ECONOMICS OF NUCLEAR POWER FOR IOWA

by

Edward Mary Walsh

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INTRODUCTION

The feasibility of nuclear power for Iowa is essentially governed by economic considerations and it is therefore appropriate that this thesis should be mainly concerned with factors which directly or indirectly affect the economics of both conventional and nuclear power. A detailed examination of the conventional as well as the nuclear power situation is of importance since the adoption of nuclear power during the next decade will certainly depend on its ability to produce a competitive or cheaper unit of electrical energy.

One of the principal objectives of this thesis is to determine as precisely as possible when nuclear power will be economically competitive with conventional power in Iowa. Absolute nuclear or conventional power costs are then not as important as are relative power costs, and in order to provide a basis for comparison all estimates will be governed by compatible ground rules. Data used throughout will be applicable to Iowa and any estimates or predictions made will be based on, and governed by, conditions pertaining to Iowa.

Most data available on the cost of electricity from large scale nuclear plants are based on paper studies. At best they represent the considered judgment of those most familiar with the various technical and economic factors involved. In general the estimated power costs are more strongly affected by the various non-technical assumptions employed, such as plant write-off, inventory charges and load factor, than by factors related to reactor technology. Since the selection of non-technical assumptions reflects the degree of optimism or pessimism of those making the estimate, one can say that such projected costs have no real significance. The fact that the optimists outnumber the pessimists and most predictions indicate a promising outlook for competitive nuclear power is very encouraging. The most important question to be asked now is in fact, "When will we have competitive nuclear power in Iowa?" rather than, "Will we have competitive nuclear power?" The object of this thesis is to provide information relative to answering the question of "when" and in so doing it is hoped that planning for the future expansion of the Iowa Power Grid will be simplified.

Nuclear power concepts are at a relatively early stage of development. The growth is rapid and radical changes take place regularly in every branch. Several different power systems are under separate and simultaneous development and it is not possible to predict with any certainty which of these systems will be most successful. Under such conditions it is not surprising that satisfactory power cost estimates are difficult to make and that different estimates for even the same systems differ so greatly. Since the field is new there is little past experience to guide future planning. However, use should be made of whatever experience is available and the

Table 1. Construction costs, estimated and actual, of specific nuclear plants

Plant	Capacity (MW)$_e$	Original Estimate	Current Estimate	Actual Cost	Physical constr. completed by Sept. 30, 1960, %
		Millions of dollars			
EBWR[a]	4.5	3.6		4.6	100
Vallecitos[b]	5.0	3.4		2.5	100
SM-1	1.8	1.9[c]		3.9	100
Shippingport	60.0	47.8		72.9	100
SRE[d]	6.0	3.5		6.3	100
Yankee	110.0	32.7	46.0[e]		100
Elk River[f]	22.0	6.2	12.8		95
Fermi	94.0	45.0	56.3		95
Indian Point	255.0	52.5	100.3[g]		86
Hallam	75.0	24.5	45.0[e]		34
Bonus[h]	16.3	11.0	11.8[e]		1

[a] Does not include cost of recent modifications.

[b] Does not include cost of recent modifications. Includes cost of recent first core cost but excludes $0.6 million for turbine generator.

[c] It has been estimated that the accelerated construction schedule later adopted would have increased this to $2.1 M.

[d] Does not include $2.3 M for power generating equipment.

[e] Based on recent estimates.

[f] Includes cost of fuel fabrication.

[g] Includes $10.8 M for research and development.

[h] Does not include cost of land.

comparison in Table 1 between estimates and actual costs of specific nuclear plants is instructive (20, p. 11-12).

In all but one case the deviation between predicted and actual construction cost has been due to considerable underestimation. There are many reasons for these increased construction costs, and their relative importance varies with the different projects. For example, in the case of SRE, several major items of equipment, such as a metallurgical hot cell, storage for liquid waste and for dry fuel were added after the original estimate. Marked advances in technology for a sodium graphite system occurred during design and construction and were incorporated into the plant as information became available, resulting in the use of more expensive graphite, increased cooling for core shielding, increased sodium pre-heat equipment, etc.

The increases from March 1955 to September 1957 in the estimated costs of the Indian Point nuclear plant have been explained by the Consolidated Edison Company of New York as follows (20, p. 12):

	Millions of dollars
Cost of conventional portion	
Estimate of March 1955	36.5
Increase in gross capacity[a]	4.0
Design changes	1.0
Escalation	3.5
Estimate of September 1957	45.0

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[a] From 236 to 275 Mw(e).

	Millions of dollars
Cost of nuclear portion[a]	16.0
Increase in gross capacity[b]	2.7
Escalation	2.1
Waste disposal system	2.1
Safety requirements	3.2
Engineering, research, and development	7.4
Underestimate and design changes	6.8
Contingencies, overhead, and interest during construction	4.7
Estimate of September 1957	45.0

The estimated total cost of construction therefore increased from $52.5 million in March 1955 to $90 million in September 1957. The cost increases resulting from increased gross capacity and escalation represent situations that can also arise in the construction of fossil-fuel plants. With regard to the other items, the amount of basic nuclear research and development involved was much greater than originally estimated and plans were modified a number of times, thereby increasing the cost of engineering. In addition, many items were underestimated and design changes increased the cost of the hardware, quickly using up the original allowance for contingencies. The most recent cost estimate for the entire plant is $100.3 million, including $10.8 million for research and development.

In view of such gross initial underestimates it would appear that future work should err on the side of conservatism

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[a] Estimate of March 1955.

[b] From 236 to 275 Mw(e).

in the hope that these errors will counteract the costs incurred by unforeseen difficulties and additional requirements.

REVIEW OF CURRENT LITERATURE

Little if any literature has been published specifically concerning the feasibility of nuclear power for Iowa, however a considerable amount is available on the more general subject of the economics of nuclear power for the United States (4, 5, 9, 21). Much of this has appeared since 1958 and the growing interest in economical nuclear power, rather than simply nuclear power itself, is very evident in the steadily increasing quantity of literature published on the subject. Since most publications are of a general nature, the information presented requires analysis to determine whether it

a. is directly applicable to Iowa,
b. requires modification, or
c. is not applicable to Iowa.

Literature generally available in the field may be classified under the following main headings:

a. Unclassified Atomic Energy Commission reports
b. Periodical literature
c. Industrial status reports and articles.

Unclassified Atomic Energy Commission Reports

In 1958 four reactor studies (4) were initiated by the Division of Reactor Development, U.S. Atomic Energy Commission, to assess the feasibility of power generation through the use of certain types of nuclear reactors. Several contractors participated and in general each investigated and reported on a particular reactor concept (3. 7. 19, 22). The reports were made public in 1959 and were followed by supplements in 1960 which introduced several modifications and reported in more detail on certain aspects which were not so thoroughly investigated in the initial study.

The economic data reported by the various contractors reflected different design philosophies, different estimating policies, and in some cases a technology not verified by the AEC definition of current status. In July 1959 Sargent and Lundy was requested to review the reports and to prepare normalized cost estimates of each reactor concept (18).

The 1959 nuclear reactor studies and the subsequent power cost normalization studies in the civilian power reactor program have provided a basis for the work and development which has taken place during the last three years. Also comparison of current and 1959 status provides a means of assessing the development of a particular concept.

The design and cost estimates presented in the study reports do not specifically apply to a particular location.

However, ground rules have been set up so that conditions and costs are representative of those existing in many parts of the United States. Thus, although the studies do not apply directly to any specific location and electrical system, they constitute the basis of a particular design when modifications are made to fulfill system requirements, and corrections are made for existing site conditions and economic factors particular to the proposed reactor location.

Periodical Literature

Developments in the field of nuclear engineering have taken place rapidly in recent years with the result that most material is outdated soon after it is published. Periodical literature provides the necessary current information and up-dates existing reports (10).

The views expressed in periodical literature are often very different and more varied than those found in Atomic Energy Commission or industrial reports. AEC reports are often subject to misinterpretation due mainly to a different method of cost accounting. On the other hand, industrial reports are generally written with the objective in view of making the particular product of the firm appear as attractive as possible.

It may therefore be concluded that periodical literature is an important source of current information and tends to contain more original ideas and candid views than would be found in either AEC or industrial reports.

Industrial Reports

As private enterprise is assuming an important role in the field of nuclear engineering industrial reports form a significant source of information. It is most probable that in future years much more dependence will have to be placed on these reports, since development will be conducted to a greater extent by individual contractors, rather than by the AEC. There are certain disadvantages associated with such a condition since a private enterprise legitimately safeguards its important findings from its competitors and is tardy in divulging any recent break-throughs until such time as marketing prospects are unlikely to be adversely affected.

The required general background information for the state of Iowa is available from many and varied sources. "The Iowa Business Digest" (15) provides details on the commercial and economic situation in the state, as well as indicating expected trends from extrapolation of existing data. The various U.S. Government Census Reports, in particular "Historical Statistics of the U.S." (25) provide the necessary information on such points as population growth, availability of labor force, interstate migration, fossil fuel deposits, fossil fuel production, and electrical power consumption. "The Handbook of Basic Economic Statistics," published monthly by the Economic Statistics Bureau of Washington, D.C., is found to be a valuable source of current information. In particular, the consumer and wholesale price indexes, reported each year since 1913, are required in this study for cost normalization (26).

ECONOMIC GROWTH AND GENERAL POWER SITUATION IN IOWA

Iowa's economy has been centered about agriculture and only within recent years has industry shown any signs of becoming the influencing factor in future economic growth. Study of the industrial development rate within the state is important if reliable predictions are to be made of future power demand and load concentration. The labor force is of necessity balanced between agriculture and industry. A shift to industry results in an increase in production and a greater increase in the demand for power. Industry also tends to cause a concentration of power demand and so permits an increase in maximum unit capacity. Figure 1 shows the actual and predicted division of population in Iowa from 1900 to 1980 (12).

A turning point in the relationship of industry and agriculture came in 1950. For years industrial output in Iowa had trailed the dollar productivity of agriculture. Industry drew ahead, however, in 1950, when industrial output was estimated at $2.5 billion as compared with $2.1 billion for agriculture. Since then industrial output in Iowa has more than doubled that of the farms, even though the latter has gained. Industrial production is nearing $5.5 billion a year and agriculture is at a $2.5 billion a year level (11). In mid-1961 the Federal Reserve Bank of Chicago announced that

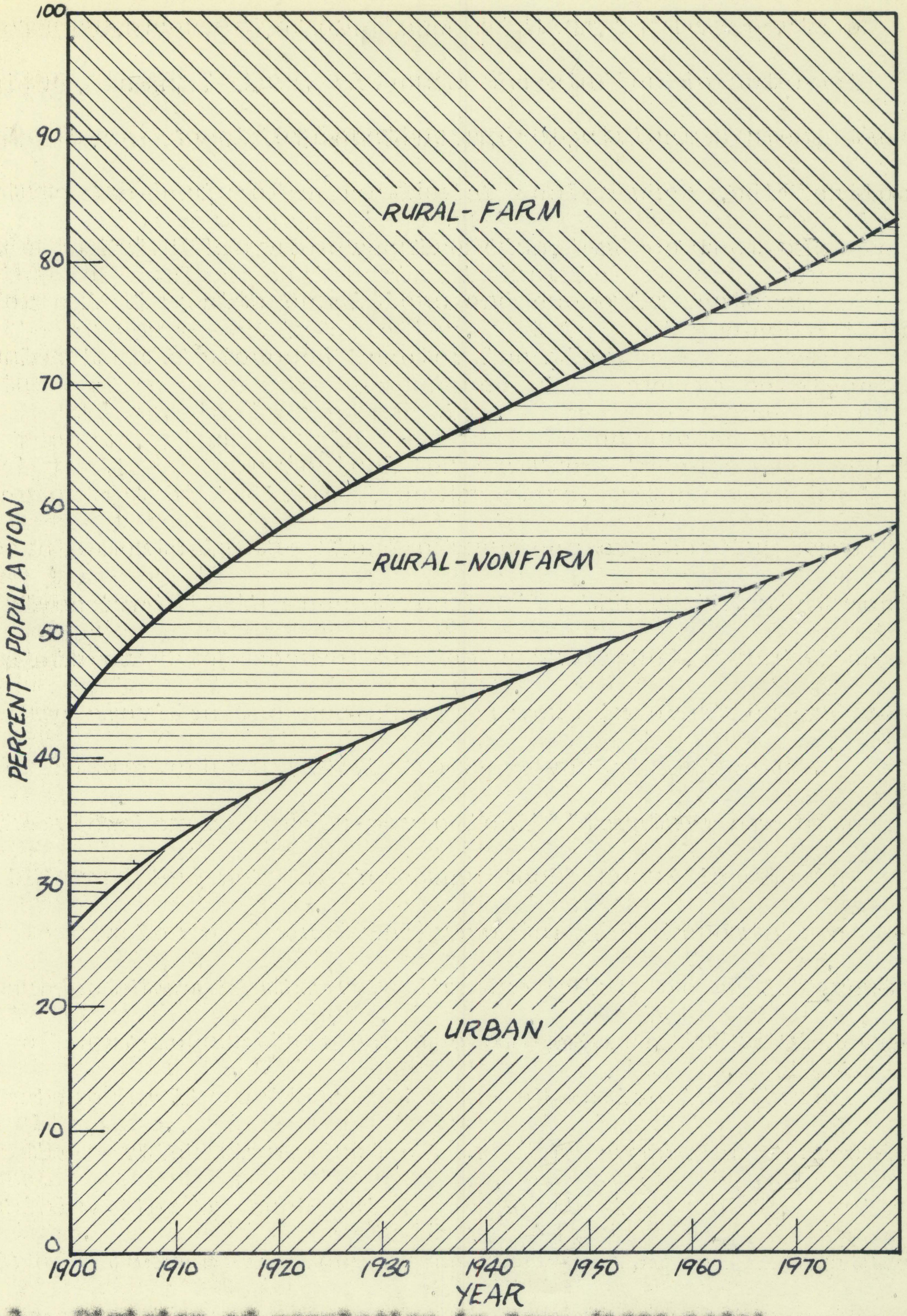

Figure 1. Division of population in Iowa (1900-1980)

Iowa has the highest growth rate in manufacturing among the states in its district in recent years (16).

The industrial shift has brought an enormous shuffling of people and jobs. The flow is from farm to city. The 1950-1960 Census shows that the Iowa increase in industrial workers was 18 per cent during the decade compared with the national average of 13 per cent. However, there was only a 5 per cent population growth compared to 18 per cent nationally (24, p. 180). The rate of growth is increasing, and by 1975 Iowa will have a population of 2.28 million if the rate of growth is at the same level as in the 1950's, or a population of 3.18 million if the rate of growth continues to increase as it has since 1930 (16). Curves are shown in Figure 2.

The Iowa College-Community Research Center estimates that in 1965 there will be 190,000 more members of the farm labor force than there will be farm jobs. The machine age has permitted fewer farmers to produce more. In 1950 the production of one farm worker supported 14.56 persons, in 1960 his production supported 23.69 persons (11). It is probable that a large labor force will become available each year due to population growth and to redundancy on the farm.

The availability of labor is a major attraction to industry. Also Iowa is the only state bordered by two navigable rivers, the Mississippi and the Missouri. The Mississippi has a stabilized nine foot channel that serves twelve Iowa communities with 33 water terminals. Iowa is

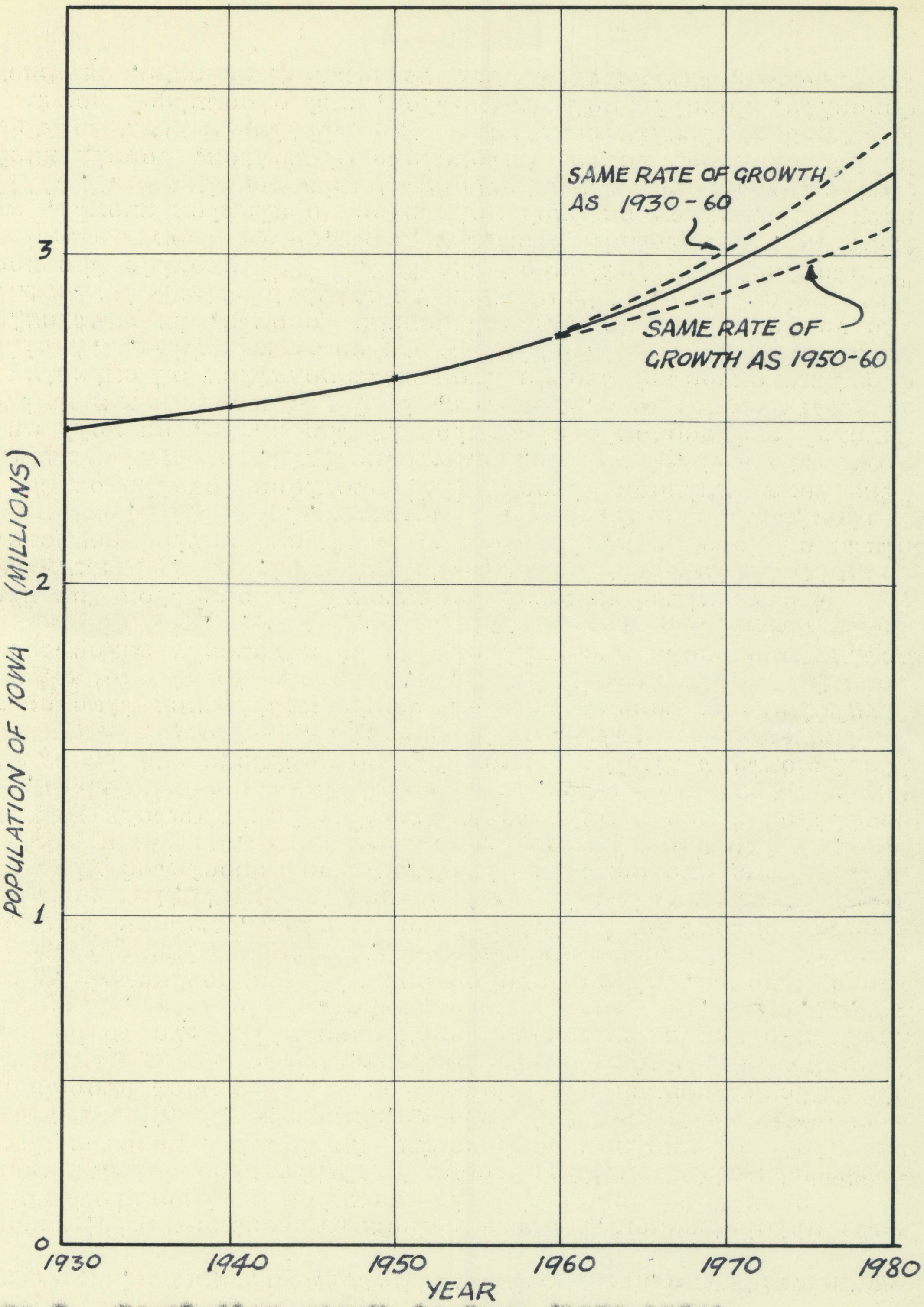

Figure 2. Population growth in Iowa (1930-1980)

near the center of a ten-state industrial market in the upper midwest which employs half the nation's machinery manufacturing workers and 40 per cent of all employees in fabricated metals, primary metals and transportation equipment. Almost one-third of the U.S. population, retail sales and effective buying power is within one day's time of Iowa by truck and two days' time by rail.

