ECONOMIC EFFECTS OF NUCLEAR ENERGY IN JAPAN

by

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I. INTRODUCTION

The availability of an abundant and assured supply of energy at a stable and relatively moderate cost compared to that of other countries has been considered an essential and necessary prerequisite for economic growth and improvement of the standards of living in a nation.

The demand for energy in Japan has been increasing so fast owing to the rapid economic growth that it has been no longer possible to meet the needs with only domestic sources. In order to assure the supply of energy at a stable and reasonable cost, national policies must be established for securing energy supply only after careful consideration. Such consideration should be based on the long-term projection of the national demand for energy and matched with the world trend of the supply and demand relation of energy as Japan has limited natural energy resources, and it usually takes a long time to explore natural energy resources and build up equipment for the supply of energy even though some recoverable energy resources exist.

Although domestic coal had occupied a prominent position in the energy supply in the past, other fuels are becoming competitive. In addition to the rapid expansion of demand of energy and customers' preference, the fierce competition of cost among energy sources has caused a shift of the energy patterns to liquid type energy sources which must be imported from foreign countries because of lack of liquid energy sources in Japan. The declining demand for coal caused such social troubles as unemployment problems in the coal mining industry and depressed local regional economy around coal mining areas.

In the present situation the increasing predominance of liquid type energy and its eventual predominance over the domestic coal (1) has induced greater dependence on foreign energy supplies resulting in sensitive economic influence to the Japanese economy and international balance of payment, which might limit and handicap the degree of freedom of the economic growth. Increasing consumption of liquid type energy sources, especially petroleum, has caused environmental pollution problems which present serious hazards not only to man but also to other living beings. Thus the aspects concerned with supply and demand patterns of energy involve social concern as well as economic interest.

While the established supremacy of liquid type energy, e.g., petroleum which must be imported, places some restrictions on the national economy and the energy industry, the economic renumerativeness of nuclear energy that has been gradually proved during recent years, and whose practical generating power is now being started, is important to study relative to its significant effects or influences as a new energy source and a new competitor to the imported liquid type energy, in the field of generating electricity.

In evaluating nuclear power, the author chose the light water type reactor which uses slightly enriched uranium and which has recently utilized for commercial power plant to generate electricity with relatively favorable power cost after intensive investigation mainly in the United States of America, and which has been imported to Japan.

The purpose of this paper is to discuss the effects of a new energy source, nuclear energy, which has a relatively large amount of resources in the world and is expected to share a main role in the energy supply of Japan in the near future in spite of the limited nuclear fuel resources in Japan.

II. FEATURES OF ENERGY SOURCES

"Energy" is a generic word of many applications and nuances, associated with the general idea of "capacity to do work." For purposes pertinent to an economic study of energy, it may be confined mainly to functions related to activating mechanical equipment and using heat in other useful ways (7).

Conventional terminology distinguishes between primary and secondary sources. The primary sources of energy may be listed as crude oil, natural gas, natural gas liquid, coal, and waterpower. Most recently, nuclear fuel has been added to the list as an economically usable source. On the horizon of economic utilization, oil shale will be an available energy form in the future (7). Primary sources such as geothermal, tide-waterpower, and solar are still not judged to be of sufficient weight in the Japan's foreseeable energy supply to raise policy issues calling for positively strong research in the next few years.

Electricity is classified as a "secondary" source of energy because the primary sources are used to produce it. Once produced, it performs various services that are unique to it; but it also performs some services of the same sort as those provided by the primary energy sources (1). Two of the primary energy sources, water and nuclear fuel, are most closely related to electricity in the present technology of utilization of energy. Their current usefulness in the context of energy is confined almost solely to the generation of electricity although other applications of nuclear energy such as desalination and furnace heating are now being developed. The geothermal energy is also used for generation of electricity.

Coal has a close relationship in that a major fraction of all coal produced in Japan is used for generation of electricity in the electric utility because the demand for the electric utility has been supported strategically and politically due to the fact that though coal is higher cost than liquid type energy sources such as crude oil and its products (called "oil"), it is the only domestic energy source which is relatively abundant in Japan. Oil and natural gas, including liquified natural gas, are also used for generation of electricity.

The various energy sources are substitutable for one another over a wide range. Railway locomotives may be fired by oil or coal, or run by electricity. Buildings may be heated with coal, oil, natural gas, or electricity. The boiler fuel to produce steam pressure for process heat or for activating industrial equipment may be coal, oil, or natural gas. Industrial furnaces for processes that do not require steam may derive heat from fossil fuel or from electricity. Nuclear energy will be able to be used for producing steam, heating furnaces and powering ships etc., more effectively in the future.

The extent to which particular forms of energy are applied to particular uses in part is the result of changing supply conditions and prices of the various sources; in part, it is dependent on changing technology which establishes preferable efficiencies in various uses. In some cases a single source of energy will entirely replace another; oil, for example, has replaced coal as locomotive fuel and for residential and commercial usages. Electricity has replaced oil and gas for lighting purposes.

More commonly, however, two or three energy sources are possibly in use at the same time for the same purposes, as for space heating and industrial boiler fuel. The margins of use are usually established by economic cost-price factor, and frequently contain a geographical factor.

In spite of high cost of coal, higher transportation cost of other energy sources to customer sites allow coal to be used competitively in the areas where coal mining is close and from which the places of producing or refining of oil and natural gas are far.

Though interchangeability of energy sources is the rule of the utilization, in some cases single energy sources take over the whole field, mainly for technological reasons but partly for reasons of cost. Oil provides the sole fuel for internal combustion motors though other fuels could be used and means other than internal combustion engines could be employed for mobile vehicles. For a variety of industrial process, the electrical motors are sole applicable agents.

Because the sources of energy are so generally interchangeable, for many planning and policy purposes energy must be considered in the aggregate. In all projections of economic growth the future requirements for energy may expand significantly much faster than population, and almost the same as the gross national product (9).

Public policy is necessarily concerned, among other things, with assuring the availability of expanded supplies adequate to these needs. This concern often needs not take the form of separate concern for supplies from individual sources - gas, oil, coal, nuclear energy, etc. - with their sum, whatever the sources are. The sum is, of course, made up of the parts; and thought must be given to the contribution of the parts severally.

"Energy sources" are taken to mean the primary sources of energy available in nature. These are measured in this paper by their contained energy in kcal unit according to the commonly accepted quantity ratios in Appendix A - except for waterpower which is measured by kilowatt-hour (kwh) of electricity obtained from waterpower. Electric power in kwh is theoretically equivalent to kcal in the ratio of 1 kwh=860 kcal, but in summing total primary energy sources, the equivalent of 1 kwh of electric power is taken as the number of kcal that would have to be consumed in producing 1 kwh from other primary energy sources, e.g., the fossil fuels.

Throughout this paper, the term "power" is used to refer to electric energy, while the term "energy" is used in a broader sense.

Animate energy sources, including human and animal work energy, are ignored in measuring primary energy on the grounds that they are not primary sources.

III. THE PRESENT AND PROJECTED FUTURE SITUATION AND THEIR PROBLEMS

A. Energy and the National Economy

Energy is an essential prerequisite for a modern industrial society. It must, therefore, be supplied sufficiently and continuously at as a low cost as possible. Broadly speaking, the Industrial Revolution introduced the substitutions of controlled mechanical energy for human and animal energy. Not only has this substitution been long underway in industrialized economies, but the total amount of consumed energy has increased faster than population as the result of changing technology, new products, and improving standard of living. The trend of the total energy supply which is almost linear with the final consumption of energy has shown very close correlation to the gross national product.

1. Past trend of supply of energy

During the past decades, energy demand which is measured at the energy supplier's side and which is called demand of energy in this paper has increased to about 4.5 times, from 55.7 x 10^{13} kcal or 55.7 million kl (in terms of oil equivalent of about 10,000 kcal/liter (29). The sign * in the following parts means the same conversion) in the fiscal year 1954 to 253.0 million kl* in the fiscal year 1968 (29). The annual average rate of increase of energy is 11.5%. The gross national product (GNP) in the corresponding terms to that of energy rose about 3.9 times, from 11,811 billion yen or 32.8 billion dollars in the fiscal year 1954 to 46,418 billion yen or 129 billion dollars in the fiscal year 1968 (29). The annual average increase rate of GNP is 10.0 %. Energy demand has been, therefore, rising at a little higher rate than GNP. Energy demand per capita has increased 3.96 times, from 6.3×10^9 kcal in the fiscal year 1954 to 24.95×10^9 kcal in the fiscal year 1968 (29). The annual average increase rate of energy demand per capita is 10.0%.

When final consumption of energy, which is defined as the actually consumed energy at customer's sides, is classified by the kind of consumers, the iron and steel industry shows the greatest expansion, 6.15 times during the same period as mentioned, which is an annual average increase rate of 16.0% (29). In comparison with the share for residential and commercial usages, a greater share for the mining and manufacturing industries is a feature of energy consumption in Japan so far as the categories of consumers are concerned. The shares for the mining and manufacturing industries to the total final consumption were 50.4% in the fiscal year 1954, 54.8% in the fiscal year 1960, 51.2% in the fiscal year 1965, and 50.4% in the fiscal year 1968 respectively (29). It may be attributable to the fact that the mining and

Table 1. Total energy supply, electric power supply, population, GNP and index of industry productivity (29)

Fiscal year[a]	Total energy supply (10^{13} kcal) (A)	Electric power supply (10^{13} kcal) (B)	Population (million) (C)	GNP (10^{11} yen[b] 1965[c] value) (D)
1955	60.70	15.98	89.28	131.56
1960	101.89	28.30	93.42	203.48
1965	180.17	47.07	98.28	323.05
1968	257.06	66.94	101.41	464.18

[a]Fiscal year begins on April 1st and ends on March 31st, next calendar year.

[b]Yen = $ $\frac{1}{360}$.

[c]1965 is calendar year.

Index of Industry productivity (1965=100.0) (E)	Total energy supply per capita (10^6 kcal) (A/C)	Electric power supply per capita (10^6 kcal) (B/C)	Total energy supply per GNP (kcal/yen) (A/D)	Electric power supply per GNP (kcal/yen) (B/D)
28.3	6.81	1.79	46.1	12.2
60.5	10.9	3.04	50.2	13.9
101.3	18.4	4.78	55.8	14.3
164.9	25.3	6.83	55.4	14.4

manufacturing industries as a whole have been growing fast, and of those industries, the iron and steel industry and the petrochemical industries which generally need a relatively large amount of energy have expanded their production at higher rates (29).

A classification of consumption by the forms of energy showed that the increased amounts of oil and electricity were larger than the reduced amount of consumption of coal (1). Of 165.8×10^{13} kcal or 165.8 million kl* which represented the net increased amount in final consumption of energy between fiscal year 1954 and 1968, oil or petroleum products occupied 108.7×10^{13} kcal or 65.8%, electricity 50.0×10^{13} kcal or 30.0%, and other forms of energy except coal 15.4×10^{13} kcal or 9.3%, while coal showed minus 8.5×10^{13} kcal or minus 5.1% (1).

A shift toward petroleum products was quite remarkable in final consumption of energy. In the fiscal year 1968, consequently, the relative final consumption of energy were 55% for petroleum products, 29.3% for electricity, 3.3% for coal and 11.9% for others (1).

2. Public involvement with energy industry

In approaching the subject of energy from this collective point of view, we must first pay attention to the forms of the separate industries that supply energy. Each industry has developed its own characteristic form. The business firms in each industry are in competition with one another for their places in the market. At the same time, the members of each industry are in competition with other industries, all of which are attempting to expand their positions in total energy market since most energy forms are interchangeable.

The method of relying on private enterprise, not only to establish for each firm its position in its own industry but also to establish its favorable role of the industry in the total economy, is the primary characteristics of the Japanese liberal economy system (19). This method is normally carried out under the slightly restricted provisions of the "antitrust law" policy designed to prevent excessively concentrated or monopolitic businesses, except for a few special industries, such as some public utility industries which are usually regulated by other special laws.

To the extent that the energy industry conforms to its characteristic patterns of industrial organization, it is a simple member of the Japanese economic universe. The fact is, however, that the separate energy industries have given rise to special problems which bring all of them under special and diverse methods of direct public regulation.

Strictly speaking, the price control is adopted only to public utilities, such as electric utility and gas utility which undertake supplying electric power and gas to meet the demand of the general public respectively (12, 13). In consideration of the energy policy in Japan the electric utility plays an important role which will be mentioned later related to nuclear power.

The trend of the total energy demand shown in Figure 1 indicated some interesting aspects;

1. The increasing rate of the total energy demand had been much larger than that of the population, in other words, the total energy demand per capita had increased at higher rate.

2. Before fiscal year 1965 the index of the energy demand lay below that of GNP, and after fiscal year 1966 that of the energy demand lay above that of GNP, in other words, the recent trend of the energy demand showed that the energy demand per GNP increased and more energy was required to get the same value from products in spite of the improving thermal efficiencies in most producing processes. On the contrary, the trend of the energy demand lay above the trend of the index of the industry productivity until 1962 and after 1963 the position was changed reversely. Roughly speaking, some fraction of the energy demand seemed to be used for less contributed purposes to increase GNP at higher rate than to be used for more contributed purposes to do it. This implies the annual increasing rate of the required energy for residential and commercial usages seemed to expand their

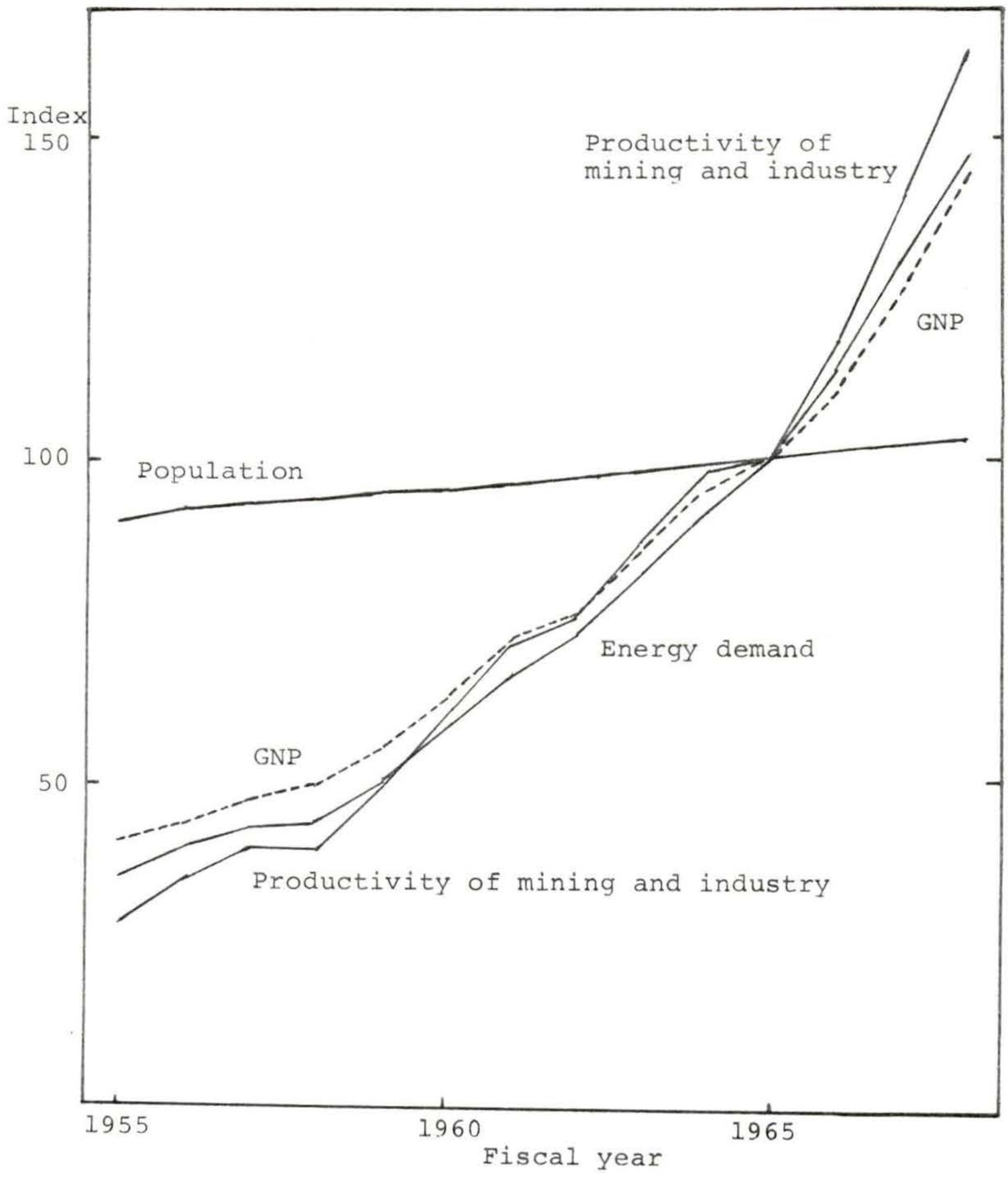

Figure 1. Index of population, GNP, productivity of mining and industry, and energy demand (1965 value = 100.0) (29)

shares in the total energy demand due to the improvement of the standard of living and development of commercial service.

Table 2. Ratios of industrial and other usages to the total energy demand (29)

Fiscal year	1954	(unit: %) 1960	1965	1968
Industrial usage	50.4	54.8	51.2	50.4
Other usages	49.6	45.2	48.8	49.6

It can be said that energy forms which are suitable and preferable for the usages of the residential and commercial purposes will be increasing their shares in the total demand in the future if the efficiencies of energy of industrial usages continue to be improved or be kept at the present level under the technical and economic situation which is not so greatly changed that it is considered unusual conditions continue for long time.

As a preferable energy is required to have such characters as inexpensiveness, convenience and cleanness, liquid type or gas form energy is favorable compared with solid form energy under the present technical condition and at the same energy cost as that of solid. Electricity may be more favorable than liquid, gas, or solid form energy if it can overcome its higher cost to the extent that it can compete with others.

B. Trend of Transformation into Secondary Sources of Energy

At the stage of transformation of energy, the fast growth of the iron and steel industry has brought about a substantial expansion in consumption of raw materials for coke as well as of energy for electric power generation which has increased at the high rate. As for raw materials of coke there has been an obvious trend in the consumption of coal, namely a change of the ratio of the indigenous to imported coal because the indigenous coal is not suitable for making high quality coke.

In the fiscal year 1955, 7.15 million tons of coal was used to produce coke, and of it, the indigenous coal occupied 65% and the imported 35% (29). As a result of increasing imported high grade coal for coking the corresponding ratios were changed to 52% for the indigenous coal and 48% for imported one in the fiscal year 1960, 33% for the indigenous and for 67% for imported in the fiscal year 1965, and 27% for the indigenous and 73% for imported in the fiscal year 1968 (29). The amount of the indigenous coal for coking in quantity has kept almost the same level since 1960, while imported coal has increased its amount and share at high rate (29).

Table 3. Primary energy demand (29)

	(unit: 10^{13} kcal)							
	Hydraulic power		Coal[a]		Oil[b]		Natural gas	
		%[c]		%		%		%
1955	11.88	19.6	31.17	51.4	12.37	20.4	0.24	0.4
1960	14.33	14.1	43.23	42.4	39.20	38.4	0.93	0.9
1965	18.77	10.4	49.96	27.8	106.47	58.0	2.01	1.1
1968	18.55	7.2	62.51	24.3	171.16	66.5	2.39	0.9

[a]Included anthracite, bituminous, lignite and imported coke.

[b]Included crude oil and its products.

[c]Is a ratio of each amount of energy source to that of total energy of corresponding fiscal year.

[d]Included charcoal.

Wood[d]		Nuclear power		Total energy demand		Ratio of imported to total energy demand
	%		%		%	%
4.46	7.3	-	-	60.70	100.0	23.8
3.62	3.6	-	-	101.89	100.0	44.2
2.70	1.5	0.0	0.0	180.17	100.0	66.1
2.22	0.8	0.26	0.1	257.06	100.0	77.4

The electric power generated had recorded a remarked increase from 65.2 billion kwh in the fiscal 1955 to 273.2 billion kwh in the fiscal year 1968. Out of the net increase during the same period, 26.1 billion kwh or 12.6% had been produced by hydraulic power, 180.8 billion kwh or 86.9% by fossil fuel burning power, and 1.0 billion kwh or 0.5% by nuclear power (29). Fossil fuel burning power had been predominently responsible for the electric power increase (5).

48.5 billion kwh or 75.2% was produced by hydraulic power and 16.7 billion kwh or 24.8% by fossil fuel burning power in the fiscal year 1955, and 74.7 billion kwh or 27.4% by hydraulic power, 197.5 billion kwh or 72.3% by fossil fuel burning power, and 1.0 billion kwh or 0.3% by nuclear power in the fiscal year 1968 (29). A shift from hydraulic power to thermal power has been remarkable. The same trend as the power production had reflected on the construction of new additional generating facilities. Of 38.6 million kw which had been newly constructed in the electric power industry from fiscal year 1955 to 1968, 8.9 million kw or 23.1% represented hydraulic power facilities, 29.1 million kw or 75.5% fossil fuel burning power ones, and 0.18 million kw or 0.4% nuclear power ones. And some other type power plants including geothermal shared 0.4 million or 1.0% (4).

Fuel consumption of thermal power generation also increased rapidly reflecting the increase of thermal power generation. 0.3 x 10^{13} kcal of oil and 3.8 x 10^{13} kcal of coal were burned for generating power at thermal power plants in the fiscal year 1955, 12.4 x 10^{13} kcal and 10.1 x 10^{13} kcal in the fiscal year 1965, and 24.4 x 10^{13} kcal and 13.2 x 10^{13} kcal in the fiscal year 1968 respectively (4, 29).

In the field of nuclear power generation, the Tokai Plant of Japan Atomic Power Co. emerged from the experimental stage when it started continuous operation on the nuclear power reactor in July 1966 in despite of difficulties in the course of its construction since December 1959 (15). Following the Tokai Plant the construction of a few nuclear power reactors for generation of power, of which most main equipment parts have been imported, has been already launched under the foreign supervision since the technology and industrial background related to the nuclear power complex are still not developed in Japan.

It may well be said that not only the time of nuclear power generation for practical use but also the development of the technology in Japan are now at a starting point.

C. Trend of Demand of Primary Energy Sources

1. Trend of total demand of primary energy sources

The changes in the final consumption form and transformation of energy have been reflected by the supply pattern of primary energy in the form of remarkably important changes of structure - a rapid expansion of oil supply and a deterioration of the status of coal, particularly, the indigenous coal. This fact was well demonstrated by the analysis of the net increase of demand of primary energy in the past trend (29).

Of the total demand of primary energy, 60.7×10^{13} kcal in the fiscal year 1955, 11.9×10^{13} kcal or 19.6% was supplied by hydraulic power, 31.2×10^{13} kcal or 51.4% by coal. Of the total demand of primary energy, 257.1×10^{13} kcal or 257.1 million kl* in the fiscal year 1968, 18.6×10^{13} kcal or 7.2% was supplied by hydraulic power, 62.5×10^{13} kcal or 24.3% by coal, 171.2×10^{13} kcal or 66.5% by oil, and also 0.26×10^{13} kcal or 0.1% was occupied by nuclear power generation as a commercial power production which was still expensive compared with other power production and which had a significance to practice and learn through the construction, maintenance and operation of a nuclear power plant (30).

In Japan the demand of energy has been growing much

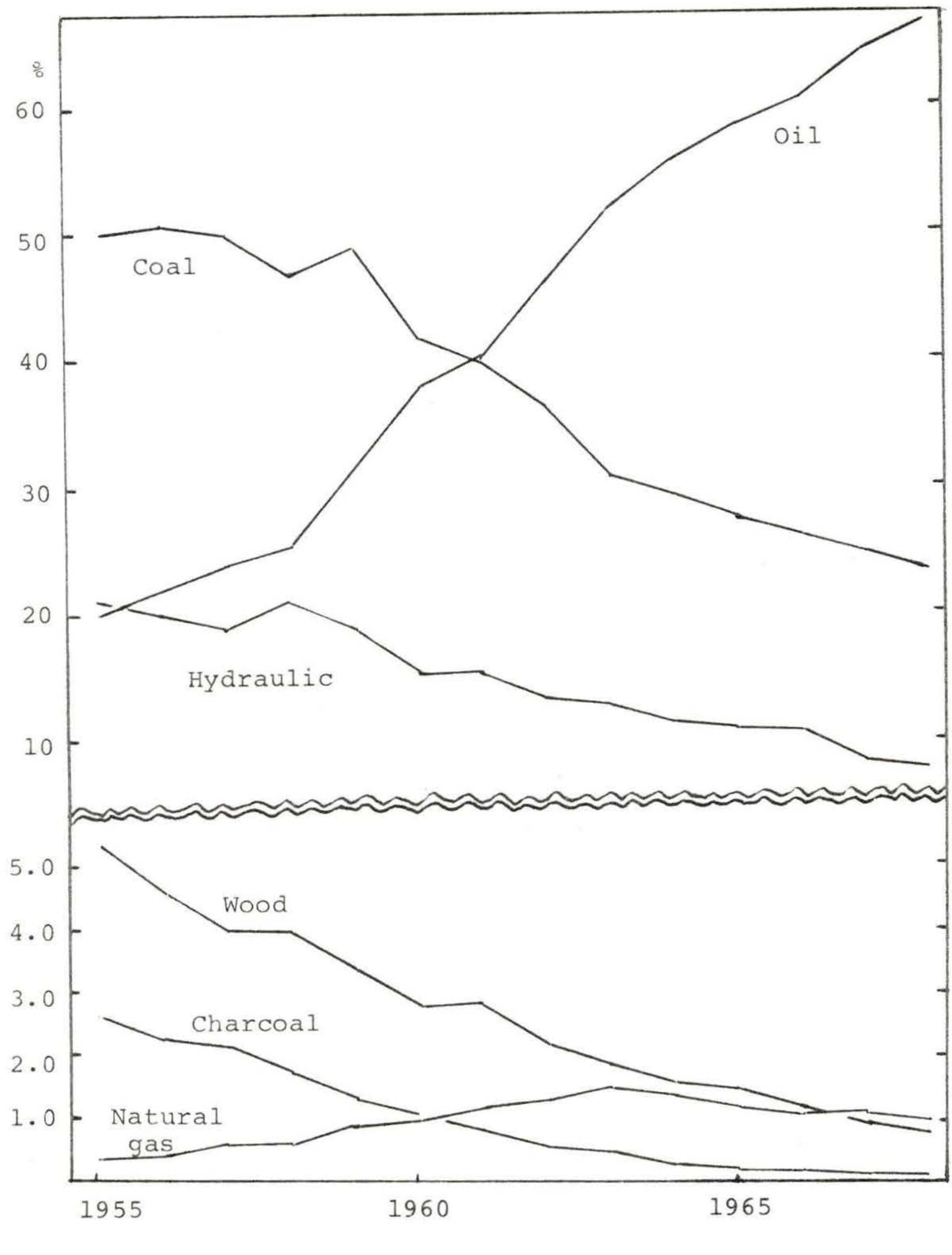

Figure 2. Shares of primary energy sources (29)

faster than those in the Western European industrialized countries (27). Oil has been responsible for the bulk of the increase of demand of energy and the tendency toward the liquid form energy sources has been more pronounced in Japan (1).

2. Trend of demand of primary energy sources for generating electric power

The geological and meterological conditions in Japan give favorable hydraulic power resources. Historically the electric power industry has owned greatly to hydraulic power. In the fiscal year 1955, hydraulic power plants occupied 74%, coal burning plants 24%, and oil burning plants only 2% in the supply of electric power (29).

Keeping pace with the rapid growth of Japan's economy, demand for electric power as a basic element has greatly increased with an average annual rate of increase 11.8% during the fiscal year 1955 to 1968 (29), so that the development of power should have been actively promoted to meet the fast growing demand. The hydraulic power is dependent on geological and meterological conditions, and the narrow land limits the hydraulic power resources quantitatively. In a result of active promotion of development of hydraulic power plant in the past time, favorable places to be developed have been gradually decreasing. On the contrary, thermal power plants which use steam heated mainly by

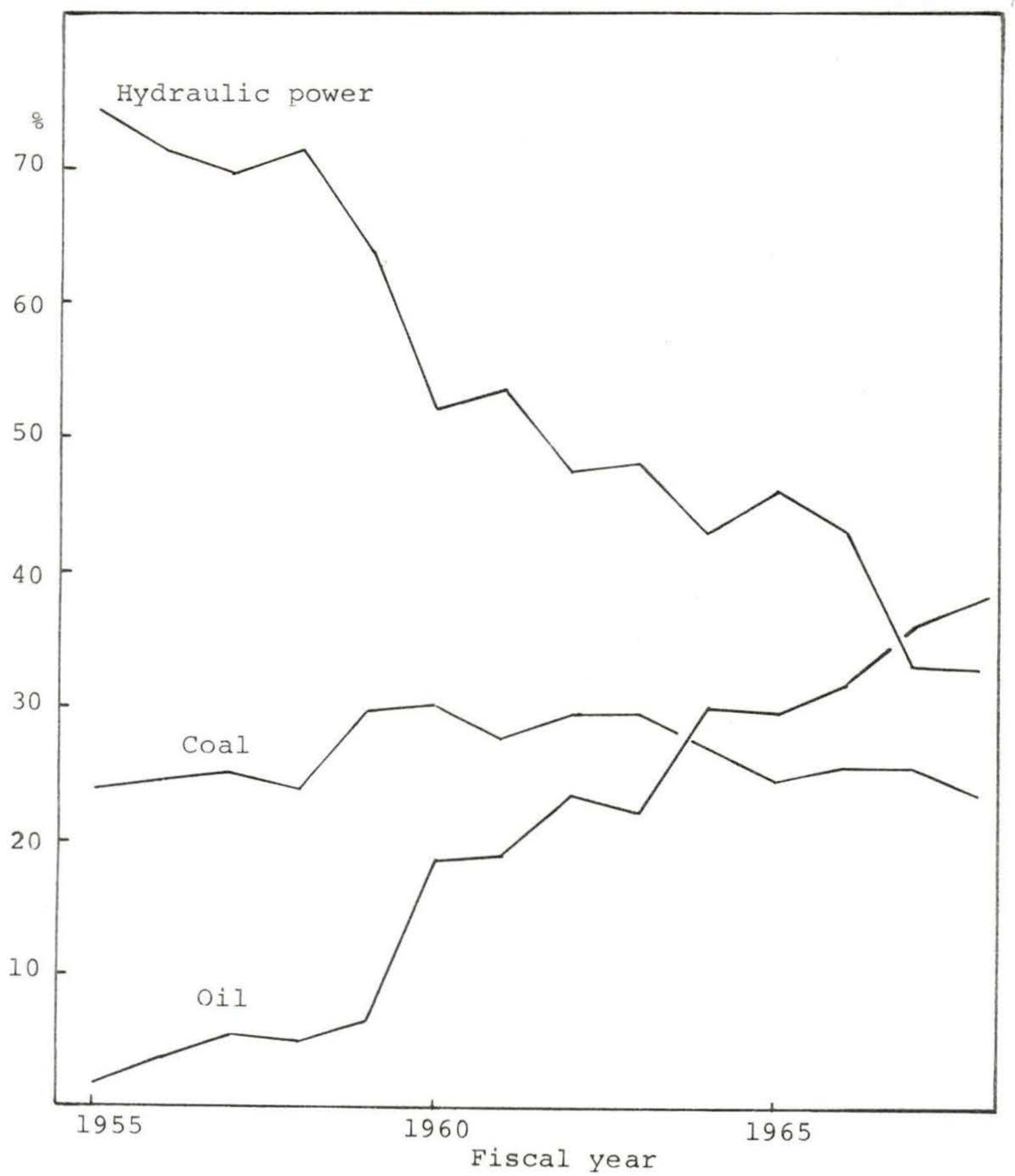

Figure 3. Shares of primary energy sources for generating electric power (29)

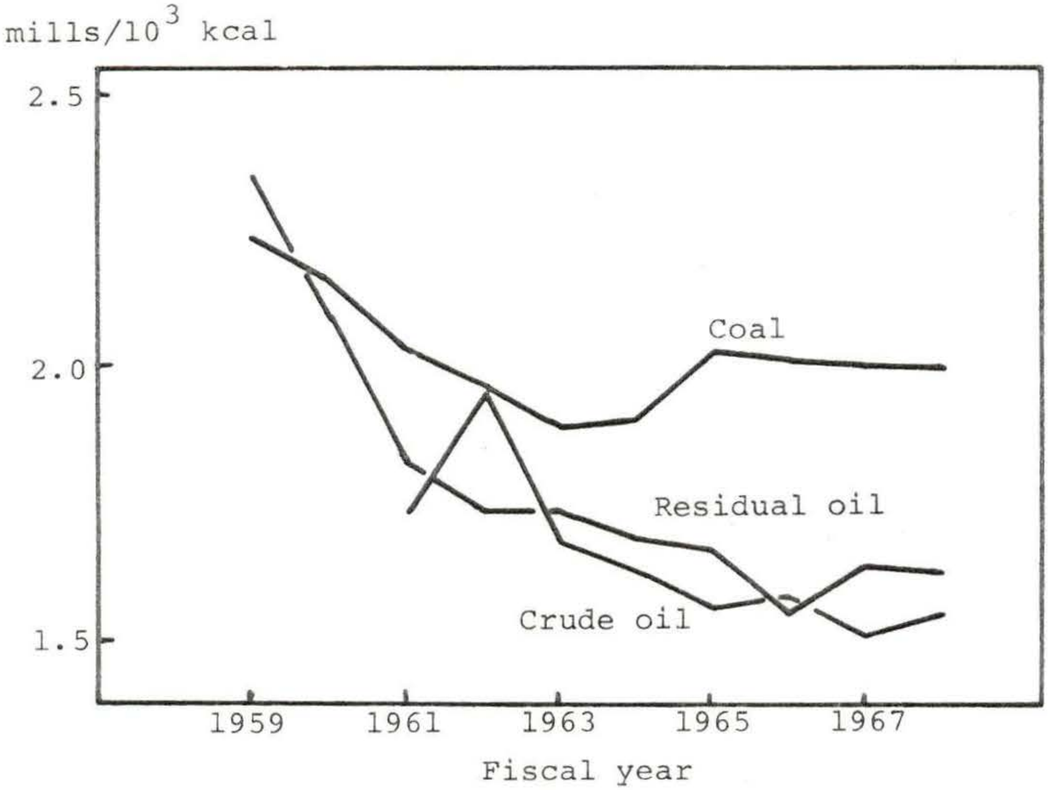

Figure 4. Price of fossil fuel for generation of electric power (29)

fossil fuel, especially, coal and oil have advanced their technical improvements, e.g., thermal efficiency, reduction of construction cost and reduction of construction period.

