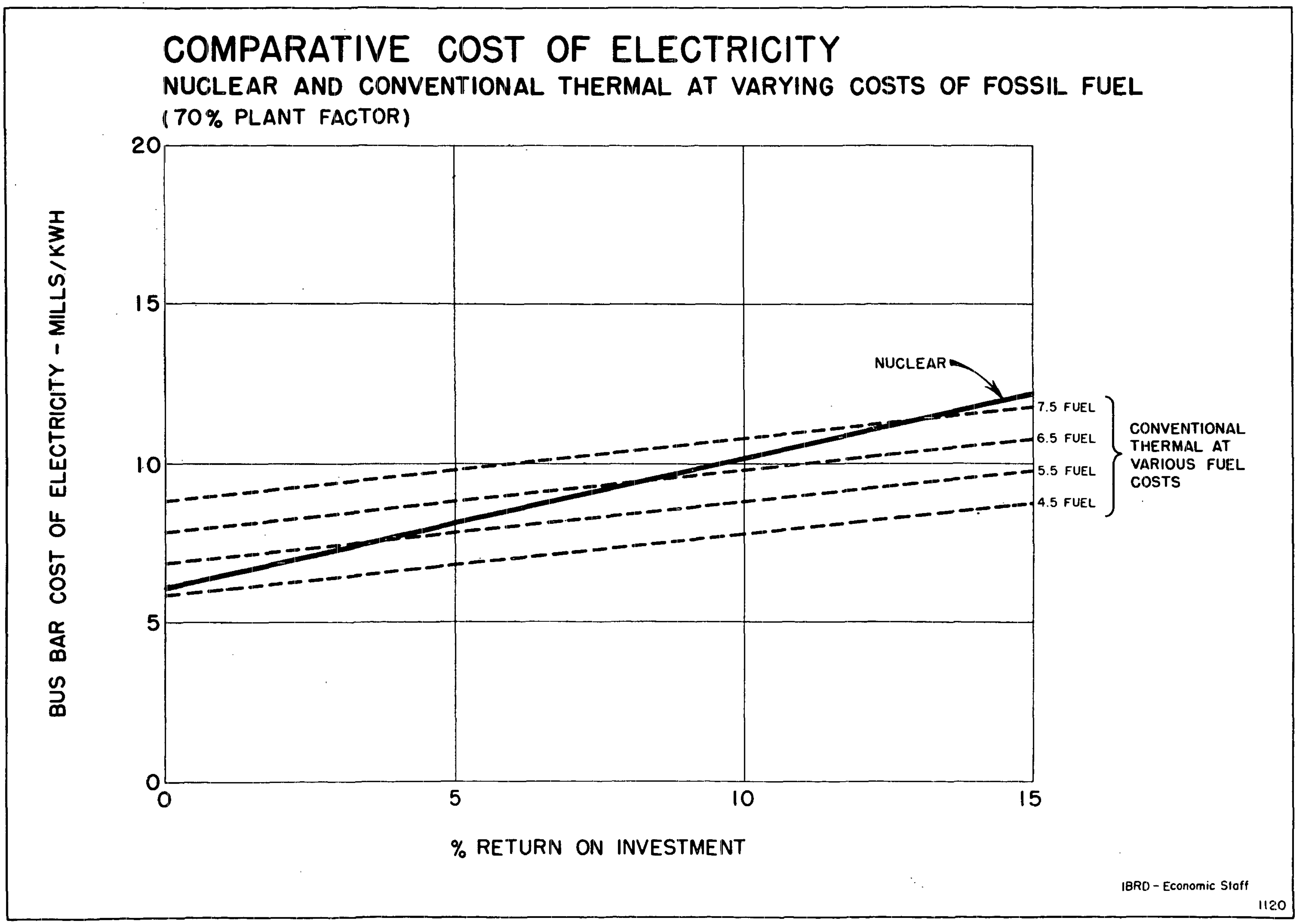
COMPARATIVE COST OF ELECTRICITY
NUCLEAR AND CONVENTIONAL THERMAL AT VARYING COSTS OF FOSSIL FUEL
(70% PLANT FACTOR)
BUS BAR COST OF ELECTRICITY - MILLS/KWH
20
15
10
5
0
0
5
10
15
% RETURN ON INVESTMENT
NUCLEAR
7.5 FUEL
6.5 FUEL
5.5 FUEL
4.5 FUEL
CONVENTIONAL THERMAL AT VARIOUS FUEL COSTS
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CHART 6