It is unlikely that these attractions will fail to maintain the high rate of industrial growth already experienced. Since industrial growth and the required generating capacity are closely associated it is likely that the demand for electrical power will continue to increase sharply. Based on this assumption the total generating capacity curve for Iowa is extrapolated to 6,000 MW installed by 1980 (Figure 3). This is in line with the assumption often made, and also with past experience, that the generating capacity doubles every ten years. On such a basis the capacity in 1980 would be 5,200 MW, but considering the high rate of industrial growth experienced and expected, the estimate of 6,000 MW does not appear excessive.

At present the industrial growth is more noticeable in Eastern Iowa and Central Iowa. Western Iowa is poised to move up industrially. Its future depends on the improvement of the Missouri River channel, scheduled to be stabilized to nine feet as far north as Sioux City by the late 1960's and local initiative is seeking new firms.

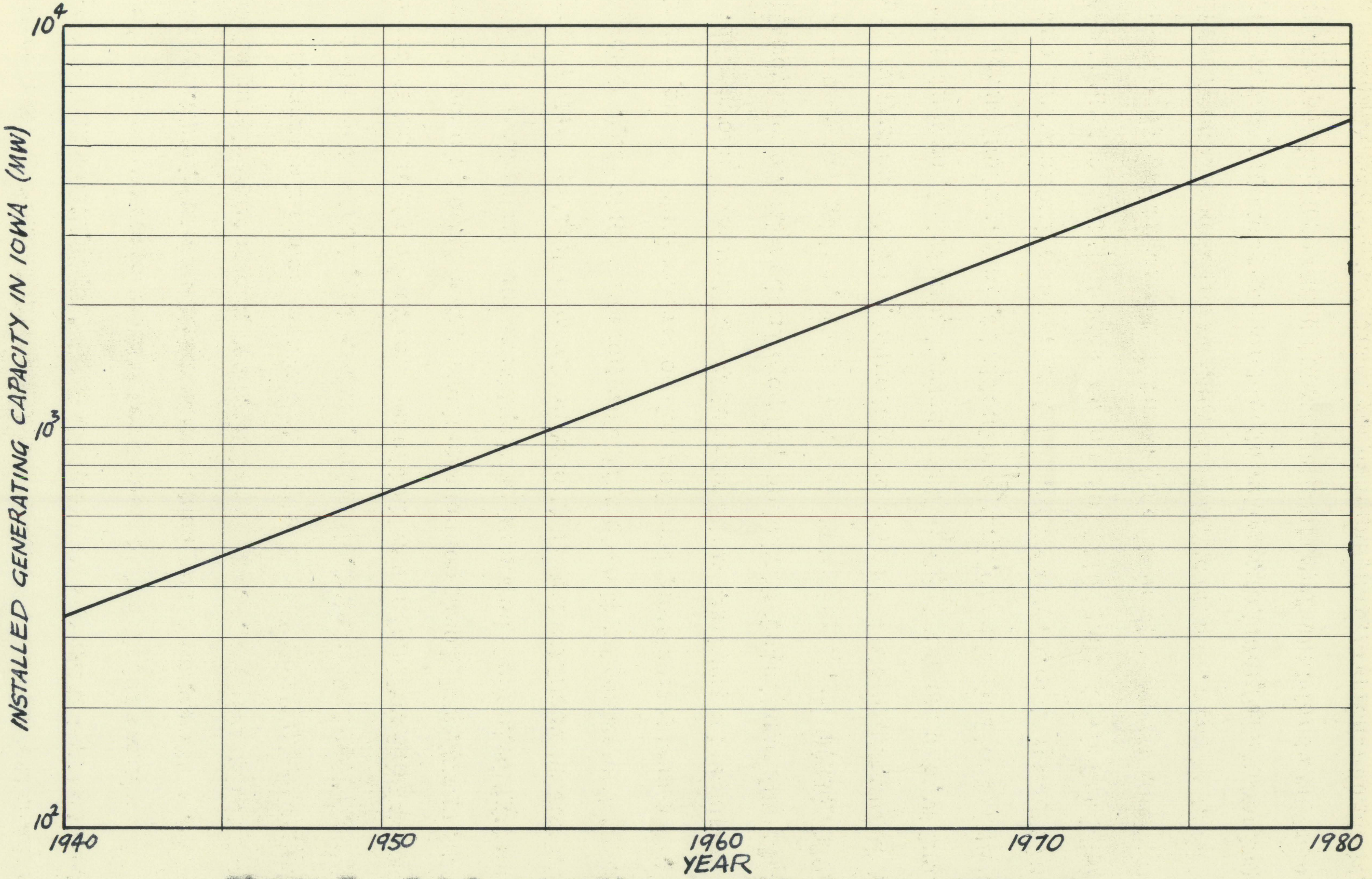

Figure 3. Total generating capacity in Iowa 1940-1980

Iowa's agricultural background is reflected in the characteristics of its electrical grid system: large low-power density regions requiring service and few urban areas where the power density is high. Such conditions require many small power generation units, evenly distributed, so that transmission losses are reduced and the system stability problems associated with long lines averted. Despite the inefficiency and high operating cost of the small units there are many 1 to 5 MW Diesel stations in operation today. Many of these small units take up the peak load but a large number are simply on a stand-by basis.

The average steam station capacity in the Iowa Pool Company grid is 70 MW and the average diesel station capacity is 4.5 MW;[a] giving an overall average station capacity of only 43.5 MW.

The installation of so many small and uneconomic stations in the past has been caused by the fear that the failure of a large unit would affect an extensive area, as well as probably causing tripping on neighboring overloaded lines. Prior to the formation of the Iowa Pool less cooperation existed between the various power companies and each tended to provide its own reserve capacity. This resulted in a reserve capacity of 22 per cent being built up within the state, compared to a

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[a] Iowa Power and Light Co., Des Moines, Iowa. Interconnecting transmission system of the Iowa Pool Cos. Private communication. 1961.

national average of 12.5 per cent. The formation of the Iowa Pool and subsequent coordination of the various planning divisions is helping to improve the situation. The advantages are substantial in the form of economy interchange, lessened costs of spinning reserves, increased efficiency and lowered unit cost of larger units, plus greater dependability of service to the consumer.

By 1963 the Iowa Pool should be approaching the 14 per cent reserve level. Thereafter, it is hoped to keep it in the 10 per cent to 15 per cent range.

The general trend appears to be towards planning on a "One-Company" basis and the adoption of three major load areas in Iowa, as indicated in Table 2.

Table 2. Major load areas in Iowa

Load area	Region	Electric utility
I	Quad-Cities area	Iowa-Illinois Gas & Electric Co.
	Cedar Rapids area	Iowa Electric Light & Power Co.
	Eastern Iowa area	Iowa Southern Utilities Co.
II	Des Moines area	Iowa Power & Light Co.
	Marshalltown area	Iowa Electric Light & Power Co.
	Waterloo area	Iowa Public Service
	South central Iowa	Iowa Southern Utilities Co.
	Fort Dodge area	Iowa-Illinois Gas & Electric Co.
III	Sioux City area	Iowa Public Service
	Council Bluffs area	Iowa Power & Light Co.

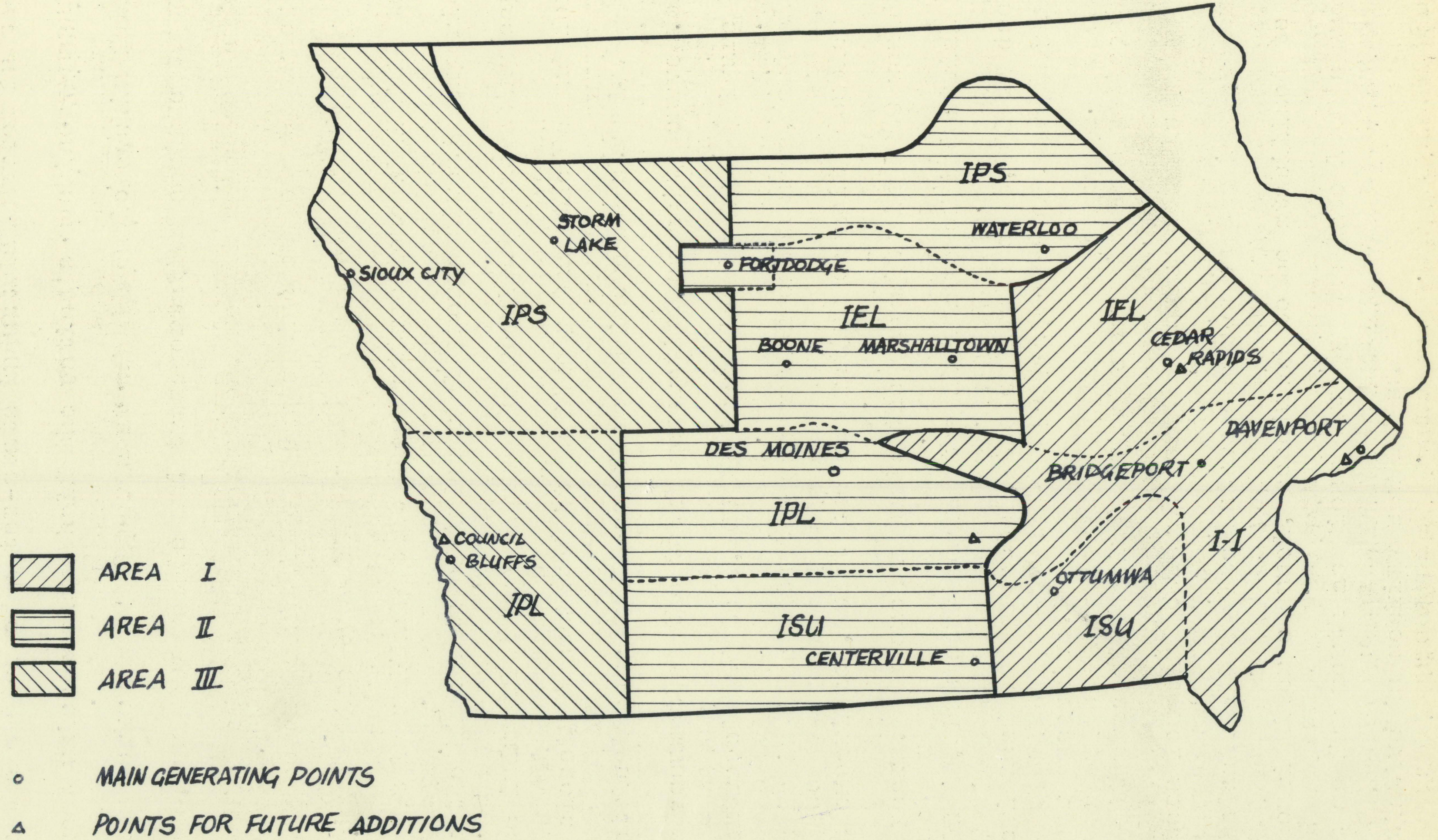

Figure 4. Iowa Pool regions, major existing and proposed generating points

These areas are shown on the map in Figure 4 and also the four major generating points for future additions in Iowa. Such a plan would undoubtedly help to reduce operating costs as well as permit the installation of units with greater capacity. This latter point is stressed since it will be shown to be of primary importance concerning the feasibility of nuclear power for Iowa.

A study is now being made for the Iowa Pool Companies by the Electric Utility Engineering Department of the Westinghouse Electric Corporation. The study, using high-speed computers, is being made to determine the optimum mode of operation for the Pool, that is, whether it is best to operate with a few very large plants and high voltages, or with a larger number of small plants near load centers. Definitive results of the study are not yet available. These results will have an important bearing on when nuclear power should be adopted by the Iowa Pool companies.

NUCLEAR POWER SYSTEM ANALYSIS

To date the development of a particular reactor system has not been influenced greatly by economics. In fact, most of the civilian power reactors in operation, or under construction, were not intended, and are not expected, to produce energy at lower than conventional power costs. The primary objective has been to obtain the essential technical information which is only available from these large-plant prototypes.

There are numerous nuclear reactor systems under intensive study today, and it is impossible to say with certainty which of these will in time prove itself most effective and be generally adopted. It is fortunate that work is at present progressing on so many reactor concepts. This helps to ensure that the most satisfactory system will evolve in the minimum time. Break-throughs in one system may very often be applied to another, and since the relative status of each may be compared it should simplify the task of evaluation and determination of the most suitable system.

Such a diverse nuclear power program is sadly lacking in Britain. Their first reactor was gas-cooled and nearly all subsequent work has been based on this concept. The result is that now they are forced to continue with gas cooling even though they may not consider it the best. However, their initial movement onto this path was inevitable; in 1946 when work started they had no heavy water for moderator and no enriched uranium.

Here in the United States conditions were different. Due to the large supplies of cheap conventional fuels the nuclear program was not influenced greatly by the need to supplement these resources. After the war, the next logical military development in the light of requirements was submarine propulsion. For this the Pressurised Water Reactor (PWR) was selected and has proved very successful. When in 1953, it was decided to build a land-based nuclear power plant it was natural to base it on the PWR system.

Since then nuclear reactor systems have developed along many diverse paths. The Boiling Water Reactor (BWR) was introduced to achieve higher temperatures in the heat cycle. The use of liquid metal coolants, such as sodium, have still further increased the cycle temperatures, while on the other hand the Organic Moderated & Cooled system (OCR) overcomes corrosion problems. More recent development has indicated the economic and technical feasibility of the high temperature Gas Cooled Reactor (GCR). Each of these systems has its associated advantages and disadvantages and the choice of any particular concept should not only be governed by its present and potential status, but also by the requirements of the system in which it must function.

Pressurised Water Reactors

Description

The pressurised water reactor is a heterogeneous fueled, thermal reactor that uses ordinary water as moderator and coolant. The system utilizes an intermediate coolant loop between the reactor and turbine. The water in the primary coolant loop is maintained under high pressure to keep the bulk temperature of the coolant leaving the reactor below the saturation temperature during normal operating conditions. A simplified flow diagram is shown in Figure 5.

Technical status

The PWR concept is at present the most technologically advanced system in the civilian power reactor program. More than four times as much capital has been invested in research and development on the PWR than on any of the other reactor systems.

The considerable experience gained with the PWR has proved that it is safe, dependable and easy to control.

Key problems

In order to prevent bulk boiling in the reactor, and yet produce reasonable temperatures, high pressures must be maintained. At present the pressure vessel must be designed for operation in the 2,000 psia and 600° F range for the

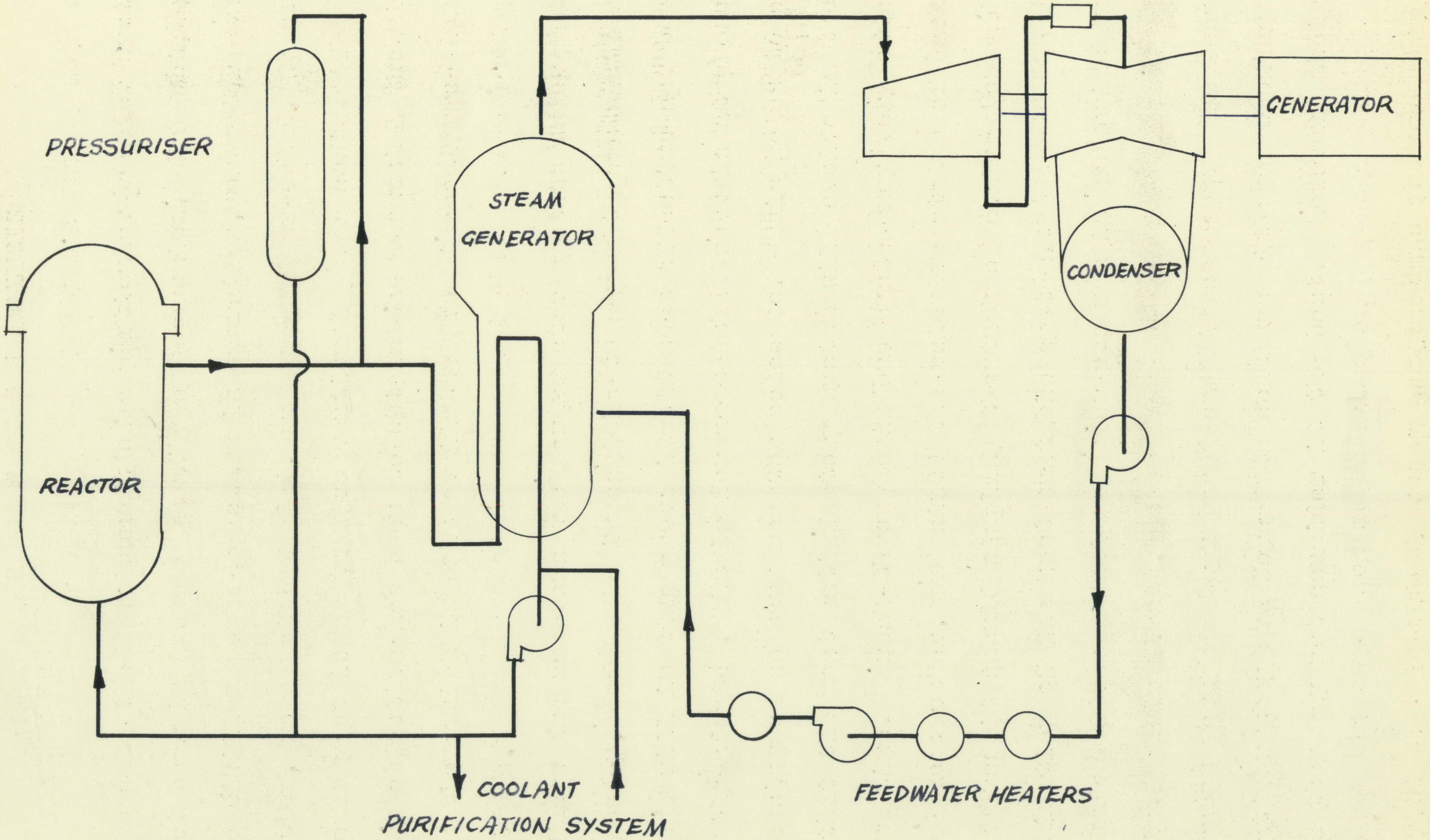

Figure 5. Simplified flow diagram of the pressurised Water Reactor System

generation by sensible heat exchange of steam at about 1,000 psia and 550° F. It is exceedingly difficult and expensive to design and fabricate a pressure vessel and primary system to withstand such pressure. Yet, the steam produced does not satisfy the high pressure requirements of the modern turbine.