These improvements of the technology of thermal power plants and the tendency of declining cost of fuel oil have been economically attractive to build up thermal power plants in order to meet fast growing demand of power. The rate of thermal power plants has been so fast that the thermal power supply overcame the hydraulic power supply in the fiscal year 1962, and in the fiscal year 1968, 67% of the total electric power was generated by thermal power plants and only 33% by hydraulic power (29). Since the concern of the electric power industry is to generate cheaper electric power, the choice of primary energy sources is decided mainly by means of the total electric power cost including capital cost and fuel cost, which should be expected to become the cheapest. Thus, the development of hydraulic power plants has been discouraged due to less attractive economy, relatively long construction period and other complicated negotiation related to the coordination of the use of water. On the other hand, in the thermal plants, fuel used in power plants has been chosen by means of prices. In the early time, before the fiscal year 1959 coal had been favorable in price competition, but since 1960 the price of crude oil and its products have been decreasing rapidly due to the overproduction of crude oil in the producing countries and to the improvement of transportation.

The Japanese government had controlled the imported oil for generating electric power from the viewpoint of securing domestic energy market by enacting the law, "Law of Control of Installation of Boilers Using Residual Oil" (9). But the price of oil has continuously been decreasing and the difference between prices of oil and coal has spread because higher energy cost makes not only many industries impossible to compete in the international trade market but also general consumers suffered from expensive power cost. Recently the Law of Control of Installation of Boilers Using Residual Oil has been abolished and the Japanese government has set up a measure to secure a market for coal which will keep the same production rate as before by means of governmental supporting measures. Therefore, in the light of the energy cost of power oil burning thermal power plants will still increase rapidly to meet the demand for fast growing electric power in the near future unless new attractive primary energy sources appear. Here, we have a possibility to have a new primary energy source, nuclear energy, which will be expected to become favorably competitive against oil. Therefore, in this paper the effects of nuclear power is discussed in comparison with oil as a fuel of power plants.

D. Future Trend of Energy Demand

A projection of the future demand of energy was conducted by the Advisory Committee for Energy in 1967. The fiscal years, 1970, 1975, and 1985 were selected as the target times for the projections, and the gross national product (GNP) which would be considered as the most important parameter for the projection was assumed to grow at an average rate of 8% for the fiscal year 1965 to 1970, 7.5% for the fiscal year 1971 to 1975, and 6.5% for the fiscal year 1976 to 1985 (1).

The following were the results of the projections (1):

Total demand of energy, which had been estimated 145.8 million kl*, was actual value, 177.8 million kl* in the fiscal year 1965. They were estimated 242.5 million kl* in the fiscal year 1970, 340 million kl* in the fiscal 1975, and 604 million kl* in the fiscal 1985. The rate of growth would go down from 11.6% for the fiscal year 1961-1965 to 8.5% for the fiscal year 1966-1970, 7.1% for the fiscal year 1971-1975, and to 5.9% for the fiscal year 1976-1985.

Demand of energy per capita was 1,780 l* in the fiscal year 1965 and estimated to rise 2,350 l* in the fiscal year 1970, 3,150 l* in the fiscal year 1975, and 5,000 l* in the fiscal year 1985.

The forecast of final consumption of energy classified

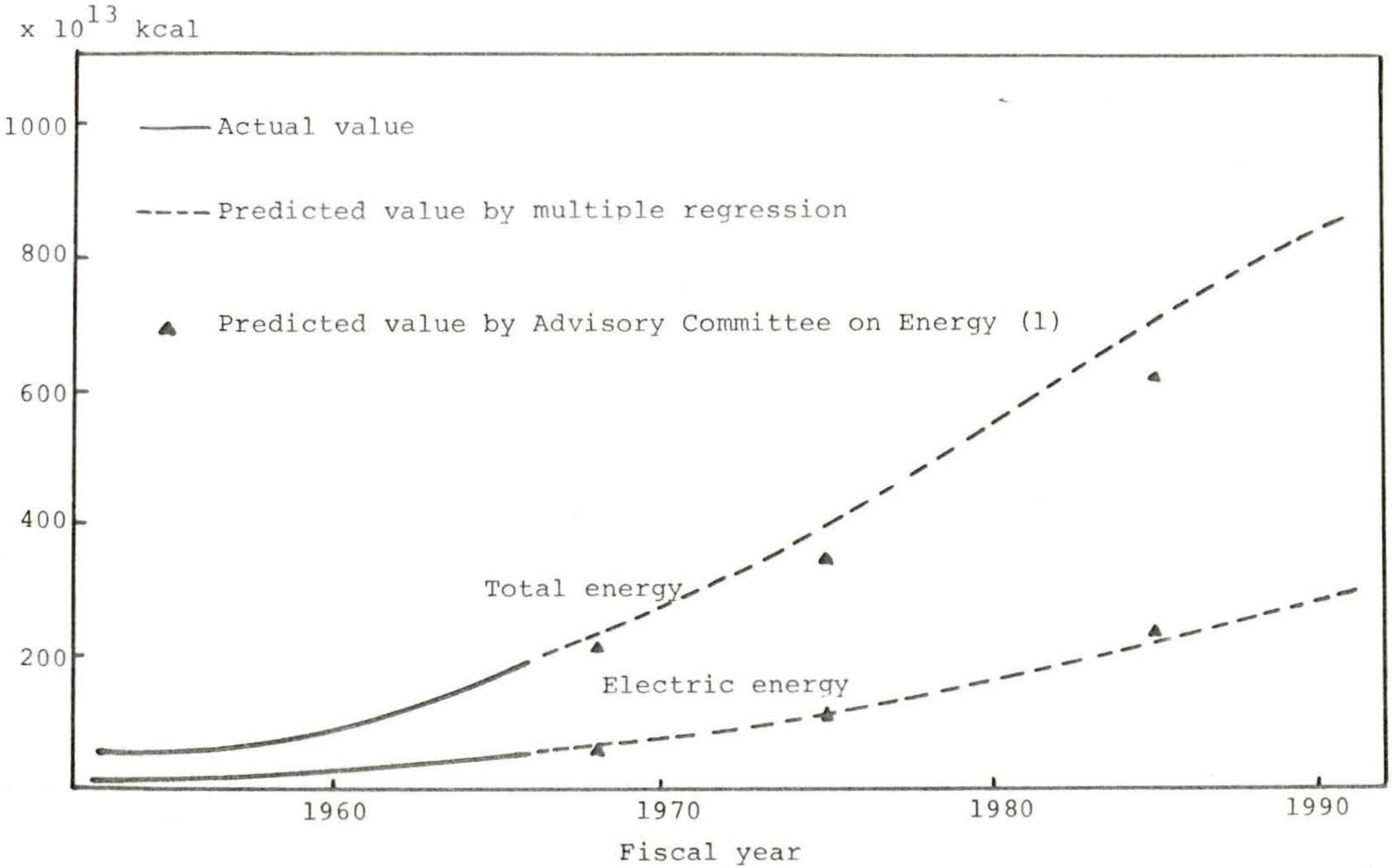

Figure 5. Predicted values of total energy and electric energy demand

by the form of consumers said that the consumption by the mining and manufacturing industries would show a large increase from 74.6 million kl* in the fiscal year 1965 to 110 million kl* in the fiscal year 1970, 150 million kl* in the fiscal year 1985. The consumption in the fiscal year 1970 would be 150% of that in the fiscal year 1965, 200% in the fiscal year 1975, and 344% in the fiscal year 1985.

The final consumption for uses other than energy would grow more remarkably as the future development of petrochemical industry would be expected certainly. This kind of the final consumption would go up 10 million kl* in the fiscal year 1965 to 19 million kl* (1.9 times) in the fiscal year 1970, 30 million kl* (3.0 times) in the fiscal year 1975.

In the area of specific demand, it was expected that industrial and household electrification would increase electric power demand, motorization and other factors would expand for gasoline and other petroleum products, and growing iron and steel production would push up demand of energy.

Due to the rapid growth of Japan's economy, production of electric power as a secondary energy source has increased at an average annual increase rate of 11.8% from the fiscal year 1955 to 1968, which has been higher than that of GNP during the same periods. To meet the fast growing demand, electric power development was positively and actively promoted with an emphasis on securing power supply quantitatively. Japan had been seriously suffering from the shortage of electric power supply since the end of the World War

II, but in the fiscal year 1962, the imbalance of supply and demand was solved.

It was expected that the demand of electric power including nonelectric utility's power stations would increase from actual figure, 192.1 billion kwh or 47.1 million kl* in the fiscal year 1965 to 300.0 billion kwh or 73.5 million kl* in the 1970, 450.2 billion kwh or 110.3 million kl* in the fiscal 1975 and 931.0 billion kwh or 228.1 million kl*. The average annual increase rate would be 9.4 percent from the fiscal year 1965 to 1970, 8.5 percent from the fiscal year 1971 to 1975, and 7.6 percent from the fiscal year 1976 to 1985. The rates of increase might appear to be lower due to slowing down the expected increase rate of GNP and the expected saturated demand per capita of the residential and commercial usages, but it should be noted that the absolute amount of increasing demand in the ten year period from the fiscal year 1966 to 1975 would be double amount of demand in the past ten year period from the fiscal year 1956 to 1965. The share of electric power in the total final energy consumption is projected to rise from 26.3% in the fiscal year 1965 to 34% in the fiscal year 1985 (1).

In this paper new predicted values which have been estimated using the multiple regression method where population and fiscal year are taken as parameters because the projected values by the Advisory Committee for Energy (1) are going far from the actual figures which have been increasing at higher rate than they were estimated.

E. Future Trend of Primary Energy Sources

In order to assure the future supply of primary energy sources, it is necessary to foresee the potentiality of possible primary energy sources not only qualitatively but also quantitatively.

Table 4. Electric power generated (29) (10^9 kwh)

Fiscal year	Hydraulic power		Thermal power[a]		Nuclear power		Total	
		%[b]		%		%		%
1955	48.5	74.4	16.7	25.6			65.2	100.0
1960	58.5	50.7	57.0	49.3			115.5	100.0
1965	76.4	39.8	115.7	60.2	0.04	0.0	192.1	100.0
1968	74.7	27.4	197.5	72.2	1.0	0.4	273.2	100.0

[a]Included geothermal and others rather than hydraulic and nuclear power.

[b]Is a ratio of each amount of energy source to that of total of corresponding fiscal year.

1. Coal

Coal represents more than 50% of the domestic indigenous primary energy produced in Japan (29) and has a relatively large amount of recoverable reserves; 28 billion tons; marginal and submarginal deposits are more than 70 billion tons (24).

The coal mining industry, being a major industry responsible for Japan's economic reconstruction and development after the completely destroyed national economy due to the World War II, steadily increased the production of coal and has taken the major role as a domestic energy source. Coal, however, has lost its former dominant position owing to its relatively high cost compared with that of oil in recent times.

Table 5a. Primary energy source for generating electric power (29) (10^{13} kcal)

Fiscal year	Hydraulic power		Coal		Oil		Natural gas		Nuclear power		Total energy	
		%[a]		%		%		%		%		%
1955	11.88	74.3	3.80	23.7	0.31	2.0	-	-	-	-	15.99	100.0
1960	14.33	51.7	8.19	30.0	4.96	18.3	0.0	0.0	-	-	27.43	100.0
1965	18.77	46.0	10.15	24.5	12.41	29.5	0.04	0.0	-	-	41.52	100.0
1968	18.30	32.9	13.18	23.3	24.44	43.3	0.0	0.0	0.26	0.5	56.84	100.0

[a]Is a ratio of each amount of energy source to that of total energy of corresponding fiscal year.

In addition to this disadvantage of the cost of production, the expensive transportation cost which is required for coal to be carried from the coal mining areas to energy consumers' sites accelerates to make it more unfavorable. Unfortunately, the main coal mining areas are located in the southern parts and northern parts, while the energy consumers' centers are in the center of Japan. The energy cost of coal used by electric power industry in the center is 1.8 times (4) as that in the northern parts where power plants are relatively near the coal mining areas. Although the production cost can be reduced to some extent, lowering the transportation cost seems to be limited (1). Even so, consumers' preference for the more easily handled energy sources, especially oil, may offset the reductions in the transportation costs. Even though technical innovations foster a rapid increase in the productivity of the coal mining industry, it will be difficult for the technical innovations to overcome the transportation cost disadvantage and the rising labor cost as far as fuel is concerned.

In the light of the competition of energy cost, it is clear that coal except one field in some northern parts of coal mining areas can not absorb the rise in labor cost and other production costs, and transportation cost to the extent that coal can keep a competitive cost against that of oil. There seems to be some justification for the Japanese government's support for the coal mining industry from the viewpoint of securing a stable indigenous primary energy source and keeping local and regional economy related to the coal mining industry in moderate condition (1) even though it is not easy to estimate the value of the security of the domestic coal industry.

According to the report on the energy policy by the Advisory Committee for Energy in 1967 (1) it said that:

> about 50 million tons of the domestic coal would be maintained from the viewpoint of the security of the national economy by means of the governmental price supporting policy in spite of its relatively high cost.

This implies that the relative position or share of the domestic coal as fuel in primary energy market will decrease year by year because total demand of energy is projected to increase, and that this domestic primary energy source, coal, will not be able to recover a major role in the primary energy market even though the total demand of coal is expected to increase for coking since the domestic coal can not be satisfied with the requirement of quality for making coke as well as of cost reduction compared with imported coal. Most of the high grade coke has been made of the imported coal. Other possible sources of coal except those supported by the Japanese government are also limited because of the preference and less expensive cost of oil.

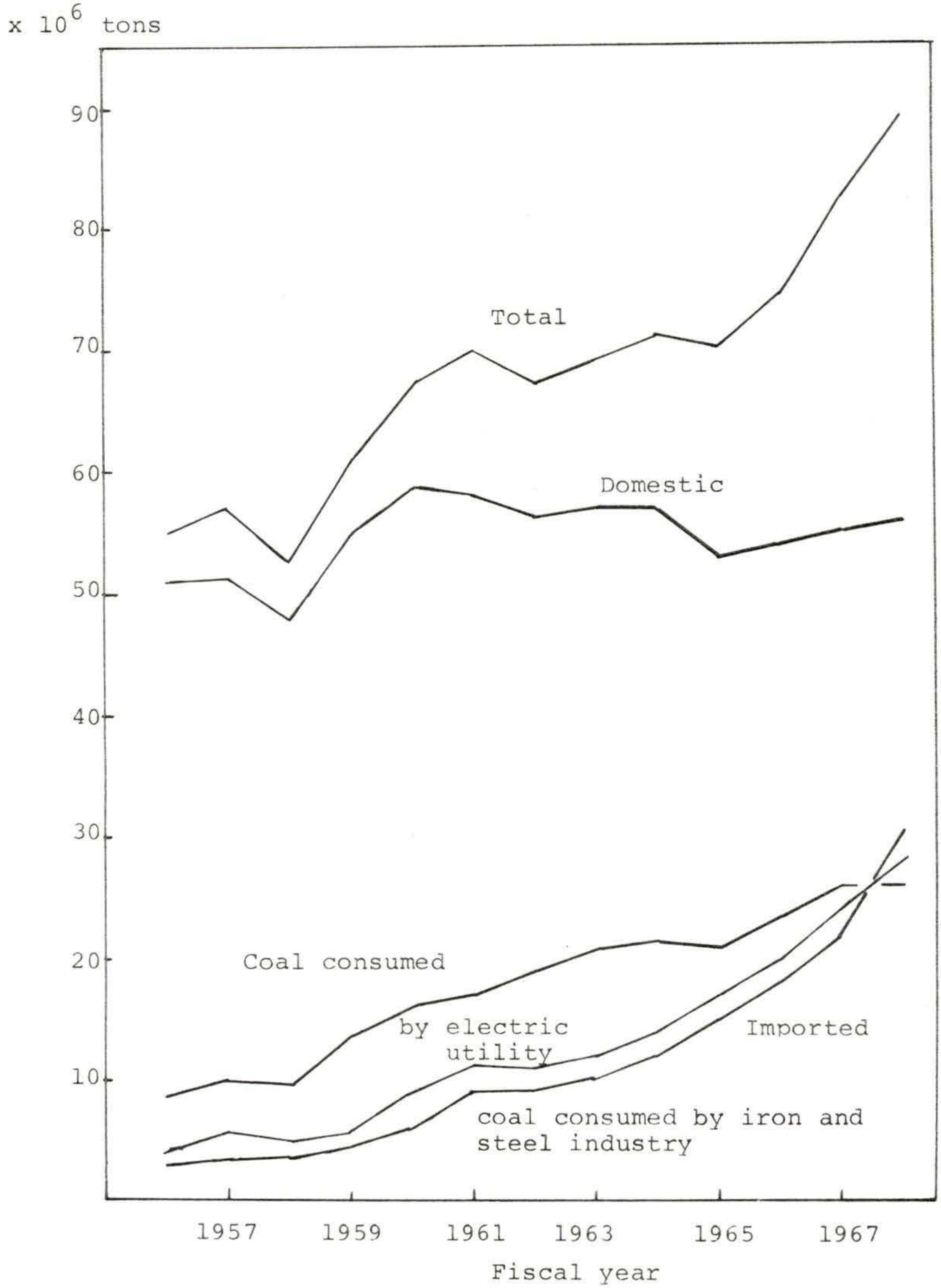

Figure 6. Coal supply (29)

Table 5b. Coal supply (29) (10^6t)

Fiscal year	Domestic coal	Imported coal	Total	Coal demand by electric utility	Imported coal for making coke
1955	50.0	3.8	53.8	7.2	2.5
1956	54.6	4.7	59.3	8.6	3.1
1957	59.1	6.8	65.9	9.9	3.6
1958	58.8	5.7	64.5	9.6	3.7
1959	62.1	6.5	68.6	13.7	4.6
1960	64.3	9.5	73.8	16.6	6.4
1961	65.5	13.2	78.7	17.2	8.9
1962	64.9	12.5	77.4	19.1	9.0
1963	63.4	13.3	76.7	20.9	9.5
1964	62.8	15.5	78.3	21.6	11.2
1965	62.5	19.0	81.5	20.8	15.2
1966	66.0	22.7	88.7	23.4	16.6
1967	63.7	29.6	93.3	26.2	22.3
1968	59.5	37.0	96.5	26.1	27.8

Therefore, we assume that coal just maintains the same production rate as that of the present situation, and that it does not increase its share in the primary energy market.

2. Hydraulic power

Hydraulic power has contributed an important role in the power supply though its relative share has been decreasing year by year. Table 6a shows that potential of hydraulic power in Japan.

Table 6a. Potential of hydraulic power (4) (1,000 MW)

Developed hydraulic power	17.6
Under construction	2.8
Undeveloped hydraulic power	16.8
Total	37.2

From the viewpoint of the hydraulic power as a major primary energy source, in addition to the fact that the potential of hydraulic power sources is too small in quantity to meet increasing demand of power, the conditions of the development of hydraulic power have been continuously deteriorating since sites of hydraulic power to be developed are now limited only to remote, technically difficult and less economical places in order to compete economically with thermal power.

Problems of land indemnity and coordination with other rights of the utilization of water related to the construction of hydraulic power plants have been getting more and more complicated and spreading in the wide range. The complexity of the development of hydraulic power seems to discourage the electric power industry from promoting the construction.

Thus, hydraulic power has been declining not only its relative share in the primary energy demand but also in economic importance due to small potential of hydraulic power reserves, complicated coordination at the development, and expensive construction cost which can not be offset by cheaper operation cost including maintenance cost compared with the cost of thermal power.

Though hydraulic power plants have qualitative superiority over thermal power plants, such as quick adaptability to change in load and to emergency, and low pollution, and the development of hydraulic power plants has some favorable effects on the national economy which implies securing stable domestic primary energy source, saving international payment, and contributing to local and regional economic development through the utilization and control of water, it clearly becomes less attractive and less economic, and is expected to lose its share as a primary energy source. Therefore, hydraulic power plants which will be additionally constructed in the future may be given an auxiliary position, instead of a major, such as adjusting peak load and sharp fluctuation as a form of pumped type hydraulic power plants which are also expected to improve the operation of thermal power plants in a result of helping to flattening load curve of power output, and which can reduce some necessary capacity of power facilities compared with the case in which only thermal power plants supply power (1).

Neglecting the economy of the development of hydraulic power, its small potential reserves may cause it to give up its major position. In discussion of the future energy pattern we may be able to assume that hydraulic power will keep the almost same power production as before it did.

3. Wood and charcoal

Wood and charcoal were major fuels for residential and commercial usages in the past. These energy sources supplied 4.4×10^{13} kcal or 7.3% in the fiscal year 1955, and they reduced rapidly to 2.2×10^{13} kcal or 0.8% in the fiscal year 1968 (29) because of the preference and inexpensive cost of liquid and gas form energy sources.

As an increasing population and the accompanying need to develop land for housing and industrial usages will decrease wood reserves, and wood will be used for other purposes, such a pulp, in order to produce more valuable things, the use of wood and charcoal as a fuel will be decreased at faster rate. As a matter of fact, wood and charcoal have been replaced by city gas and liquid form fuel in the residential and commercial uses except for special needs. Therefore, we can assume wood and charcoal will not increase their supply as fuel.

4. Tidal power, wind power, geothermal energy and controlled thermonuclear fusion energy

The potential of tidal power which may be considered as a possible primary energy source since Japan is surrounded with sea, does not have any economic feasibilities at present even though it should be studied extensively as a future projection (1, 7).

Little use of wind power is anticipated because the size of wind power generators is inherently restricted (7) and the power generated is unpredictable and interruptible. In spite of possibilities of harnessing this wind power, it will be only small percentage at special places.

Recently, geothermal energy has been successfully used for generation of power which has been reached 30,000 kw (30). The use of geothermal energy will be expanded, particularly, on a regional basis. In order to develop this geothermal energy efficiently, considerable efforts will be required to extract geothermal energy. First of all, an accurate geothermal energy survey should be made. However, after the accurate survey of the geothermal energy and the development of technology related to the geothermal power generation, this will still not be expected to become a new major primary energy source in the near future.

Without significant technical interest, solar energy will still have little prospect of extensive use except under special circumstances in the near future, and the use of thermal energy from the ocean around Japan will be little possibility since the high temperature sea water is not expected around Japan's territory and no feasibility of the use of the energy from the ocean is achieved (1).

Generation of power using controlled thermonuclear fusion reaction would be expected to provide a virtually unlimited source of energy, with many advantages relative to nuclear fission, no rational economic analysis and feasibility study of fusion power plants is possible before self-sustaining reaction is achieved at least (7).

Some other energy sources are found but they do not seem to be expected to take major positions in the near future.

5. Natural gas

Natural gas increased its supply from 0.24×10^{13} kcal or 0.4% in the fiscal year 1955 to 2.39×10^{13} kcal or 0.9% in the fiscal year 1968 (29). The resources of natural gas are concentrated on the northern coast of Japan (10). Though natural gas has good characteristics as a fuel, such as low sulfur content, the limited reserves and the indemnity of land due to production of natural gas can not help but restrict its production in spite of increasing demand. Therefore, indigenous natural gas can not expect to increase its production fast. Reflecting such situation of natural gas production, strong demand to gas fuel has led some city gas and electric utility companies to push importing liquified natural gas (18, 30).

6. Oil

The international extensive exploration of crude oil and the development of the technology of utilization related to oil have been inducing the overproduction and the reduction of the cost in addition to consumers' preference (1). Particularly, in Japan which is poor in primary energy sources, the effect of the declining cost has been greatly significant in primary energy supply pattern and its demand increased from 12.4×10^{13} kcal in the fiscal year 1955 to 171×10^{13} kcal in the fiscal year 1968 (29).

According to the survey of crude oil in Japan, only 9 million kl or 50 million barrels has known as the proved and probable reserves (10). Thus, except very small scale companies, there are not fully integrated oil companies in Japan. As of March 1966 oil companies with foreign affiliates and subsidiaries of international oil companies accounted for 59.3% of the total oil sales, 61.7% of the total refining capacity, and 58.9% of the total paid-up capital of oil companies in Japan (10).

Oil, of which more than 99% has been imported, has had a major role and will continue to improve its position because foreseeable sufficient domestic primary energy may not be found to compete with oil qualitatively and quantitatively, and indigenous oil may not make any significant contribution to the increasing energy demand except the viewpoint of

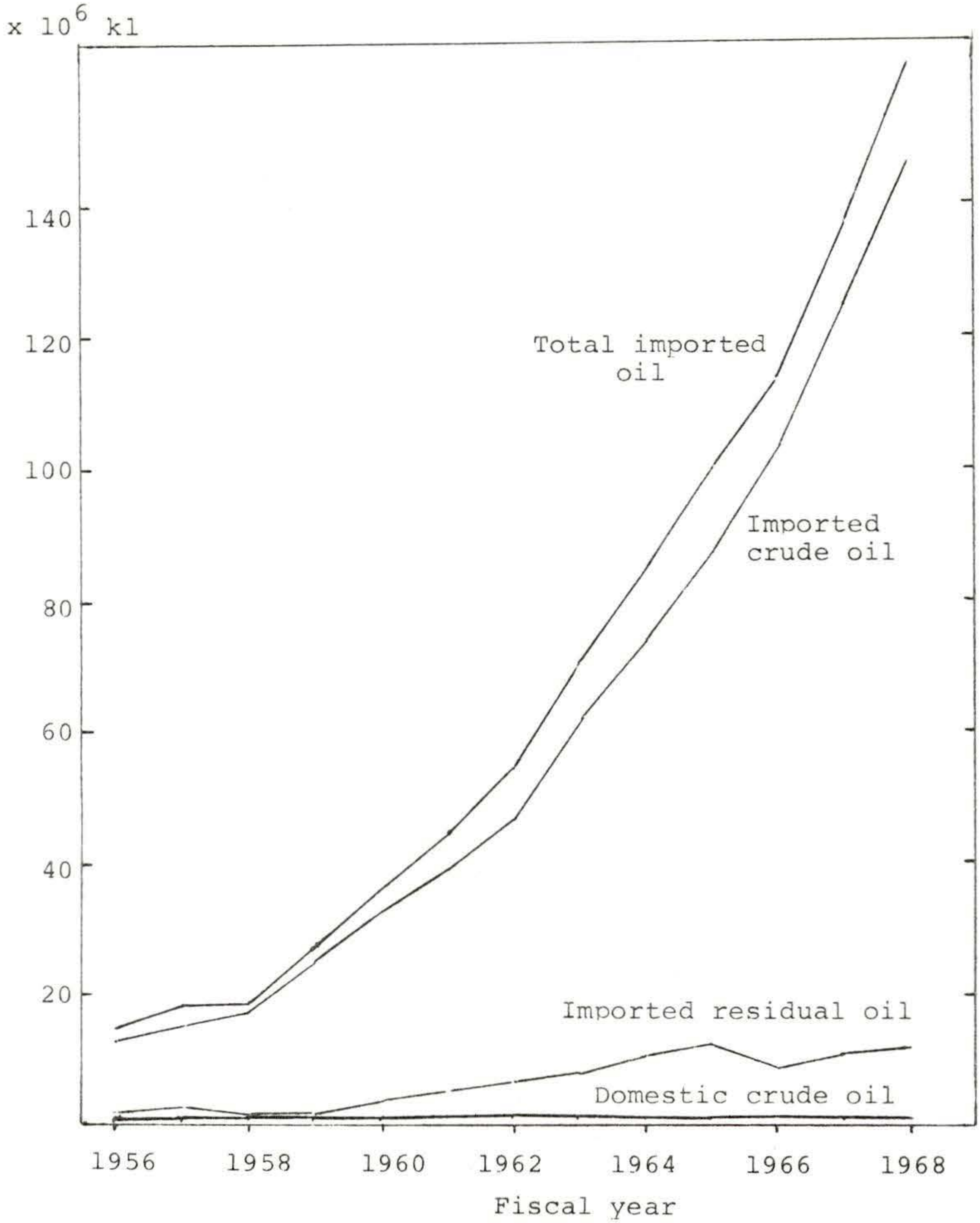

Figure 7. Oil supply (29)

Table 6b. Crude oil and residual (29) (10^6kl)

Fiscal year	Crude Oil				Residual Oil			
	Domestic	Imported	Total	Demand by Elec. utility	Domestic[a]	Imported	Total	Demand by Elec. utility
1955	0.4	9.3	9.7	-	4.5	1.9	6.4	0.3
1956	0.3	12.5	12.8	-	6.3	1.9	8.2	0.7
1957	0.4	14.9	15.3	-	7.5	3.2	10.7	11.2
1958	0.4	16.9	17.3	-	8.4	1.6	10.0	1.1
1959	0.5	25.0	25.5	-	12.7	2.1	14.7	1.6
1960	0.6	32.9	33.5	-	17.9	3.9	21.8	5.0
1961	0.8	39.2	40.0	-	21.4	5.5	26.9	6.0
1962	0.9	47.3	48.2	0.0	25.8	7.0	32.8	7.6
1963	0.9	62.4	63.3	0.3	33.5	7.9	41.4	7.7
1964	0.7	74.2	74.9	0.7	40.5	10.5	51.0	11.2
1965	0.8	87.6	88.4	0.7	46.5	12.3	58.8	11.9
1966	0.9	104.2	105.1	1.4	57.2	9.3	66.5	13.1
1967	0.9	125.1	126.0	2.2	68.1	11.3	79.4	19.0
1968	0.9	146.8	146.7	3.0	77.9	12.0	89.9	21.9

[a]Domestic residual oil was refined from the imported crude oil.