COMPARATIVE COST OF ELECTRICITY

NUCLEAR AND CONVENTIONAL THERMAL AT VARYING COSTS OF FOSSIL FUEL

(80% PLANT FACTOR)

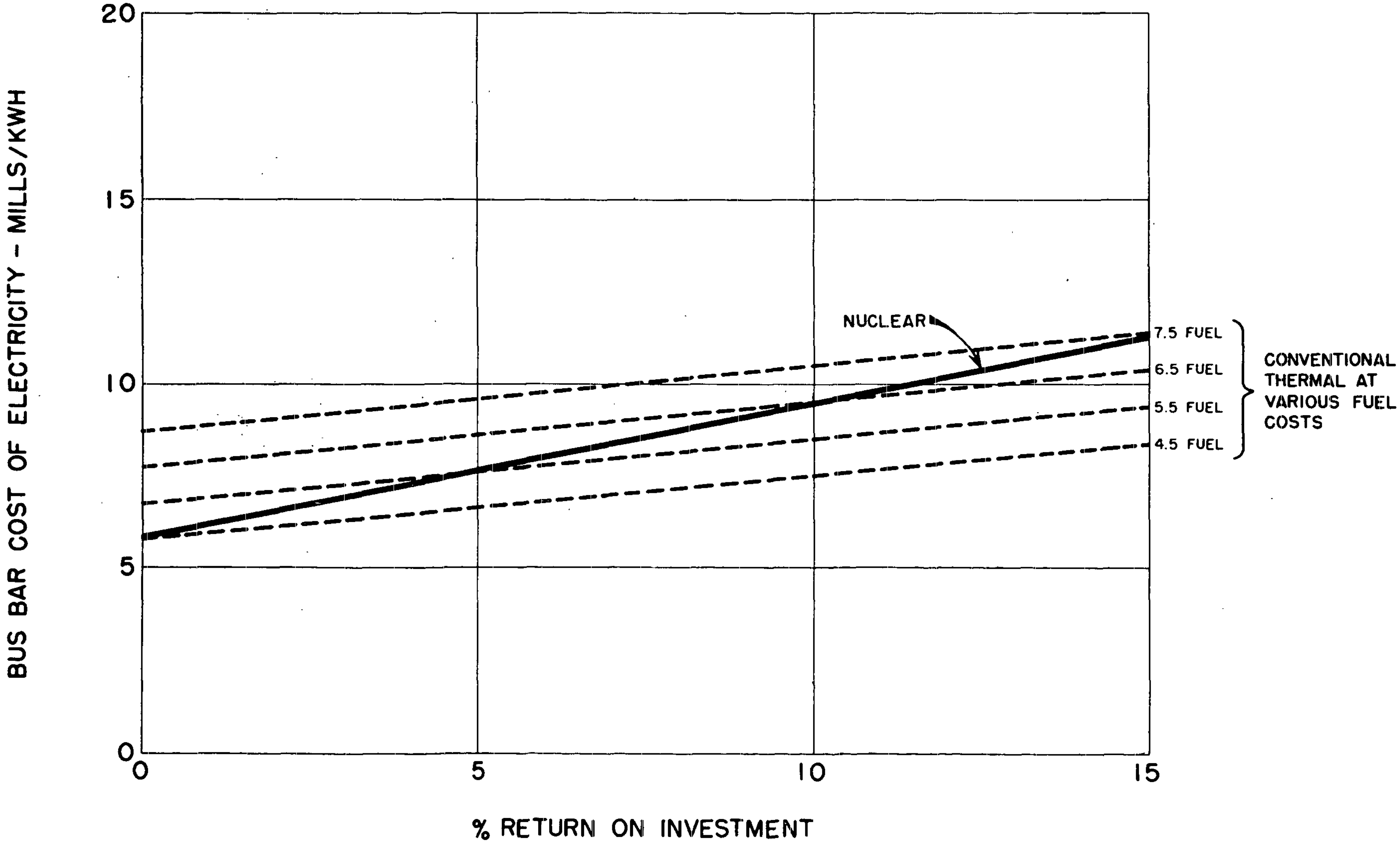

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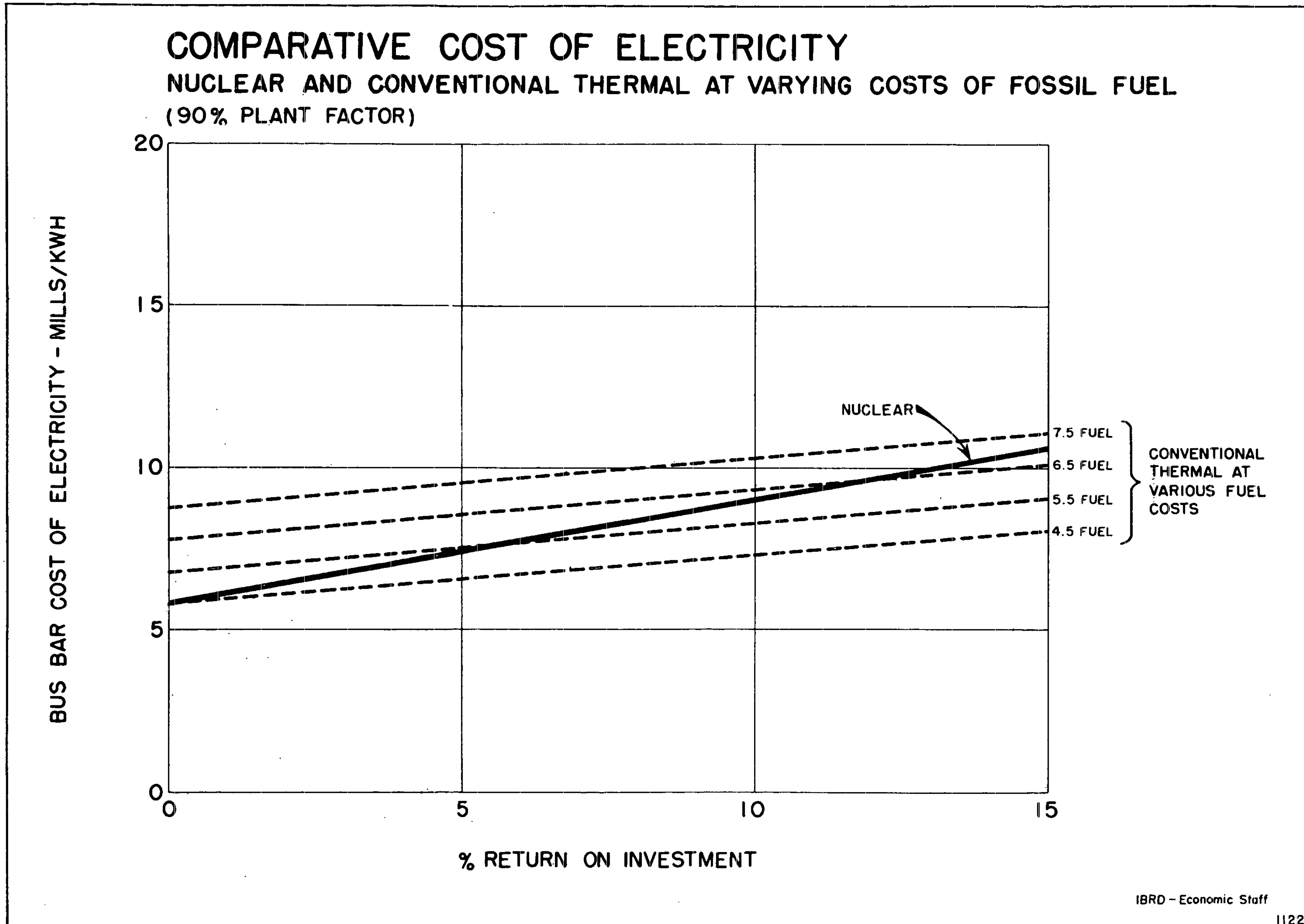
CHART 7