The problem of fuel development is associated with most systems. Since a low fuel cost is essential for competitive nuclear power every effort is being made to introduce fabrication savings and develop fuels for operation at higher power densities and longer burnup periods.

Potential

It is unlikely that improvements in steam quality will continue to be obtained by greater pressurization of the primary system. In fact the idea of permitting bulk boiling in the hottest channels and so increasing the performance is now under study. The system then of course enters the boiling water reactor field and has associated with it the problems of core stability and heat transfer.

Fuel development promises the greatest potential saving by reducing fabrication costs and increasing the fuel life. Fabrication costs can be reduced by developing improved pelletization techniques that will eliminate the expensive grinding operation and permit longer pellets to be made. Thinner cladding would result in better neutron economy and hence lower fuel cost. The cladding now must be non-collapsing; should collapsed-clad be feasible, wall thicknesses as low as 0.012 inches may be used. Also development of inexpensive, low-cross-section cladding materials, such as iwon-aluminium materials could also improve cladding costs. Test data shows that fuel burnup can be extended to at least an average 27,500 MWd/ton in UO_2 fuels, with peaks as high as 50,000 to 60,000 MWd/ton.

Previously surface temperature of fuel elements has been restricted by desire to avoid center melting of the fuel rods. Tests have indicated that this need not be a source of serious concern.

Several component developments promise cost reductions. For example, it is expected that less expensive shaft-seal primary coolant pumps will replace present canned motor pumps. Currently the reactor coolant pumps cost approximately 7 per cent of the capital cost of the plant and this is equivalent to 0.33 mills/KWh of fixed charges. The introduction of pumps employing shaft seals would result in a reduction of about 0.11 mills/KWh. Replacement of the present conservatively designed containment shell with a "burp" system in which the initial steam release is allowed to escape to the atmosphere, or with a vapor-suppression system in which the released vapor is cooled and condensed by large supplies of cold water stored within the shell, would result in a reduction of approximately 25 per cent of the construction cost of containment, or 0.09 mills/KWh. Since the maximum credible accident does not lead to core melting in most designs, future designs may be able to eliminate the shell completely.

Boiling Water Reactors

Description

The boiling water reactor (BWR) (7) is a heterogeneous fueled, thermal reactor that uses light water as moderator and coolant. There are several variations of the BWR concept. These are: (1) the direct cycle system, in which the water is boiled in the reactor pressure vessel and the steam is bled directly to the turbine; (2) the dual cycle in which part of the energy from the reactor forms steam which goes directly to the turbine and part of the energy is transmitted by hot water to a steam generator, where additional steam is formed to help supply the turbine demand; and (3) the indirect cycle which utilizes a steam generator between the reactor and the turbine. The BWR can utilize natural circulation, forced circulation, or a combination of both. Steam can be separated either inside the reactor (smaller sizes) or externally. A simplified flow diagram is shown in Figure 6.

Superheated steam may be produced using a nuclear or fossil fuel superheater. It is considered that the use of a fossil fuel superheater is only an intermediate step and that

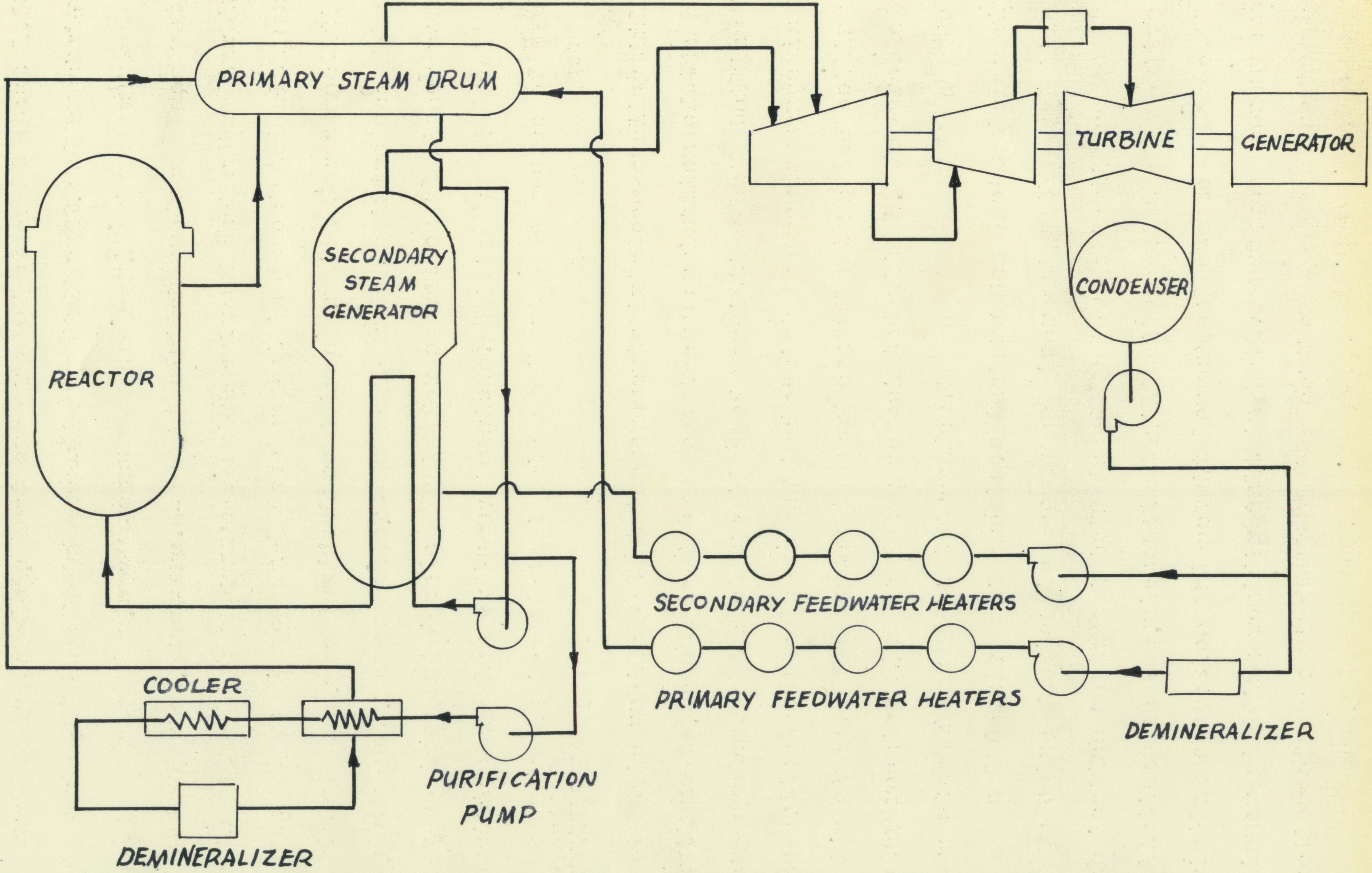

Figure 6. Simplified flow diagram of the Boiling Water Reactor system

the nuclear superheater incorporated into the Pathfinder plant will prove successful. However, there are many problems associated with a nuclear superheater. These are mainly concerned with control and heat transfer.

At the Pathfinder plant the nuclear superheater is located in the center of the reactor. The reactor core consists of two regions: (1) an annular boiler region in which saturated steam is produced and flows to the dome of the reactor vessel, and (2) a central region in which the steam is conducted down through 429 stainless steel clad fuel elements. The steam at 825° F is fed directly to the turbine.

Technological status

Only $36.7 million has been spent on the research and development of boiling water reactors between 1950 and 1960 as compared to $172.3 million on pressurised water reactors during the same period. However, the boiling water reactor has drawn heavily on the technology developed for pressurised water reactor systems. This is true especially in the areas of fuel and materials development. The physics of the BWR is similar to that of the PWR although the system is complicated by the presence of steam voids, which introduce a variable in the analysis not found in other reactor types. However, it has been found that by using the proper water-to-fuel volume ratio, the desired void coefficient at a particular operating condition can be obtained. Control of the BWR is made difficult by the fact that the void coefficient tends to oppose the steam demand changes.

The most widely accepted fuel for the BWR is UO_2. This is due to its good corrosion resistance in water as well as its radiation damage resistance. In general, use has been made of components and auxiliaries already developed for conventional steam plants or for non-boiling water reactors. However, the conventional equipment is often the major cause of operational delays and plant malfunctions.

Boiling water reactors are inherently safe since a power surge tends to reduce power by increasing void formation. The reactor pressure is less than in the primary circuit of the PWR, yet the same pressure is delivered to the turbine. The elimination of a number of pumps and heat exchangers tends to reduce the cost. The adoption of a nuclear super-heating region in the center of the core promises higher temperatures and better quality steam,

It is hoped that the use of a low pressure containment vessel and a vapor suppression system in future plants will provide a capital cost saving of up to $2 million. The 50 MW BWR Humboldt Bay plant at Eureka, California incorporates the first pressure suppression containment system.

Key problems

1. The development of high temperature fuel element capable of operation at 1200° F for 10,000 MWd/ton, with geometry suitable for superheated steam.

2. Improvement of superheat technology. It is hoped that the first nuclear superheater in the Sioux Falls plant will provide the necessary practical experience.

Potential

The expected reductions in power cost are as follows (27):

1. The successful increase in the power density from 28 to 50 KW/liter of core would result in a net saving of 0.63 mills/KWh.

2. The realization of the development program for reducing the requirements of vapor containment either by the "burp" method or vapor suppression would result in a saving of 0.09 mills/KWh.

3. Major reductions in fuel cycle cost will occur through a lower fabrication cost and increased fuel exposure. The estimated fuel exposure from UO_2 is 40,000 MWd/ton maximum by 1968. The reduction in fuel cycle cost going from 13,000 to 19,000 MWd/ton would be 0.53 mills/KWh.

4. The use of an integral boiler, superheater reactor is expected to reduce costs by 0.73 mills/KWh. This gain is

achieved because of an estimated 0.43 mills/KWh reduction in capital cost as well as an approximate 0.3 mills/KWh reduction in fuel costs.

Sodium Graphite Reactor

Description

The sodium graphite reactor (SGR) is a heterogeneous fueled, graphite moderated, sodium cooled thermal reactor. The reactor generated heat is delivered through two coolant loops to the turbine. Radioactive sodium circulates in the first loop, removing the heat from the fuel and transmitting the energy through a heat exchanger to the secondary loop. The non-radioactive secondary sodium transmits the heat to a steam generator where superheated steam is formed to drive the turbine. A simplified flow diagram of the sodium graphite reactor plant is shown in Figure 7.

Technological status

The sodium graphite reactor technology has drawn heavily on experience obtained through the Naval Submarine Intermediate Reactor program (SIR) and the Fast Breeding Reactor program (SRE). Experience to date has shown the feasibility of the concept. However, the present complexity, high cost of the system and the lack of a high-temperature long-life fuel element make it unlikely to be an economic proposition in

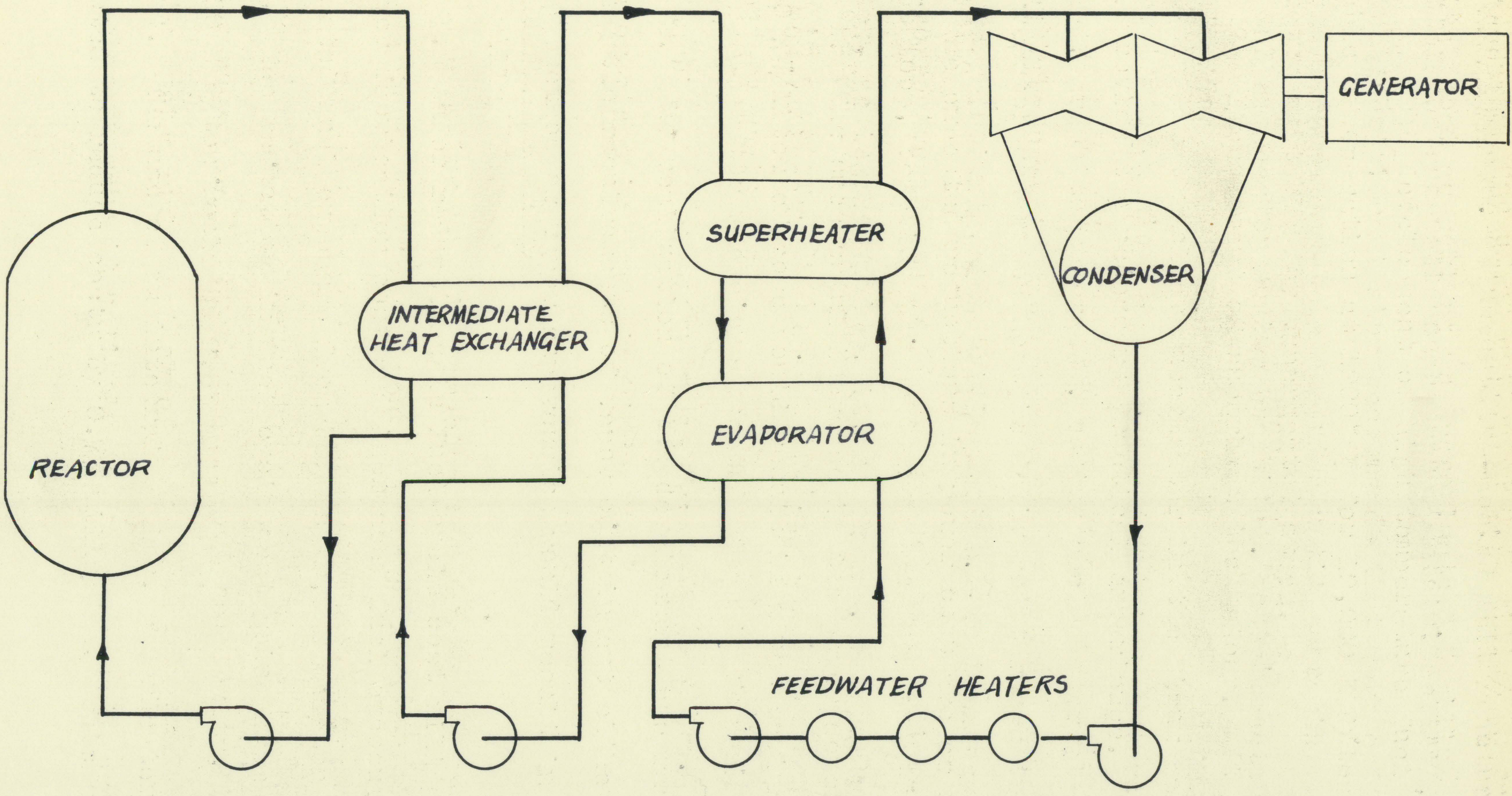

Figure 7. Simplified flow diagram of the Sodium Graphite Reactor system

the near future. Since sodium-cooled fast reactors offer most of the same advantages plus breeding as well, the U.S. Atomic Energy Commission recommends that work on the sodium graphite concept not be expanded until operating results from the Hallam reactor can be evaluated. This reactor went critical on August 27, 1962 and is expected to be at full power in the spring of 1963.

The SGR system has the advantage of operating under lower pressures in the primary system because of the liquid metals relatively high boiling point. Sodium appears to be a non-corrosive substance. The product of a sodium-water reaction, sodium hydroxide, is, of course, extremely corrosive when in a water solution. This is the main reason for using a secondary sodium loop. In the event of a sodium-water reaction the vapor released would not be radioactive.

Key problems

1. Fuel development is the most important problem. The fuel must have a high thermal conductivity and the ability to withstand average exposures of at least 17,000 MWd/ton at a surface temperature of 1400° F. Uranium carbide looks promising at present and study is centered around it.

2. Steam generators probably have the largest potential for improvement of any single out-of-core component. The present design employs double walled tubes containing a

monitoring fluid and costs could be greatly reduced through utilization of (a) high strength ferrite steel, (b) "once-through" concept, and (c) single-walled tubes.