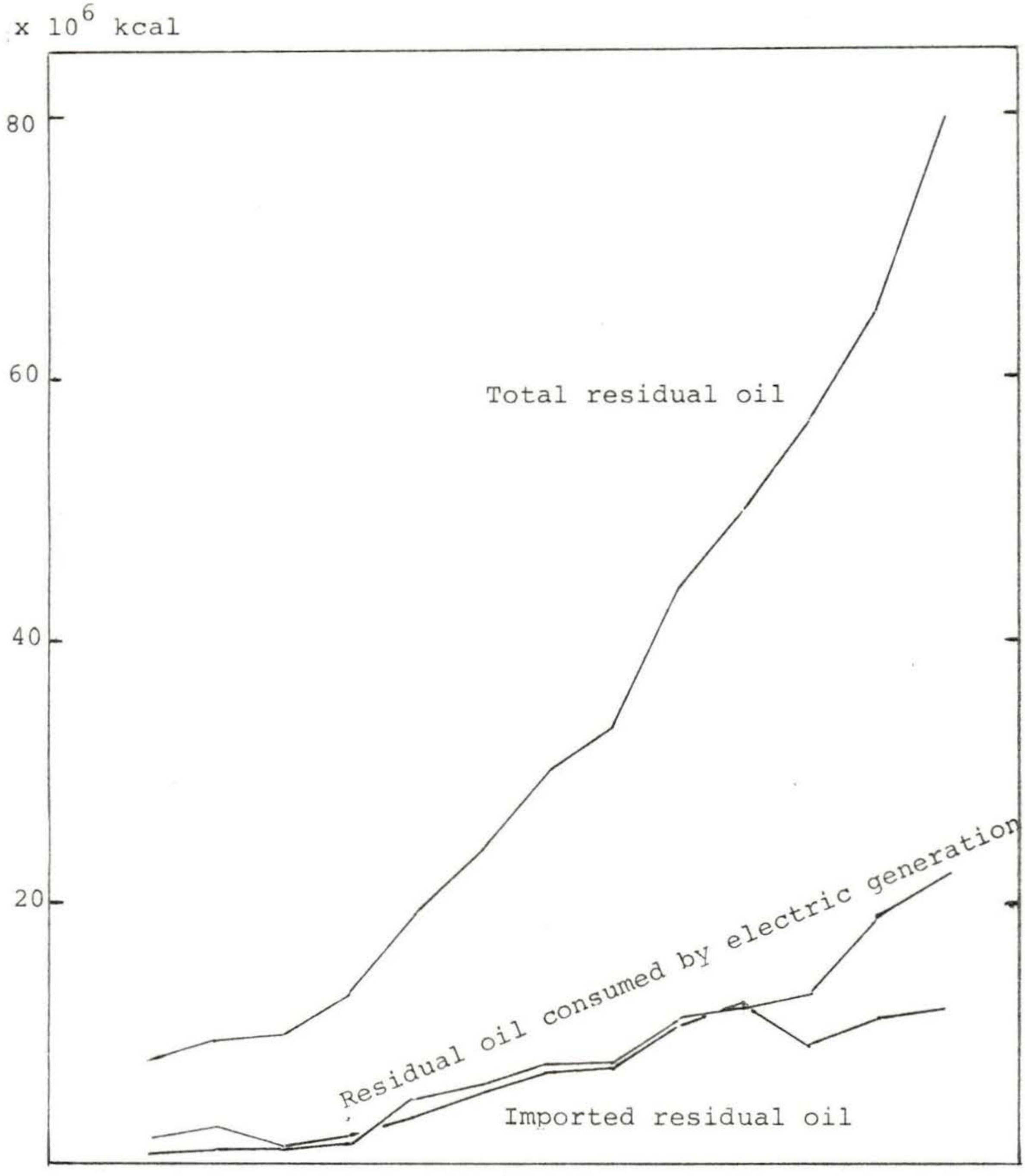

Figure 8. Residual oil consumed (29)

technical interest (1).

7. Brief summary of future energy supply pattern

According to the brief discussion of primary energy sources none of indigenous primary energy sources may play major roles in the increasing demand of energy in the future and the overwhelming supremacy of imported oil cver other forms of primary energy sources is predicted to be maintained in the future because it is inexpensive and convenient under the present situation of Japan, and oil expands its uses in the wide range from fuel to chemical raw materials.

F. Problems of Primary Energy Supply

In considering the problems related to the primary energy supply those concerned with oil and the oil industry are the most significant because oil has shared more than 65% (29) of the total energy demand and it may be expected to fulfill almost all of net increase in demand in the future. Thus, it can be said that oil can provide all of the solution and problems to Japan's energy supply pattern.

1. Greater dependence on foreign energy supply

As oil cost has been decreasing due to the tendency of overproduction of crude oil and the reduction of the transportation cost (1), the energy consumption pattern has shifted from coal to oil. Japan has been heavily dependent on imported oil in recent years to meet to its rapidly growing demand of energy. In the fiscal year 1955, 24% of the total demand of primary energy was imported, 53% in the fiscal year 1962, 66% in the fiscal year 1965, and 77% in the fiscal year 1968 (29). Since fiscal year 1962 imported energy has been occupying more than 50% of the total demand.

In comparison with the situation of Western European countries which now possess relatively poor domestic oil resources (27), the situation of imported energy in Japan has been an extremely high degree of dependence on foreign energy supply. It can also be foreseen that degree of dependence on imported energy will unavoidably become heavier since the demand of energy will grow at high rate which will be slowing down a little bit compared with previous rates and that the bulk of supply of primary energy will be obliged to be mainly occupied by imported energy as the domestic energy resources can not meet requirements of cost and bulk (1, 9).

The situation of the primary energy supply indicates that the condition of supply and demand of energy is sensitively affected by the situation of international market of fuel which is usually closely related not only to economic but also to political affairs. Heavier dependence on imported energy may enforce the Japanese economy to pay extremely careful attention to international relations and

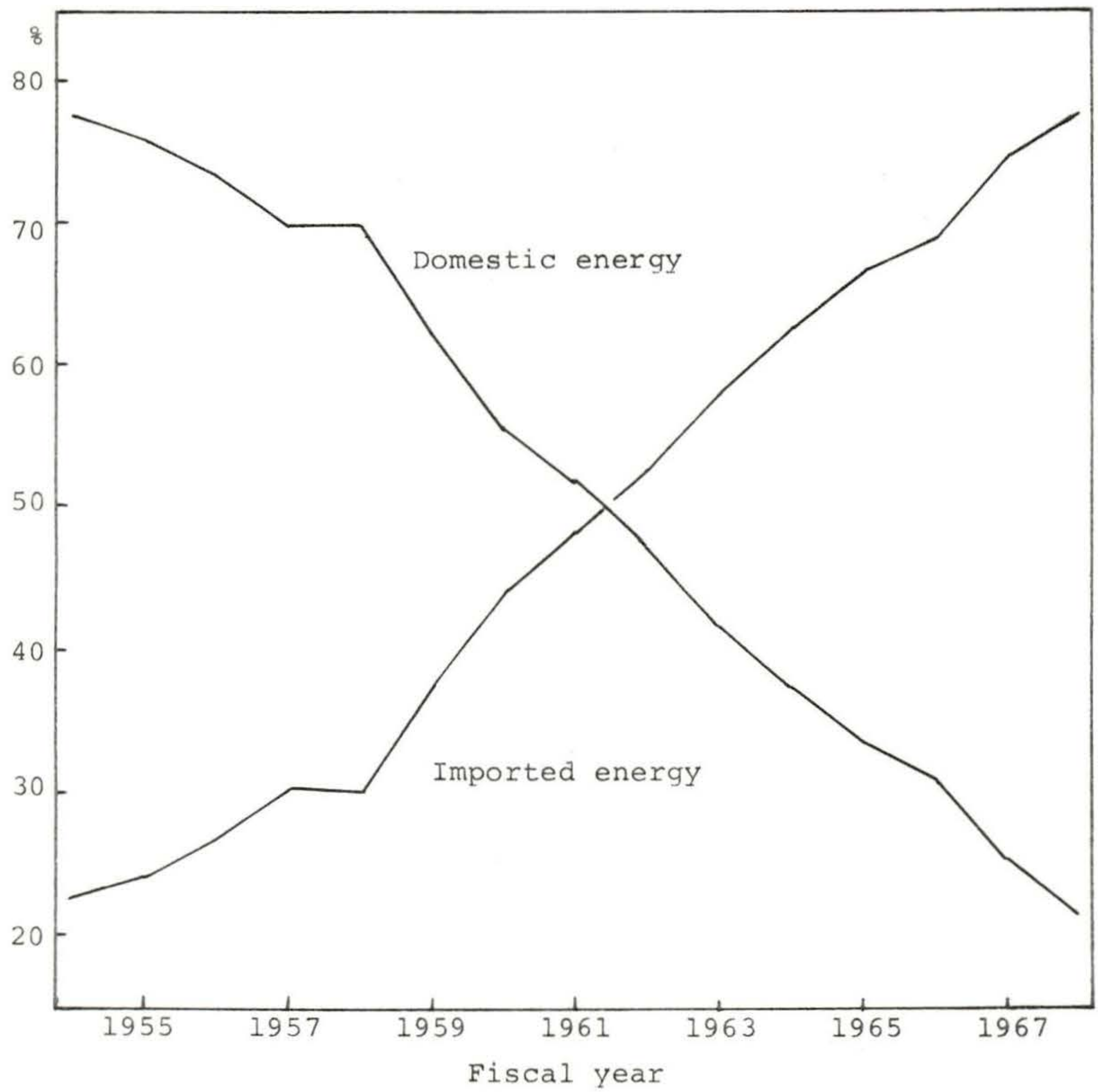

Figure 9. Trend of domestic energy and imported energy (29)

Table 7. International balance of payment between export and import (3) (million dollars)

Fiscal year	Export (A)	Import (B)	Balance (A)-(B)	Imported oil & coal (C)	(C/B) %
1961	4,236	5,810	-1,574	932	16.1
1962	4,916	5,637	- 721	1,041	18.5
1963	5,452	6,736	-1,284	1,211	18.1
1964	6,673	7,938	-1,265	1,407	17.8
1965	8,452	8,169	283	1,626	19.9
1966	9,776	9,523	253	1,807	18.9
1967	10,442	11,663	-1,221	2,239	19.3
1968	12,972	12,987	- 15	2,675	20.5

situations, and sometimes to meet difficulties to enable it to keep pace with unpredictably changed situations in order to secure stable and low cost energy as well as the national security because most of international troubles are clearly beyond Japan's control or influence.

An increasing dependence on imported energy sources which requires more than 20% of the total international payment for imported materials and products in the fiscal year 1968 (3) will also burden the Japanese economy. The tendency to increase imported energy sources will continue in the future (1).

Consideration of the security of imported energy sources with low cost and the international balance of payment will be indispensable in the implementation of the sound economic development and the national security.

2. Growing demand for oil and its supply mechanism

Japan is now the biggest importer of crude oil and its products in the world (10). The share of the imported oil has increased rapidly every year and such tendency is foreseen to increase inevitably as other primary sources do not seem to improve their situation favorably. Thus, the import of oil, especially crude oil, will have to increase much more rapidly and will reach a tremendous amount.

The imported crude oil, however, implies the following problems:

1. Most of the imported crude oil have come from the Middle East areas. The statistics of the imported crude oil in the fiscal year 1968 showed that 86% of the total imported crude oil came from the same areas, the Middle East. Though Western European countries are similarly dependent on the crude oil supply from these countries, they have, however, strenuously endeavored to reduce the dependence upon these limited areas by means of the exploration of other areas and other national projects (1, 9, 10,

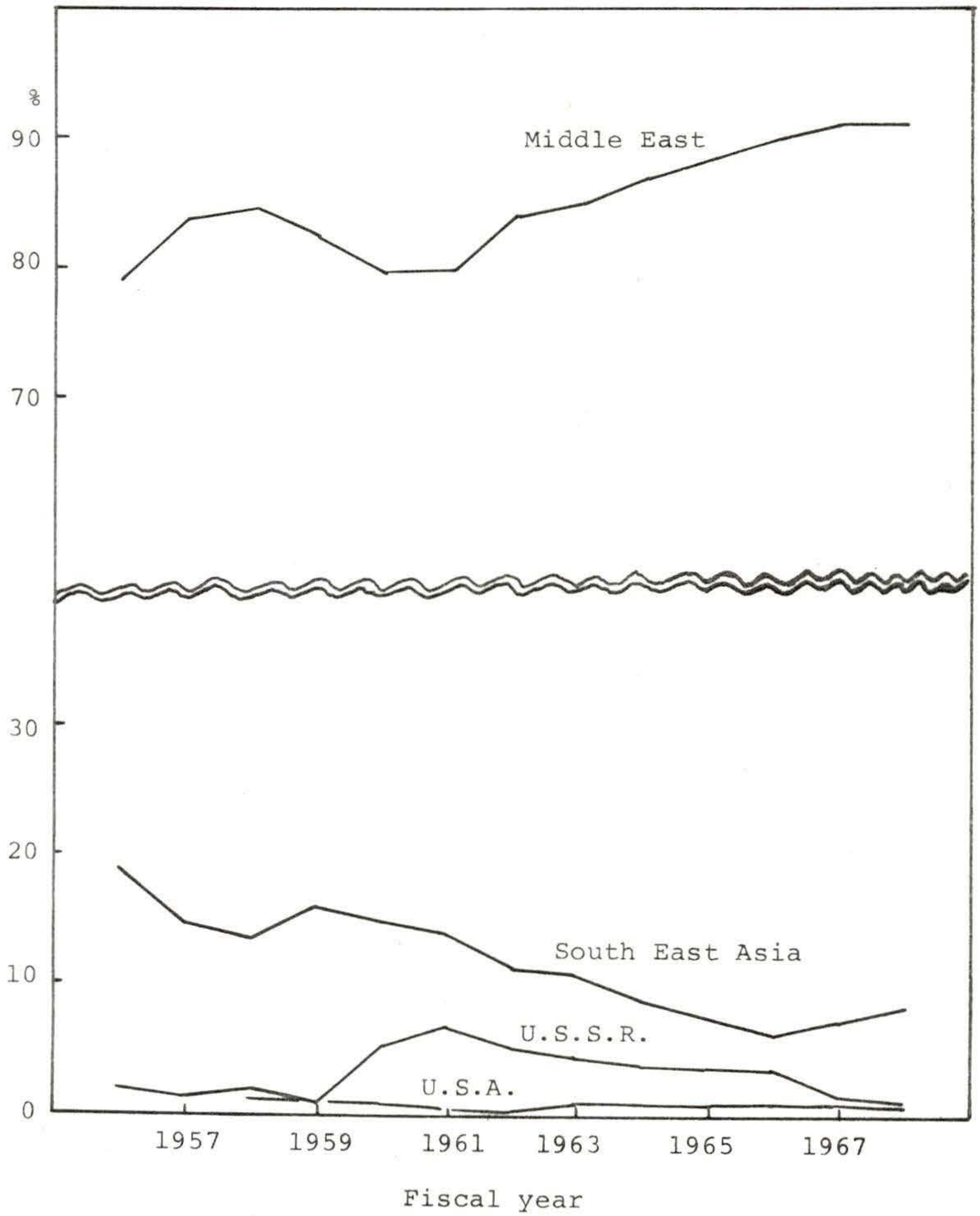

Figure 10. Area of exporting crude oil to Japan (29)

28). It may well be said that Japan is in an unfavorable situation as compared with the Western European countries so far as the stability of securing energy source supply and the degree of the freedom of selection of energy supply areas.

2. Japan has very limited option to import crude oil freely under the conditions of overproduction of crude oil in oil producing countries and favorable market for buyers. As the investment to meet rising oil demand has been so high that the domestic bond market is inadequate to provide the required capital, international oil companies loaned capital to the Japanese oil refining companies in return for guaranteed crude oil outlets. As a result, over 80% of imported oil are "tied" - and the prices of tied oil have been believed about 10 cents per barrel higher than other free oil prices (10). Therefore, the obligation to buy tied oil should be lessened to the reasonable level even though the stability of the long-term supply has been emphasized as well as the fact that the refining companies could not have been rebuilt without financial assistance.

3. In recent years the adverse effect on the natural environment of effluent-polluted air and water, and

of despoiled landscape has become a matter of urgent public concern. The adverse effects of two types are those affecting health and those affecting uniqueness and beauty of the physical environment.

The phase of policy most likely to pose early and serious problems for the energy industry are those concerned with air pollutants - especially, from oxides of sulfur - caused by combustion of oil and coal in power plants and in other industrial and space heating uses. Legislation takes the form of specifying emission control levels and regional air quality standards (14). As most imported oil from the Middle East countries contains relatively large amounts of sulfur, the additional cost of de-sulfurizing could cause oil to become a high cost energy source. Effects to control pollution give an inside track to natural gas which is a clean fuel, the amount of natural gas resources will limit its possibilities as a main primary energy source against imported oil. The cost of de-sulfurizing oil would become an important factor which may be a key point for oil to be replaced by other energy source, especially in the generation of power.

G. Influence to National Security

Here, security simply means that the state or feeling is being free from fear, care, or danger of shortage.

Because national security affects virtually all aspects in the life of the individual as well as the nation, assured supply of energy, in time of emergency as well as in time of peace, is essential. It has come to be concerned most intimately however, with the question of oil supplies.

To what degree should the country allow itself to become dependent on foreign energy source and how does such dependence affect the prospects of the domestic industry? The oil import program should become the focus of the debate over the proper role of national security considerations because Japan has less option of the degree of dependence on foreign energy sources since the domestic energy production, especially, coal will not increase in a short time and it can not meet the growing demand of energy. Thus, the only option which Japan has, is how Japan avoids so serious fluctuation or change of imported energy supply that its national economic activities can not endure such hardship as stopping supply, rapidly escalated price, etc.

First, an inquiry into the national security calls for rational classification of the concept itself. A whole congeries of security concepts now invade the sphere of public discussion - a war contingency concept, a national self-sufficiency concept, an alliance self-sufficiency concept, a good foreign relation concept, and finally, though without exhausting the list, a whole heartedly protectionist concept that is impossible to be adopted in Japan (26). These concepts swirl around in the controversial discussion of import policy, creating a general obfuscating of study. However, national security considerations can be limited to kinds of precautions to be taken to assure energy supplies in a variety of contingencies that might arise in the international situation.

Second, we must ask, "What measures are appropriate for meeting what situations are?", "What risks are to be met by what means?" (26)

Third, to the extent that national security is the basis some policies, it is important to know the cost to the economy of this security. As economists may point out, to achieve security at higher degree of freedom, Japan might require sacrificing faster economic growth and standard of living. It is necessary to determine the trade-off or change point between higher cost and higher risks, but today scarcely even a framework exists within which to analyze this problem. Moreover, since there are alternative ways of achieving a security goal, the cost of the alternatives needs to be analyzed if the national security cost is to be minimized. Such an approach is not free from error, but it might well be adapted to studying the security of energy policies (19).

H. Fundamental Principle of Securing Energy Sources

As discussed in the preceding sections, energy sources and the energy supply industry should satisfy at least two requirements from the viewpoint of the national economy.

1. Achievement of stable and inexpensive energy resources supply.

   As industrial activities and living of people are based on the foundation of energy, the stable and inexpensive cost of supply of energy is indispensible.

   The following requirements of securing energy must be fulfilled (1).

   a. Price of energy should be kept as low as possible on the long term of the projection.
   b. Quantity of energy should be secured necessarily and sufficiently to meet the demand.
   c. Minimum necessary quantity of energy for the maintenance of the national economy should be stored in order to avoid destructive influence in case of international disturbances in the supply and demand of

energy sources owing to political unrests and conflicts.

2. Coordination with objectives of other national policies.

Energy policy concern is primarily for the achievement of stable and inexpensive cost of supply of energy to meet the requirement of the quantity and price of energy have an important bearing on the international balance of payment, regional land development, employment, public hazards, related industries and also any industries since the energy industry occupies an important role in the national economy (1, 24).

It is, therefore, necessary in the implication of the energy concern to consider the influences caused by the energy supply, especially, because the international trade is one of the most concerned in Japan.

IV. ELECTRIC POWER INDUSTRY

A. Position of Electric Power Industry in the National Economy

Since World War II which resulted in fatal damages to the electric power plants as well as other industrial facilities, Japan had been suffering from an extreme shortage of power in order to reconstruct the national economic activities. Therefore, the Japanese government has invested a large fraction of the budget to recover the energy industry at first, especially, the mining industry and electric power industry (9). Of the total investment to the national economic activities in the fiscal year 1956, 10.4% came to the electric utility for the development of power plants. This, 10.4% was equivalent to 69% of the total investment of the energy industry. The situation of power supply had been gradually improved.

As the recovery of other economic activities has begun as a result of the development of energy industry, the weight of the investment to the electric utility has been declining, but its share was 5.3% of the total national investment in the fiscal year 1968 and occupied 57% of the investment of the energy industry (29).

On the contrary, the electric utility shared only about 2.5% of GNP (4, 29). This fact shows that the ratio of the sales income to investment capital is relatively low compared

Table 8. Position of electric power industry (29)

Fiscal year	GNP (billion yen[a])	Total energy demand 10^{13} kcal	Total electric energy demand 10^{13} kcal	Electric energy supplied by electric utility
	(A)	(B)	(C)	(D)
1955	13,156	60.70	15.98	14.73
1956	14.051	68.45	18.03	16.67
1957	15,211	76.95	19.90	18.58
1958	16,083	78.40	20.93	19.64
1959	17,966	88.21	24.28	22.67
1960	20,348	101.89	28.30	26.24
1961	23,275	116.89	32.35	29.98
1962	24,610	125.31	34.39	31.67
1963	27,763	141.93	39.25	36.00
1964	30,644	159.05	44.00	40.17
1965	32,305	180.17	47.07	42.63
1966	35,980	203.98	52.75	47.41
1967	40,612	228.03	59.99	53.79
1968	46,418	257.06	66.94	59.24

[a] yen = $ $\frac{1}{360}$.

Sales Income of electric utility (billion yen) (E)	Sales Income of electric utility/ GNP (E/A) %	Total electric energy demand/ total energy demand (C/B) %	Electric power supplied by utility/total electric power demand (D/C) %
230.7	1.76	26.3	92.2
263.4	1.87	26.4	92.6
304.1	2.00	25.9	93.2
333.0	2.07	26.7	94.0
287.9	2.15	27.6	93.6
460.6	2.27	27.8	92.7
556.8	2.39	27.7	92.7
625.4	2.52	27.4	92.2
722.7	2.61	27.7	91.7
820.6	2.67	27.6	91.1
899.5	2.78	26.1	90.5
1006.4	2.80	25.9	89.8
1144.0	2.81	26.2	89.8
1273.0	2.98	26.0	88.5

Table 9. Position of electric utility (29) (billion yen)[a]

Fiscal year	GNP (A)	Sales Income of electric utility (B)	A/B %	Total Investment (C)
1955	13,156	230	1.76	-[b]
1956	14,051	263	1.87	1,486
1957	15,211	304	2.00	1,904
1958	16,083	332	2.07	1,709
1959	17,966	387	2.15	2,220
1960	20,348	460	2.27	3,231
1961	23,275	556	2.39	4,231
1962	24,610	625	2.52	4,105
1963	27,763	722	2.61	4,388
1964	30,644	820	2.67	5,122
1965	32,305	899	2.78	4,804
1966	35,980	1,066	2.80	5,646
1967	40,612	1,144	2.81	7,584
1968	46,418	1,273	2.78	9,349

[a]yen = $\$\frac{1}{360}$.

[b]Not available.

Investment by energy industry (D)	Investment by electric utility (E)	D/C (%)	E/D (%)	E/C (%)
-	-	-	-	-
225	154	15.15	68.8	10.43
284	193	14.90	68.0	10.13
323	233	18.9	72.1	13.6
316	225	14.25	71.3	10.15
414	293	12.81	71.0	9.08
504	350	11.9	69.5	8.3
485	351	11.8	72.4	8.56
479	326	10.9	68.1	7.43
461	301	9.0	65.3	5.86
532	359	11.1	67.5	7.48
583	374	10.32	64.3	6.63
697	399	7.89	57.5	5.28
854	495	9.15	58.0	5.8

with other industries' income. Thus, the mining and manufacturing industries could keep their power cost in manufactured product cost less than 1.6% (30).

The power supply occupied 27% of the total final energy consumption in the fiscal year 1955, and 26% in the fiscal year 1968 (29).

B. Position of Electric Utility in Electric Power Industry

The Electric Power Industry in Japan is classified in two categories. One is an electric power generating enterprise which generates electric power for the purpose of self-consuming it, and which here is called a nonelectric utility. Another is an electric power generating enterprise which generate electric power mainly for supply to the general demand of public. The latter type is called electric utility according to the "Electric Utility Industry Law" (13). The electric utility has two kinds of utilities. One is a general electric utility which is defined as an undertaking of supplying electric power to meet the demand of the general public. The second is a wholesale electric utility which is defined as an undertaking whose principal purpose is to furnish general electric utility or utilities with electric power.

The electric power industry consists of nine major general electric utility companies, the Electric Power

Development Co., and some other electric utilities such as provincial and municipal utilities, and nonelectric utility companies.

As of the end of the fiscal year 1968, of the total generating facilities, 53.1 million kw, 37.7 million kw or 71% belonged to the nine major general electric utility companies, 9 million kw or 7.8% to wholesale and minor general electric utilities and 6.5 million kw or 12.2% to non-electric utility (4). Therefore 88.8% belonged to electric utility facilities. And of the 273.2 million kwh generated in the fiscal year 1968, 86.5% came to electric utility (4).

C. Characteristics of Electric Power Industry

As the share of electric power in the final energy consumption is projected to increase, and the demand for electric power is scarcely replaceable by other forms of energy, the importance of electric power is expected to be more significant in the future (1). As nuclear energy will be mainly used for generation of electricity in the near future, it is interesting to point out characteristic of electric power industry, especially the electric utility.

1. Unique character of electric power industry

The electric power industry has an unique character in that while it is a supplier of secondary energy which is defined as an energy form converted by primary energy sources for the purposes of consumers, and plays an important role in meeting final energy consumption, it demands a large amount of primary energy sources to transform them into the secondary energy, power, and the forms of primary energy sources which are used for generation of electricity range over hydraulic power, coal, oil, natural gas and nuclear energy etc. In the choice of primary energy sources for its use, the electric power industry which is one of the biggest customers should take into account economic renumerativeness as a supplier of energy, and possible influence not only on the national pattern of energy supply but also the entire national economy.

2. Position of electric utility industry as a monopoly enterprise

a. Features of electric utility

The necessarily monopolistic character of local elective utilities was recognized early in the history of the industry. The regulation in the Japanese law centers around the concept of "public utility". Based on the Japanese common law concept of activities "affected with a public interest", it has been developed by judicial decisions to determine what business activities may be publicly regulated because the public interest is not sufficiently protected by the operation of competitive forces. The attainment of public utility status by an industry entails the combined characteristics of providing services of special importance which are essentially necessary in the livelihood and economic activities and hard to be got substitutional ones, and which are provided under the circumstances that lead to monopoly, or highly wasteful or ineffective operation of competition. An electric utility falls into this category because of the high ratio of fixed to total costs, the economy of having all users served by a single source, and the safety concerns originating from the physical property of electricity itself. Competitive sources of service would be extremely wasteful of capital investment and could multiply the costs to meet demand of consumers.

The Law of Electric Utility Industry (13) clearly mentioned about these points in the article 1 as follows:

> The purpose of this law shall be to protect the interest of consumers of electricity and contrive sound development of the electric utility industry by rendering its management equitable as well as rational, and to secure public safety by regulating its work of installation, construction maintenance and operation of its electrical facilities.

Any person who intends to undertake an electric utility which is defined as an undertaking of supplying electric power to meet the demand of the general consumers shall obtain permission for such undertaking (13). In the case of a general electric utility the electrical facilities to be employed for conducting businesses of the electric utility shall not be caused to become excessively superfluous in terms of either a part or the whole of said service territory due to the commencement of the businesses.

Each general electric utility normally has an exclusive service area as a regulated monopoly. It is obliged to hold specified service standards, and required to serve all customers equally. In practice, the most important regulation is to control the rate of return.

This has two aspects: the general level of rates and the detailed rate structure. The general level entails the fixing of a rate base, or capital value of the assets, upon which an electric utility company is entitled to earn a specific rate of return; and the detail rates, generally set to cover the assignable costs to each customer class plus an allocated portion of the costs, are designed to produce an amount of revenue sufficient to provide this rate of return after meeting all authorized costs.

The legal rules applicable to determining of a rate base and a rate of return is permitted by the Japanese government. In a general way, a rate base is normally attached to capital investment with various adjustments; and the idea of a "fair return" is related to a competitive norm - an amount necessary to induce the desired investment.

However, the problems are complex in nature and the body of judicial reasoning surrounding them is prodigious. The structure of rates involves setting a number of different rates for different classes of customers. To a degree these attempt to assign differential costs to various groups; but they also take advantage of different group demand elasticities for the purpose of stimulating sales and improving load factors. The law is, of course, charged with seeing that such rate structures are not "unreasonably disriminatory".

In this paper the estimation of the power cost by nuclear power plants and fossil fuel plants is simply adjusted to meet all necessary expenditure to sales income of power because nonelectric utility companies have less chances to build nuclear power plants for commercial purposes in the near future.

b. Position of electric utility More than 85 percent of the total electric power produced is supplied by a few major electric utility companies that have been granted regional monopoly supply as a privilege of the public utility industry by the Electric Utility Industry Law (13). Consequently, customers of electricity have a rigidly restricted option in consumption of power so that electric utility companies should have much greater responsibility than suppliers of any other forms of energy, in order to secure sufficient amount of supply and lower the cost of power. Therefore,the electric power industry has always paid attention to lower cost energy and its stability of securing primary energy sources as fuels of power plants. In the course of the price competition the lowest cost of energy is selected for generation of power because the electric power industry has relatively more degree of freedom in the choice of fuel, and the capital costs of the construction cost of power plants are not greatly different for the various fossil fuels used.

Thus, the electric power industry, particularly, the electric utility, has been looking for inexpensive fuel in addition to trying to reduce the construction cost of power plants and improve thermal efficiency through the development of the technology in cooperation with the manufacturers.