COMPARATIVE COST OF ELECTRICITY
NUCLEAR AND CONVENTIONAL THERMAL AT VARYING COSTS OF FOSSIL FUEL
(90% PLANT FACTOR)
BUS BAR COST OF ELECTRICITY - MILLS/KWH
20
15
10
5
0
0
5
10
15
% RETURN ON INVESTMENT
NUCLEAR
7.5 FUEL
6.5 FUEL
5.5 FUEL
4.5 FUEL
CONVENTIONAL THERMAL AT VARIOUS FUEL COSTS
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CHART 8

fossil fuel cost is 4.5 mills per Kwh or less (equivalent to $10.15 per metric ton for 10,000 BTU per pound coal burned in a plant having a 35% efficiency), a conventional thermal station is more economical than a nuclear station, irrespective of what rate of return is attributed to the investment in the plant. On the other hand, if the fossil fuel cost is 7.5 mills per Kwh ($17.00 per metric ton for 10,000 BTU per pound coal burned in a plant having a 35% thermal efficiency) a nuclear plant could afford to pay up to 7½% return (after depreciation) on the investment and still produce electricity more economically than a conventional thermal plant.

50. At a 90% plant factor (Chart 8), again a nuclear station could not compete with 4.5 mills/Kwh fossil fuel. It could compete with 5.5 mills/Kwh ($12.35 per metric ton for 10,000 BTU per pound coal burned at a thermal efficiency of 35%), fuel at a 6½% return or less. If cost of fuel were 6.5 mills/Kwh ($14.77 per metric ton for 10,000 BTU per pound coal burned in a plant having a 35% thermal efficiency) a nuclear plant could afford up to 12½% on investment and still be more economical.

CONCLUSIONS

51. It is concluded that a nuclear power station having an electrical capacity of 75-100 Mw, or larger, could be designed and built on essentially present technology. In certain locations such a plant would have a high degree of probability of producing electricity at costs competitive with those of electricity produced from fossil fuels. It appears possible to establish circumstances that would have to be met in order for it to do so today:

(a) The generation and distribution system into which the nuclear plant is to be integrated must be large, capable of accepting a 100 MW plant at a high plant factor.

(b) The nuclear plant would have to be located in a country with relatively high fossil fuel costs, and with sufficient availability of capital so that the return on investment in the plant could be moderately low.

(c) The country must have executed whatever political agreements that are necessary to assure a continuing supply of fuel at prices consistent with those used in this paper, reprocessing, and, if necessary, the import of components.

(d) The country must have a degree of economic stability so that if the nuclear plant should cost more than expected or should not perform as anticipated, the excess cost could be absorbed without a significant adverse effect.

(e) Until further operational experience has been obtained, it would not be prudent to establish the nuclear plant in a system where it would represent a considerable proportion of the total system generating capacity. X

X this wd. leave eligible only a few underdeveloped countries or areas, e.g. Brazil, Mexico Bombay

HEAT, PROPULSION, AND SMALLER POWER NUCLEAR REACTORS

Heat Reactors

1. The considerations that have been discussed relative to power reactors apply to the process or space heat reactors, and to propulsion reactors with some modification. The capital cost of a process heat reactor would probably be less -- perhaps as much as 20 or 30 percent less -- than for an electric power reactor, since the turbo-generator side of the plant would be essentially eliminated. On the other hand, the problem of finding a suitable system or plant to utilize the large amount of heat produced is limiting. Also, while the nuclear power plant would have an overall thermal efficiency of perhaps 20% (in other words, a 100 Mw electric capacity nuclear plant would have close to 500 Mw of heat capacity), the process heat plant would have a thermal efficiency of perhaps 90 percent.

2. While the effect of size on process heat reactor costs would not be the same as was noted in the case of the nuclear power reactor, it will be felt, and there will be a size below which the process heat reactor will steeply rise in cost per unit output. Just what that range of size will be is yet to be determined. In sum, as concerns process or space heat reactors, no calculations or analyses of their economics have been published; thus, while that application is of interest to the Bank, it appears premature to attempt to arrive at judgements as to its economic feasibility. It should be noted that Sweden is planning an experimental space heating reactor of about 90 Mw thermal capacity to be completed around 1960. This reactor is planned to provide space heating to portions of the City of Vasteras (population about 65,000). Norway is also considering an experimental industrial heat reactor for use in conjunction with a wood processing plant

at Halden. This reactor would have a thermal capacity of 10-12 Mw and would begin operation in about three years. It is expected to provide about 20-25% of the plant's hourly steam requirements. Detailed information on these reactors, and the estimated economics of their operation, should begin to be available for analysis soon.