3. Liquid metal pumps, both mechanical and electromagnetic, are expensive to maintain because some of their parts are in direct contact with the radioactive sodium.

4. Stop-valves developed so far cost $3,000 per inch of valve opening. The potential cost reduction here is considerable and other types--freeze seal and ball-disk types--are being investigated.

Potential

Current estimates for a 300 MWe sodium graphite reactor run about 11 mills/KWh. It is expected that there will be a reduction of at least 3.5 mills/KWh by 1969.

The economic potential of the sodium graphite reactor is dependent primarily on the development of a ceramic type of fuel that will provide long exposures, and simplification of reactor design. The cost of steam generators associated with the advanced sodium graphite reactor is $80/ft.^{2}. The successful development of simplified steam generators would reduce this cost to $45/ft.^{2}, which is equivalent to a saving of 0.25 mills/KWh. The potential of the sodium graphite reactor lies in the development of the uranium carbide or similar fuel. The U-10 w/o Mo currently used is unsuited due to high temperature limitations. It is hoped to increase the average irradiation level from 10,000 to 19,000 MWd/ton and reduce the fuel cycle cost by 0.67 mills/KWh.

Organic Cooled Reactor

Description

The organic cooled reactor (OCR) (3) is a heterogeneous fueled, thermal reactor utilizing an organic material as coolant. The reactor is usually moderated by the same fluid utilized as a coolant, however, other moderator materials can be used (2). The heat is removed from the fuel by the organic coolant and transmitted to a steam boiler. A simplified flow diagram of the organic cooled reactor plant is shown in Figure 8.

Technological status

The technology of the OCR concept is in the early stages of development. Experience with this concept is limited to the Organic Moderated Reactor Experiment and the Piqua reactor. As indicated by the U.S. Atomic Energy Commission, it is likely that the organic cooled reactor will be competitive in the high cost areas by the middle 1960's and in many other areas later. The concept is expected to reach this stage with less research and development and fewer experimental and prototype plants than will be required by the other reactor concepts. This will

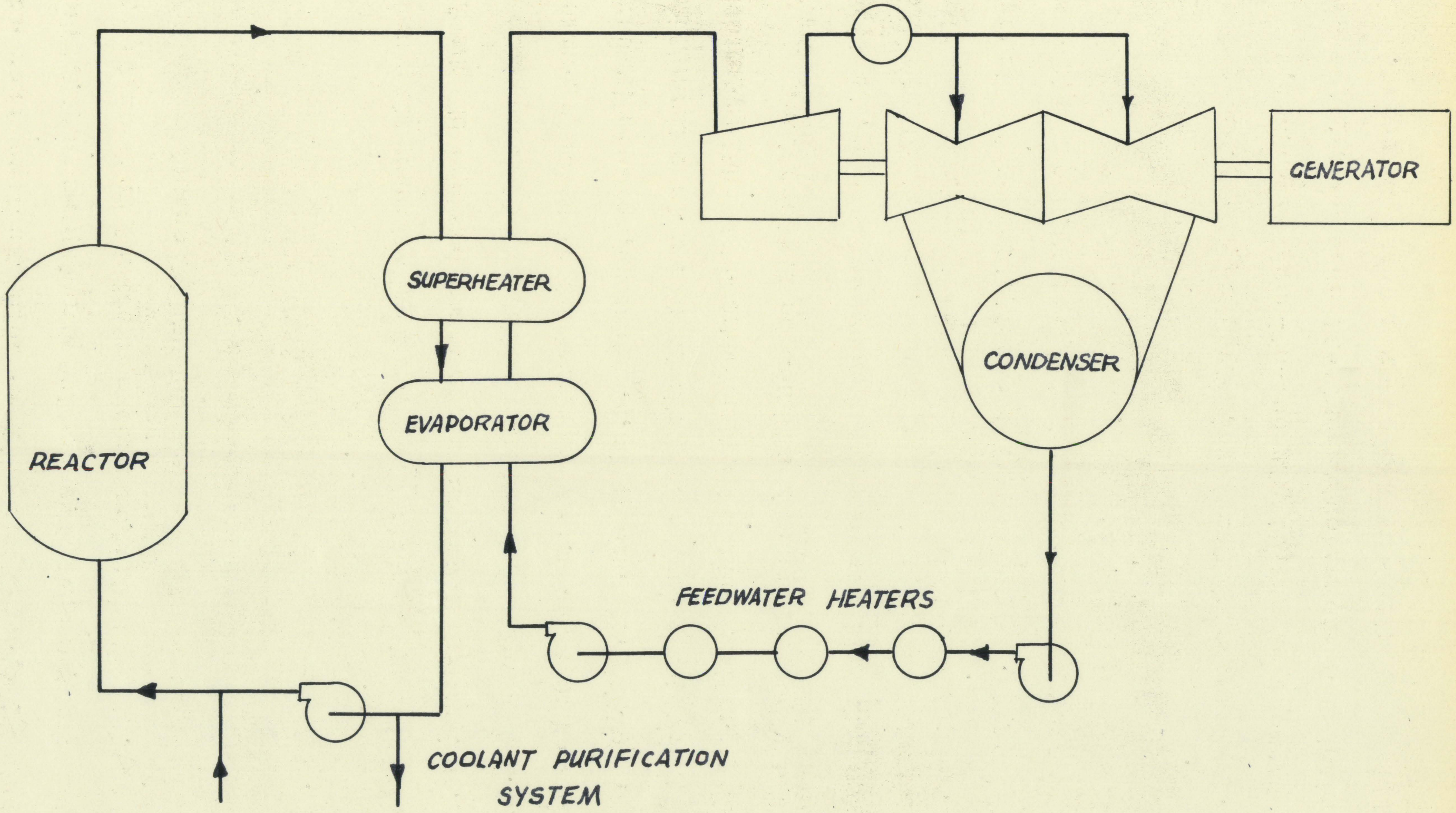

Figure 8. Simplified flow diagram of the Organic Cooled Reactor system

be possible because the system is relatively simple; it has been able to borrow much from water-reactor technology and the developmental difficulties encountered so far have been easily overcome. When the more immediate problems of the organic concept have been solved, the development effort will switch to an investigation of plutonium recycle and other advanced features for organic systems.

The organic cooled reactor has many attractive features:

1. Low pressure in the primary system for temperatures in the range of 600° F to 800° F.

2. No corrosive difficulties or hazardous chemical reactions with the fuel or core materials.

3. Standard materials and components for construction (aluminum for fuel cladding and low carbon steels in standard pipes).

4. Low induced activity in coolant. Since the pressure is also low, containment costs are greatly reduced.

5. Fluid moderator-coolant gives large negative temperature coefficient of reactivity.

Key problems

1. Heat transfer is a limiting factor on performance because of the low thermal conductivity of the organics. Development work is intended to ascertain whether improved forced convection or nuclear boiling is the best way to increase heat transfer.

2. Fuel-element development, the most critical area for the organic reactor, aims at a long burnup element with a large heat transfer surface area. Uranium-molybdenum metal alloy is presently being developed. The most important item is a cladding material with a high thermal conductivity which can be easily extruded with fins and is compatible with the coolant up to 900° F. The most promising cladding material so far is a sintered aluminum containing 6-8 per cent Al_2O_3.

3. Organics are subject to radiolytic decomposition. A high decomposition rate can result in high coolant make-up costs.

Potential

The successful economic potential of the organic reactor concept is dependent on achieving a fuel capable of a high heat transfer rate to the organic coolant and high burnup. Increasing the power density from 19 to 44 KW/liter of core will permit a reduction in core size and number of control rods. A saving of 0.3 mills/KWh is estimated. It is hoped to increase the fuel exposure from 11,000 to 19,000 MWd/ton with a cost reduction of 0.61 mills/KWh.

Gas Cooled Reactor

Description

The world's first commercial nuclear power station employed gas cooling (air) and natural uranium as a fuel. Since then the concept has been developed considerably by the United Kingdom Atomic Energy Authority, but until recently, when the enriched high-temperature gas cooled concept was developed, gas cooling has received little attention in the United States. Enrichment permits use of higher-temperature fuel element materials and also allows a smaller core volume. Helium is used as a coolant rather than carbon dioxide in order to avoid the carbon dioxide graphite chemical problem on reactors where the temperature would be 500 to 600° C. Helium is chemically inert and compatible with the fuel and moderator materials throughout the temperature range of interest. The helium coolant is transmitted to a steam generator in current designs. A simplified flow diagram is shown in Figure 9.

Technological status

The technology of enriched fuel gas reactors has not yet been fully demonstrated. All present designs use UO_2 and the recent HTGR concept employs fuel elements consisting of a homogeneous mixture of 25 vol. per cent and 75 vol. per cent of UO_2 and graphite respectively. The fuel element is unclad and designed for surface temperatures up to 2,000° F. The Atomic

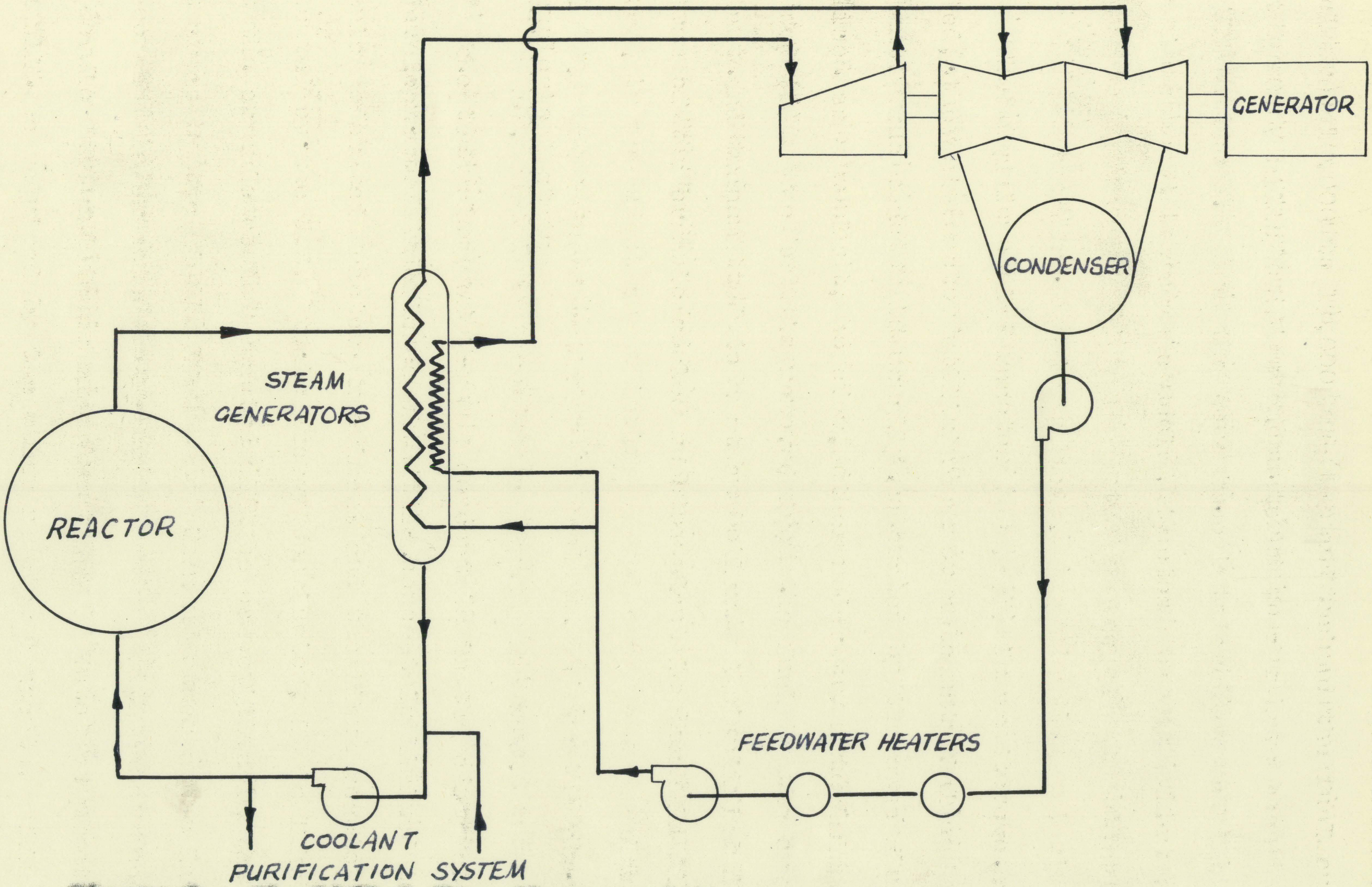

Figure 9. Simplified flow diagram of the Gas Cooled Reactor system

Energy Commission is encouraging two versions of the concept: the Experimental Gas Cooled Reactor (EGCR) at Oak Ridge National Lab., and the High Temperature Gas Reactor (HTGR) being built at Peach Bottom, Pa. Further reactor construction is to await the operating results from these two projects.

Key problems

At present most problems are associated with lack of test data. However, the EGCR at Oak Ridge will serve as a flexible facility in which to test advanced fuels, materials and components.

1. A realistic method of determining helium leakage is not known and pressure experiments on blowers, valves and piping are not yet completed.

2. Fuel handling equipment and remote maintenance techniques require development.

3. Possible solutions to the piping problems of high temperature gas systems must be found and the blowers for circulating the gas coolant are a particularly important component.

Potential

There is considerable scope for improvement in current design based on experimental results. All current designs employ a gas-steam cycle between the reactor and turbine. However, since the primary coolant is a gas it appears likely that with the development of improved seals and gas cleanup practices a direct gas cycle between reactor and turbine will be feasible. Such an innovation would eliminate the costly steam generators and associated valves, blowers and pumps, as well as increasing the cycle efficiency and reducing the complexity of the plant. Much will depend on the results of the EGCR and HTGR projects.

Properly designed gas cooled reactors may require no containment. This is because (1) the energy released upon loss of coolants in gas systems is much less than in water systems, and (2) the solid moderator acts as a heat sink and limits temperature excursion. Furthermore, it appears possible to design gas cooled reactors so that no single accident can lead to complete loss of coolant.

Conclusions

If it were desided that construction on a nuclear power station should start immediately in Iowa then the choice would surely be limited to a pressurised or boiling water system. If the most reliable system was the governing factor then a pressurised water plant would be the choice. Most of the boiling water reactor troubles have been resolved since the start-up of the Shippingport plant in 1957. This plant generated its billionth kilowatt-hour of electricity in December 1957 and the Yankee plant, also designed by the Westinghouse Atomic Power Division, generated its billionth kilowatt-hour in February, 1962. Three other Westinghouse-designed pressurised water reactor plants, ranging up to 260 MW, are in various stages of construction. A letter-of-intent exists for a 375 MW plant, and serious negotiations are underway for even larger units. These latest reactor plants are being offered to major United States utilities on the basis that the plants are competitive with fossil plants of the same rating in the higher fossil fuel cost areas. The plants themselves are offered on a firm price, turnkey basis.

On the other hand, the natural circulation boiling water reactors have a small capital cost advantage over pressurised water reactors in ratings up to about 150 MW and forced circulation boiling water reactors have a similar advantage over pressurised water reactors in ratings up to about 300 MW. Thus, from a cost view point the boiling water reactor is more attractive. At present the decision must be based on whether the initial saving in capital cost will compensate for the cost of unexpected operating difficulties.

Then, in summary:

1. Immediate plans for a nuclear power station should be confined to the boiling water and pressurised water reactors and the final selection should depend on whether the lower capital cost of the boiling water reactor is likely to compensate for the operational difficulties which may be encountered.

2. Plans for adoption of nuclear power in the near future should probably be confined to the boiling water

reactor only; the use of nuclear or fossil superheat being dictated by results from the Pathfinder and Elk River projects.

Plans for the late 60's and 70's should not be confined to any particular project. Since there are so many variables involved, from fuel fabrication costs to the development of completely new concepts, such as a practical fusion system, a more general outlook should be adopted. Projection of future patterns of discovery, technology of utilization and demand for energy resources is, at best, a kind of informal speculation.

NUCLEAR POWER ECONOMICS AS APPLIED TO IOWA

If the merits of a system under economic study are to be significantly evaluated, then a comparison must be made between it and some similar system (18). In the case of a nuclear power cost study the basis for comparison is the conventional system existing in the region for which the study is being made. Therefore, the economics of the conventional power system in Iowa must be thoroughly investigated if well-founded and reliable conclusions are expected from the subsequent nuclear study.

The most important objective of the study is to determine as specifically as possible when nuclear power costs will become equal to, or less than, conventional power costs for the Iowa Pool system, and more generally, when nuclear power will be competitive in Iowa State as a whole. Predictions will be made for the twenty-year period from 1960 to 1980 and all data and information used will pertain as closely as possible to the regions served by the Iowa Pool companies.

The Conventional System

Conventional power costs derived from the Iowa Pool system as a whole, or from units already installed, are not of great significance in this study. The system contains a large assortment of equipment and many very small units which produce relatively expensive electrical power, have poor load factors and many other characteristics and peculiarities which on averaging with the more normal units would give an erroneous basis for comparison. Most of the existing small units would not be deemed necessary if the whole system was being installed today. The existing power grid and power stations are characteristic of a gradually growing agricultural community where small and inefficient units were installed to meet the immediate needs of the day.

Comparison must be made between conventional and nuclear power plants of the same capacity, erected under similar conditions and at the same time. This necessitates determining the costs of conventional plants of given capacities over the 1960 to 1980 time period. In effect, the comparison will be made between the cost of power from a nuclear plant and the cost of power from the most modern conventional plant available at the time, rather than between nuclear power cost and existing power cost averaged over the system, for from the economic view point extra power requirements will be met by the cheapest means available, be it conventional or nuclear.