The electric utility which shares more than 85% (29) of the total production of power has an advantage in adopting new technology of electric facilities because it has larger and more stable demand and is given a privilege to use other parties' land or buildings in order to construct electric facilities (13). Most advanced economical electrical facilities are usually large scale including power plants and transmission lines. The present tendency of the construction is for larger power plants with larger unit capacity which are generally beyond the nonelectric utility's power demand. In addition to this, the construction of transmission lines, which are needed to send power from power plants to consuming sites, is extremely difficult in nonelectric power companies. In consideration of the construction of nuclear power plants which are usually required built in remote and isolated sites from populated areas, nonelectric utility companies will have less chances to build them in the near future.

3. Slight influence to export and great influence to import

The electric power industry has also other interesting features. The physical character of electricity makes it impossible to store in the usual commercial generation of power, in other words, the production and consumption of power are done almost at the same time. Therefore,the electric power industry has not contributed to export its goods, electricity, and on the contrary, most of thermal power is generated by imported oil, especially, in the future. As the demand of power increases, the required fuel for generation also increases. Thus, the increasing demand of power expands the amount of imported fuel, oil, linearly, but the relation between the demand of power and the amount of export is generally not linear though the power cost occupies less than 2% (31) of exported goods on the average value and indirectly influences the cost of exported goods.

Consequently, we may simply say that the increasing demand of power needs proportionally increasing international payment, and saving cost of power and international payment is directly realized by reducing the amount of energy sources imported.

V. GENERAL PROSPECTS OF NUCLEAR ENERGY

A. General Prospects of Nuclear Energy

Here is a new primary energy source, nuclear energy, which is expected to become an excellent primary source of energy even though the utilization of it requires much higher technology than conventional primary energy sources.

The world first self-sustaining nuclear fission chain reaction was produced in the United States of America in December 1942 (8) and immediately showed possibilities of becoming a new energy source as controllable energy even though the first large scale effective use of nuclear energy was destructive rather than peaceful purpose. Especially after the World War II the extensive research in some developed countries was directed toward nuclear energy's economic potential in the production of energy from fissile materials, particularly, in generation of electric power.

Controlled nuclear energy can be theoretically used for the same purposes as other primary energy, such as coal, oil and natural gas, but the most attractive use of nuclear energy is generation of steam, particularly, electric power.

Economic efficiency of nuclear power generation has been rapidly improved through the extensive development of the technology and the spreading of the market of the nuclear power generation. If the cost of nuclear power generation of which some have been proved and are projected in actual nuclear power plants and planned ones in the United States of America had been to be able to be allowed in Japan without any additional expenditure in the construction, maintenance and operation of nuclear power plants when they would be adopted in Japan (39), would have been able to compete with present oil burning power plants which usually give the lowest power cost in Japan.

The reserves of nuclear energy sources exist enough to overcome reserves of other primary sources of energy in the forms of the theoretically recoverable energy if the technology related to the utilization of nuclear energy can be developed fully.

Uranium and thorium are two potentially usable fission fuels as natural sources. Though thorium has been utilized as part of the fuel in a few reactors at present time, uranium is the principal source of recoverable nuclear energy. The current thermal reactors use only a few percent of the potential energy which the fuel contains, but the recovery of nuclear energy from uranium may increase as reactors and fuel cycling technology are improved. Advanced type reactors such as fast breeder reactor now under development can lead not only to better use of uranium but also greater utilization of thorium or of plutonium which uranium-238 is converted into after capturing a neutron.

Table 10. Fossil fuel resources of the world (7)

Fuel	Known recoverable resources	All other resources
Coal (tons)	850×10^9 (18Q)[1]	$15,150 \times 10^9$ (320Q)
Petroleum (barrels)	300×10^9 (1.7Q)	$4,000 \times 10^9$ (23Q)
Natural gas (cubic feet)	$1,800 \times 10^{12}$ (1.9Q)	$19,000 \times 10^{12}$ (20Q)
Oil in bituminous rocks (barrels)	40×10^9 (0.23Q)	$1,060 \times 10^9$ (6.1Q)
Natural gas liquid (barrels)	45×10^9 (0.21Q)	700×10^9 (3.2Q)
Shale oil[2] (do)	150×10^9 (0.87Q)	$13,600 \times 10^9$ (79Q)
Total in fossil fuels	23Q	452Q

[1] The number in parentheses represent the energy equivalent in Q(quintillion), and the total energies are round values.

[2] Estimated by D. C. Duncan of the U.S. Geological Survey.

In spite of the fact that Japan which has about 3,000 tons uranium reserves (15) in the form of U_3O_8 this country is still poor in nuclear energy sources. Tremendous reserves of recoverable nuclear energy source exist in the world and the development of the nuclear power to reduce the power cost may give favorable solution to the energy problems.

Table 11. Uranium resources of the world (7)

Country	Known deposits, in thousand tons of uranium metal[1] (and theoretical maximum energy value)	Country	Known deposits, in thousand tons of uranium metal (and theoretical maximum energy value)
United States of America	323[2] (22Q)[3]	Australia	13.2 (0.93Q)
Canada	236 (16Q)	Asia and Eastern Europe	110-400 (7.7-28Q)
South Africa	127 (9Q)	Argentina, Congo, Germany, India, Japan, Mexico, Portugal, and Spain	21 (1.5Q)
France	34 (2.4Q)		
Total, world (round)	860-1,150 (60-80Q)		

[1]Deposits minable at \$5 - \$10 per pound of U_3O_8.

[2]Includes known reserves of 142,000 tons plus cumulative amount of uranium delivered to AEC.

[3]The numbers in parentheses represent the energy equivalent in Q and assume complete burnup. With light water reactors, using current technology, only 1 or 2 percent of this energy contained in U^{235} as well as U^{238}. With advanced technology, most of this energy is expected to be recoverable.

Table 12. Thorium resources of the world (7)

Country	Known deposits minable at \$5-\$10 per pound of ThO_2 (tons)	Country	Known deposits minable at \$5-\$10 per pound of ThO_2 (tons)
United States of America	100,000 (7Q)[1]	India, Ceylon, Afghanistan, Nepal, and Pakistan[2]	220,000 (15Q)
Canada	175,000 (12Q)	Asia and Eastern Europe	90,000 (6Q)
Brazil	25,000 (2Q)		
Africa	45,000 (3Q)	Australia[3]	45,000 (3Q)
Total, world	7000,000 (48Q)		

[1]The numbers in parentheses represent the energy equivalent in Q and assume complete burnup.

[2]An additional 250,000 tons is possible in the inland places of Bihar and West Bengal, but these areas have not been thoroughly explored.

[3]Bowie, S. H. U. The Uranium and Thorium Resources of the Commonwealth. Roy. Soc. Arts J., V. 107, 1959, p. 706.

Tables 10, 11, and 12 show the reserves of fossil fuel, uranium and thorium in the world respectively.

B. Influences of Nuclear Power to Energy Producing Industries

The present group of industries is divisible into two subgroups, depending on whether they are likely affected favorably or unfavorably by the advent of nuclear power. One sub-group includes the conventional energy producing industries and their satellites supplies, or supporting activities. This sub-group includes coal, oil and oil refining and gas production; various transportation media, such rail, track and tanker; mining equipment suppliers and material suppliers which share little influence in the national economy because of little resources in Japan; and service industries in area predominantly dependent on these, mainly these of which are related to coal mining regions. This group also includes steam generating equipment and engines which are necessary to convert conventional energy to electric power.

The second sub-group consists of the nuclear complex industries and its satellites that would stand to gain directly from the projected entry of nuclear energy.

Diminished activity in the conventional industries which will have negative repercussions can be classified into the following categories.

1. Direct market losses by each conventional energy supplying industries, especially, oil and oil

refining industries.

2. Direct losses by supporting industries, derived from the initial losses above.
3. All other losses throughout industries generally, derived from the initial losses in categories 1 and 2.

A similar classification can be also applied to the nuclear industries, but in this case the change would be favorably positive.

Most generally, most industries that will lose indirectly in coal, oil and oil refining, and gas production, will also enjoy direct and indirect benefits in producing nuclear power equipments and fuel, etc. The decrease in primary metal requirements in producing either conventional boilers and piping, or mining equipment, or transportation will tend to be offset partially or fully by the increased requirements for nuclear power equipments, fuel, etc.

While a comprehensive analysis[1] of all impacts, direct and indirect, on each industry is theoretically possible, there are numerous practical as well as conceptional difficulties in its path, that might well introduce such errors in the resulting estimates as to yield meaningless results.

[1] A conceptionally complete analysis of all the direct and indirect effects of an initial change from coal, oil and oil refining industry and gas to nuclear energy could be carried out using the interindustry or input-output approach if sufficient supplementary information were available (26).

In consequence we undertake, on a more modest scale, to assess the implication of the projections only for the more prominent industry, oil and oil refining industry.

In discussion we use the term "losses" in referring to activity level reductions in conventional energy industry e.g., oil and oil refining industry. More properly this refers to the extent to which industry production or selling would be less than might otherwise have prevailed. As we consider a growing economy, the loss is defined as an extent to which production or selling due to introduction of nuclear power in the future market would be less than might have retained in the future market without nuclear power (26).

Let us first consider the oil and oil-refining industryy which is the greatest competitor against nuclear power in the generation of power will lose greatly. In Table 13 the net increasing demand of energy will be mainly offset by oil, so that the competition of power cost between oil and nuclear power will be occurred in the generation of power. As the demand of electric power is predicted to increase at higher rates than that of the total demand of energy is, and the technical and economical aspects of nuclear power will be improved, for the time being the competitive market for both oil and nuclear power will be spreading.

Table 13 column (B), indicates the maximum market potentially replaced by nuclear power in each selected year.

Table 13. Predicted energy demand (10^{13} kcal)

Fiscal year	Total Energy			Electric Power		
	Predicted value A'	Predicted value by Adversary Committee on energy (1) A"	Net increase from the amt. in the fiscal year 1968 (A)=A'-value of 1968	Predicted value B'	Net increase from the amount in the fiscal year 1968 (B)=B-value value of 1968	B/A
1968(actual)	253.0	-	-	67.2	-	-
1970	282.7	(242.5)	29.7	70.8	2.6	0.086
1975	410.5	(340.4)	157.5	105.0	37.8	0.216
1980	567.4	-	314.4	149.2	68.4	0.217
1985	723.4	(597.5)	470.4	196.6	129.4	0.277
1990	858.9	-	605.9	239.6	172.4	0.285

Although oil will lose part of energy market in the generation of power, it may eventually become a large scale raw material for producing both chemicals products, and liquid and gaseous fuels (1). The demand of oil for petrochemical products rose rapidly from 2.4 million kl* in the fiscal year 1960 and 9.1 million kl* in fiscal year 1965 (1). This figure represents 6% of the total final energy consumption in the fiscal year 1965. In this case the potential increase in oil product could offset the possible loss mentioned above or prevent a rapid decrease rate in the market. Unlike oil, the coal industry is of little interest in the generation of power ignoring the national security as an effect of domestic energy resource and its share will undoubtedly more greatly diminish due to its high cost if the governmental policy does not support its market.

As oil covers wide range demand of energy from residential to industrial usages, the continuing rise in relative prices of lighter refined products will probably be much more important and serious in reducing the proportion of residual fuel oil in the Japanese refining industry than will the reduction in its price be following replacement by nuclear energy.

The total quantity of gas that may be replaced is very small since only imported liquified natural gas is used for generating power in order to prevent air pollution and most gaseous fuel is used for residential and commercial not for industrial purpose.

The relative change or loss of activity aside from losses in producing and processing fossil fuels could be in transportation, especially, tankers. Some losses will occur in the case of decline of imported oil and coal due to the transportation cost saving features of nuclear energy which has tremendous energy per unit weight compared with fossil fuel.

The conventional boiler shop product industry is also likely to suffer losses from the projected substitution of energy sources. Here, too, opportunities will exist to offset such losses by turning to the manufacture of the fabricated metal components of reactors and chemical plants. As high standards are required of the technology related to nuclear power engineering, some changes in that industry will occur even though there may be little difference between the losses and gains due to nuclear power.

We now turn to the growth implication for the nuclear complex of industries. To better comprehend the structure of this complex, however, we list an outline of the successive stages through which nuclear material may move. The outline (26, 41) is schematic and emphasizes nuclear features but differences between common elements in the complex are neglected.

1. Mining and importing of nuclear raw material, including also prospecting and mine development in this country and foreign countries.
2. Nuclear raw material treatment, including milling, concentration, and purification into metallic or other suitable forms.
3. Conversion of nuclear raw material and production of natural uranium or thorium.
4. Enrichment of uranium.
5. Fabrication of nuclear fuel including necessary conversion.
6. Loading nuclear fuel into a reactor and production heat.
7. Spent fuels are unloaded from the reactor, cooled off, and then sent to chemical separation plants for recovery of fissionable plutonium as well as the unburned uranium-235 and uranium-238. The uranium-235 and uranium-238 which are recovered jointly, may first be recycled through the enrichment stage. Plutonium which is not used as a fuel in the light water reactor of this paper will be sold.
8. The remaining radioactive waste products may be treated further to separate out the long lived isotopes, particularly, cesium-137 and strontium-90,

and then be disposed. Irradiated isotopes including cesium and cobalt may also represent use sources of radiation energy for various industrial, medical, or other application although this stage is not a main concern in the generation of power.

One group of industries that will gain from the projected shift in energy sources will be the producers and fabricators of various materials having unique nuclear properties. Chemical separation and processing of fuel elements will be another class of activity for which no visible offsetting losses are foreseen. Requirements for instrumentation also fall in this category, because of the necessity in handling nuclear materials for remote controls, automatic operations, and maintenance.

The possible gains to producers and fabricators can be measured because the upper limitation of prices which is given by manufacturers in advanced countries controls also the cost of domestic products if any special governmental finance supporting and any other supporting policies are not expected. As nuclear power generation requires larger scale units in order to improve its economic situation and high standard technology, the number of nuclear power plant units in the future will not increase as much as that in the past time increased even though demand of power grows as the same amount as that in the past time. Reasonable cooperation and coordination in the nuclear complex industries is necessary since the nuclear complex industries have recently been starting in Japan where the nuclear technical backgrounds are behind in the research and industrial applications, and nuclear power requires that the nuclear complex industries cover wide range of technology and the investment of large sums of capital money.

C. Influences to Energy Consumers

Since electric power is essential for the national economic activity and the share of the electric utility in the gross national product, 3.0% in the fiscal year 1968, has had a tendency to be increased, it is very important to have an adequate and stable supply at a minimum cost.

As the annual income per capita increases, the standard of living is being improved and this induces a fast growing demand of power for the residential and commercial usages which do contribute the gross national product indirectly rather than directly.

The convenience and cleanness of electricity are very attractive for these purposes but the relatively high cost of electricity has inhibited its full use. Thus, inexpensive power cost is derived. We now look at the most important energy consuming industries.

These may be identified by

1. Relatively large consumption of energy, either absolutely or per unit of output.
2. High cost of fuel or power consumed per money value of output.

The average delivered price of energy for the nation as a whole may have risen because factors such as expensive land and pollution require additional investment to the transportation and to the refining facilities.

As differentials in the price of energy among fuel resources are being reduced,

1. in general terms, therefore, all the energy intensive industries will find more degrees of freedom in their choice of new plant location and a kind of energy resources, and
2. in some industries, especially, the aluminum industry[1], the primary influence of nuclear power may be industrial relocation, but with no necessary

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[1]Historically, the Japanese aluminum industry has gone to the remote places from its market to assure low-cost electric energy, e.g., hydraulic electric power. Choice of these locations in spite of the heavy transportation costs for raw materials and for finished products may serve to emphasize the fundamental significance of low-cost for this industry. Nowadays, new aluminum factories are located along the Pacific Ocean coast for convenience of unloading and transporting imported raw material as the localized power cost factor diminishes in significance due to the increase of thermal power plants.

technological changes to take advantages of possible nuclear energy's cost-saving features.

VI. ASSUMPTIONS OF ESTIMATION OF COSTS OF NUCLEAR AND OIL BURNING POWER

It is necessary to estimate costs of nuclear power and oil burning in order to compare them.

A. Selected Models

The majority of the reactor concepts under development for central power stations may be considered to fall into one of several categories by classifying parameters, such as pressurized-water reactors (including boiling water reactors), advanced-converter reactors, and breeder reactors. The usefulness of this particular classification of power reactors is related to the time periods in which reactors of each category are likely to be built for commercial purpose (37).

The light-water pressurized or boiling water reactors which use slightly enriched uranium as a fuel, and which have been technologically and economically advanced, have been imported to Japan for commercial power generation. Therefore, light water pressurized reactors are chosen as nuclear power plant units to estimate nuclear fuel cost even though some other type reactors may be more suitable because the Japanese manufacturing background has no commercial enrichment plant of uranium. The background of manufacturing technology of the enrichment in Japan seemed a main reason why the Japan's first commercial power reactor was a carbon dioxide moderated and cooled natural uranium reactor which was imported from the United Kingdom.

The oil burning power plant used for comparison is a super-critical high thermal efficiency large power plant typical of some which have already been operated.

Table 14. Summary of selected power plants

	Nuclear power plant (38)	Oil burning plant (30)
Electrical output	1,000 Mw	1,000 Mw
Net thermal efficiency	30%	38%
Load factor	70-80%	70-80%
Fuel	slightly enriched uranium	oil

B. Assumption of Calculation of Electric Power Cost

Power cost (mills/kwh) falls into two categories, construction capital charge cost and fuel charge cost.

1. Estimation of construction capital charge cost

Construction capital charge cost (mills/kwh) is a function of construction cost ($/kw), interest rate (%) lifetime of power plant, and load factor. In order to simplify the procedure of estimating capital costs, the following assumptions were made.

In projects of the type that private owned construction of conventional power plants and nuclear power plants are concerned with, there are usually two kinds of capital to be recovered, namely, capital represented by bonds and by stock. These will normally earn different rates of return. The combination of bonds and stocks will be altered depending on the situation of companies involved in construction, operation and maintenance.

The rules governing the construction of the payout in this paper may be summarized as follows (21, 22):

1. The bond interest for a given period is equal to the bond interest rate multiplied by the bond principal outstanding at the start of that period.
2. The return on equity for a given period is equal to the earning rate on stock multiplied by the equity capital outstanding at the start of that period. In this paper it is assumed that all capital will be covered with only bonds so that the return on equity is not needed to pay because of government backing.
3. Income and expenses are assumed to occur at the end of each fiscal year which begins on the first day of April and ends on the last day of March of

the next calendar year.

4. The cash income from sales which should meet all expenses of the power plant and which is assumed to be received at the end of a given period divides into four portions;
   (a) part goes to pay the cash expenses for that period, including taxes, but not including income tax and depreciation;
   (b) part goes to pay bond interest;
   (c) part goes toward reduction of the outstanding bond principal (the amount used for this purpose depends on the schedule of bond repayment specified); and
   (d) nonremainder goes toward reduction of the outstanding equity capital, or investment in stock because of non equity.
5. At the end of the final period, the outstanding investment in bonds must reduce to 10 per cent of of the total investment for the construction.
6. At no time during the calculation may the outstanding investment become negative and each year income will meet expense.

Fixed charged rate method (21):

is a concept that a certain portion of the annual sales is allocated toward recovery of investment, return on investment, and income taxes on this return. This portion of the sales income represents the annual fixed charges on the investment. The fixed charge rate is defined as the ratio of the annual fixed charges to the original investment. Thus, using cash flow terminology, the fixed charge rate may be defined as the ratio R'/P, where R' is the annual before-tax cash flow required to pay off an investment P in a specified number of years, at a specified after-tax rate of return (21).

Depreciation calculation method:

is a straight line depreciation method under the condition where the residual value of the investment is 10 per cent (30) at the end of final period.

Sinking fund method:

is used to calculate the amount of the bond at the end of each fiscal year.

Present worth method is used:

to calculate average electric power cost during entire plant life-time under the constant interest rate of bond.

Average present worth fixed charged rate including depreciation and interest rate of bond is given under a constant interest rate of bond as follows:

$$\sum_{n=1}^{m} \frac{R}{100} \left(1+\frac{a_1}{100}\right)^{-n} = \sum_{n=1}^{m} \frac{0.9}{m} \left(1+\frac{a_1}{100}\right)^{-n} + \sum_{n=1}^{m} \frac{m-0.9(n-1)}{m} \times \frac{a}{100} \left(1+\frac{a_1}{100}\right)^{-n}$$

Thus, we can get

$$\frac{R}{100} = \frac{0.9}{m} + \frac{a_1}{100} + 0.9\,\frac{a_1}{100m} - 0.9\,\frac{a_1}{100m} \times \frac{\sum_{n=1}^{m} n\left(1+\frac{a_1}{100}\right)^{-n}}{\sum_{n=1}^{m} \left(1+\frac{a_1}{100}\right)^{-n}}$$

where

n is the number of years after the operation of the plant.

Operation and maintenance cost which includes labor, replacement, contingency and owner's administration cost is expressed as fixed charge rate that is usually used in calculation of power cost of the electric utility (30) though some of fractions of these are dependent on load factor. As we assume constant load factor, 70% or 80%, this simplification may be justified without significant errors.

2. Selected parameters

a. Construction cost The actual construction costs of the light water pressurized reactors which have been imported have been widely varied depending on the time when they started to be built, unit capacity of power plant and ordinal number of reactors. Therefore, construction cost are taken in the range from 200 $/kw to 100 $/kw. Actual construction cost have ranged from 325 $/kw to 180 $/kw in Japan (31). USAEC Report (39) indicated that construction cost of light water pressurized plant would range from 174 $/kw to 120 $/kw depended on unit capacity and ordinal number of power plant in a site.

As oil burning super critical steam high thermal efficiency large power plants which are under operation or construction are from 122 $/kw to 78 $/kw, projected construction costs are assumed in the range from 100 $/kw to 60 $/kw. Using learning curve in order to predict the tendency of decreasing construction cost of oil burning power plant the result shows that the future construction cost will expect to be around 100 $/kw which seems to be higher compared with actual figures of construction cost. In the Japanese manufacturing situation the learning curve method to predict the future values of the power plant cost seems not be fitted well since most of advanced technology related to power plant manufacturing have been induced by foreign countries.

b. Life-time and interest rate to bond   The life-time of power plant and interest rate of bonds are assumed in the range from 5 years to 30 years, and in the range from 3% to 30% respectively. According to the accounting of the electric utility (16), the life-time of thermal power plant on the average is 16 years and interest rate or fair return rate is 8%.

c. Load factor   Load factor is defined as the ratio of actually produced power to theoretically possible power produced in a year according to a rated output is assumed 70-80% following the actual operation data (30).

d. Tax   An average rate of property tax on the power plants, which is a kind of local state tax is 0.36% (30). Revenue tax which is also a kind of local state tax is neglected because revenue tax is charged over the total sales income and this tax does not change relative positions of nuclear power plant and oil burning power plant.

Table 15. Actual construction cost of nuclear power plants (30)

Reactor type	BWR_1 [a]	BWR_1	BWR_2	PWR_1	PWR_2
Capacity (Mwe)	322	400	784	340	500
Cost ($/kw)	325	284	180	244	200

[a] Is ordinal number of plant at site.

Table 16. Actual construction cost of oil burning power plants (30)

Fuel	Oil_1[a]	Oil_2	Oil_3	Oil_1	Oil_2
Capacity (Mwe)	600	600	600	450	450
Cost ($/kw)	122	79	84	128	93

[a]Is ordinal number of plant at site.

3. Fuel cost

a. Assumption of estimation of nuclear fuel cycle cost

In order to estimate nuclear fuel cycle cost, nuclear physics data of USAEC report (37) are used and the following assumptions are made;

1. Nuclear fuel and its necessary inventory which are completely fabricated are considered as consumable supplies that are not required to be depreciated.

2. Costs are paid at the beginning of each process in the nuclear fuel cycle and sales income of power is received uniformly during the life time of power plant.

3. Interests of bonds and borrowed money to pay nuclear fuel cycle cost do not change their rates during the life time.

4. Single interest rate method is used because nuclear fuel cycle is relatively short compared with the life time of power plant.

5. The present worth method is also used even though

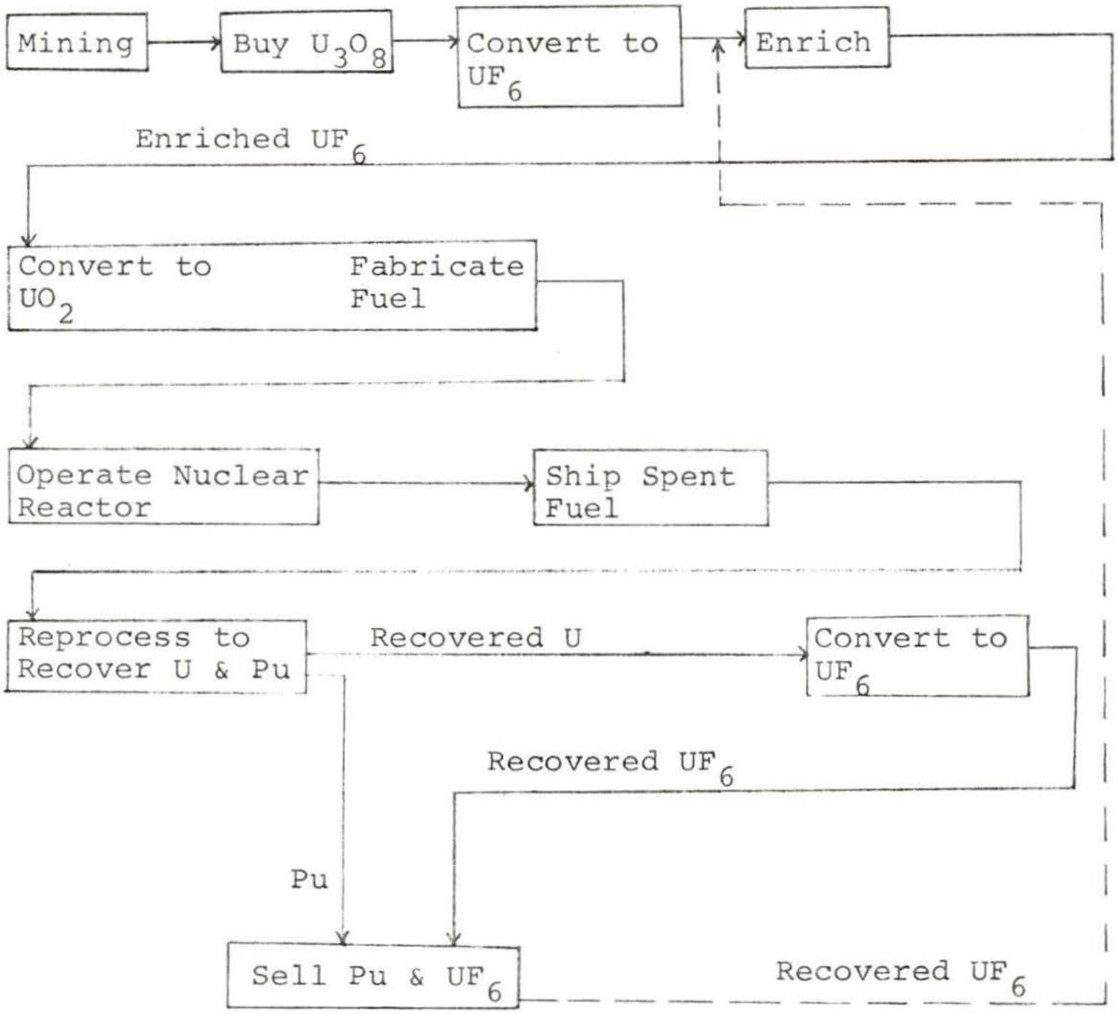


Figure 11. Typical nuclear fuel cycle of light water reactor

the single interest rate is adapted, and present time is defined as starting time when power plant is operated at first at full rated output power.

6. Reactor fuel burning condition is in the equilibrium core.

7. Value of recovered plutonium from spent fuel is equivalent to 70% of that of 93% enriched uranium (35).

8. Recovered plutonium and recovered depleted uranium should be able to be sold in spite of their usages.

9. No domestic or import tax is paid.

10. Transportation cost of nuclear fuel and fuel materials except shipping spent fuel from reactor site is included its main processing cost.

11. Required time for shipping and processing is assumed as shown in Appendix D.

12. Any additional compensation problem, such as environment pollution, is not included.

13. Costs of processing, including reprocessing and enrichment, follows Appendix D.

b. Assumption of estimation of oil fuel cost Oil fuel cost is calculated as follows:

$$F = \frac{F_u \text{ (mills/}10^3\text{ kcal) x 0.86 (}10^3\text{ kcal/kwh)}}{\frac{E_{ff}}{100}\text{ (\%)}} = \frac{86\ F_u}{E_{ff}}$$

where

860 kcal is 1 kwh.

In order to establish the above formula the following assumptions are made:

1. Interest of bonds and borrowed money is not paid since oil fuel is burnt in a relatively shorter time, about two months (16).

2. Since no interest is paid, inventory of oil fuel does not affect oil fuel cost of power.

3. Any additional compensation problems, such as environment pollution, are not included.

VII. RESULTS OF ESTIMATION OF POWER COSTS

A. Construction Capital Charge Cost

1. Construction cost effect

If life time, load factor, and annual interest rate of bond are held constant, construction capital charge costs (mills/kwh) are proportional to construction costs because depreciation, interest rate, operation and maintenance charge, and property tax are normalized by fixed charge rates which are acceptable in the accounting of the electric utility (16). In an estimation of nuclear power cost one percent is added to the normal operation and operation supplies, contingency and owner's administration expenses, as unknown factors such as reasonable reliable power plant insurance which is not set up yet in the accounting regulation of the electric utility and an additional unknown factors.

The results are shown in Figure 12 and 13. At life time, m=30 years, interest rate, a=8%, and load factor, L.F.=80%, construction capital charge of cost nuclear power ranges from 1.8 mills/kwh to 3.7 mills/kwh while that of oil burning power plant is from 0.8 mills/kwh to 1.7 mills/kwh depending on the construction cost.

At m=16, a=8%, and L.F.=80%, the construction cost of nuclear power plant is from 2.1 mills/kwh to 4.3 mills/kwh while that of oil burning power plant is from 1.0 mills/kwh to 2.0 mills/kwh.