Propulsion Reactors

3. As for propulsion reactors, again the field looks interesting from an economic point of view; the information on it published today is not sufficient to form the base of any judgements on its practicability. The first application of a reactor to propel a vehicle is in the atomic submarine "Nautilus". The Nautilus is powered by a pressurized water reactor and because the reactor needs no oxygen to support "combustion", she has in effect an unlimited range at very high speed submerged at great depth. Conventionally powered submarines, on the other hand, are severely limited in such a situation, being capable of only about an hour's operation at high speed when deeply submerged. In comparison, the U. S. Navy has announced that the Nautilus cruised over 1600 miles at an average speed of 16 knots submerged at depth. The relatively unlimited range underwater of the Nautilus has been likened in significance to the development of ironclad naval vessels in that it will demand a revolutionary change in naval tactics both defensive and offensive.

4. The application of nuclear power to the propulsion of naval vessels is only in its infancy, but already a half dozen nuclear submarines are being built and the Navy and AEC are beginning work on a land-based prototype of a large surface ship reactor. In these naval applications, however, the cost of propulsion is secondary to performance and displacement. A higher cost

per mile or per hour can be tolerated because of the unique performance of the nuclear propelled ship.

5. In the case of commercial ship propulsion, however, costs must be considered. The higher nuclear costs tend to make commercial ship propulsion unattractive at least insofar as the U.S. is concerned. Work is going on both in the U.S., the U.K., and Norway, however, to develop a practical and economic reactor system for merchant ship propulsion. Such applications, however, are much farther from realization than the propulsion of military ships where cost is a minor consideration.

Small Power Reactors

6. The discussion that has preceded has concerned the feasibility of building 75-100 Mw and larger nuclear power reactors which might produce electricity at costs competitive with conventionally fuelled thermal power stations in some situations. The development of small nuclear power stations, suitable for use in remote locations such as the Arctic or in under-developed countries where the demand for electricity occurs in relatively small units, has not progressed as far as has the development of larger central station units. Work is going on, particularly in the United States and Canada, to develop reactor systems for such smaller, specialized uses. As a rough estimate, if nuclear power can be produced for 20 to 30 mills/Kwh in plants having capacities of 3 to 5 Mw electric, there would be a demand for such reactors in the remote areas of Canada, for example, in some areas of Africa, and undoubtedly in Asia and South America. To make 20-30 mills/Kwh nuclear power, the capital cost for the reactor would probably have to be no more than $600/Kw. This implies a production rather than a custom scale manufacture. As of today, however, it is not possible to evaluate the

economic feasibility of building a reactor in the 3-5 Mw range.

7. For reactors in the 10 Mw range, some estimates have been made. There, the capital costs might be about $400/Kw, and the fuel and inventory costs perhaps 9 mills/Kwh. The operating and maintenance costs might be about 2 mills/Kwh. If a 10% return on investment is assumed, and a plant factor of 80%, such a plant might produce power which could be sold at the bus bar for under 20 mills/Kwh. It is to be expected that the fuel cost and the capital cost will lower as the technology develops. It is not unreasonable to expect plants of this size to produce power which could be sold at the bus bar at about 15 mills/Kwhr at a plant factor of 80% and perhaps lower depending upon financial charges. The three reactors being considered by American Foreign Power for installation in South America fall in this category. It will be possible to arrive at a somewhat more definitive appraisal of the economic feasibility of reactors in this size range after t[illegible] bids for the three AFP reactors have been submitted, and the designs made available for analysis later this year. The 10 Mw reactor which Westinghou[illegible] is to build for the Brussels exposition also falls in this category.

8. In the medium size reactor range, the problems of development are much like those for the larger central power plants, and their introduction will follow, rather than precede, the commercial entry of the larger plants which are already under development. It is to be expected that the capital cost of such reactors will be higher per kilowatt of capacity than for the larger stations, since the cost of turbo-generator equipment and the cost of the reactor are affected more exponentially than linearly by a decrease in electric capacity. However, the fuel costs of such reactors should not be significantly different than for the larger central station nuclear plants.

Because the cost of electricity from conventional stations in this size rang
is usually higher than electricity for larger thermal stations, the nuclear plant will undoubtedly be able to compete in the size range also. However, as of today, it is not possible to develop a detailed analysis of what cost to expect since little developmental interest has so far been directed towar such a reactor. The United States is planning to design and construct seve reactors in this size range, but no estimates of cost or of performance are yet available.