Unit capacity

The capacity of the largest unit installed in a system is governed by several factors:

1. The total existing system capacity
2. The stability of the system

3. The availability of emergency supply from neighboring systems

4. The outage frequency experienced.

The total existing system capacity has a large influence on the maximum unit capacity. A large system in general can accommodate units of greater capacity than a smaller one, since it is the percentage loss of power which determines whether a recovery is possible. On this basis an estimate may be made for the average percentage of system capacity permitted in a single generator. The following relationship between unit size and system capacity has been obtained from data published by the Atomic Energy Commission (7).

Table 3. New steam-electric generating unit capacity as per cent of total system capacity at time of installation[a]

System capacity before unit installation	Average per cent of system capacity of new steam-electric generating units[b]
Below 500 MW	35.7
501 MW to 100 MW	20.7
1001 MW to 1500MW	14.9
1501 MW to 2000 MW	11.3
2001 MW to 2500 MW	10.8
2501 MW to 3000 MW	9.4
Above 3000 MW	8.4

[a] For all steam-electric units installed in 1958.

[b] There is a range within each of the indicated average percentages.

In 1960 the total system capacity in Iowa was 1300 MW and therefore from Table 3 the maximum system capacity permitted could have been 14.9 per cent of 1300 MW, which is 194 MW. Assuming a doubling of capacity every ten years the total capacity of the Iowa system in 1980 should be 5200 MW, permitting a maximum unit capacity of 8.4 per cent total, i.e., 440 MW.

It must be remembered that the above results are based on total system capacity considerations and will require modification when the remaining governing factors are investigated.

System stability. Any given transmission line has a maximum value for the power which it can transmit and still maintain stability. This value is governed by the characteristic impedance and the length of the line. The reactances associated with the transmission line cause phase shift between the voltage at sending and receiving ends. As the transmitted power is increased, the phase difference increases until a point is reached where the product of receiving end voltage, current and power factor is a maximum. Any further increase in load results in instability.

This may be demonstrated mathematically using a simple case and applying "Equivalent π " analysis methods. Figure 10 shows the Equivalent π circuit for a single transmission line fed at a voltage $\overline{U}_1$ and loaded at the other end, where the voltage is $\overline{U}_2$. The line has total equivalent resistance,

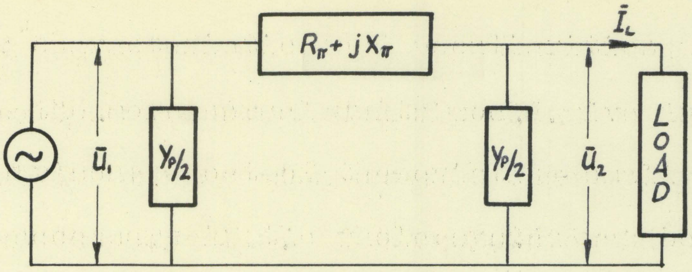

Figure 10. Equivalent circuit for transmission line

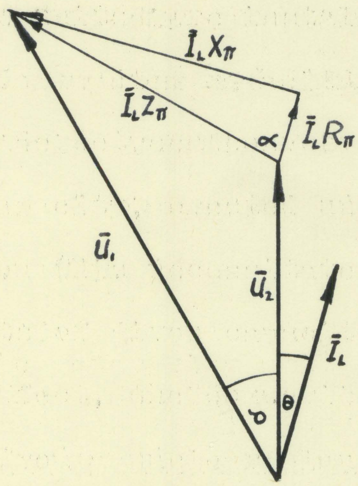

Figure 11. Vector diagram for transmission line

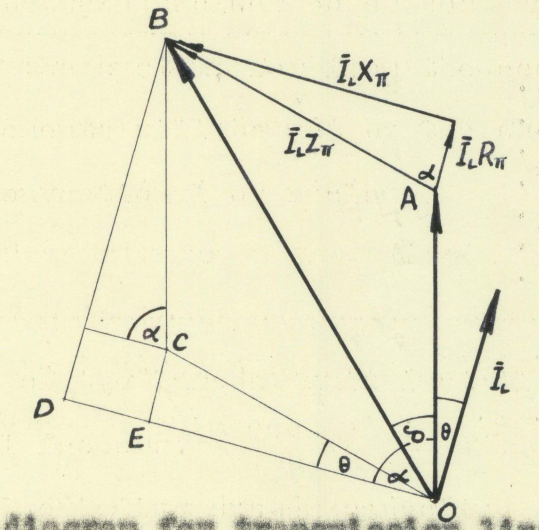

Figure 12. Vector diagram for transmission line with geometric construction

inductance and susceptance of R_π , X_π and Y_p respectively. A current I_L feeds the load.

The vector diagram in Figure 11 shows relative phases and magnitudes of the current and voltage vectors. The phase angle at the load is θ and the phase angle between sending and receiving ends is δ . Using the geometrical construction in Figure 12, a relationship may be obtained between the power transmitted and the other variables.

$$EO = DO - DE$$

$$I_L Z_\pi \cos\theta = U_1 \cos(\alpha - \delta) - U_2 \cos\alpha, \text{ where } \alpha = \tan^{-1} X/R$$

$$I_L U_2 \cos\theta = \frac{U_1 U_2 \cos(\alpha - \delta) - U_2^2 \cos}{Z_\pi} = P_L, \text{ which is}$$

the power transmitted to the load. On differentiating the above expression and setting equal to zero:

$$\frac{dP_L}{d\delta} = \frac{U_1 U_2 \sin(\alpha - \delta)}{Z_\pi} = 0$$

Therefore for maximum power transfer $\delta = \alpha$. Thus the maximum power is transmitted when the phase shift between sending and receiving end voltages is equal to $\tan^{-1} X_\pi / R_\pi$, which is a characteristic of the line.

In practice the line is not loaded above the dynamic stability limit, which is often set at 50 per cent of the maximum power rating. This limit provides for oscillations due to switching, lightning and other surges.

A long, lightly-loaded line may also prove unstable if resonances are set up between the associated inductive and capacitive elements. It is apparent, therefore, that a system with long transmission lines is likely to have stability difficulties, and more especially if a small number of large units are installed.

The need for system stability has been one of the factors influencing the erection of so many small capacity units in Iowa. In 1959 the average steam plant unit capacity in Iowa was 70 MW compared with 132 MW averaged over the United States. In view of this fact the initial values for maximum unit capacity, derived from total system capacity on the basis of a United States average, require reduction. The reduction factor for 1959 is 70/132 or 0.53. On the basis of this reduction factor, the estimated maximum unit capacity for 1960 is 104 MW and for 1980 is 235 MW.

Availability of emergency supplies. Availability of emergency supplies from neighboring systems plays an important part in determining maximum unit capacity. If the intersystem links are strong then all the spinning reserves need not be provided from within and so provision for large unit failure is not as expensive.

Prior to the formation of the Iowa Pool each company tended to rely on its own spinning reserves, and as a result a reserve capacity of 22 per cent was built up within the state, compared to a national average of 12.4 per cent. Present cooperation and planning has reduced the reserve to 15 per cent and it is hoped to maintain this between 10 and 15 per cent. As well as internal supplies, Iowa has relatively strong transmission links with the Minnesota, Omaha, Kansas City, St. Louis and Decatur, Illinois grids.

Outage frequency. Some systems are much more susceptible to failure than others. Natural causes such as frequent thunder storms, or strong winds are often the cause. However, the use of modern fast reclosure circuit-breakers and protection equipment can greatly reduce the frequency of outage, and so, with the danger of supply failure reduced, unit capacity may be increased.

Replacement of superseded equipment is underway in the Iowa Pool system.

In light of the above factors the estimate in Figure 13 is made for future maximum unit capacity. The capacity of 150 MW for 1960 is consistent with actual installation and the exponential increase to 300 MW by 1980 is a conservative estimate and is considered reasonable by Iowa Power & Light Company engineers.

Conventional power cost

For the sake of simplicity the value of the U.S. dollar will be considered fixed at its 1960 level and all data used will be normalized to this date. Such procedure will not detract from the value of the study since it is the relative cost of conventional and nuclear power which is being considered.

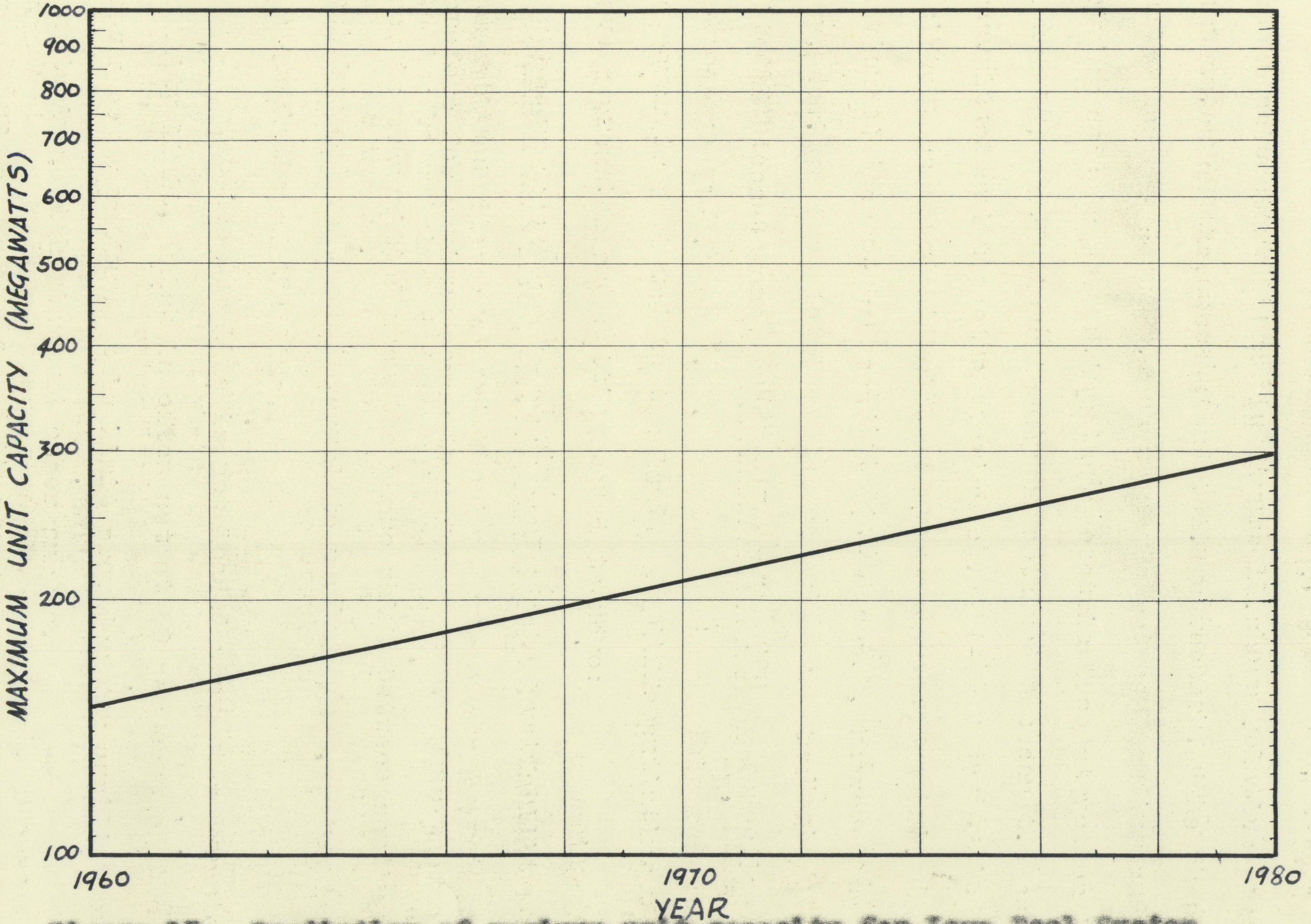

Figure 13. Prediction of maximum unit capacity for Iowa Pool System (1960-1980)

The Consumer Price Index in Figure 14 has been extrapolated to 1980 and so provides a means for cost normalization (26).

Fuel cost predictions. The conventional fuel cost predictions for 1960 to 1980 made by fifteen U.S. utilities are utilized (8). Assuming a price index of 100 in 1960, a plot of gas, oil and coal index predictions is shown in Figure 15. Points are scattered, but on averaging the costs for each type of fuel relatively smooth trend lines result. The average estimate, made by the fifteen utilities for this region, shows that gas costs are expected to increase more rapidly than coal and oil costs.

The present fuel consumption by the Iowa utilities is approximately equally divided between gas and coal, and the consumption of oil may be considered negligible. As gas costs increase, the trend will be towards greater use of coal and the assumption is made that by 1980 there will be a three to one ratio between the quantities of coal and gas used. On this basis the fuel cost predictions for Iowa are made.

Using the extrapolated Consumer Price Index the fuel cost trend may be expressed in terms of the 1960 fixed dollar. Figure 14 shows the predicted gas price index and the predicted coal price index. Based on the assumption that more coal will be used as the gas becomes relatively more expensive, the total fuel price index for the Iowa utilities is predicted.

The rate of fuel cost increase is expected to be greater than for other consumer goods. This is reasonable since