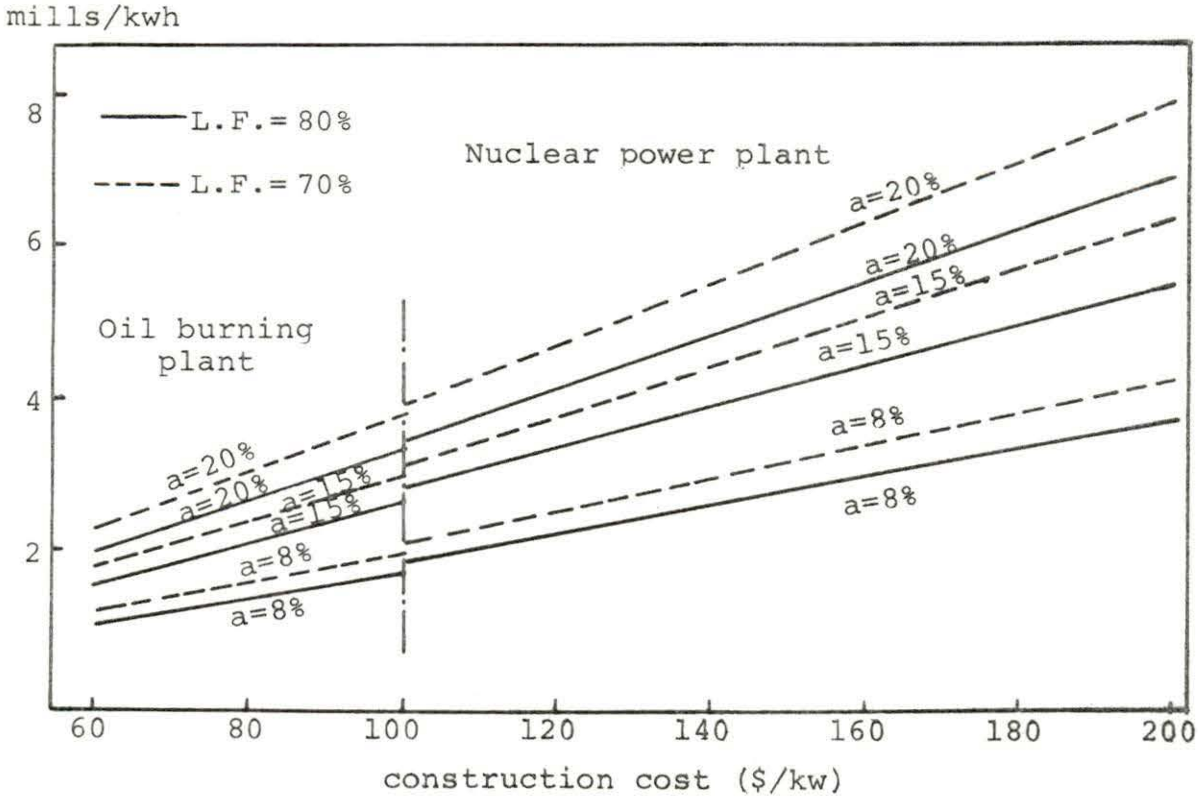


Figure 12. Capital costs of power plant construction at m=30 years

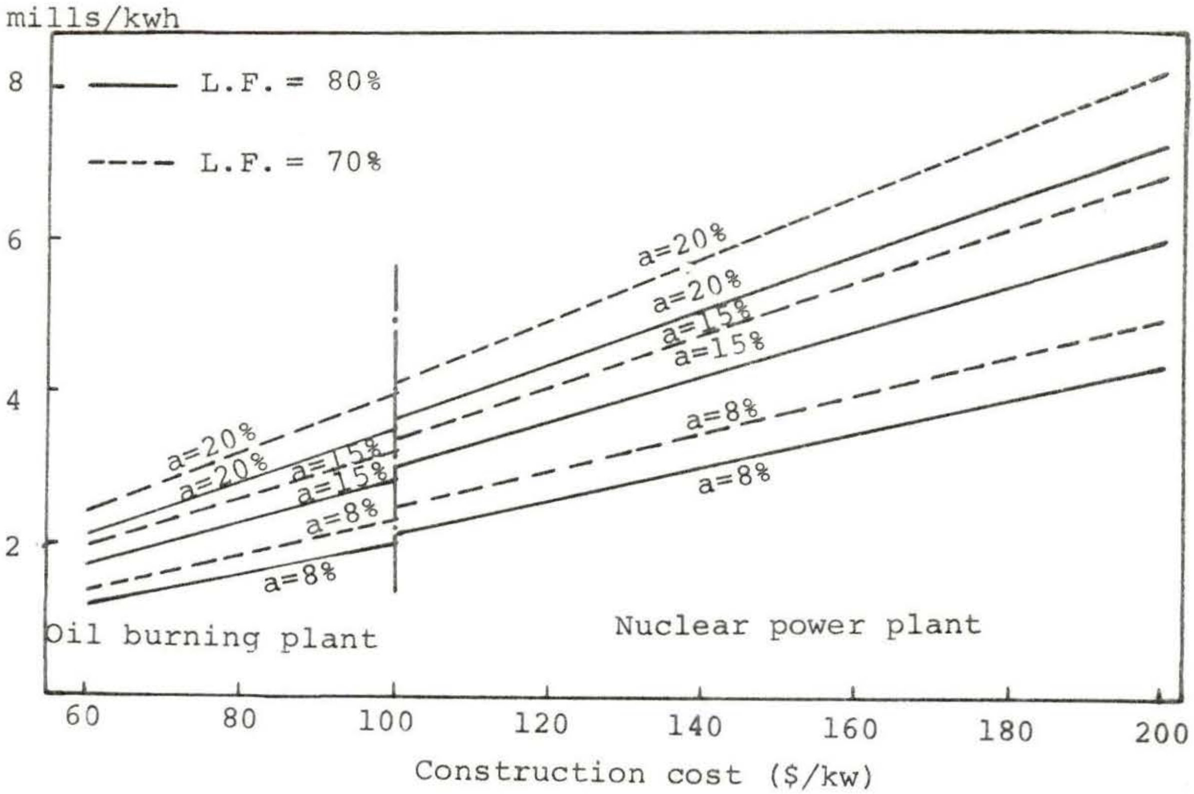


Figure 13. Capital cost of power plant construction at m=16 years

Actual data show that construction costs of nuclear power plants are more than twice those of oil burning power plants. As increasing construction costs of nuclear power plants give greater absolute difference of capital charge cost between these two type power plants, construction cost affects directly strong influence to promotion of construction of nuclear power plants in electric power industry.

2. Life time effect and interest rate effect

Figure 14, 15, and 16 show effects of life time and interest rate to the cost of construction capital charge of power plant. The shorter the life time of power plant is, the sharply higher the capital charge cost is. In comparison of the cost of five year life time at interest rate, a=8%, with that of thirty year life time at the same interest rate the former is 2.3 times as the later. However, relatively longer life time, more than 15 year life time, makes smaller difference among the costs. The cost of sixteen year life time, which is now used in the accounting of electric utility, is 1.2 times as that of thirty year life time.

As the interest rate of bonds goes up, the difference of cost among life times becomes relatively small. In comparison of the cost of five year life time at interest rate, a=15%, with that of thirty year life time at the same interest rate the former is 1.48 times as the latter.

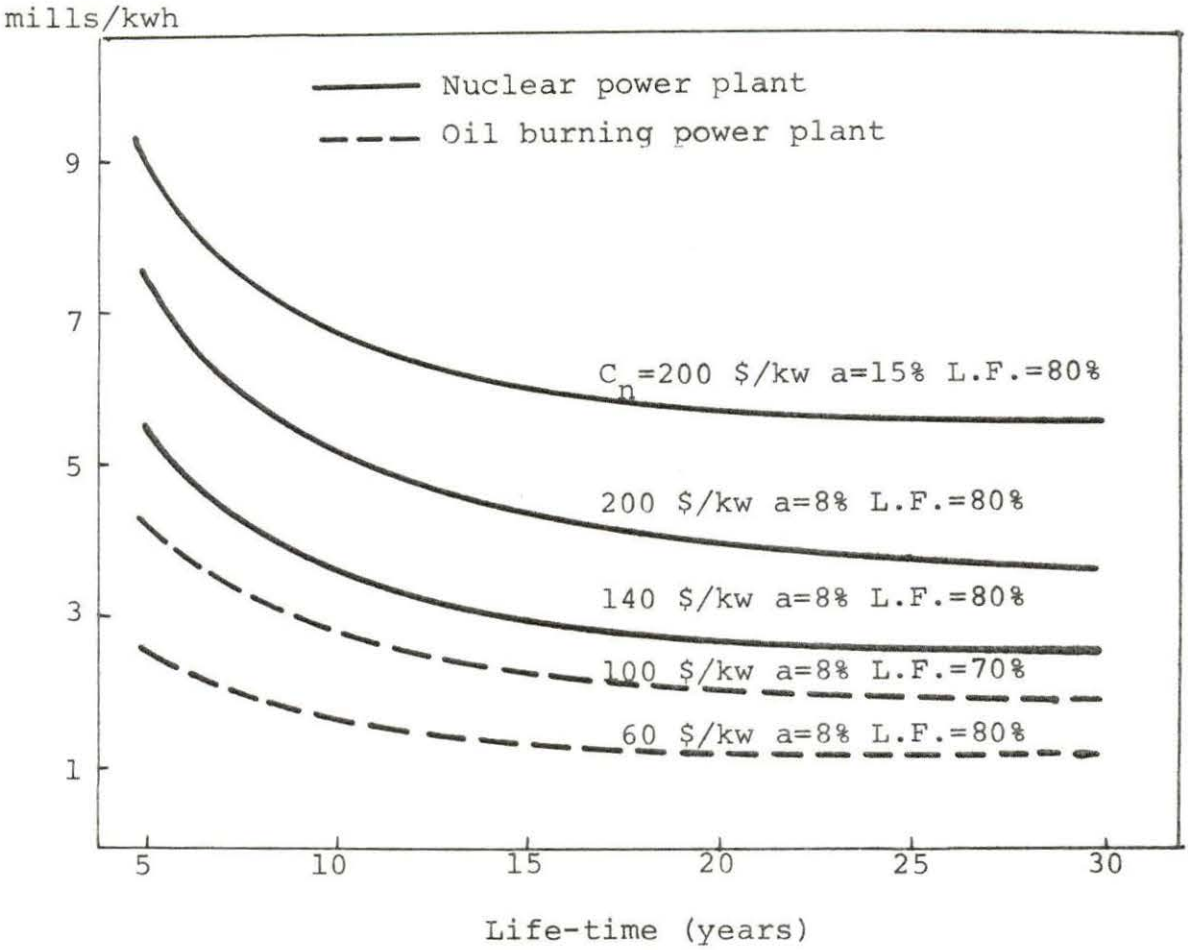


Figure 14. Capital cost of power plant construction

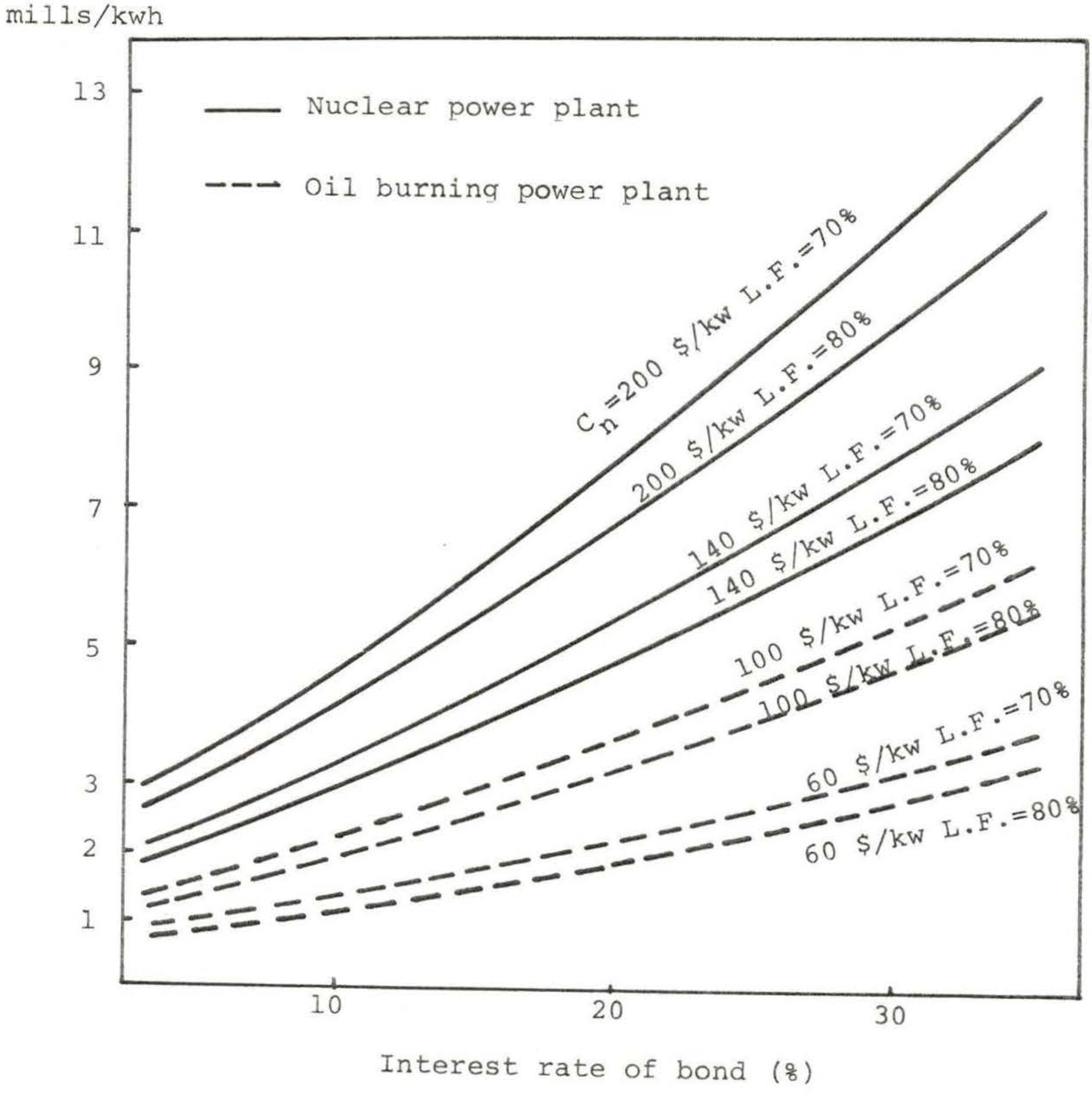


Figure 15. Capital costs of power plant construction at m=30 years

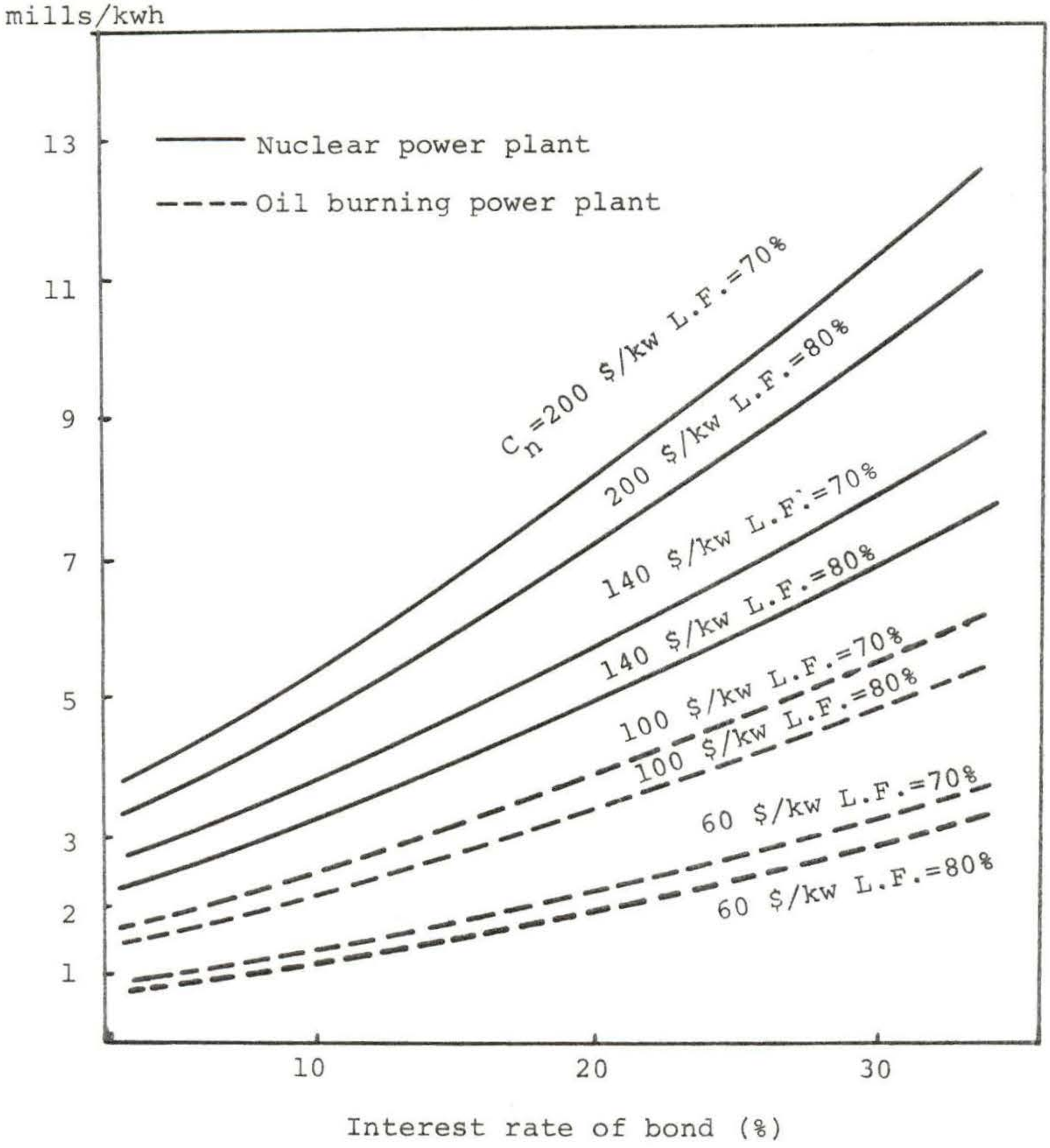


Figure 16. Capital costs of power plant construction at m=16 years

Higher construction costs of nuclear power plants presents a disadvantage under the condition of shorter life time and higher interest rate.

If the same life time is used for nuclear power and oil burning power plants, the construction capital charge cost of nuclear power plant is about twice that of oil burning power plant at present time since the former construction cost is about 2 times as the latter in actually constructed plants.

3. Load factor effect

Capital charge cost is inversely proportional to load factor, therefore, the higher load factor makes construction capital charge cost lower. A load factor of 70%, gives 14.3% higher cost than that of 80%. From the viewpoint of economical combination of several types of power plants, it is better that nuclear power plants are operated at as a high load factor as possible since energy cost per kwh is low, which is mentioned in nuclear fuel cycle cost.

B. Nuclear Fuel Cycle Cost and Oil Fuel Cost

1. Price of U_3O_8 effect

At interest rate, a=0,
the nuclear fuel cycle costs at U_3O_8=\$7/lb are ranged from 1.17 mills/kwh to 2.11 mills/kwh depending on model cases of

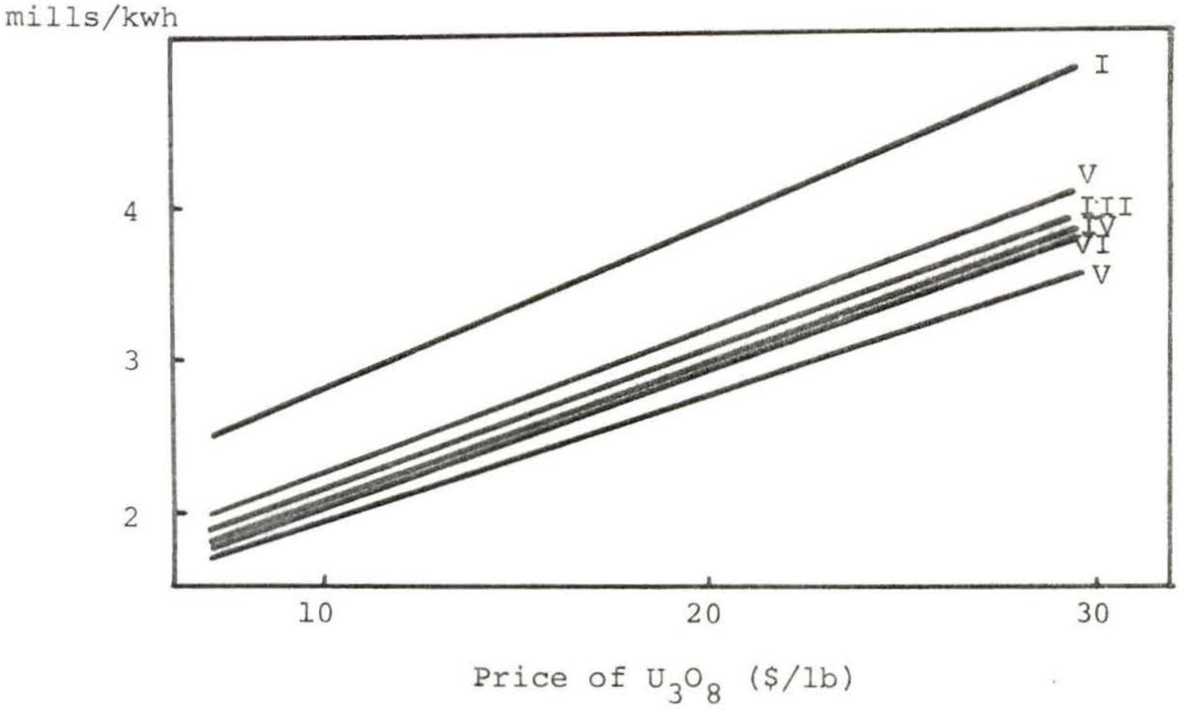


Figure 17. Nuclear fuel cycle cost at a_2=8%, C_f=70 $/kgU charged (Numbers in the figure are corresponding number of cases shown in Appendix D)

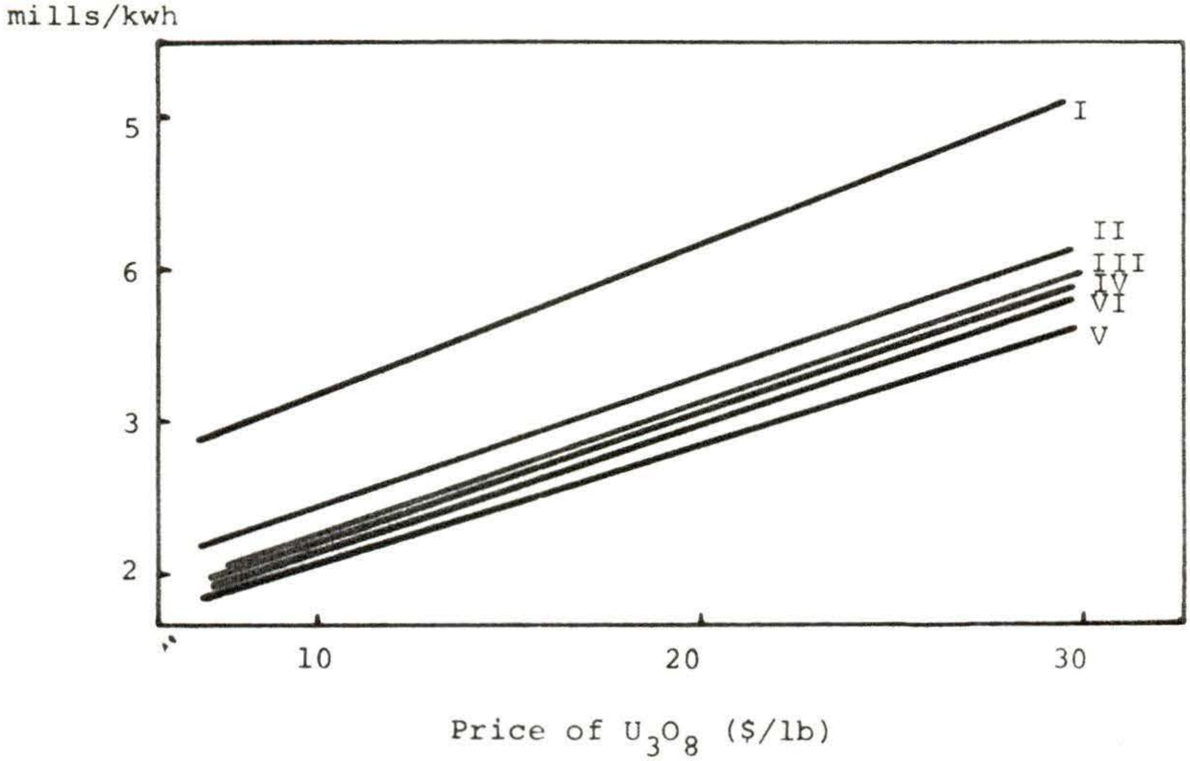


Figure 18. Nuclear fuel cycle cost at a_2=8%, C_f=100 $/kgU charged (Number in the figure are corresponding numbers of cases shown in Appendix D)

reactor and fabrication cost, and these at U_3O_8=$30/lb varied from 2.21 mills/kwh to 3.15 mills/kwh. This implies as the price U_3O_8 rises up by 4.3 times, the nuclear fuel cycle cost increases 1.5 times. As the price of U_3O_8 is predicted about $8.0/lb in the near future (36), the fuel cycle costs (except case 1 which is too low burnup compared with recent commercial light water type reactor) range from 1.22 mills/kwh to 1.73 mills/kwh depending on fabrication cost, in the range from $70/kgU to $100/kgU. This means nuclear fuel cycle costs range from 0.36 mills/10^3 kcal to 0.52 mills/10^3 kcal. According to Table 17 the price of U_3O_8 occupies about one third of the total nuclear cycle cost.

2. Burnup effect

The effect of burnup of fuel on nuclear fuel cycle cost can be shown in Figure 19. Generally higher burnup of fuel gives rise to lower nuclear fuel cycle cost at the same considerations rather than burnup. Enrichment of initial charged fuel, burnup of fuel, and enrichment of discharged fuel may have some suitable relation in their combination to minimize the nuclear fuel cycle under a specific price of plutonium. Nuclear fuel cycle costs at U_3O_8=8.0/lb and fabrication cost 100 $/kgU range from 1.32 to 1.73 mills/kwh so that 0.42 mills/kwh or 32% is difference between the lowest and the highest nuclear fuel cycle cost.

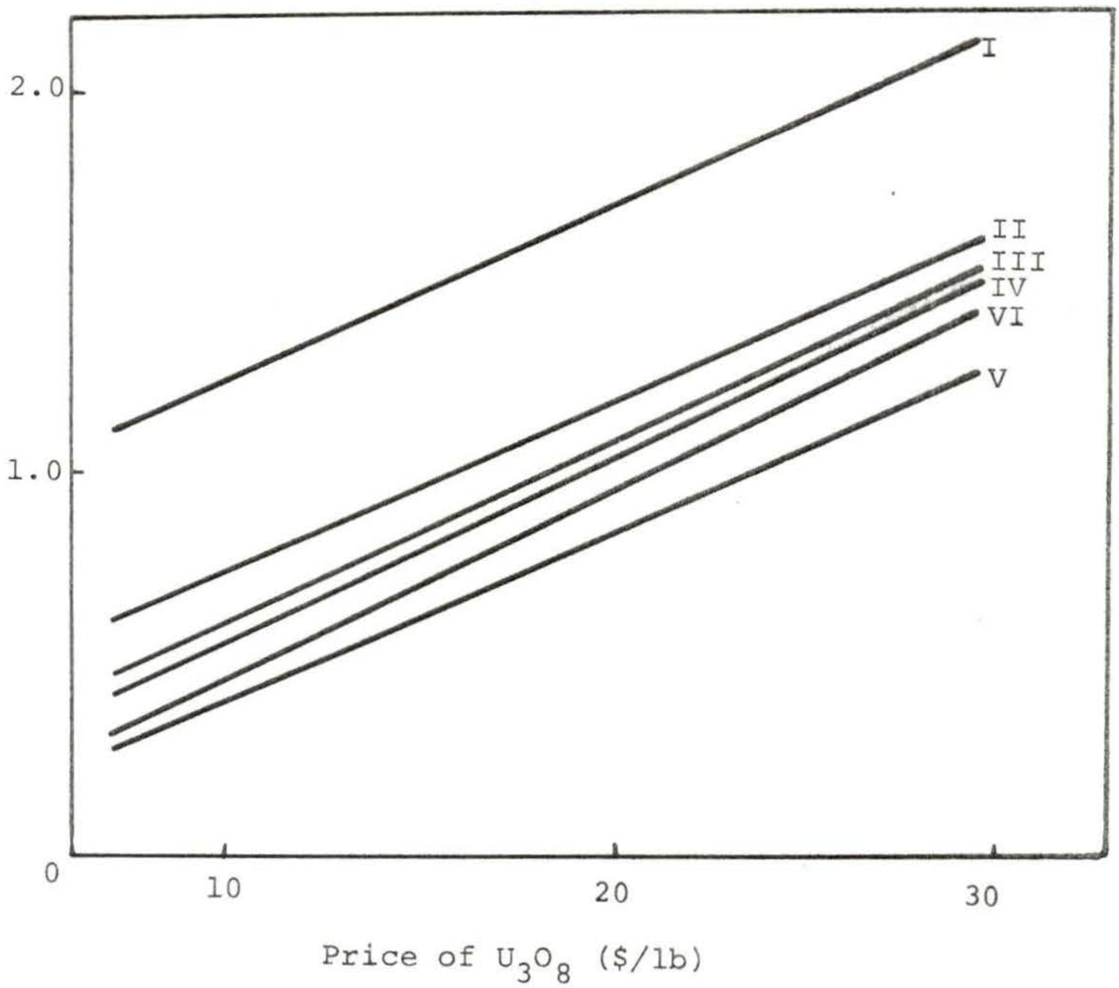


Figure 19. Nuclear fuel cycle cost without interest at C_n=100 $/kw, L.F.=80% and m=16 years (Numbers in the figure are corresponding numbers of cases shown in Appendix D)