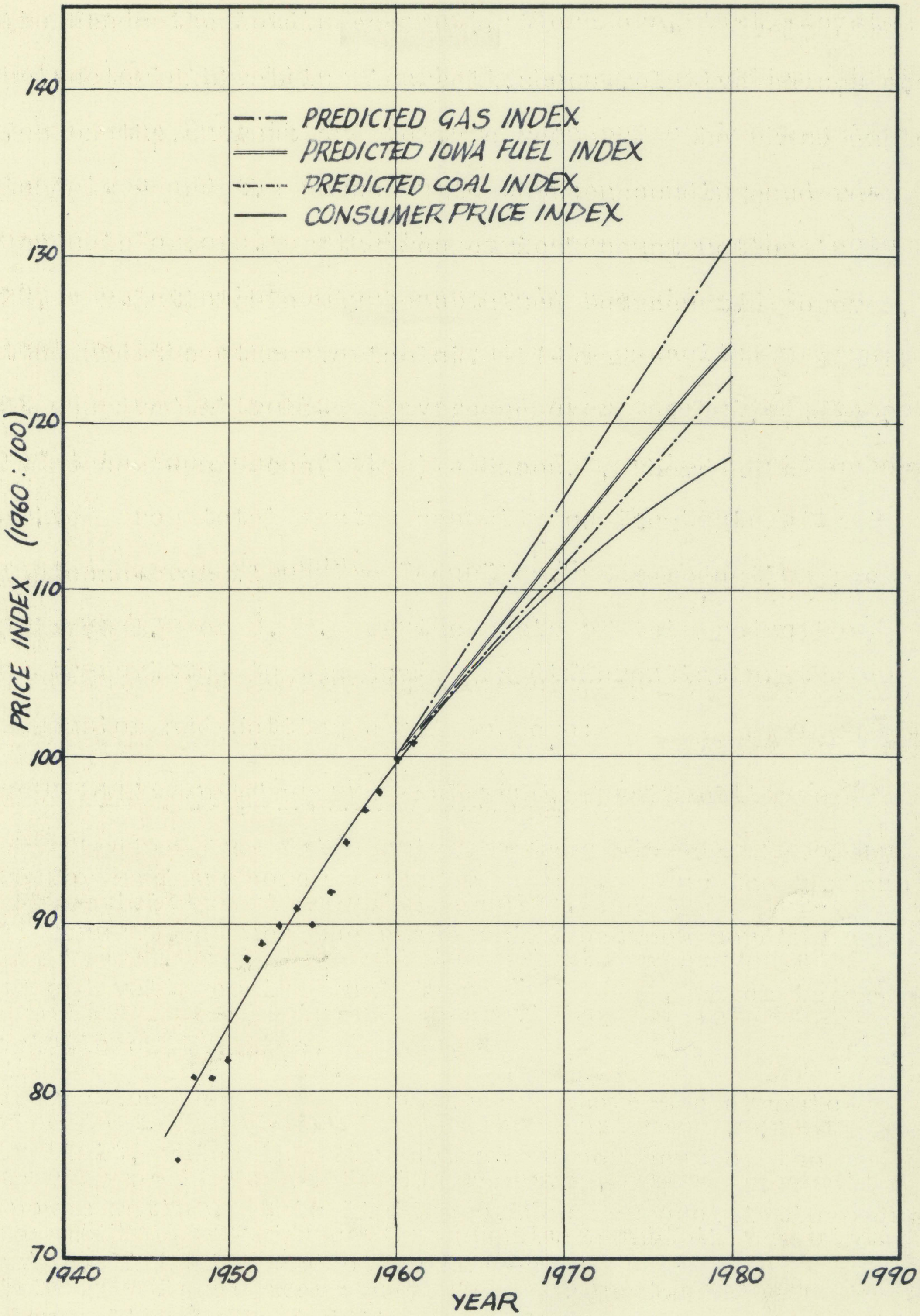

Figure 14. Fuel price index for Iowa

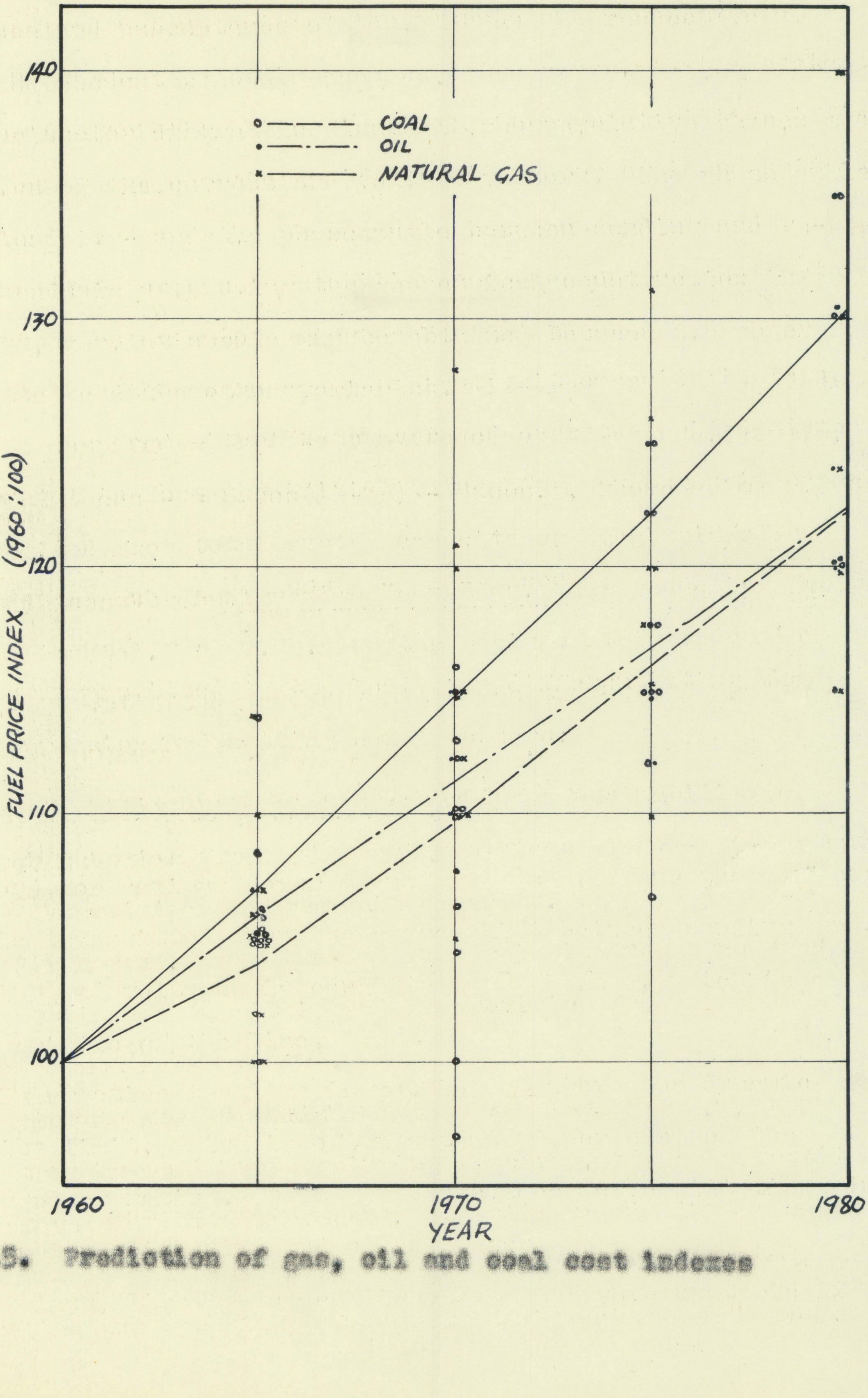

Figure 15. Prediction of gas, oil and coal cost indexes

mining and transportation costs per BTU should increase as lower grade fuels are resorted to.

Figure 16 shows the relationship between conventional generating costs and fuel costs and is based on a report prepared by Bechtel Corporation and Atomics International for the Atomic Energy Commission (3). From this the percentage increase in generating cost attributed to a particular increase in fuel cost is obtained. As far as advances in technology are concerned, it is considered reasonable to assume that these will be required to compensate for the lower calorific value of the fuel which will be burned.

Unit capacity has an important effect on energy costs. As the capacity is increased the unit energy cost is reduced. The relationship between unit energy costs and unit capacity, Figure 17, is based on a report made by Sargent and Lunday for the Atomic Energy Commission (18).

By combining the effect of fuel price and unit capacity changes a net estimate for the percentage change in unit energy costs in the conventional system from 1960 to 1980 results. Curves for various 1960 unit energy costs are shown in Figure 18.

On the basis of the fixed 1960 dollar the predictions indicate only a 5 per cent decrease in conventional energy cost and this is attributed to the larger capacity units which will

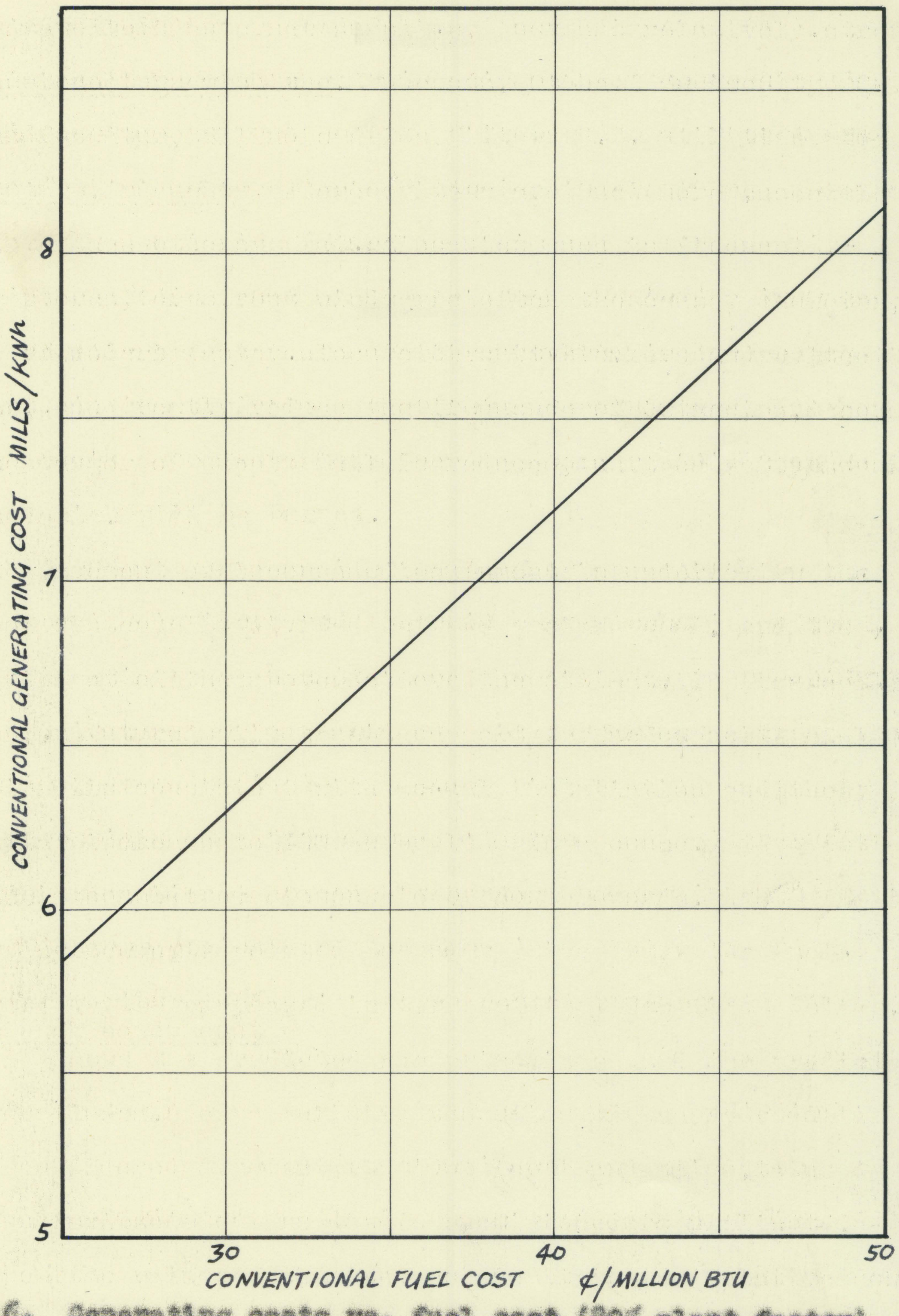

Figure 16. Generating costs vs. fuel cost (80% plant factor)

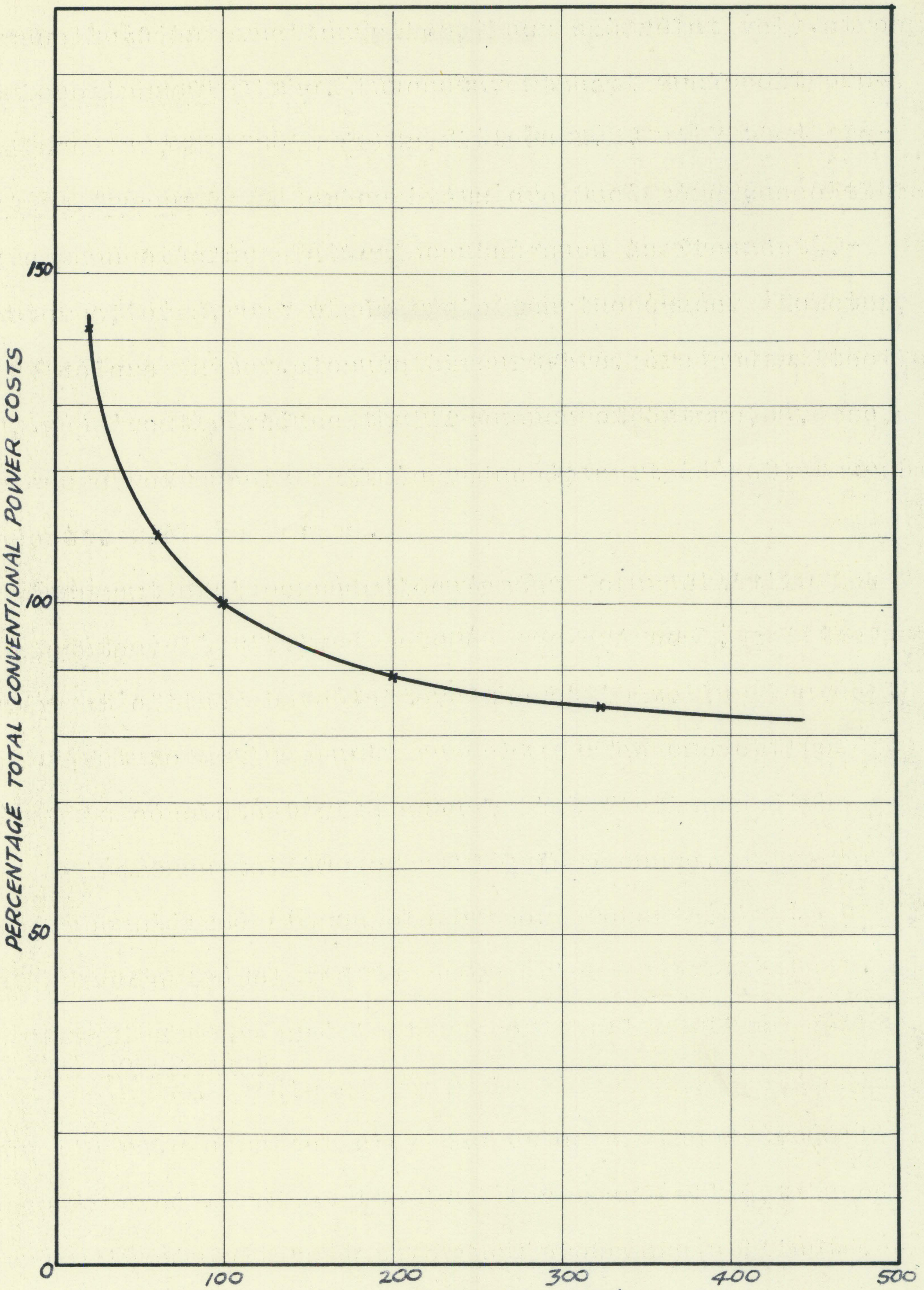

Figure 17. Percentage conventional unit energy costs vs. unit capacity (MW)

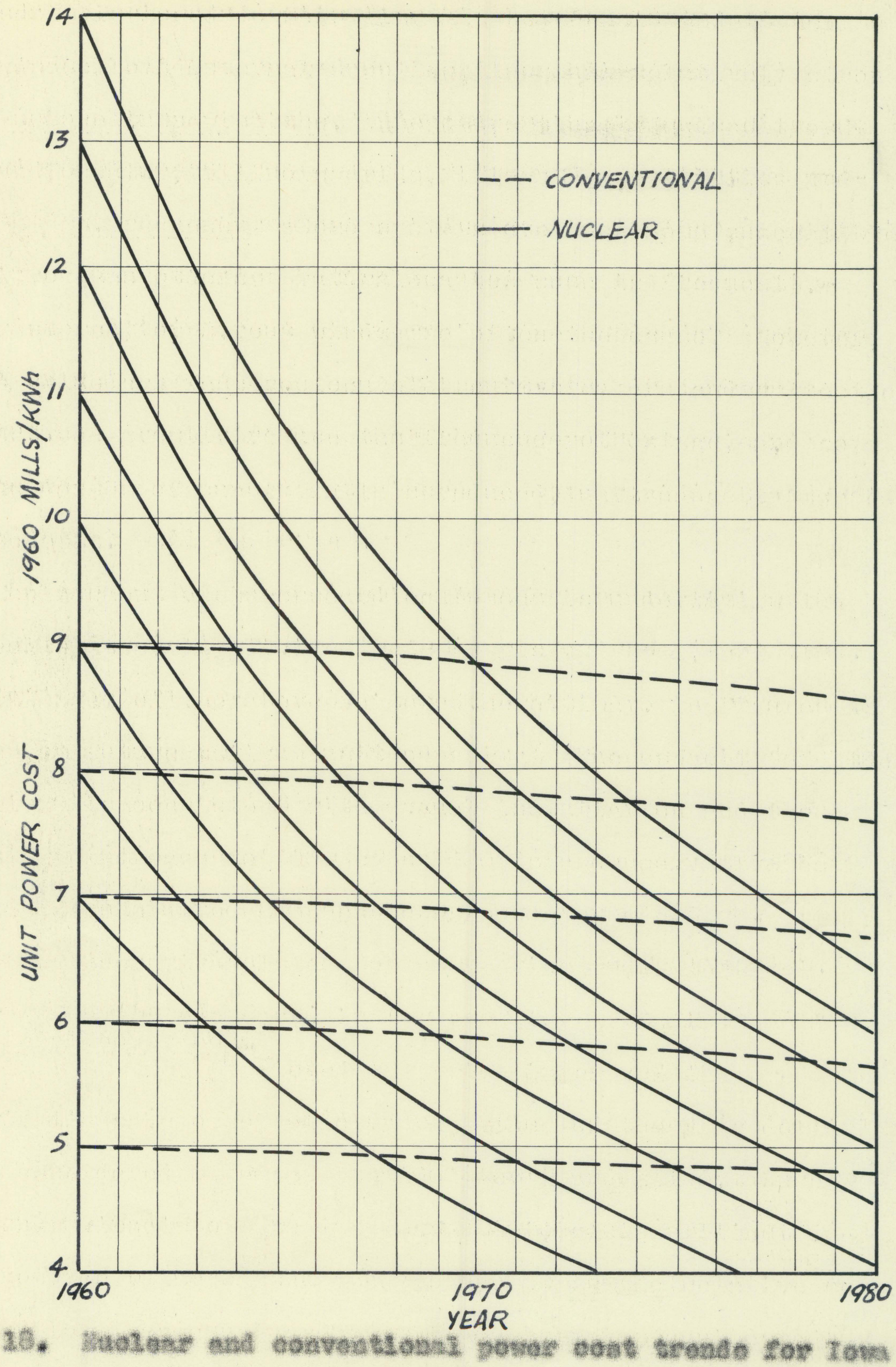

Figure 18. Nuclear and conventional power cost trends for Iowa

be adopted as the system expands. This is in line with the assumption often made in similar studies that conventional energy costs will remain constant (14).

Nuclear Energy Costs

Relative cost patterns

Relative cost patterns for nuclear and conventional plants differ considerably. Currently the capital cost of a nuclear plant is considerably greater than that of an equivalent conventional plant. Another significant difference exists in the cost-size relationship. Nuclear plants presently begin to emerge as economically competitive in the 300 MW range and upwards.

Conventional fuel costs are, and will continue to be, determined by fuel availability, labor cost escalation and advances in mining techniques. Nuclear costs are sensitive to many factors which have little bearing on conventional fuel costs such as reactor core technology, reprocessing costs, fabrication technique improvements, the cost of natural uranium and government pricing practices.