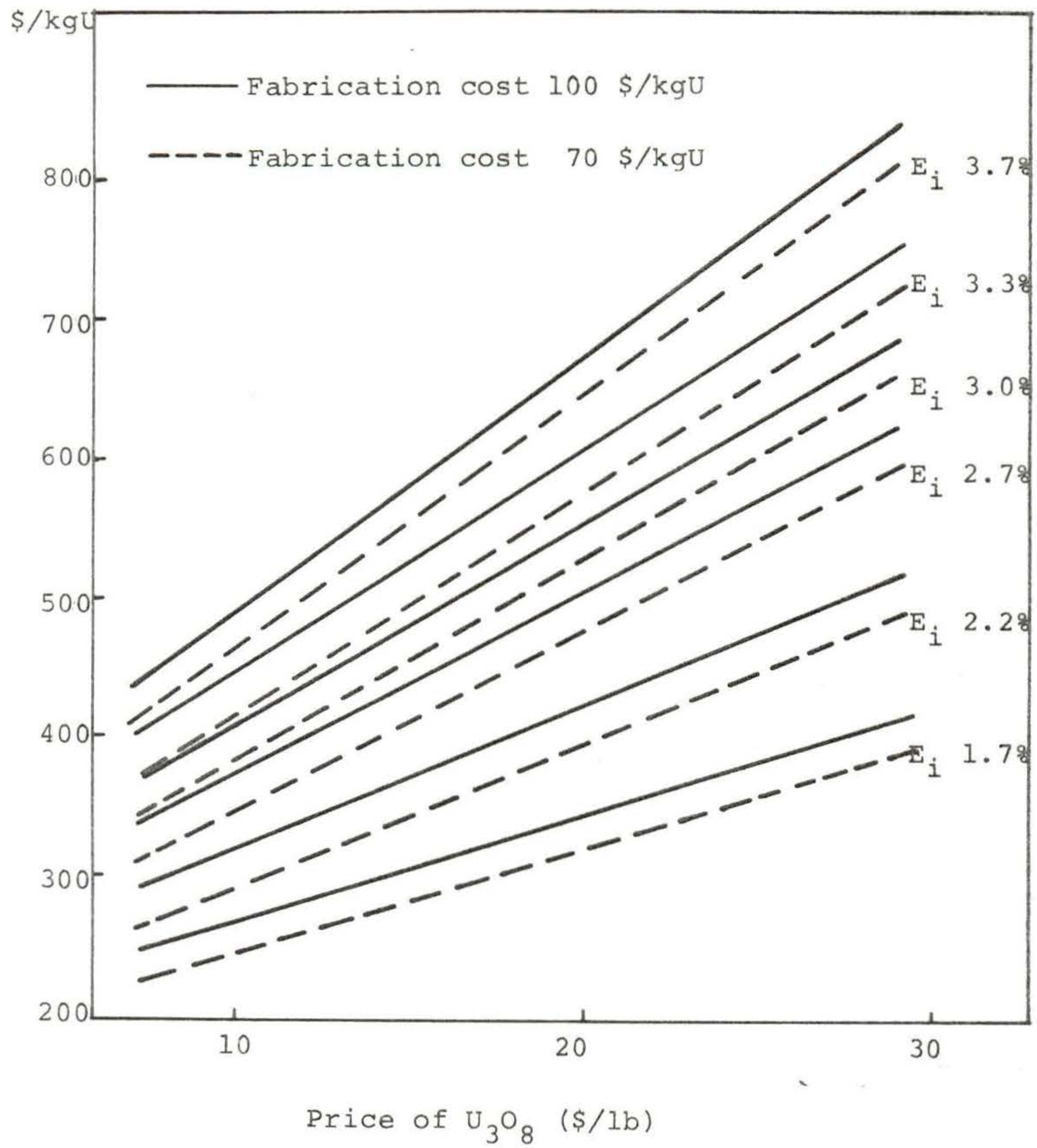


Figure 20. Price of completely fabricated nuclear fuel without interest

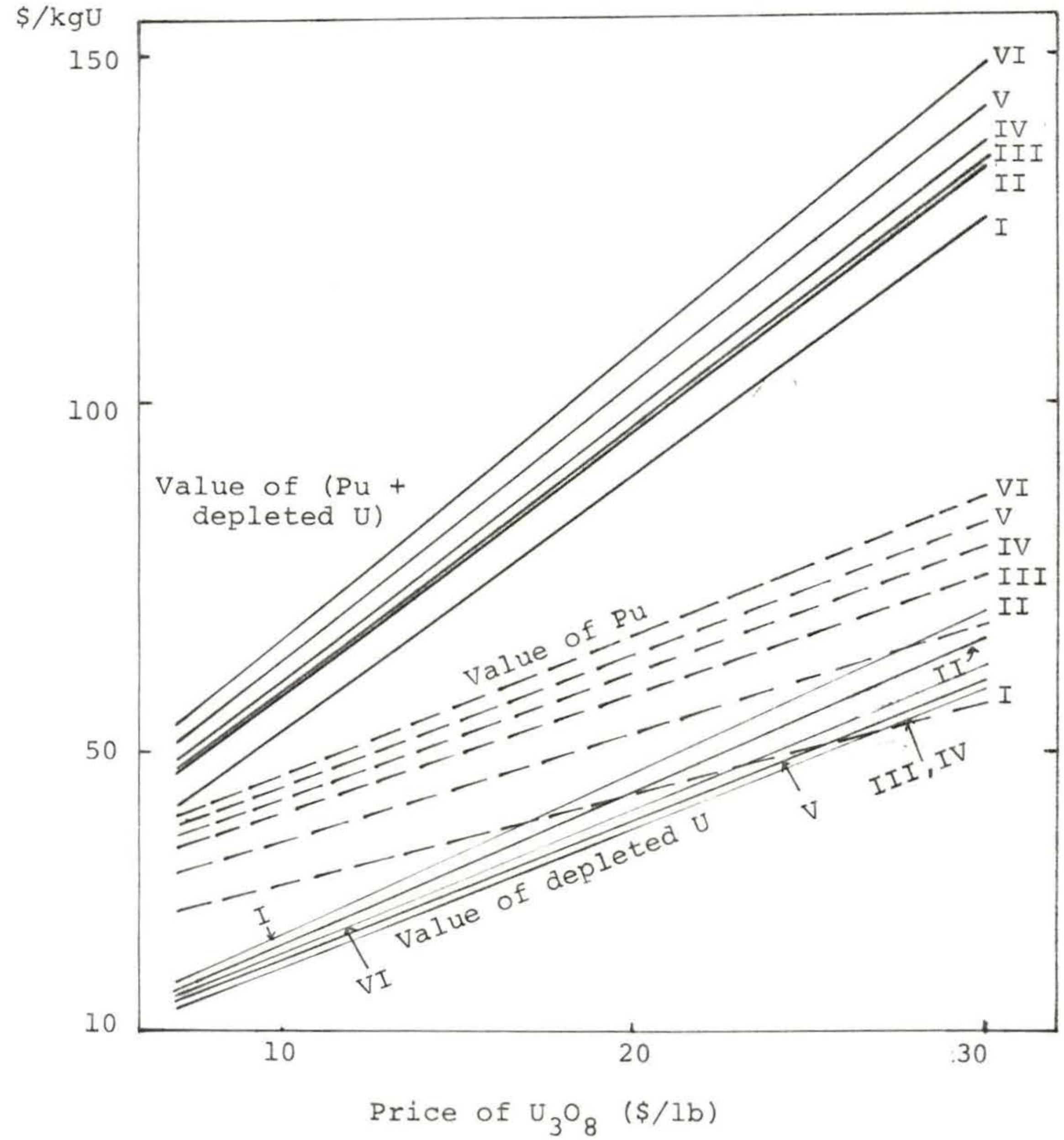


Figure 21. Recovered value of Pu and depleted U at $a_2=0$ (Numbers in the figure are corresponding numbers of cases shown in Appendix D)

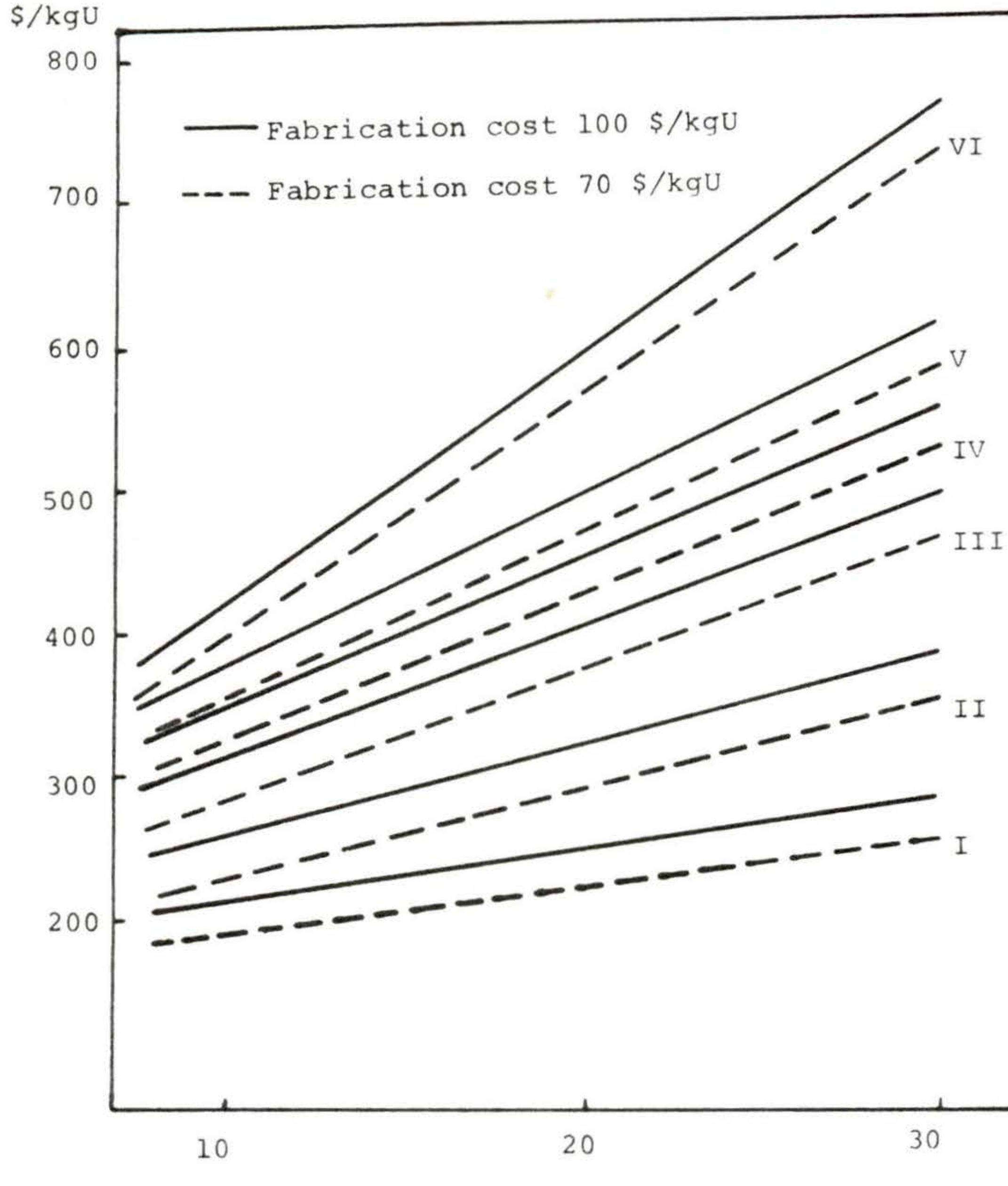


Figure 22. Net nuclear fuel cost without interest, which is given by subtracting recovered value of Pu and U from cost of completely fabricated fuel (Numbers in the figure are corresponding numbers of cases shown in Appendix D)

3. Interest rate effect

The effect of interest rate to nuclear fuel cycle cost in case II is shown in Figure 23. At price of U_3O_8, 8 \$/lb and fabrication cost, 100 \$/kgU nuclear fuel cycle cost varies from 1.59 mills/kwh at interest rate, a=0, to 2.4 mills/kwh at a=10%. This implies that the nuclear fuel cycle cost at a=10% is 1.5 times that at a=0. The time interval from buying fuel material, U_3O_8, to selling recovered plutonium and uranium is long enough to be affected greatly by interest rate.

4. Fabrication cost effect

Figure 22 shows the difference between fabrication costs. At lower burnup of fuel the effect of fabrication cost is larger but most of cases except case 1, the difference of nuclear fuel cycle cost between different fabrication cost, 70 \$/kgU and \$100/kgU, is less than 0.05 mills/kwh.

5. Load factor effect

Contrary to construction capital charge cost, load factor does affect nuclear fuel cycle cost slightly. The calculation result indicates the difference of nuclear fuel cycle cost, 0.03 mills/kwh between load factors, 70% and 80%. This is less than 2% of total nuclear fuel cycle cost.

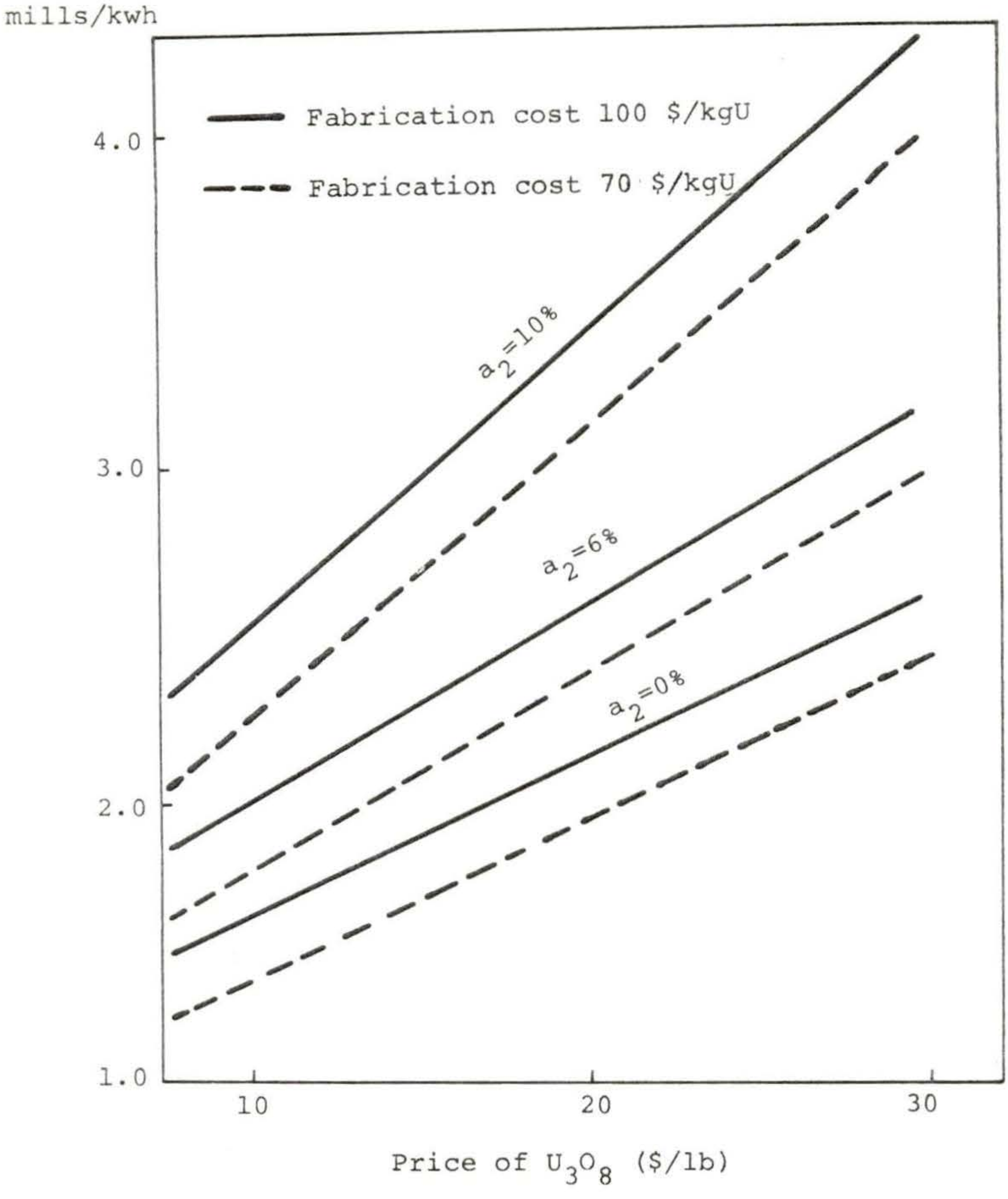


Figure 23. Nuclear fuel cycle cost of Case II at L.F.=80%

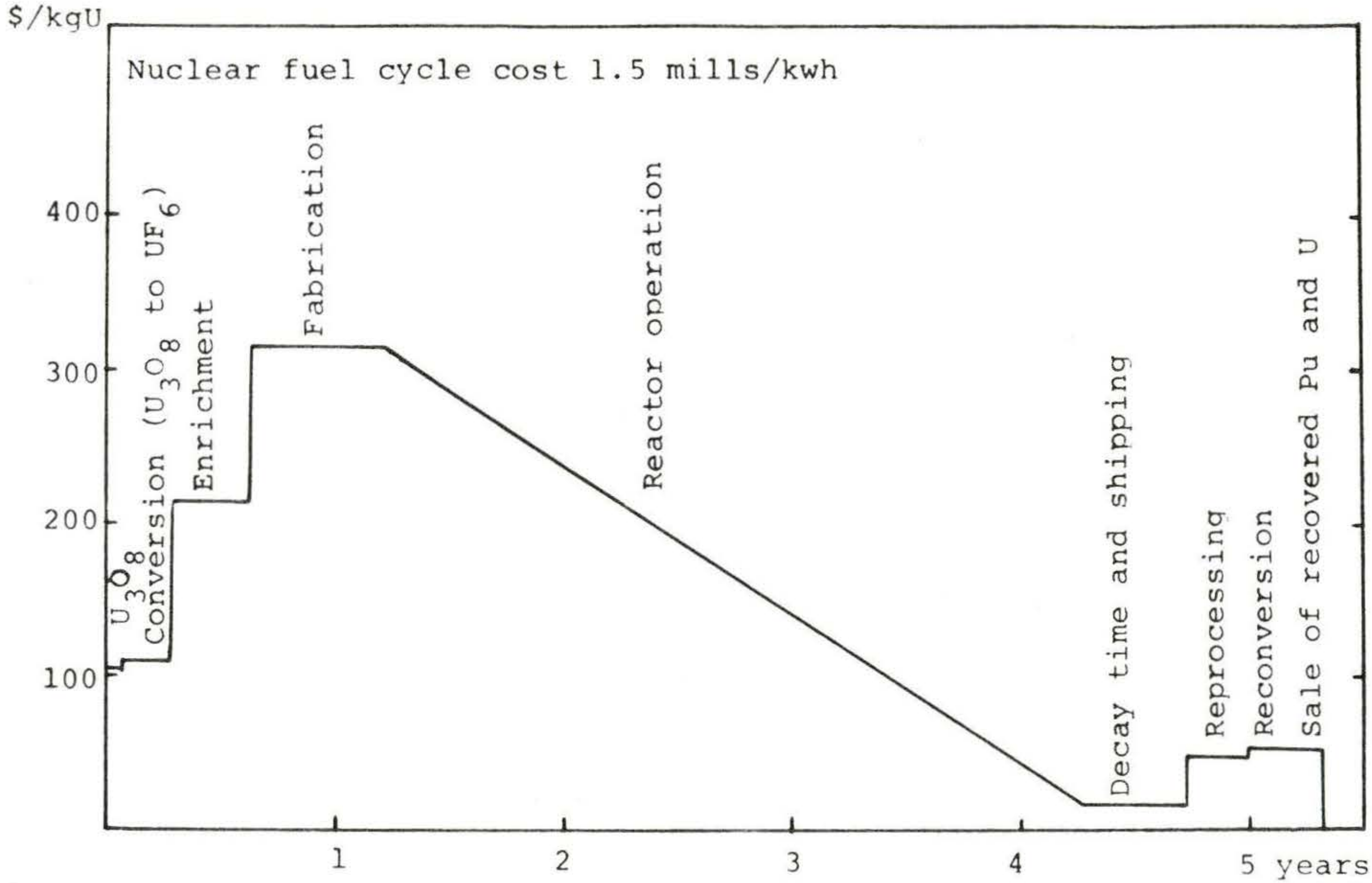


Figure 24. Nuclear fuel cycle cost expenditure U_3O_8 8 $/lb, fabrication cost 100 $/kgU, initial enrichment 2.7%, discharge enrichment 0.59%, load factor 80%, net thermal efficiency 30% and interest rate 0

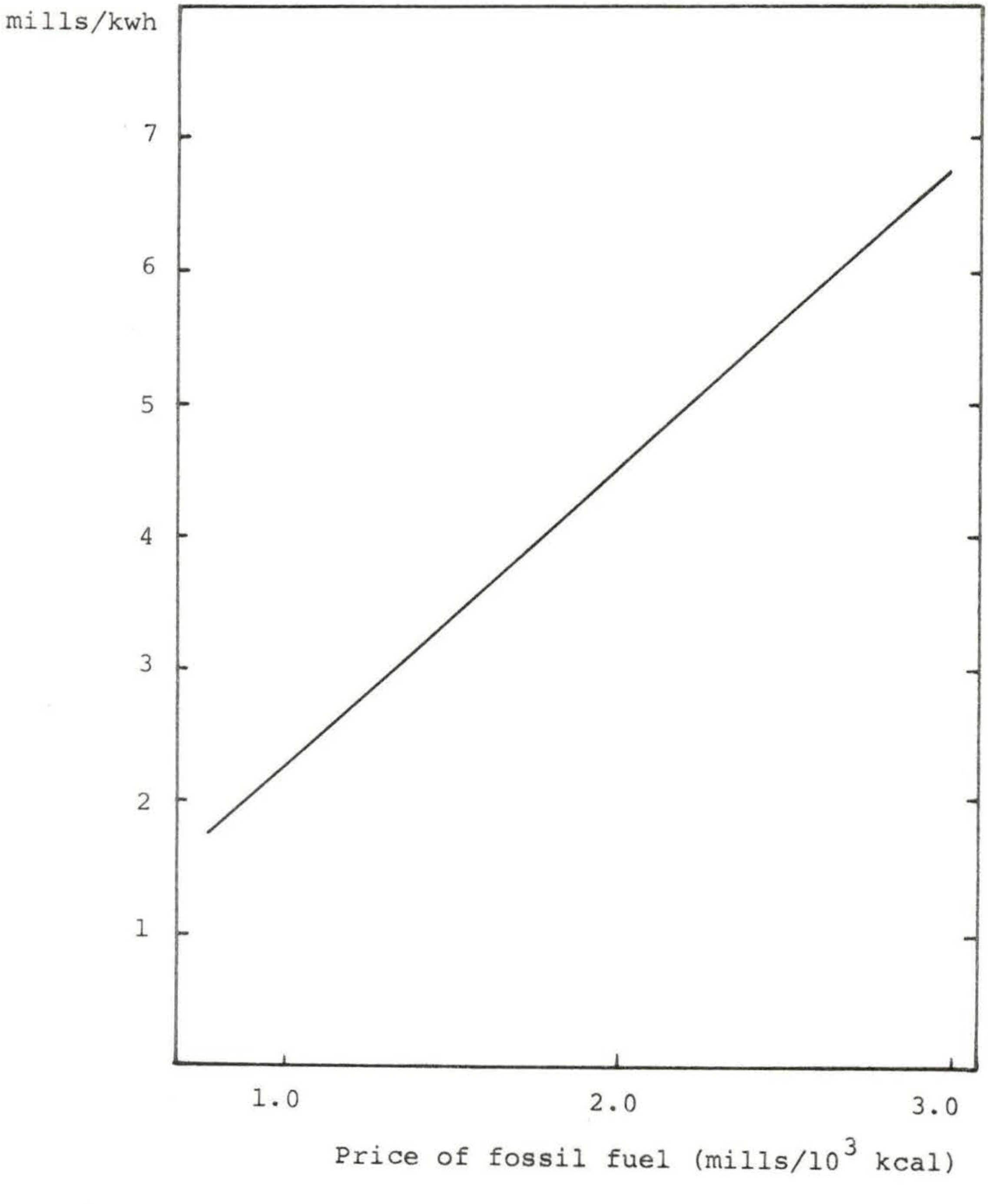


Figure 25. Fossil fuel cost at net thermal efficiency 38%

6. Oil fuel cost

Oil fuel cost (mills/kwh) is linearly proportional to the price of oil (mills/10^3 kcal) and inversely proportional to thermal efficiency which is assumed 38% (30), so that oil fuel cost is linearly dependent on the price of oil. At present time the price of oil fuel lies in the range of 1.4 mills/10^3 kcal to 1.65 mills/10^3 kcal on the average of the electric utility (4). The results of oil fuel cost (mills/kwh) are shown in Figure 25.

C. Interesting Features of Nuclear Fuel Cost

1. Less weight of cost of uranium

Table 17 shows the ratios of each process to the total fuel cost including reprocessing cost. The cost of required feed natural uranium is in the range of 30% to 36.2% in the model cases. If recovery value from spent fuel is attributable to raw material, U_3O_8, net cost of required feed natural uranium is in the range of 12.5% to 23.5%. This feature has a favorable potentiality in order to promote nuclear power plants. Though nuclear raw fuel material, uranium ore, can not be refined from domestic resources at reasonable cost since Japan is still a poor country of uranium and thorium resources, conversion, enrichment, fabrication and reprocessing of nuclear fuel will be possible in the future.

Table 17. Nuclear fuel cost ratio to total fuel cost (%)

Initial Enrichment (%)	1.7	2.2	2.7	3.0	3.3	3.7
Discharge Enrichment (%)	0.65	0.63	0.59	0.59	0.6	0.61
Required feed uranium cost	30.0	31.4	33.7	34.6	35.5	36.2
Enrichment cost	16.6	22.4	26.9	29.2	31.1	33.3
Fabrication cost[a]	39.8	33.2	28.2	26.0	24.0	21.9
Shipping cost of spent fuel and recovery cost of Pu and depleted	15.6	13.0	11.1	10.2	9.4	8.6
Total cost[b]	100.0	100.0	100.0	100.0	100.0	100.0
Recovery value	17.5	16.6	14.4	14.0	13.2	12.7
Net fuel cost	82.5	83.4	85.6	86.0	86.8	87.3

[a]Fabrication cost including conversion cost of enriched UF_6 to UO_2 is assumed 100 $/kgU.

[b]Interest rate is zero.

In addition to cheaper fuel cost, nuclear fuel has a possibility to save international payments.

2. Greater dependence on technology

While burning fossil fuel is naturally possible regardless of its burning scale, burning nuclear fuel is much more dependent on the technology. Therefore, it requires highly advanced technology to sustain chain fission reaction effectively and economically in order to produce controlled power. Therefore, though nuclear fuel material exists in nature, we can say that nuclear energy under controlled operation is a man-made energy.

Consequently, less fraction of cost of uranium to nuclear fuel cost suggests that reduction of costs such as these of processing, fabrication and reprocessing are required and that such technical affairs will be able to be improved greatly through expanding market and extensive researches.

D. Comparison of Power Costs

Table 18 and 19 show nuclear power cost and oil burning power cost respectively. Actual typical nuclear power cost is 9.0 mills/kwh and actual typical oil burning power cost is 8.3 mills/kwh (30). These power costs include revenue tax, 1.5%. At present time the construction costs of nuclear power

Table 18. Nuclear power cost

Construction cost	200 $/kw			160 $/kw			140 $/kw			120 $/kw		
Construction capital cost (A) (mills/kwh)	4.3			3.5			3.0			2.6		
Interest rate of nuclear fuel payment	0%	6%	8%	0%	6%	8%	0%	6%	8%	0%	6%	8%
Nuclear fuel cycle cost (B) (mills/kwh)	1.6	1.9	2.3	1.6	1.9	2.3	1.6	1.9	2.3	1.6	1.9	2.3
Total power cost (mills/kwh) (C)	5.9	6.2	6.6	5.1	5.4	5.8	4.6	4.9	5.3	4.2	4.5	4.9
Ratio (B/C)(%)	27.1	30.7	34.9	31.4	35.2	41.4	34.8	38.8	45.2	38.2	42.1	49.0

Assumption:

Price of U_3O_8 is 8 $/lb and fabrication cost is 100 $/kgU.

Fuel burnup 21,000 MWD/MUT.

Load factor is 80% and net thermal efficiency 30%.

Life time of power plant is 16 years and interest rate of bond for construction of power plant is 8%.

Table 19. Oil burning power cost

Construction cost	100 $/kw			90 $/kw		
Construction Capital cost (A)		2.3			2.1	
Oil fuel cost (mills/10^3 kcal)	1.4	1.6	1.9	1.4	1.6	1.9
Fuel cost (B) (mills/10^3 kcal)	3.2	3.7	4.3	3.2	3.7	4.3
Total Power cost (C)=(A)+(B)	5.5	6.0	6.6	5.3	5.8	6.4
Ratio (B/C) (%)	58.2	61.6	65.2	59.3	63.7	67.2

Assumption:

Life time of power plant is 16 years and interest rate of bond for construction of power plant is 8%.

Load factor is 70% and net thermal efficiency is 38%.

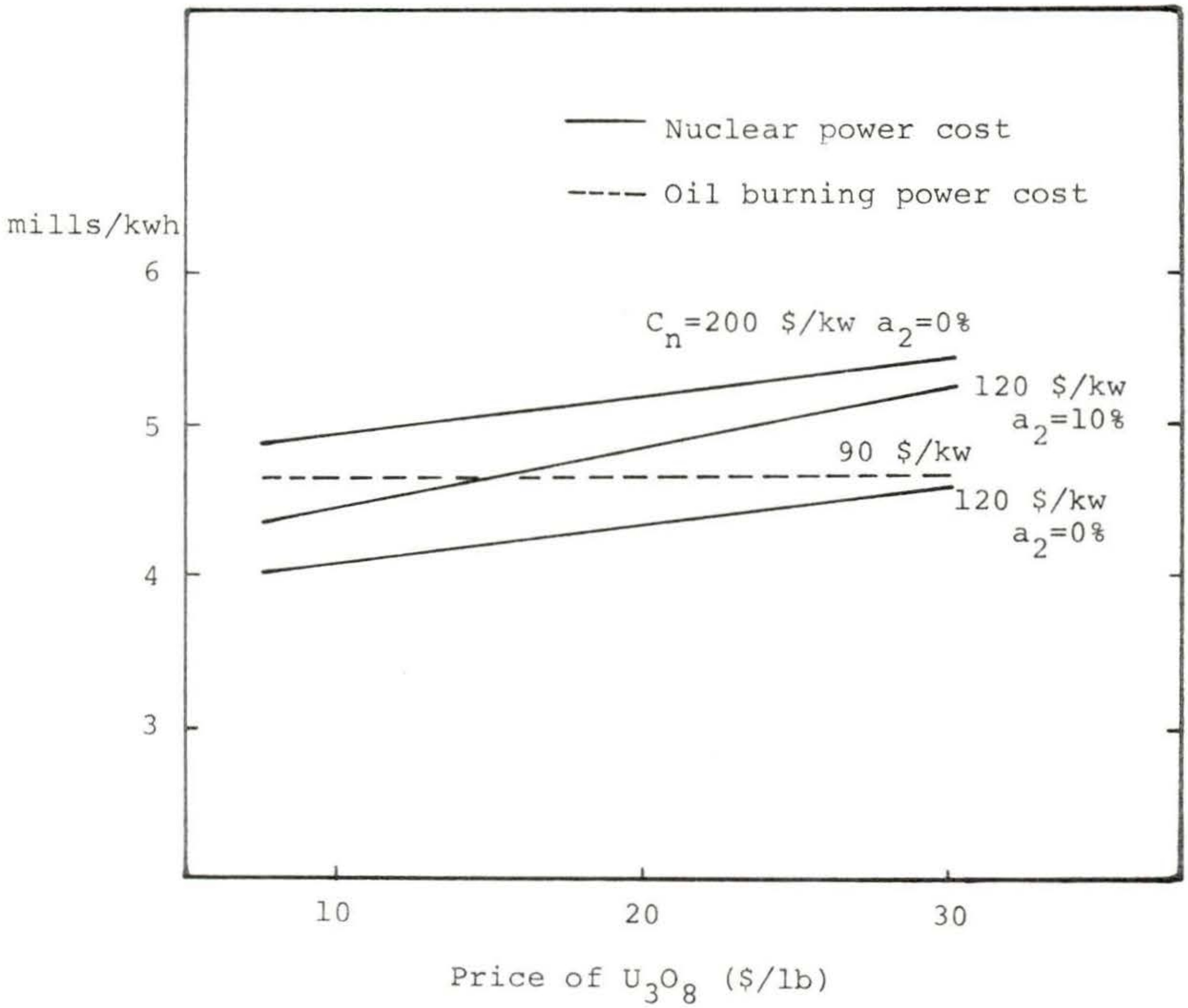
80 $/kw			70 $/kw			60 $/kw		
1.8			1.6			1.4		
1.4	1.6	1.9	1.4	1.6	1.9	1.4	1.6	1.9
3.2	3.7	4.3	3.2	3.7	4.3	3.2	3.7	4.3
5.0	5.5	6.1	4.8	5.3	5.9	4.6	5.1	5.7
64.2	67.2	70.5	66.8	69.8	72.9	69.5	72.5	75.5

plant and oil burning power plant are around 200 \$/kw and 90 \$/kw respectively (30). Oil fuel cost is around 1.6 mills/10^3 kcal. This gives oil burning power cost 5.8 mills/kwh which requires nuclear power take zero interest rate for nuclear fuel payment at construction cost, 200 \$/kw cost.

In comparing nuclear power cost with oil burning power cost, we can find distinguishing difference between them. The ratios of fuel costs to total power costs show this distinguishing feature. Nuclear power cost consists mainly of construction capital cost while oil burning power costs contributed mainly by oil fuel cost.

In consideration of technical aspects of these two power plants, most of the techniques related to turbine and generator are common for both plants even though a boiling water type reactor power plant uses steam directly out of core, and only different parts are of steam generation. Therefore, advanced techniques which have already achieved in oil burning power plants will be able to be applied to nuclear power plants.

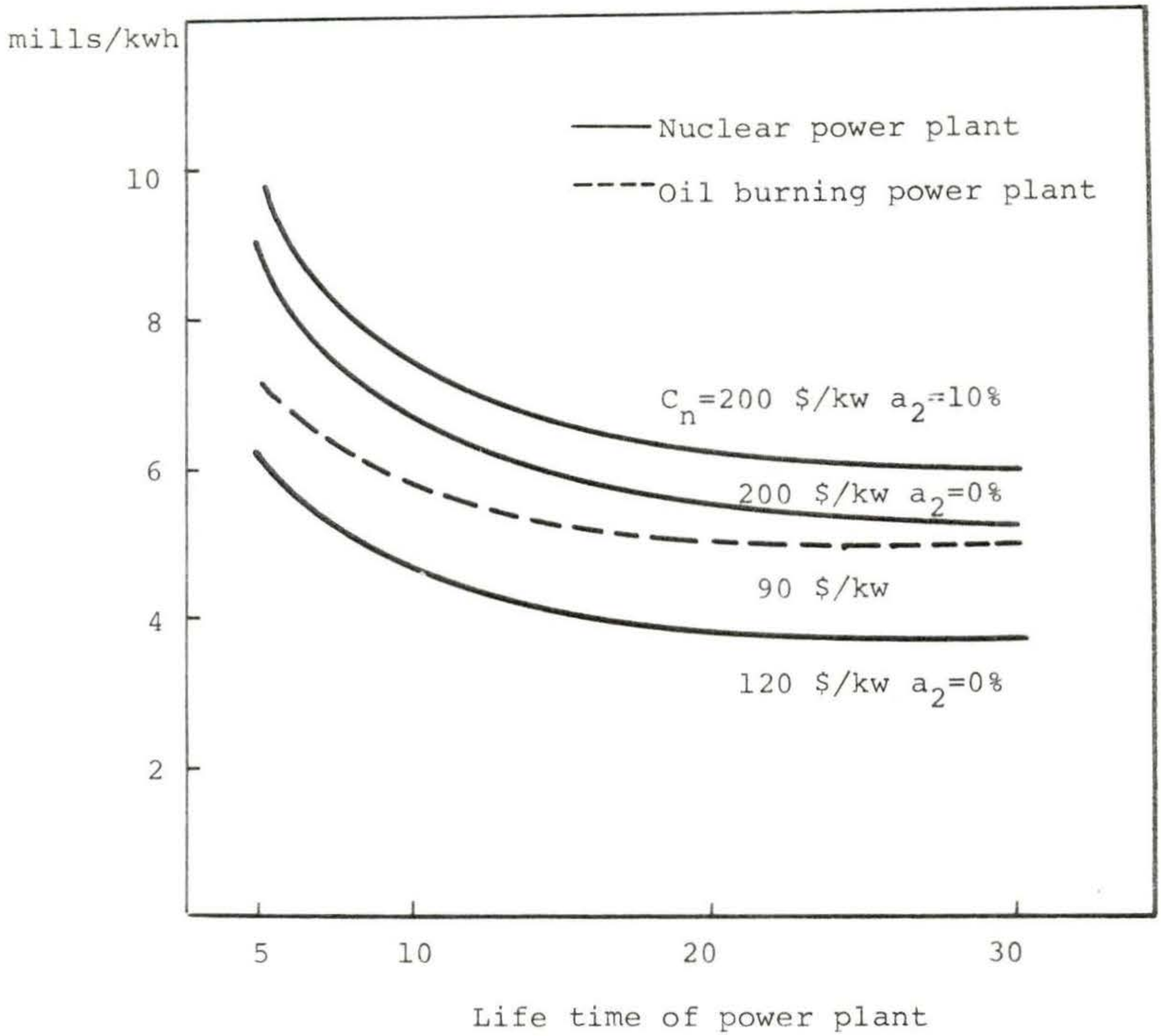
As the number of nuclear power plants increase, their construction cost will be reducing. Figure 30 shows the tendency of reduction of construction cost in the United States of America. This indicates that we can expect to have lower construction cost, 120 \$/kw in the near future. Even



nuclear power plant: L.F.=80%, C_f=100 \$/kgU, B=27.600 MWD/MTU, m=16, and a_1=8%

oil burning power plant: L.F.=70%, m=16, and a_1=8%

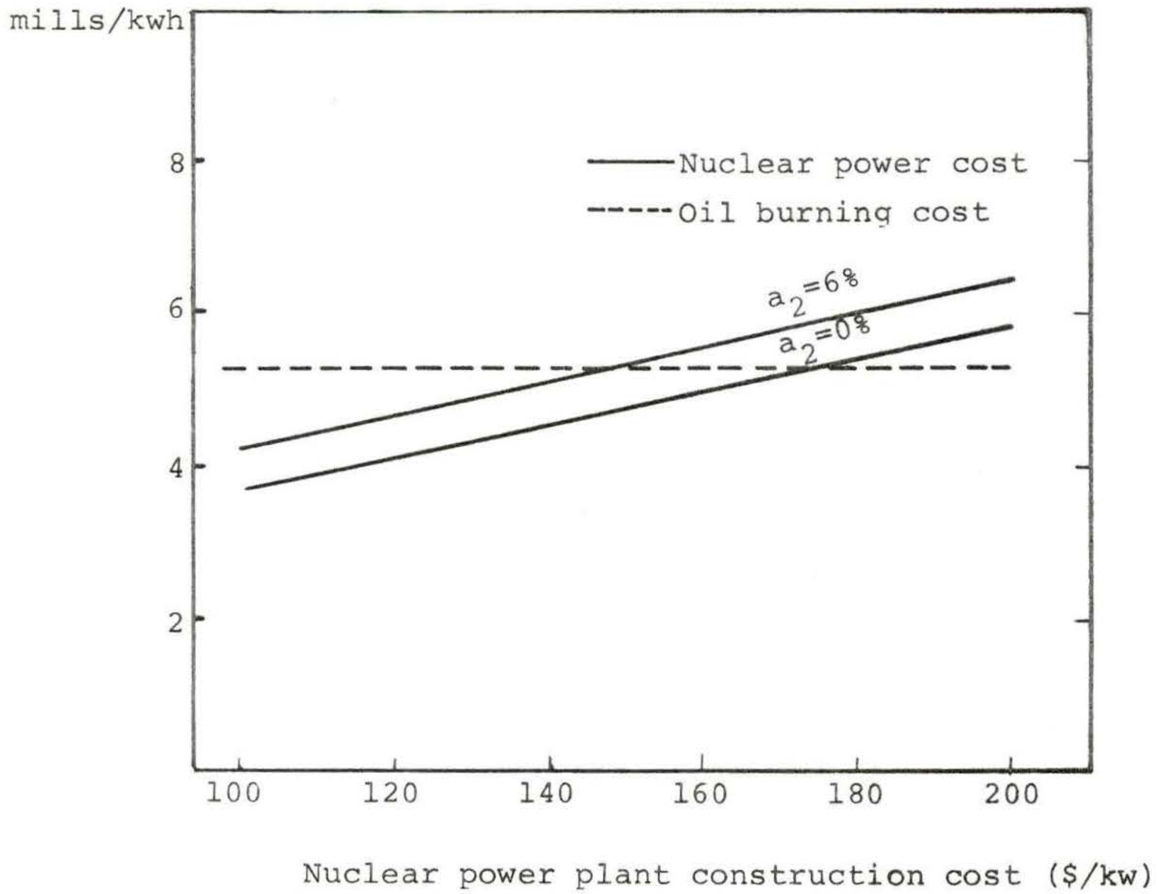
Figure 26. Power cost of nuclear and oil burning power plant



Nuclear power plant: L.F.=80%, C_f=100 \$/kgU, U_{n1}=8 \$/lb, B=27,600 MWD/MTU, and a_1=8%

Oil burning power plant: L.F.=70%, F=3.2 mills/kwh and a_1=8%

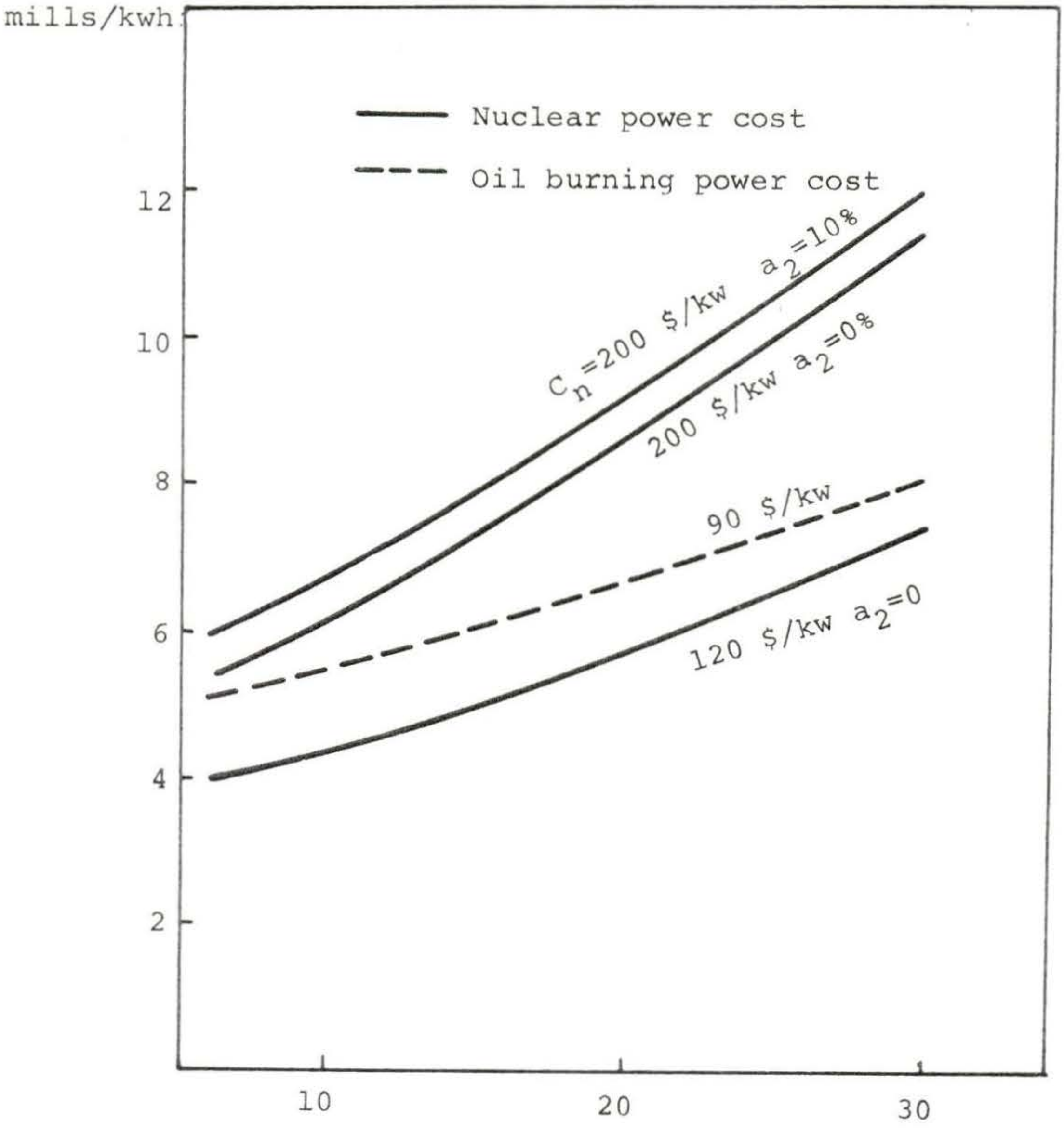
Figure 27. Power cost of nuclear and oil burning power plant with variable life time



Nuclear power plant: L.F.=80%, C_f=100 \$/kgU, U_{n1}=8 \$/lb, B=27,600 MWD/MTU, a_1=8%, and m=16 years

Oil burning power plant: L.F.=70%, F=3.2 mills/kwh, a_1=8%, and C_n=90 \$/kw

Figure 28. Power cost of nuclear and oil burning power plant with variable construction costs



Nuclear power plant: L.F.=80%, C_f=100 \$/kgU, U_{n1}=8 \$/lb, B=27,600 MWD/MTU, and m=16 years

Oil burning power plant: L.F.=70%, F=3.2 mills/kwh, and m=16 years

Figure 29. Total power cost with variable interest rates

if nuclear fuel cycle cost can not be improved and 8% interest rate for fuel cycle costs is required, this construction cost, 120 \$/kw which produces 4.9 mills/kwh power cost, can compete with oil burning power plant which requires 60 \$/kw construction cost of 1.6 mills/10^3 kcal oil fuel cost.

Inexpensive nuclear fuel cycle cost and expectation of reduction of construction cost of power plant give great hope to solve the energy problems in Japan.

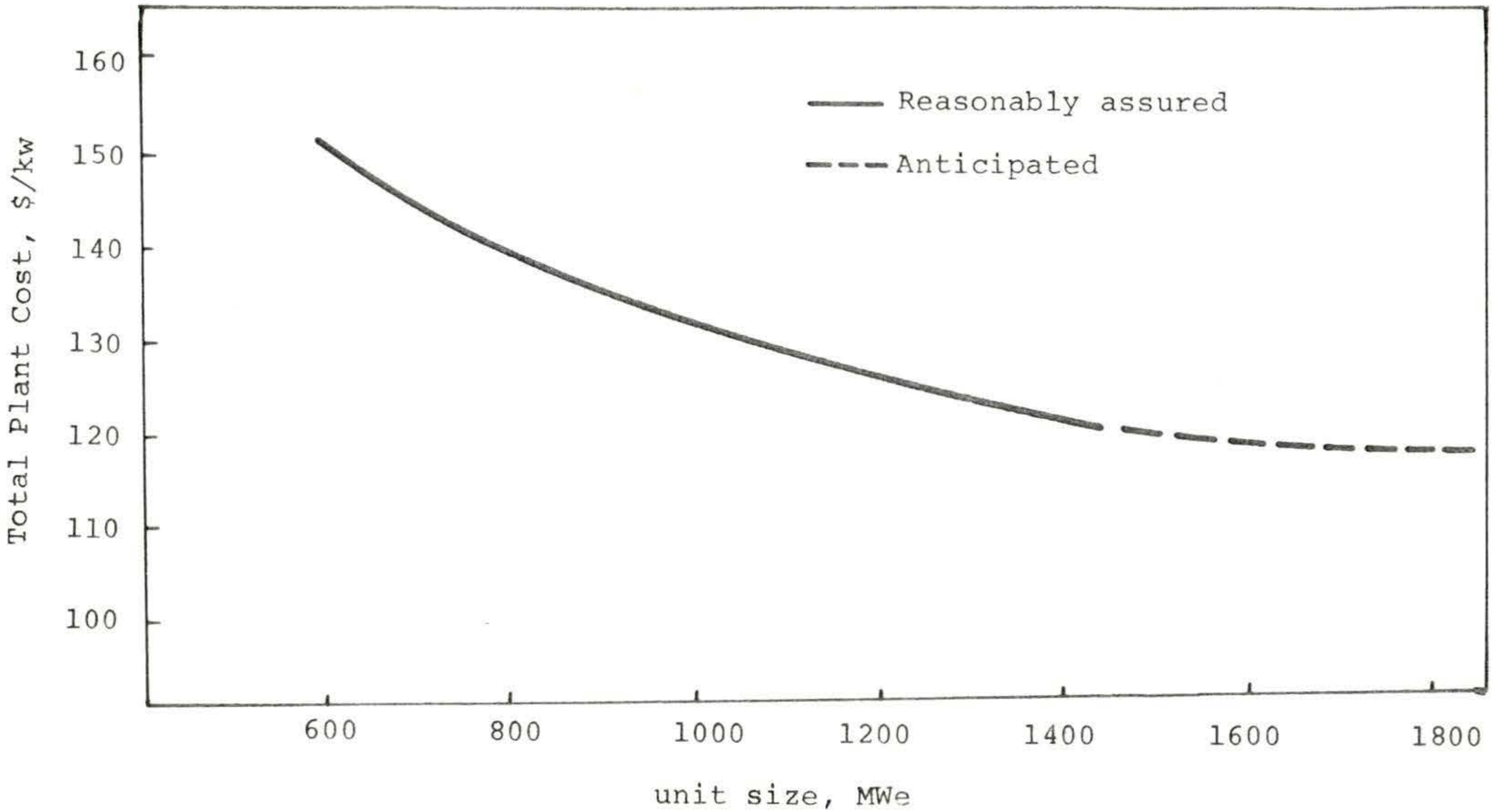


Figure 30. USAEC's projection of light water plant (38)
(Included all indirects and contingencies)

VIII. PROBLEMS OF NUCLEAR POWER GENERATION

A. Problems of Nuclear Power Generation

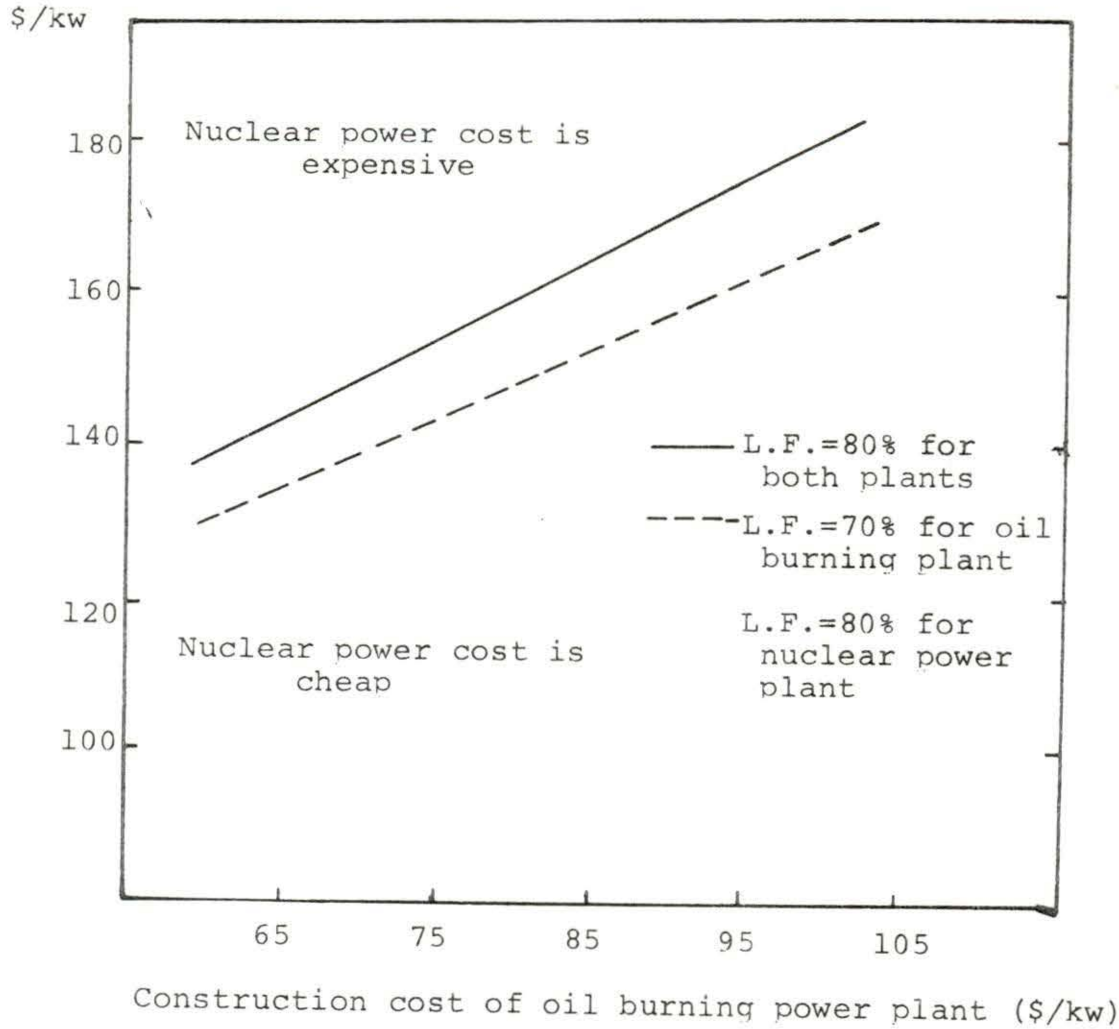
1. Expensive construction cost of nuclear power plants

The main reason for increased nuclear plant construction is the attractiveness of low nuclear fuel cycle costs. Unlike a fossil-fired plant, the cost of nuclear fuel plays a major role when evaluating nuclear power because its relatively higher construction cost sometimes reduces or overcomes this advantage. Therefore, the low cost of nuclear fuel cycle cost should be balanced against construction capital charge cost to produce power with a competitive cost.

The construction costs of nuclear power plants with the light water type reactors are more than twice those of oil burning power plants and the lower nuclear fuel cost can still not offset this gap. Therefore, first of all, reduction of construction cost of nuclear power plants is required.

Therefore, the most urgent thing to promote nuclear power plant construction is to reduce the construction cost about to 150 $/kw which seems to be possible to be reached according to the construction costs of nuclear power plants built up in the United States of America (31), if the number of nuclear power plants is increased.

If oil burning power plant keeps its construction cost $90/kw on the average it gives 2.1 mills/kwh as a capital cost, this allows nuclear power plant to take 3.6 mills/kwh



Nuclear power plant: F=1.9 mills/kwh, m=16 years, and a_2=6%

Oil burning plant: F=3.4 mills/kwh, m=16 years, and a_1= 8%

Figure 31. Power cost competitive area of nuclear power plant against oil burning power plant

or 160 \$/kw as construction cost. Thus, it is not easy for nuclear power to compete commercially with oil burning power plant because the present construction is around 200 \$/kw, and it is required to reduce its construction cost.

Figure 31 shows the area under the lines, where nuclear power plant can compete against oil burning power plant according to the accounting rule used by the electric utility. This shows that the light water type reactors which are now built in Japan still have a disadvantage in the power cost competition against oil burning power plants though they have important significance as pioneers to examine the possibility whether nuclear power plants can be constructed and operated successfully in spite of following the foreign country's design and instruction.

Oil fuel cost is about 1.53 mills/10^3 kcal or 3.46 mills/kwh (4) which includes import tax, about 12%, therefore, before-tax-paid oil fuel cost is 1.34 mills/10^3 kcal or 3.03 mills/kwh. The difference of cost between nuclear fuel cycle cost with fabrication cost, 100 \$/kgU, and interest rate, 8%, and after-tax-paid oil fuel cost is 1.2 mills/kwh. In order to compete against oil burning power plant, nuclear power construction capital charge cost can not be allowed to be 1.2 mills/kwh higher than that of oil burning power plant.

Actual construction cost of supercritical high thermal efficiency oil burning power plants range from 128 \$/kw to

79 $/kw. Taking this lowest construction cost, 70 $/kw or 1.8 mills/kwh at load factor, 70%, allowable capital charge cost should be 3.0 mills/kwh which is corresponding to the construction cost, 140 $/kw at load factor, 80%. If the same load factor, 80% is taken for oil burning power plant, nuclear power construction cost should be less than 130 $/kw.

Taking 6% interest rate for nuclear fuel cycle cost payment, the favorable difference for nuclear fuel cycle cost between them is 1.5 mills/kwh. This allows nuclear power plant to take 3.3 mills/kwh or 153 $/kw at load factor, 80%, under the condition where oil burning power plant is operated at load factor, 70%.

2. Lack technical background in the manufacturing industries

As nuclear power generation is deeply dependent on the technology, the technology related to designing and manufacturing nuclear power plants, treating nuclear fuel and operating nuclear power plants are very important to promote and develop nuclear power. All nuclear power plants which have been imported, and for which fuel is also imported as a completely fabricated form and is reprocessed in foreign countries have shown that the technical background related to designing and manufacturing nuclear power plants, and processing nuclear fuel including enrichment is still far behind advanced countries. Therefore, at present the technology of nuclear power is greatly dependent on foreign countries as well as that most of oil is dependent on imports.

Nuclear fuel materials which exist in nature have much more tendency as man-made fuel because the cost of nuclear fuel material ores is relatively smaller. Thus, the nuclear power complex is highly dependent upon advanced technology. For effective introduction of nuclear power the development and improvement of the technological background related to nuclear power are urgently required.

3. Problem of utilization of plutonium

As a result of fission reaction about 5 grams of fissionable plutonium per kilograms of initially charged uranium metal (38) are produced. The recovered plutonium from spent nuclear fuel has now value of about $40 per kg of initially charged uranium metal in Figure 21 and its price affects the nuclear fuel cycle cost greatly. At present, the recovered plutonium is stored for future purposes or is bought back by the countries which sells nuclear fuel. Plutonium is used for nuclear weapons and for nuclear reactors experimentally, but the peaceful utilization of plutonium is not fully developed yet for commercial purposes. Therefore, the thermal reactor, e.g., the light water type reactor indicates that we should develop reactors to use plutonium peacefully and economically. If we can not develop useful utilization of plutonium in the near future, in addition to the limitation of uranium resources, the nuclear fuel cycle cost rises up more than 10 percent of the present cost due to less of plutonium value.

4. Safety of nuclear power plant operation

The nuclear reactors have basically hazardous features as a result of fission, so that safety of operation of nuclear power plants is the most important consideration. Less experience of operation of nuclear power plants may yield some uncertain factors for the safety.

5. Life time and load factor

The life time of the nuclear power plants may be determined by their reasonable physical life time and the development of the technology of other advanced reactors.

Life time affects construction capital costs greatly, thus, it should be discussed whether the same life time as that of oil burning power plant is reasonable. Most of nuclear power plants which have been built in Japan may be operated as base power supply plants and can be kept operating at a high load factor, but as the number of nuclear power plants increases, it will be a problem of how to keep the operation of nuclear power plant at high load factor in the future.

6. Need large capital investment for nuclear fuel cycle

Nuclear fuel cycle requires large capital investment to processing, fabricating and enriching facilities as well as the capital investment for manufacturing nuclear power plant equipments. As a different reactor needs different kind of fuel, it should be projected what type reactor or reactors will be suitable for the situation of Japan including future reactor models.

Even though the light water type reactor is favorable in Japan, careful consideration of investment to each nuclear fuel cycle process should be made because each process of economic unit is so large that it can meet extremely big demand of power.

7. Secure stable nuclear fuel materials

Sufficient and stable nuclear fuel or nuclear fuel material should be secured at reasonable cost because economical nuclear fuel material must be imported.

8. Secure sites of nuclear power plants and factories related to nuclear power

The sites of nuclear power plants must satisfy not only geological requirements of the construction but also the requirements of minimum radioactive levels from a reactor in addition to general requirements of conventional power plants. The factories related to nuclear fuel may be required to meet special additional conditions depending upon their radiological features. Therefore, it is essential to secure suitable sites of nuclear power plants and the factories related to nuclear fuel.

IX. ECONOMIC EFFECTS OF NUCLEAR POWER

A. General Economic Effects of Nuclear Power

1. Increase degree of freedom of primary energy source

Nuclear power's competitive entry increases the degree of freedom of energy intensive industries to choose. Nuclear energy is also expected for the uses of production process (low temperature) heat and furnace (high temperature) heat as well as that of generation of power, in such industries as iron and steel, chemicals, petroleum refining, cement and paper. Some portion of commercial ocean shipping capacity may be nuclear in the future.

2. Increase tremendous energy resources

Nuclear power's competitive entry introduces tremendous new energy resources. As the technology of utilization of nuclear fuel materials is advanced the applications of the heat produced from them may spread remarkably.

3. Stabilize energy prices

Crude oil prices reflect primarily the demand for refined products relative to its supply, hence the impact of nuclear power on crude oil via the boiler fuel market will not be large since crude oil burning boilers are not adopted to wide range extent and crude oil in the boiler fuel market is small. Thus, crude oil prices will probably be influenced more by supply limitations and competition of synthetic oil products than nuclear energy invasion.

The influence of nuclear energy prices in the boiler fuel market may force a reappraisal of this expectation. For example, nuclear energy will have been projected to displace almost 16% (1) of projected net increase of oil in fiscal year 1985, by which time the net increase of energy demand is assumed to be met. Perhaps most of this "loss" would be by residual fuel oil.

This "loss" would probably be easily offset by changes in refinery output mix of oil if a substantial price reduction for residual fuel oil were required to retain this share of the boiler-fuel market. In the fiscal year 1968 residual fuel oil represented 59% of total domestic refining throughout, and 61% of total supply including imported residual oil. If only a small price reduction were required due to higher construction cost of nuclear power plant, the oil industry may find a way to shift prices of other lighter oil products in order to respond to nuclear competition, and imported residual oil would be reduced. The effect of nuclear energy will first appear over the imported residual oil and then over the domestic refined residual oil. Because of lower marginal fuel cost in a nuclear power plant and small transportation costs, the result of this competition will be likely to be a gradual displacement of fuel oil in the high cost markets.

Generally speaking, nuclear energy will not be directly competitive with natural gas in the boiler fuel market. Indirectly, however, in the residential and commercial market, electric cooking and heating could reduce the growth potential of natural gas. Similarly, the cost advantage offered by gas for industrial high-temperature heat may be matched by nuclear electric power or nuclear process heat. These indirect forces could impose a restraining influence on the natural gas price rises or imported price because the net increase demand for natural gas will be filled with imported one. Therefore, nuclear energy will be able to give upper limit of prices of other primary energy sources through nuclear power.

4. Reduce international payment

Nuclear power has now a feature that it has relatively higher construction cost of plant and lower fuel cost. In consideration of the fact that net increase demand of primary energy should be filled with imported energy sources, and that the technology related to designing and constructing nuclear power plants will be expected to be mastered by domestic manufacturers, and hardwares of nuclear power plants will be supplied by the domestic industries even though part of construction cost should be paid as charges of patents and know how. Nuclear power will save great international payment. Also part of the fuel cost of nuclear power will be attributable to domestic fabricators, processors and others depending upon the situation of the industries related to nuclear fuel cycle. This implies that the international balance of payment will be improved and the national economy may be encouraged as a fraction of saving international payment can be invested to economic activities.

5. Projected saving international payment

Nuclear power cost is still slightly higher than that of oil burning power plants in Japan, but the amount of saving of international payment may be estimated by making certain groups of assumptions.

Assumption 1:

The cost of nuclear power plants is equal to that of oil burning power plants. All equipment needed for nuclear power plants can be supplied by domestic manufacturers, but nuclear fuel is imported as completely fabricated elements and reprocessing of spent fuel is done in a foreign country. Shipping cost is included in the cost of fabricated fuel cost. Fuel cycle cost is taken the value of in the model (2.7% enriched and 0.59% discharged, and burnup, 27,600 MWD/MTU average of values at interest rate, 6% and 8%). Required fuel costs for generating 7.0×10^9 kwh, which corresponds to a power plant with 1,000 Mwe and load factor, 80% are, for nuclear fuel cost

$$7.0 \times 10^9 (\frac{kwh}{year}) \times 1.9 (\frac{mills}{kwh}) = 13.3 \times 10^9 \text{ mills/year}$$
$$= 13.3 \text{ million dollars/year,}$$

and for oil fuel cost

$$7.0 \times 10^9 (\frac{kwh}{year}) \times 3.4 \ (\frac{mills}{kwh}) = 2.38 \times 10^{10} \text{ mills/year}$$
$$= 23.8 \text{ million dollars/year}$$

Required international payments are:

for nuclear fuel 13.3 million dollars/year, and

for oil fuel 23.8 million dollars x $(\frac{1.2}{1.5})$ = 19.1 million dollars/year,

where

$\frac{1.2}{1.5}$ is derived as follows:

1.5 mills/10^3 kcal was paid by the electric utility (4) and 1.2 mills/10^3 kcal which is calculated from the data (3) was paid by importers in the fiscal 1968, then, the ratio of the latter to the former shows the fraction of international payment.