Figure 19 is a hypothetical illustration of nuclear and conventional cost components for the production of one killowatt-hour of electricity (23). It illustrates the important point that at present, competitive nuclear power depends on low fuel costs to overcome the high fixed charges on the nuclear section

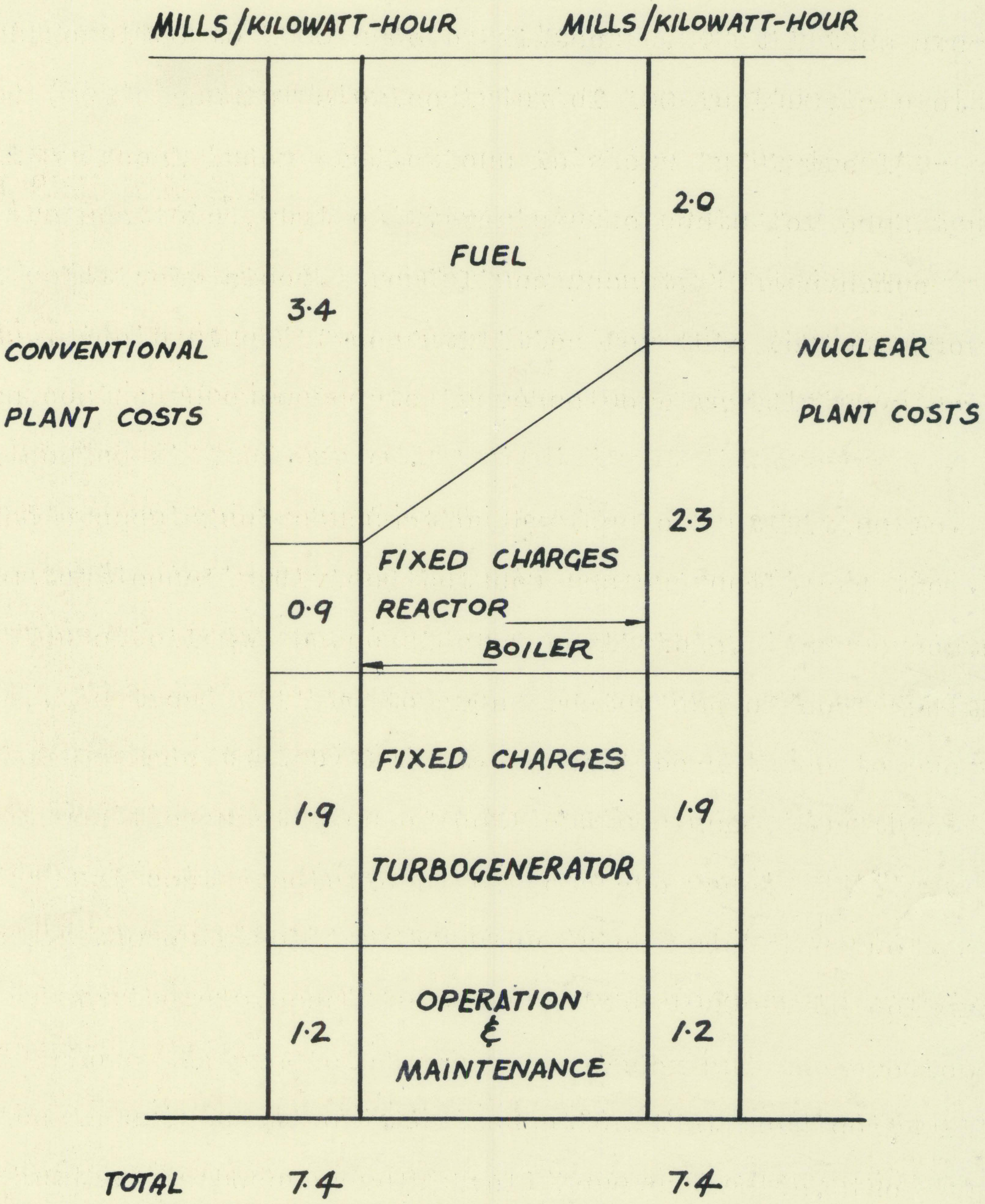

Figure 19. Hypothetical illustration of competitive nuclear and conventional unit power costs

(13).

The learning curve technique

As discussed previously, the prediction of nuclear power costs is a hazardous operation. Most short range estimates have had errors in the range of 50 per cent (20, p. 11-12), and so it is considered that the results of a 20-year study, using similar estimating techniques, would not be significant.

In this study a more statistical approach has been made to the problem by the use of what may be termed a "learning curve." This learning curve technique originated in the aircraft industry during the war (1). It was found that when a new model was put on the assembly lines the cost of the first aircraft produced was high. The second aircraft cost 20 per cent less, and with each subsequent doubling of total production a 20 per cent cost reduction was experienced. This fact was found to be of great value for making relatively accurate cost predictions.

Since the war the learning curve technique has been widely adopted by industry and has proven to be a valuable tool. It has also been found that each industry has a particular reduction factor associated with it. For example, the automobile industry may experience a 15 per cent reduction in cost for each doubling of total model production, while in the washing machine industry the reduction factor may be 10 per cent.

From past experience with application of the learning curve technique it may be stated that:

1. Best results are obtained when the production rate is high, since the technique has a statistical basis.
2. The learning curve technique is of greatest value at commencement of production when doubling of the total number of units produced occurs frequently.
3. The reduction factors for products with similar technologies may be considered the same.
4. The learning curve charts the technological improvements resulting from the application of facts accumulated from, and deductions based on, past experience.

The final point indicates that the learning curve is in effect a plot against time of the ability of the average individual to learn from past experience. It can therefore be concluded that the reduction factor is also dependent on the intelligence of the individuals concerned. Since the results based on the learning curve do not account for such variables as change in cost of raw materials, or other manufacturing restriction, such variables must be corrected for when deriving the reduction factor, and if possible when making future estimates.

Application of the learning curve

It is now postulated that the learning curve technique may be applied to cost estimation in the electric power industry (21). If this is legitimate then existing power cost records, corrected for escalation, should exhibit the characteristics of a learning curve. Figure 20 shows the variation of the electric energy cost index (1960:100) with total installed capacity and a fixed 1960 dollar (25, 26). The period from 1939 to 1946 has been rejected since the natural trend was considerably influenced by conditions existing during the war years. The slope of both trend lines give a 12 per cent cost reduction for each doubling of capacity. This is characteristic of a learning curve where the reduction factor is 12 per cent and the product is in units of installed megawatts. Conventional power costs have in the past followed a learning curve trend and it is most probable that nuclear power costs will follow a similar trend.

The most logical means for long-range nuclear power cost prediction is the learning curve. The reduction factor, established over the years, for conventional power will be used. There is substantial justification for this application.

1. The technologies of the two fields are similar and the improvements projected for nuclear plants are of the same kind as those with which conventional plants have traditionally neutralized a rising cost level and have actually realized the ?

economics shown in Figure 20.

2. There is considerable latitude for refinements in design. For example, at the Pathfinder plant in Sioux Falls the steam pressure is only 555 psia at a time when 6,000 psia and more is envisaged for conventional plants.

3. The equipment is made and designed by essentially the same supplier firms, and as illustrated by the aircraft industry, the reduction factor established during the war still applies to the manufacture of the more advanced present-day aircraft under production (1).

Prediction of total nuclear power capacity

In order to project nuclear power costs the rate of introduction of nuclear power must be determined so that the installed capacity scale may be converted into years.

Figure 21 shows three estimates, from different sources, for total installed nuclear capacity in the United States (6, 28). There is considerable deviation between them, and the more recent estimates are less optimistic. The estimates of Roddis and Davis (1957) and Mayer (1958) follow an exponential pattern and in the opinion of Zebroski lead to absurdities. Zebroski's estimate is based on growth patterns found in the liquid fuel and automobile industries. . . an initial period of closely exponential growth much more rapid than the growth of the gross national product, followed by growth more nearly proportional to that of the gross national product. This seems

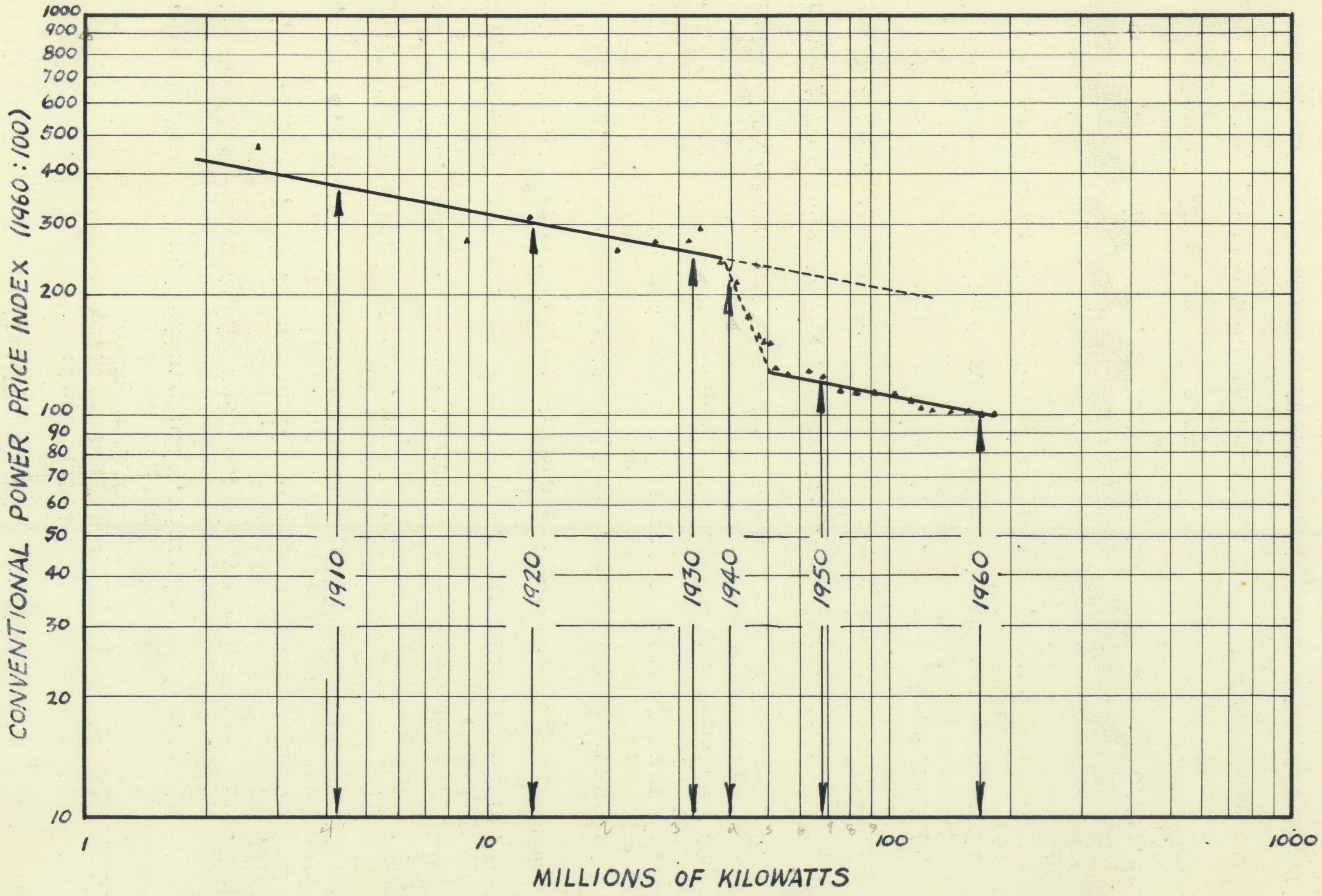

Figure 20. Absolute conventional power price index (1960:100)

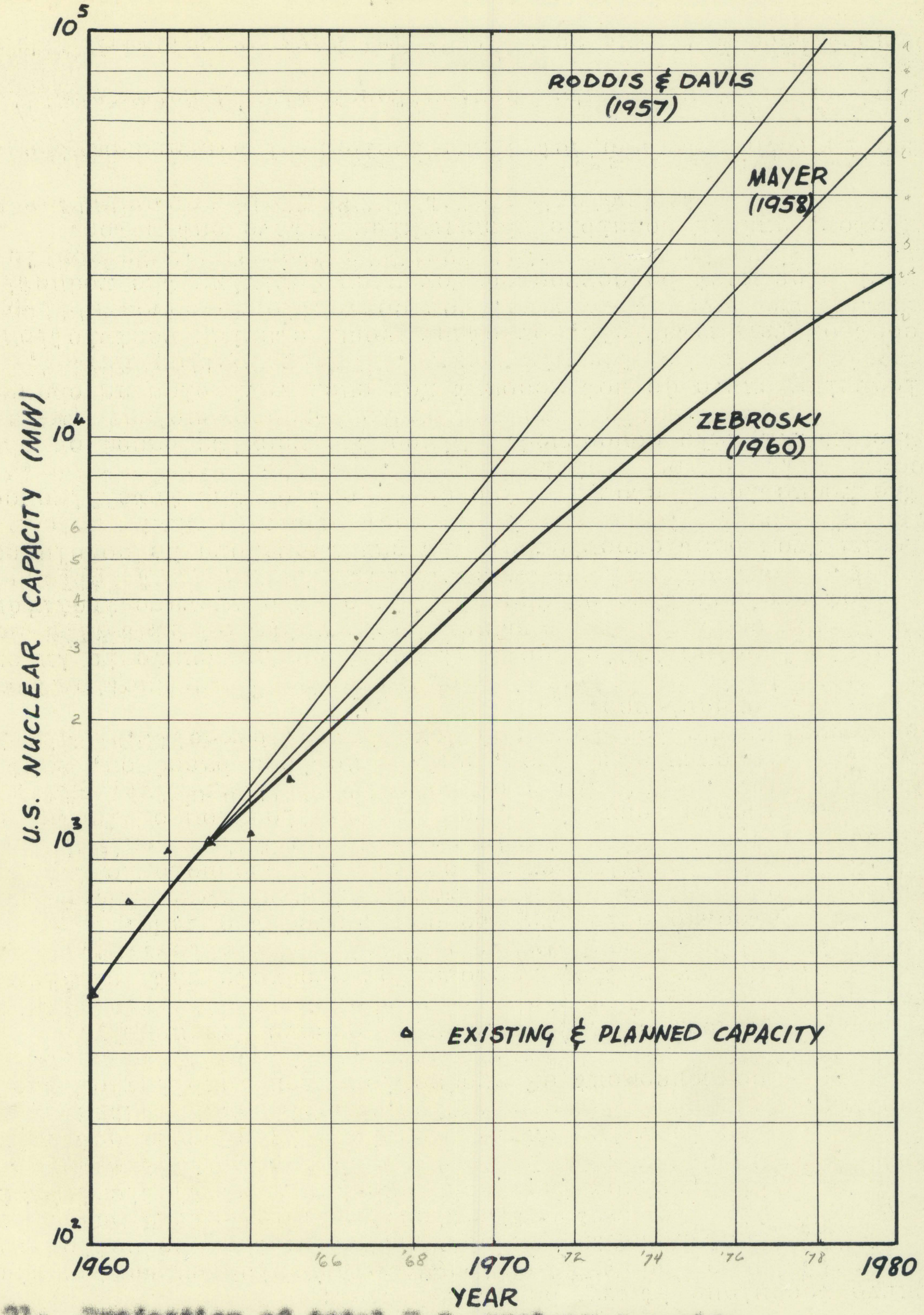

Figure 21. Projection of total U.S. nuclear capacity

the most reasonable estimate and is used in this study.

Power cost grid

Table 4 shows the dates when doubling of total nuclear capacity in the United States is expected to take place. On the basis of a 12 per cent reduction for each doubling in capacity, the curves in Figure 18 are obtained for a range of 1960 nuclear energy costs. Initially the unit energy decreases rapidly in cost and then slowly tends to level out.

The nuclear and conventional curves are presented in the form of a grid so that if the unit energy costs of conventional and nuclear are known at any time in the 20-year period, the data for competitive nuclear power at specified locations in Iowa may be estimated. The procedure may be illustrated by considering a specific example.

"The unit energy cost for a newly constructed 150 MW conventional power plant near Des Moines is found to be 6.0 mills per KWh in 1960. When should a nuclear power plant be competitive in the same region if the manufacturers quote a unit energy cost of 6.93 mills/KWh for a 300 MW unit with a 1965 operating date?"

From Figure 13 the maximum unit capacity in 1965 is estimated to be 180 MW. From Figure 22 the nuclear capacity conversion factor for a 300 MW to a 180 MW transition is 1.15. Therefore, a similar 180 MW plant would have a unit energy cost of 8.02 mills/KWh in 1965. This specifies the nuclear

Table 4. Nuclear power cost prediction for Iowa

Year for doubling of capacity[a]	Total U.S. capacity[a]	Unit capacity in Iowa[b]	12% reduction factor[c]	Cost prediction curves							
				14	13	12	11	10	9	8	7
				Mills/KWh in 1960[d]							
1960	380	150	1.000	14.0	13.0	12.0	11.0	10.0	9.0	8.0	7.0
1962½	760	161	0.880	12.3	11.3	10.6	9.7	8.8	7.9	7.1	6.2
1965	1520	179	0.775	10.8	10.0	9.9	8.5	7.7	7.9	6.2	5.5
1968	3040	198	0.681	9.5	8.8	8.2	7.5	6.8	6.1	5.5	4.8
1971½	6080	270	0.601	8.4	7.7	7.2	6.6	6.0	5.4	4.8	4.3
1975½	12160	256	0.529	7.4	6.8	6.3	5.7	5.3	4.7	4.2	3.7
1980	24320	300	0.456	6.5	6.0	5.5	5.0	4.6	4.2	3.7	3.3

[a] Based on Figure 21.

[b] Based on Figure 13.

[c] 12% Learning Curve based on conventional energy costs in Figure 20.

[d] Nuclear energy costs for Iowa from nuclear plant with unit energy costs in the 14 to 7 mills/KWh range in 1960.

curve in Figure 18.

The conventional unit energy cost of 6.0 mills/KWh in 1960 specifies the conventional curve in Figure 18. The intercept of the two curves gives the date for competitive nuclear power in Des Moines as 1974. At this time the capacity of the plant should be at least 230 MW.

The above example is based on actual estimates. General Electric gives the total unit energy cost of a 300 MW single cycle boiling water reactor of present technology (1965 operating date) as 6.93 mills/KWh (17, p. 6-8).

The conventional fuel cost varies considerably with plant location in Iowa. Higher costs are experienced in regions remote from navigable rivers and coal deposits. As a result, total conventional unit energy costs vary with plant location. The fuel costs reported in February, 1962[a] for various conventional plants in Iowa are given in Table 5. Applying the relationship between unit energy cost and conventional fuel cost, as well as a correction for change in price index, the 1960 unit energy costs for plants at various locations in Iowa are obtained. The variation between 5.58 mills/KWh at Bridgeport to 7.75 mills/KWh at Wisdom is considerable. It is apparent that the most suitable site for the first nuclear power station in Iowa should be in one of

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[a] Luhring, J.E. Iowa Power and Light Co., Des Moines, Iowa. Iowa fuel costs. Private communication. 1962.