Assumption 2:

Completely fabricated nuclear fuel is imported, but spent nuclear fuel is reprocessed in Japan. The international payment may be reduced 87.5% of that in Assumption 1 to according to the same case, model (2.7% enriched and 0.59% discharged, and burnup 27,600 MWD/MTU).

Assumption 3:

Enriched uranium is imported and other processes including fabrication are done in Japan. The international payment may be reduced to 54% of that in Assumption 1.

Assumption 4:

Only feed uranium for enrichment is imported and other processes including enrichment are done in Japan. The international payment may be reduced to 23% of that in Assumption 1.

Power cost is assumed 5.0 mills/kwh, which means that construction cost of nuclear power plant is 145 $/kw on 3.1 mills/kwh at load factor, 80% and that construction cost of oil burning power plant is 90 $/kw or 1.6 mills/kwh at load factor, 70%. Patent charge and know how charge are assumed to be paid 6% of construction capital charge cost and of corresponding fuel cost which is paid to domestic manufacturers. Additional payment for patent and know how charges are:

Assumption 1	1.31 million dollars/year
Assumption 2	1.58 million dollars/year
Assumption 3	1.89 million dollars/year
Assumption 4	2.33 million dollars/year

Let us take an example, fiscal year 1980. If all additional power from the fiscal 1975 is fulled with nuclear power instead of oil burning power, the saving of international payment for imported fuel is shown in Table 23.

Saving amount, 124 million dollars in assumption 1 is equivalent to 0.9% of the total import payment in the fiscal year 1968, 4.4% of the import of fuel and 4.1% of the annual sales income of the electric utility in the fiscal year 1968. Net increase power of the fiscal year 1980, 195×10^9 kwh compared with that in the fiscal year 1975, is 29.5% of total power demand of the same fiscal year.

Nuclear fuel cost in power generation is clearly cheaper than that of oil fuel. Its international payment is dependent on the extent of the development of nuclear fuel processing steps including enrichment, fabrication and reprocession of spent nuclear fuel as well as construction equipments' dependence on import.

6. Increase stability of energy supply

Year by year the dependence upon imported energy sources has been worse: the dependence rose from 24 percent in the fiscal year 1955 to 77.4 percent in the fiscal year 1968 (29) and the projected dependence may be about 90 percent in fiscal year 1985 (1). Most of the dependence on imported energy sources has been attributed to oil which has been imported mainly from the Middle East countries. The higher

Table 20. Comparison of international payment (million dollars/1,000 Mwe year)

	Nuclear Fuel			Oil fuel		
	Payment to fuel (A)	Payment[a] to patent charge (B)	(A)+(B)	(C)	(C)-(A)	(C)-(A)-(B)
Assumption 1	13.3	1.31	14.61		5.8	4.49
Assumption 2	11.6	1.58	13.18	19.1	7.5	5.92
Assumption 3	7.18	1.89	9.02		11.92	10.03
Assumption 4	3.06	2.33	5.39		16.04	13.71

[a]Payment includes patent and know how charge of power plant construction and fuel cycle.

Table 21. Required additional power

Fiscal year	Required Power (10^9 kwh)	Required Additional Power (10^9 kwh)	Required Additional International Payment for Oil Fuel (10^6 dollars)
1968	274	-	-
1975	464	190	517
1980	659	385	1,045
1985	869	595	1,630
1990	1,059	785	2,130

Table 22. Required international payment (million dollars/year)

Net increase power of the fiscal 1980 compared with the fiscal 1975 (10^9 kwh)	Required international payment of oil fuel cost (10^6 dollars) (A)	Required international payment of nuclear fuel cost (10^6 dollars) (B)		Saving amount (10^6 dollars) (A-B)
195	530	Assumption 1	406	124
		Assumption 2	326	204
		Assumption 3	253	277
		Assumption 4	92	438

dependence specific energy sources and specific areas in the world is not favorable for stabilizing the energy situation. Japan has only a few options to secure the energy;

(a) diversifying areas of supply of usable energy,

(b) spreading sources usable energy, and

(c) storing enough energy sources in the country.

The third measure usually requires tremendous capital investment for storing facilities and stored oil. The introduction of nuclear energy will meet three measures mentioned above because it is a new primary energy source, areas of supply of nuclear fuel material are different from those of oil, and remarkably great available energy per unit weight and low fuel cost will permit storing nuclear fuel at relatively lower cost than oil if such measure is taken.

7. Decrease air pollution

Careful designing of nuclear power can help reducing air pollution without large additional cost. The sulfur content of oil, especially, from the Middle East has induced serious air pollution problems. This means additional energy cost is chargable to oil fuel.

8. Induce new industries

New industries related to nuclear power plants and nuclear fuel may be induced. And also some new industries which are power cost intensive may be induced.

9. Shift locations of industries

Power intensive industries, such as aluminum industry, may be shifted to get cheaper nuclear power cost.

10. Shift oil refining pattern

The Japanese oil demand pattern is that the demand of the heavy fuel oil is higher than that of lighter oil at present, after nuclear power increases competitively, the oil demand pattern will be changed. If nuclear power can not stabilize or lower the price of imported oil effectively, the lighter oil may be risen up.

But unlike coal, oil may have slight influence by invasion of nuclear power because it has own favorable markets such as raw materials of chemical industry, fuel of automobiles, and weight of oil consumption in the generation of power is not extremely large compared with coal. Oil also can be expected to reduce its production cost if the difference of costs between oil and nuclear energy is not large. Only imported residual oil may be influenced greatly.

B. Effects of Nuclear Power to Electric Utility

1. Direction of the electric power industry in the future

Technology, which since the early days of the development of the electric power industry has been a dynamic factor has now begun to assert a new influence in shaping the electric power industry's, especially, the electric utility's future. Advances in technology are increasingly extending the distances over which electric power can be economically transmitted. Technological progress is also widening the cost advantages of extremely large scale power plants.

Transmission is of strategic importance in current and prospective developments of the electric power industry because large scale power plants such as super critical steam power plants using fossil fuel and nuclear power plants are built up in remote sites from load centers. It is through the interconnections among electric power systems made possible by introducing extra-high voltage transmission that economics resulting from large scale generating units can be realized as well as investment saving through sharing capacity to peak demand and providing for reserve requirements.

Economics of scale point to bulk power supply networks, served by massive generating units, are expected as the efficiency ideal for the future. Perhaps the major problem is how to achieve the efficiency ideal in the face of the existing pattern of the electric industry and the industrial structure supported by the existing pattern.

The great challenge for the future is to find ways in which the different parts of the electric power industry, competitive though they may be, can peacefully co-exist, all sharing in the benefits offered by advancing technology and passing on to the consumer the resulting cost savings.

Basically, there are three modes of adjustment by which existing systems can accommodate to increase scale requirement: merger, coordination, and wholesaling. These are not alternatives, but each is part of an over-all pattern that will have to be studied from the viewpoint of the national economy.

The social and economic losses caused by an interruption in power supply far surpass the loss of revenues to the electric utility so that it will be getting much more important to assure electric power system reliability.

With the more distant future, it would be well to look beyond the present existing structure of the electric utility and ask the question whether a fundamentally different organization of the electric utility might best serve the interests of efficiency under the advancing technology (19).

2. Effects of nuclear power to the electric utility

a. Reduce the differences among the power costs in the service territories   As nuclear fuel materials and oil are imported, nuclear power cost and oil burning power cost are not dependent on geological condition as hydraulic power. For the time being, thermal power and nuclear power will supply the most of the power needs, so that the difference among the power costs in the service territories will be reduced though consumer prices of power are now varied a little bit depending on service territories.

b. Decrease power cost   As the construction cost of nuclear power plants are expected to decrease through increasing of nuclear power plant construction, fuel cycle costs are also expected to decrease in the near future through reducing fabrication cost and processing cost and increasing burnup of nuclear fuel even though at the present time nuclear power costs slightly higher than that of super critical oil burning power cost in Japan.

c. Increase power market   Decreasing power cost may spread the power market for residential, commercial and industrial usages at a higher rate than before.

d. Require new management   The greater scale unit of electric power plants are built up, the closer corporations and coordinations will, in executing businesses of developing electric power, supplying electric power, operating electrical facilities etc., be maintained among not only electric utility companies but also non-electric utility companies so as to conduce to the rational, effective and integral development and progress of the electric power industry.

e. Increase weight of the electric utility The large unit capacity and multiple units requirement may promote the concentration of electric power generation facilities to the electric utility although multiple purpose units may be built by the non-electric utility.

X. CONCLUSION

As it may be predicted that the future trend of demand of energy will be continued to rise at high rate, Japan, which is heavily dependent on imported energy, must make strenuous efforts in securing sufficient and stable sources of energy at low cost. In the light of such prospect, nuclear energy may have attractive features such as an additional new source of energy, low cost of nuclear fuel and relatively abundant resources in the world. Nuclear energy may greatly affect the situation of energy supply and demand as a result of introduction of nuclear energy and shift of pattern of energy supply and demand. Particularly, electric utility may need a new conception of management such as closer coordination, merger, and wholesaling since nuclear power generation requires a tremendous investment.

At the present stage the cost of nuclear power generation is not cheaper than that of oil burning power generation but it can be expected to become a major energy source in the near future since low cost of nuclear fuel and expectation of reduction of construction cost of nuclear power plants may be very favorable to improve the energy situation

In consideration of the features of nuclear power which are dependent greatly on the development of the technology, the efficient utilization of nuclear power can be said to have just started in the world and many unsolved technical affairs remain before nuclear energy is fully utilized for human beings. Japan should share important roles in the development of the technology not only for itself but also all other countries under the international cooperation in order to solve the present and future problems of energy.

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XIII. APPENDIX A

Equivalent thermal energy (27):

Table 23. Equivalent thermal energy

Energy source	Practical unit	Equivalent energy (kcal)[a]
Electric power	kwh	2,260[b]
Coal		
Domestic coal	kg	5,250
Imported coal	kg	7,700
Oil		
Crude oil	l[c]	9,400
Residual oil	l	9,900
Natural gas	m^3	9,800
Charcoal	kg	10,000
Wood	m^3	1.54×10^6

[a]kcal = 3.97 BTU
= 4.2×10^{10} erg.

[b]Thermal efficiency is assumed 38%.

[c]liter = 0.0353 cubic feet
= 61.025 cubic inches
= 0.264 gallons.

XIV. APPENDIX B

Population (24):

Table 24. Population in Japan (million)

Year	Population (actual)	Year	Population (predicted)
1955	89.3	1970	103.3
1956	90.2	1975	108.6
1957	90.0	1980	113.3
1958	91.8	1985	116.5
1959	92.6	1990	118.6
1960	93.4	1995	120.2
1961	94.3	2000	121.3
1962	95.2		
1963	96.2		
1964	97.2		
1965	98.3		
1966	99.1		
1967	100.2		
1968	101.4		

XV. APPENDIX C

Models of predicted values and their coefficients determined using multiple regression method:

a. Total energy demand

$$Y_t = a_o + a_1x + (b_1+b_2t)t$$
$$= -1551.6 + 184.26x + (-23.4 + 4.9t)\ t,$$

where Y_t is total energy demand (10^{13} kcal), and a_o, a_1, b_1, and b_2 are coefficients determined using multiple regression method (25), and x is population (million), and t is fiscal year minus 1953.

Values of actual data, t and x, are taken from Appendix B and Table 1.

For prediction, x is not less than 10.19, and t in not less than 1969.

b. Electric power demand

$$Y'_e = a_o + (a_1+a_2x)x + (b_1+b_2t)t$$
$$= 2485.5 + (-586.9 + 35.6x)x + (-1.59 + 0.4t)t,$$

where Y'_e is electric power demand (10^9 kwh), and a_o, a_1, a_2, b_1, and b_2 are coefficients determined using multiple regression method (25), and x and t are the same notation as those in part a, but t is now fiscal year minus 1951 because of additional two data.

For prediction, x is not less than 10.19, and t is not less than 1969.

$Y_e = 0.226 \times Y'_e$

where Y_e is electric power demand (10^{13} kcal) which is converted from electric power demand (10^9 kwh), Y'_e, assuming net thermal efficiency 38%.

XVI. APPENDIX D

A Notation:

Notation	Description	Unit
A_d	Uncertain cost charge rate for nuclear power plant	%
A_g	Owner's general and administrative cost normalized as a form of fixed charge rate	%
a_1	Interest rate for construction cost	%
a_2	Interest rate for nuclear fuel cost	%
B	Burnup	MWD[1]/MTU[2]
C_c	Capital cost of construction	mills/kwh
C_{co}	Cost of conversion (U_3O_8 to UF_6)	\$/kgU[3]
C'_{co}	Cost of conversion (U_3O_8 to UF_6) expressed as a present worth value to get 1 kg of fabricated nuclear fuel	\$/kgU charged[4]
C_e	Enrichment charge at enrichment E_i	\$/kgU S.W.(35)
C'_e	Enrichment charge at enrichment E_i expressed as a present worth value to get 1 kg of fabricated nuclear fuel	\$/kgU charged
C'_F	Cost of fabricated nuclear fuel expressed as a present worth value to get 1 kg of fabricated nuclear fuel	\$/kgU charged

[1]MWD = 24×10^3 kwh = 2.064×10^7 kcal.

[2]MTU is metric tonne of uranium.

[3]kgU is kilogram of uranium.

[4]kgU charged is kilogram of uranium fabricated as fuel which is to be charged in a reactor core.

Notation	Description	Unit
C''_F	Cost of fabricated nuclear fuel including inventory expressed as a present worth value	\$/kgU charged
C'_{FT}	Cost of net nuclear fuel expressed as a present worth value	\$/kgU charged
C_f	Cost of fabrication and conversion (enriched UF_6 to UO_2)	
C'_f	Cost of fabrication and conversion (enriched UF_6 to UO_2) expresses as a present worth value	\$/kgU charged
C_n	Construction cost of power plant	\$/kw
C_p	Cost of electric power	mills/kwh
C_{Pu}	Price of recovered plutonium	\$/kgU charged
C'_{Pu}	Cost of recovered plutonium expressed as a present worth value	\$/kgU charged
C_r	Cost of reprocessing	\$/kg discharged[1]
C'_r	Cost of reprocessing expressed as a present worth value	\$/kgU discharged
C_{rv}	Cost of reconversion	\$/kgU discharged
C'_{rv}	Cost of reconversion expressed as a present worth value	\$/kgU charged
C_s	Cost of shipping of spent fuel	\$/kgU discharged
C'_s	Cost of shipping of spent fuel expressed as a present worth value	\$/kgU charged
C_t	Contingency cost normalized as a form of fixed charge rate	%

[1]kgU discharged is kilogram of uranium discharged from a process.

Notation	Description	Unit
C_U	Price of recovered depleted uranium	\$/kgU charged
C'_U	Price of recovered depleted uranium expresses as a present worth value	\$/kgU charged
E_d	Enrichment of nuclear fuel at discharged	%
E_{ff}	Net thermal efficiency	%
E_i	Enrichment of nuclear fuel at charge	%
F	Fuel cost	mills/kwh
F_m	Feed material factor which indicates required amount of natural uranium to get specific enriched uranium	kgU feed/kgU enriched
F_u	Fuel cost	mills/10^3 kcal
L	Cost of labor normalized as a form of fixed charge rate	%
L.F.	Load factor	%
L_1	Loss factor[1] of conversion of U_3O_8 to UF_6	%
L_2	Loss factor of conversion of enriched UF_6 to UO_2	%
L_3	Loss factor of fabrication of fuel	%
L_4	loss factor of burnup	%
L_5	Loss factor of reprocessing of recovered depleted uranium and recovered plutonium	%

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[1]Loss factor = $\frac{\text{charged initially - discharged}}{\text{charged initially}} \times 100$.

Notation	Description	Unit
L_6	Loss factor of reconversion of recovered depleted uranium to UF_6	%
m	Life time of a power plant	year
O_c	Annual throughout of nuclear fuel	kgU charged/ year
O_m	Fixed charge rate of operation and maintenance	%
P_e	Electric power output	MWe
R	Average present worth fixed charged rate including depreciation and interest	%
S	Separative work component factor which indicates enrichment cost to get specific enriched uranium	kg S.W./kgU product
T_h	Thermal power produced in a reactor during average residence time of fuel	kcal/kgU charged
T_h'	Thermal power produced in a reactor during average residence time of fuel expressed as a present worth value	kcal/kgU charged
T_p	Rate of property tax	%
T_R	Rate of revenue tax	%
T_1	Time of shipping from a refining plant (U_3O_8) to conversion plant (UF_6)	year
T_2	Time of conversion of U_3O_8 to UF_6	year
T_3	Time of shipping from conversion plant (UF_6) to enrichment plant	year
T_4	Time of enrichment	year

Notation	Description	Unit
T_5	Time of shipping from enrichment plant to conversion plant (UO_2)	year
T_6	Time of conversion of enriched UF_6 to UO_2	year
T_7	Time of fabrication of fuel	year
T_8	Time of shipping from fabrication factory to a reactor site	year
T_9	Waiting time before loading fuel in a reactor core	year
T_{10}	Average fuel residence time	year
T_{11}	Minimum decay time of spent fuel	year
T_{12}	Time of shipping of spent fuel from a reactor site to a reprocessing plant	year
T_{13}	Time of reprocessing of spent fuel	year
T_{14}	Time of shipping of reprocessed uranium from a reprocessing plant to a reconversion plant	year
T_{15}	Time of reconversion	year
T_{16}	Time of selling recovered depleted uranium and recovered plutonium including shipping time from reconversion plant after finishing of reconversion	year
U_i	Uranium loaded in a reactor	kg
U_{n1}	Price of natural uranium in the form of U_3O_8	\$/lb
U_{n2}	Price of natural uranium in the form of U_3O_8	\$/kgU

Notation	Description	Unit
U'_{n2}	Price of natural uranium in the form of U_3O_8 expressed as a expressed worth value	\$/kgU
Y_{Pu}	Yield of fissile plutonium	gm/kgU charged

T_1: Shipping uranium material to conversion (UF_6) plant

T_2: Conversion of U_3O_8 to UF_6

T_3: Shipping from a conversion (UF_6) plant to an enrichment plan

T_4: Enrichment

T_5: Shipping from an enrichment plant to conversion (UO_2) plant

T_6: Conversion of enriched UF_6 to UO_2

T_7: Fabrication of fuel

T_8: Shipping from fabrication factory to a reactor site

T_9: Waiting time before loading fuel in a reactor core

______ Present time: operation starts

T_{10}: Average fuel residence time

T_{11}: Minimum decay time of spent fuel

T_{12}: Shipping spent fuel from a reactor site to a reprocessing plant

T_{13}: Reprocessing of spent fuel

T_{14}: Shipping reprocessed uranium from a reprocessing plant to a reconversion plant

T_{15}: Reconversion of depleted recovered uranium

T_{16}: Selling of depleted recovered uranium and recovered plutonium

Figure 32. Time flow of nuclear fuel processes

Calculation of electric power cost:

Capital cost of construction:

Construction cost includes direct costs, indirect costs, contingency, and interest during construction periods. Capital cost of construction includes capital cost of construction, operation and maintenance cost, operation supplies cost, contingency, associated owner's general and administrative cost, and taxes.

$$C_c(\text{mills/kwh}) = 1{,}000 \times C_n \times \left(\frac{R}{100} + \frac{O_m}{100} + \frac{L}{100} + \frac{C_t}{100} + \frac{A_g}{100} + \frac{A_d}{100} + \frac{T_R}{100}\right) \times \left(1 + \frac{T_R}{100}\right) \div \left(\frac{L.F.}{100} \times 8{,}760\right),$$

where 8,760 is hours of a year.

Fuel cost:

Since operation cost such as labor cost, operation cost, and operation supplies cost are included in capital cost of construction, cost is a cost associated only with fuel cost

$$F(\text{mills/kwh}) = \frac{F_u}{1{,}000} \times \frac{860}{\frac{E_{ff}}{100}} \times \left(1 + \frac{T_R}{100}\right) = \frac{86 \times F_u}{E_{ff}} \times \left(1 + \frac{T_R}{100}\right)$$

where 860 is equivalent to 1 kwh/kcal.

Electric power cost:

Electric power cost is summation of capital cost of construction and fuel cost.

$$C_p\text{(mills/kwh)} = C_c + F$$

$$= (1 + \frac{T_R}{100})\{1{,}000 \times C_n \times (R + O_m + L + C_t + A_g + A_d + T_R) \div (\text{L.F.} \times 8{,}760) + 86.0 \times \frac{F_u}{E_{ff}}\}.$$

Table 25. Input data

Items	Values
C_n	Variable
LF	70, 80 (28)
E_{ff}	Nuclear power plant: 30 (28) Oil burning power plant: 38 (28)
F_u	Nuclear power plant: According to the procedure of Appendix D Oil burning power plant: Variable
R	Variable due to a_1 and m
L	Fixed: 0.38 (28)
O_m	Fixed: 2.0 (16, 28)
C_t	Fixed: 0.2 (16, 28)
A_g	Fixed: $0.258 = 0.1(L + O_m + C_t)$ (28)
A_d	Nuclear power plant: 1.0 is assumed Oil burning power plant: 0.0 is assumed
T_p	Fixed: 0.36 (16, 28)
T_R	Fixed: 0.0

Assumption of cost of process, capacity of process plant, required time, etc., and procedures of calculation

Natural uranium material:

Price:

$$U_{n2}\ (\$/kgU) = U_{n1} \times 2.206 \times \frac{\text{Mass of } U_3O_8}{\text{Mass of U in } U_3O_8}$$

$$= 2.6\ U_{n1}\ (35).$$

$$U'_{n1}\ (\$/kgU\ \text{charged}) = 2.6\ U_{n1} \times F_m \times \frac{100}{100-L_1} \times \frac{100}{100-L_2} \times \frac{100}{100-L_3} \times (1 + \frac{a_2}{100} \times \sum_{i=1}^{9} T_i).$$

Process: Any amount of order of purchasing natural uranium material is available instantly.

Shipping time:

$$T_1\ (\text{year}) = 0.042.$$

Conversion (U_3O_8 to UF_6):

Cost of process charge:

$$C_{co}\ (\$/kgU) = 2.7\ (35).$$

$$C'_{co}\ (\$/kgU\ \text{charged}) = C_{co} \times F_m \times \frac{100}{100-L_2} \times \frac{100}{100-L_3} \times (1 + \frac{a_2}{100} \times \sum_{i=2}^{9} T_i)$$

Capacity of process:

Capacity: 6,000(MTU/year).

Utilization factor: 0.8 (35).

Effective capacity: 4,800(MTU/year).

Process time:

T_2(year) = 0.25 (38).

Shipping time:

T_3(year) = 0.042.

Enrichment:

Cost of enrichment charge

C_e(\$/kgU) = W x S = 26.0 x S,

where W is 26.0 (\$/kgU X.W.) (35) and S is shown in Table 26.

$$C'_e(\$/\text{kgU charged}) = 26.0 \times S \times \frac{100}{100-L_2} \times \frac{100}{100-L_3} \times \left(1 + \frac{a_2}{100} \times \sum_{i=4}^{9} T_i\right).$$

Capacity of enrichment process:

Capacity: 5,000(MTU S.W. year).

Utilization factor: 0.8 (35).

Effective capacity: 4,000 (MTU S.W./year).

Process time:

T_4(year) = 0.25 (38)

Shipping time:

T_5(year) = 0.083

Table 26. Values of S and F_m (35)

Enrichment, E_i or E_d (%)	$S(\frac{S.W.}{kgU\ enriched})$	$F_m(\frac{kgU\ feed}{kgU\ enriched})$
0.2	-0.0	0.0
0.59	-0.115	0.763
0.60	-0.107	0.783
0.61	-0.098	0.802
0.63	-0.081	0.841
0.65	-0.062	0.881
1.7	1.603	2.935
2.2	2.602	3.914
2.7	3.656	4.892
3.0	4.306	5.479
3.3	4.968	6.067
3.7	5.864	6.849
93.0	235.550	181.605

Uranium tails assay is 0.2% of U^{235}.

Conversion (UF_6 to UO_2) and fabrication of fuel:

Cost of process charge:

C_f(\$/kgU charged) is varied from \$60 to \$100.

$$C'_f(\$/\text{kgU charged}) = C_f \times (1 + \frac{a_2}{100} \times \sum_{i=6}^{9} T_i)$$

Capacity:

Capacity of conversion process:	3,600(MTU/year)(35).
Utilization factor:	0.8.
Effective capacity:	2,880(MTU/year).
Capacity of fabrication:	360(MTU/year).
Utilization factor:	0.8.
Work days:	260 days/year (35).
Effective capacity:	206.4(MTU/year).

Process time:

$$T_6(\text{year}) = \frac{100}{100-L_3} \times O_c \div 2{,}880{,}000.$$

$$T_7(\text{year}) = O_c \div 206{,}400.$$

Shipping time:

$$T_8(\text{year}) = 0.083.$$

Cost of fabricated fuel:

$$C'_F(4/\text{kgU charged} = C'_{n2} + C'_{co} + C'_e + C'_f .$$

Cost of nuclear power plant:

Waiting time:

$$T_9(\text{year}) = 0.168 \text{ (41)}.$$

Average fuel residence time:

$$T_{10}(\text{year}) = \frac{B \times U_i \div 1{,}000}{\frac{L.F.}{100} \times P_e \div \frac{E_{ff}}{100} \times 365}.$$

Minimum decay time:

$T_{11}(\text{year}) = 0.438$ (41).

Shipping of spent fuel:

Cost of shipping:

$C_s(\$/\text{kgU discharged}) = 4.0$ (35).

$$C_s'(\$/\text{kgU discharged}) = C_s \times \frac{100-L_4}{100} \div (1 + \frac{a_2}{100} \times \sum_{i=10}^{11} T_i).$$

Shipping time:

$T_{12}(\text{year}) = 0.083.$

Reprocessing:

Cost of process charge:

$$C_r(\$/\text{kgU discharged}) = \frac{T_s(1 + 1/3) \times B_i}{T_s} = 31.2,$$

where B_i is 235($/kgU discharged) (35).

$$C_r'(\$/\text{kgU discharged}) = C_r \times \frac{100-L_4}{100} \times \frac{100-L_5}{100} \div (1 + \frac{a_2}{100} \sum_{i=10}^{12} T_i).$$

Capacity of process:

Effective capacity: 360(MTU/year) (35).

Process time:

$$T_{13}(\text{year}) = \frac{100-L_4}{100} \times \frac{100-L_5}{100} \times O_c \div 360{,}000 + 0.083 \ (8) \ .$$

Shipping time:

$$T_{14}(\text{year}) = 0.042.$$

<u>Reconversion of recovered depleted uranium:</u>

Cost of process charge:

$$C_{rv}(\$/\text{kgU discharged}) = 5.6 \ (35).$$

$$C'_{rv}(\$/\text{kgU discharged}) = C_{rv} \times \frac{100-L_4}{100} \times \frac{100-L_5}{100} \times \frac{100-L_6}{100}$$

$$\div \left(1 + \frac{a_2}{100} \sum_{i=10}^{14} T_i\right).$$

Capacity of process:

Capacity: 360 (MTU/year).

Utilization factor: 0.8.

Effective capacity: 288 (MTU/year).

Process time:

$$T_{15}(\text{year}) = \frac{100-L_4}{100} \times \frac{100-L_5}{100} \times \frac{100-L_6}{100} \times O_c \div 288{,}000 \ .$$

<u>Selling of recovered plutonium and recovered depleted uranium:</u>

Price:

$$C_{Pu}(\$/\text{kgU charged}) = Y_{Pu} \times \frac{100-L_4}{100} \times \frac{100-L_5}{100} \times 0.7$$

$$\times \left\{F_m \times \left(U_{n2} \times \frac{100}{100-L_1} + C_{co}\right) + C_e\right\},$$

where F_m and C_e correspond to those of 93% enriched uranium.

$$C'_{Pu}(\$/\text{kgU charged}) = C_{Pu} \div (1 + \frac{a_2}{100} \times \sum_{i=10}^{16} T_i).$$

$$C_U(\$/\text{kgU charged}) = \{F_m(U_{n2} \times \frac{100}{100-L_1} + C_{co}) + C_e\}$$

$$\times \frac{100-L_4}{100} \times \frac{100-L_5}{100} \times \frac{100-L_6}{100}.$$

$$C'_U(\$/\text{kgU charged}) = C_u \div (1 + \frac{a_2}{100} \times \sum_{i=10}^{16} T_i).$$

Selling time:

T_{16}(year) = 0.249

Loss factors (35):

$L_1 = 0.5.$

$L_2 = 0.5.$

$L_3 = 1.5.$

$L_4 = 3.0.$

$L_5 = 1.0.$

$L_6 = 0.3.$

Net nuclear fuel cost:

$$C'_{FT}(\$/\text{kgU charged}) = (C'_F + C'_s + C'_r + C'_{rv}) - (C'_{Pu} + C'_U).$$

Thermal power produced:

$$T_h(\text{kcal/kgU charged}) = B \times 24 \times 860 = 2.064 \times 10^4 \times B.$$

$$T'_h(\text{kcal/kgU charged}) = 2.064 \times 10^4 \times B \div (1 + \frac{a_2 T_{10}}{200}).$$

Cost of nuclear fuel:

$$F_u\ (\text{mills}/10^3\ \text{kcal}) = \frac{100 \times C'_{FT}}{2.064 \times B} \times (1 + \frac{a_2 T_{10}}{200}).$$

$$F(\text{mills/kwh}) = \frac{86 \times F_u}{E_{ff}} .$$

Cost of nuclear fuel with inventory of fuel:

$$C_F''(\$/\text{kgU charged}) = C_{FT}' + I_f \times \frac{a_2}{100} \times T_{10} \times C_F' ,$$

where I_f is assumed 0.15.

$$F_u(\text{mills}/10^3 \text{ kcal}) = \frac{100 \times C_f''}{2.064 \times B} \times \left(1 + \frac{a_2 T_{10}}{200}\right) .$$

$$F(\text{mills/kwh}) = \frac{86 \times F_u}{E_{ff}} .$$

Assumption of shipping cost:

1. The cost of hauling uranium ore to the mill is included in the price of U_3O_8.
2. The cost of shipping new fuel elements to the reactor site is included in the fuel fabrication price.
3. The cost of shipping spent fuel from the reactor site to the reprocessing site is paid and not excluded in any step price.
4. The cost of shipping reprocessed and converted Pu and/or U depleted is included in the each process price.
5. The cost of shipping of recovered Pu and U is neglected since the usages are uncertain.

Table 27. Other data (37)

Item	Case I	Case II	Case III	Case IV	Case V	Case IV
P_e (MWe)	1,000	1,000	1,000	1,000	1,000	1,000
E_{ff} (%)	30	30	30	30	30	30
L.F. (%)	70, 80	70, 80	70, 80	70, 80	70, 80	70, 80
B (MWD/MTU)	13,120	21,050	27,600	31,430	37,750	40,680
Feed fuel (tons)	103.23	103.77	104.27	104.58	104.95	105.37
E_i (%)	1.7	2.2	2.7	3.0	3.3	3.7
E_d (%)	0.65	0.63	0.59	0.59	0.6	0.61
Y_{Pu} (gm/kgU charged)	3.67	4.41	4.48	5.08	5.31	5.51