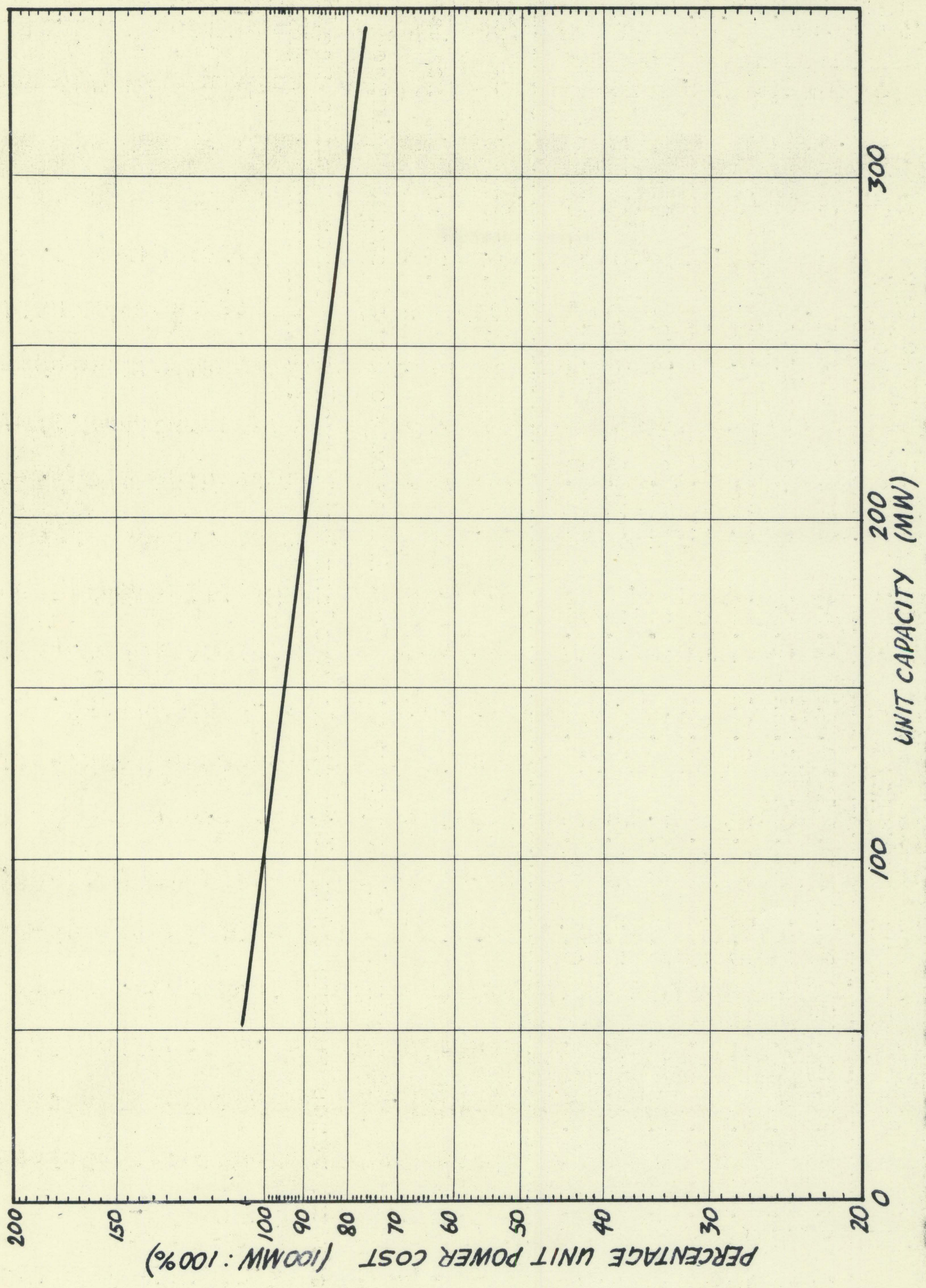

Figure 22. Total nuclear unit power cost vs. unit capacity

Table 5. Conventional fuel and energy costs at various plant locations in Iowa

Location	Fuel cost ¢/mBTU	Unit energy cost[a] ¢/mBTU
Neal	30.0	6.20
Council Bluffs	28.0	6.00
Wisdom	36.0	7.75
Fort Dodge	35.0	7.65
Humboldt	35.0	7.65
Madrid	30.0	6.21
Des Moines	26.0	5.92
Bridgeport	23.0	5.58
Marshalltown	27.5	6.02
Charles City	34.0	6.60
Cedar Rapids	32.0	6.41
Prairie Creek	30.2	6.28
Riverside	26.0	5.92
Davenport	25.0	5.78

[a] Possible unit energy cost from an average capacity 1960 plant.

the high fuel cost areas such as Fort Dodge or Charles City.

Consider the Fort Dodge area. Using General Electric's estimate of 6.93 mills/KWh for a 300 MW unit with a 1965 operating date. The nuclear energy cost curve is again specified by 8.02 mills/KWh in 1965. The conventional curve is specified by a unit energy cost of 7.75 mills/KWh in 1960. The intercept gives 1967 as the date for competitive nuclear power in this region. The plant capacity should be at least 190 MW. Whether or not a plant of this capacity is required in a high fuel cost area should be decided in light of the computer study being made for the Iowa Pool Companies by Westinghouse Electric Corporation.

In summary, nuclear power is likely to be competitive with conventional power in the high fuel cost areas by 1967, assuming that the plant unit capacity is at least as large as estimated in Figure 13. After 1967 nuclear power should become increasingly attractive and by 1974 should be competitive in regions with 1960 fuel costs greater than 26 c/mBTU. By this date also nuclear plants with capacities smaller than estimated should be competitive in the higher conventional fuel cost regions.

The use of a learning curve, developed in industry for predicting future costs of mass produced goods, may be questioned when used in connection with nuclear power cost estimates. However, there is substantial evidence to justify the application in the field of nuclear power. In addition to the three points previously mentioned there is finally the most conclusive argument: So far the costs experienced and predicted by the supplier industry coincide very closely with the initial theoretical predictions. Figure 23 shows a 12 per cent learning curve based on 100 per cent energy cost in 1960. The percentage nuclear power costs for 300 MW boiling water reactors from 1959 to 1967 are based on total energy costs experienced and predicted by General Electric in 1961,[a] and the percentage power costs for 300 MW pressurised water reactors

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[a] Hall, Robert J., General Electric Co., Chicago, Ill. Nuclear energy costs. Private communication. 1962.

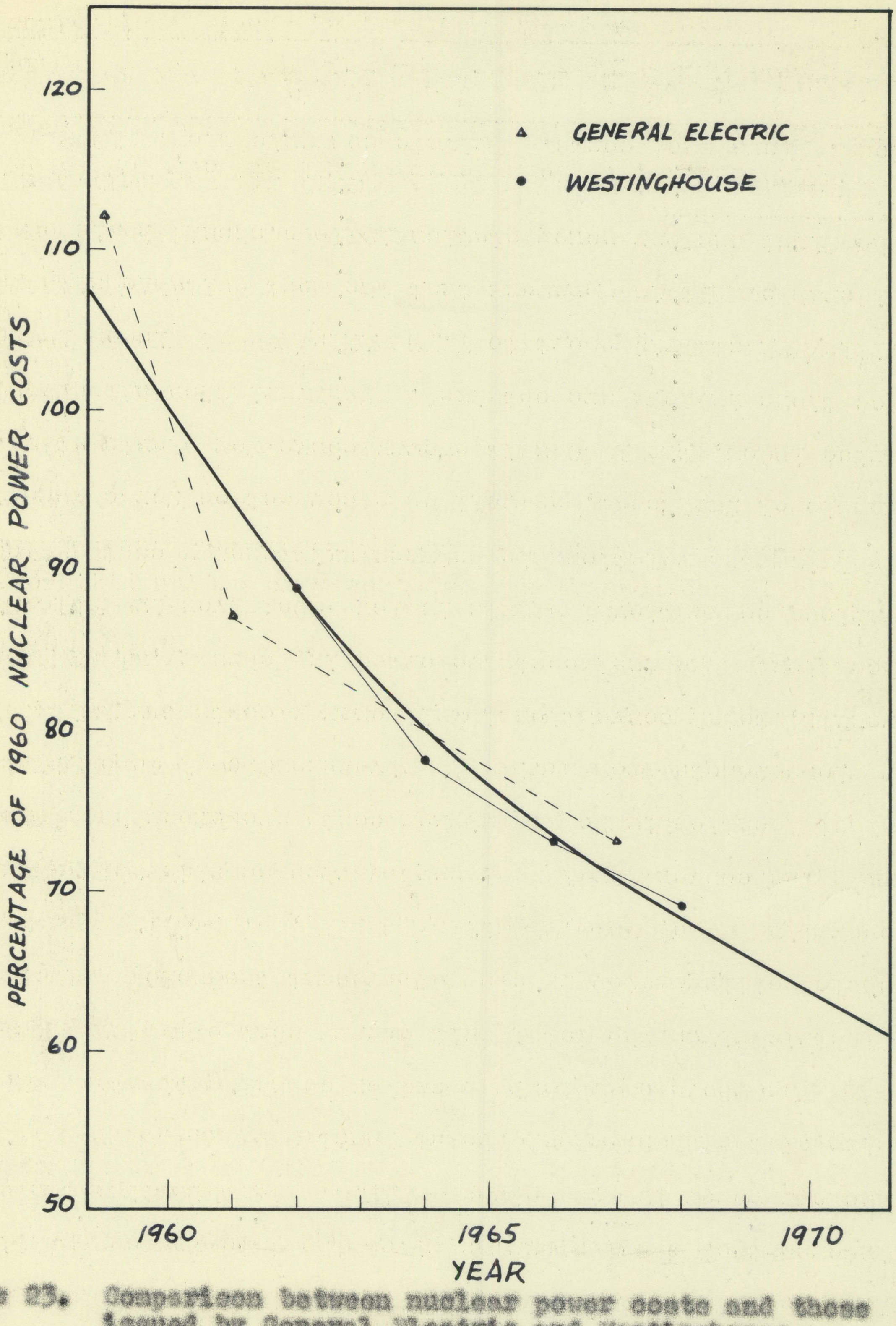

Figure 23. Comparison between nuclear power costs and those issued by General Electric and Westinghouse

from 1962 to 1968 are based on total energy costs quoted by Westinghouse in 1961.[a] The boiling water reactor costs have been normalized to 100 per cent in 1960, and the pressurised water reactor costs to 88.5 per cent in 1962.

The close relationship between the learning curve and experienced and predicted cost reductions in the period from 1959 to 1960 is ample justification for extending the principle to long range cost predictions.

The learning curve technique has a statistical basis and it must be accepted that costs in any given plant will probably differ from those predicted. Using normal estimating methods it is possible to predict with reasonable accuracy costs two or three years ahead by taking into account potential savings from the adoption of improved features under study or test. It is more difficult to predict specific break-throughs and much more difficult to estimate when these will occur. The learning curve technique, however, does not depend on the prediction and significance of specific advancements, but, based on previous experience over a considerable period, charts the predicted average advances in the form of cost reduction. Thus the learning curve appears to be of most value for long range predictions where statistical variations are less significant compared with the errors resulting from

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[a] Beal, Frank S., Westinghouse Electric Co., Pittsburgh, Pa. Nuclear energy costs. Private communication. 1962.

direct estimates of specific advancements or improvements.

The learning curve technique is well suited to this study where it is not expected that nuclear power will be immediately adopted and where no fixed views are held concerning a specified reactor system.

SUMMARY AND CONCLUSION

The second generation of nuclear power plants is currently reaching operable status. These plants incorporate numerous new additions and modifications which have been deemed justifiable by the operating experience gained since 1958. It is now generally agreed that most, if not all, plants previously erected have been over-designed. In most cases this was intentional since design policy is to err on the safe side, a policy enforced by the Atomic Energy Commission.

Public opinion plays an important role in the advancement of nuclear power and it is felt that a completely accident-free record will do much more to forward the public adoption of nuclear power than borderline design which, while reducing power costs by a few mills/KWh, may present a public hazard. The fault may be minor but such a mishap would receive extensive publicity and inevitably cost more in legal actions and potential loss of revenue than that saved by the initial close-cut design. However, most revolutionary innovations, from the steam engine and automobile to electricity, have initially received similar unwarranted vehemence and misguided apprehension. Such fear can most easily be quelled by encouraging the public to understand more about atomic energy and visit the existing nuclear power stations. The close association of nuclear power with nuclear weapons does not encourage good will and the necessary veil of secrecy maintained about the associated branches of the field, such as plutonium production, tends to increase rather than reduce resentment.

It can be expected that initial capital cost estimates will be closer to the actual cost than previously, since the difficulties encountered have been solved or at least recognised. But it can be assumed that costs quoted by manufacturers will certainly not be less than estimated and the addition of 10 or 20 per cent might give a closer estimate of the actual cost.

The presence of private industry in the nuclear power field will have important repercussions in future years. Industry will press for greater control and less restrictions as well as encouraging a free uranium market. Although at present fuel is more or less subsidized, it is not a satisfactory position. The price is completely artificial and the utilities, especially the smaller ones, are unwilling to risk a large 30-year investment in a plant whose economic success depends on the whim of a government agency.

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At present, the rate of industrial growth in Iowa is higher than the national average and in the near future the demand for extra power will be proportionately greater. Therefore, the opportunity will exist for the installation of the relatively large plants suited to nuclear power. Fuel costs in the Fort Dodge and Charles City areas of Iowa are approximately 20 per cent above the average for the state. If the load warrants a sufficiently large station in the area then a nuclear plant should certainly be economic there by 1968.

The analysis of existing nuclear systems lead to the conclusion that the pressurised water and boiling water reactors should form the basis for economic nuclear power production in the next decade. Presently, the cheapest and most reliable nuclear power is provided by the pressurised system, but indications are that the boiling water system will prove itself superior in the next few years. It is highly probable that both water reactors will be superseded by some one of the other systems presently under test or being planned.

Therefore, by the time nuclear power is economic in Iowa the boiling water reactor is likely to be at a high level of perfection and should be the main contender for erection.

The adoption of nuclear power in the United States now appears inevitable and in proffering an answer to the question of when it will be economic in Iowa, it is hoped that planning for the future expansion of the Iowa Power & Light system, and the Iowa Pool system as a whole, has been simplified.

LITERATURE CITED

1. Andress, Frank J. The learning curve as a production tool. Harvard Business Review 32, No. 1: 87-97. 1954.

2. Balent, R. and Bosworth, G. H. Design study of a 300 MW organic cooled reactor. Mechanical Engineering 81, No. 12: 72-77. 1959.

3. Bechtel Corp. and Atomics International. Organic cooled reactor study. U. S. Atomic Energy Commission Report TID-8501. Technical Information Service Extension, AEC . April, 1959.

4. Bost, William E. Economics of nuclear power. U. S. Atomic Energy Commission Report TID-3089. Technical Information Service Extension, AEC . Jan., 1960.

5. Cohen, Karl. Charting a course for nuclear power development. Nucleonics 16, No. 1: 66-70. 1958.

6. Davis, W. K. and Roddis, L. H. Prospects for economic nuclear power. New York, N. Y., National Industrial Conference Board. 1957.

7. Ebasco Services Inc. and General Electric Co. Boiling water reactor study. U. S. Atomic Energy Commission Report TID-8500. Technical Information Service Extension, AEC . March, 1959.

8. The future of fuels. III. Electric World 156, No. 4: 53-56. 1961.

9. Herron, David P. Economics of nuclear power generation. U. S. Atomic Energy Commission Report TID-2559. Technical Information Service Extension, AEC . 1958.

10. Hollands, Sidney L. National programmes in 1961. Nuclear Power 7, No. 69: 56-64. 1962.

11. Iowa's happy marriage of farm and factory. Des Moines Sunday Register, Jan. 7, Section 2: 3, 1962.

12. Kohn, Clyde F. Some spatial characteristics of Iowa's population growth. Iowa Business Digest 31, No. 2: 22-26. 1960.

13. Kuhn, Donald W. and Walton, Ray D. Fuel cycle costs for specific power reactors. U. S. Atomic Energy Commission Report TID-13293. Technical Information Service Extension, AEC . July, 1961.

14. Maloney, J. D. Estimated trend of thermal efficiency and real cost of steam power stations for the next fifty years. U. S. Atomic Energy Commission Report CF-54-3-67. Oak Ridge National Lab., Tenn. March, 1954.

15. Nordquist, Gerald L. A summary of economic and social developments in Iowa. Iowa Business Digest 31, No. 8: 4-9. 1960.

16. People, power, access to markets draw major plants to state. Des Moines Sunday Register, Jan. 7, Section 2: 5. 1962.

17. Richards, R. B. The technical and economic status of central station boiling water reactors. U. S. Atomic Energy Commission Report GER-1793B. General Electric Co., Schenectady, N. Y. 1962.

18. Sargent and Lundy Co. . Nuclear-conventional power plant cost study. U. S. Atomic Energy Commission Report AECU-4140. Technical Information Service Extension, AEC . July, 1959.

19. __________ and Nuclear Development Corp. of America. Heavy water moderated power reactor plant. U. S. Atomic Energy Commission Report TID-8503. Technical Information Service Extension, AEC . April, 1959.

20. Searl, Milton F. and Kuhn, Donald W. Costs of nuclear power. U. S. Atomic Energy Commission Report TID-8531. Technical Information Service Extension, AEC . January, 1961.

21. Ullmann, John E. Economics of nuclear power. Science 127: 739-743. 1958.

22. U. S. Atomic Energy Commission. AEC summary and evaluation of four power reactor design studies. U. S. Atomic Energy Commission Report TID-8504. Technical Information Service Extension, AEC . August, 1959.

23. U. S. Atomic Energy Commission. Atomic energy facts. Washington, D. C., Technical Information Service . 1961.

24. U. S. Census Bureau. 18th Census: 1960. Population, Iowa. 1962.

25. U. S. Census Bureau. Historical statistics of the United States, colonial times to 1957. Washington, D. C., Author. 1960.

26. U. S. Economic Statistics Bureau. Handbook of Basic Economic Statistics 16, No. 1: 118-127. 1962.

27. West, J. M. and Roy, G. M. The future of boiling water reactors. Nucleonics 17, No. 1: 42-48. 1959.

28. Zebroski, E. L. and Ergen, W. K. Breeding--how soon a necessity? Nucleonics 18, No. 2: 60-66. 1960.

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