1963

Economic integration of nuclear power into the Iowa power system

Alfred Franklin Rohach
Iowa State University

ROHACH, Alfred Franklin, 1934–
ECONOMIC INTEGRATION OF NUCLEAR POWER
INTO THE IOWA POWER SYSTEM.

Iowa State University of Science and Technology
Ph.D., 1963
Engineering, general

University Microfilms, Inc., Ann Arbor, Michigan

ECONOMIC INTEGRATION OF NUCLEAR POWER
INTO THE
IOWA POWER SYSTEM

by

Alfred Franklin Rohach

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Nuclear Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1963

TABLE OF CONTENTS

INTRODUCTION

There have been many educated guesses as to when nuclear power will become competitive with conventional power. However it is not enough to simply say that by 1968 nuclear power will be competitive with conventional power in high, fossil-fuel cost areas. It is of little value for a utility to know that a 300 MW nuclear power plant will compete in 1970 with a conventional plant using $35¢/10^6$ BTU fuel if the utility plans on adding a 175 MW unit in 1969. It will be the purpose of this thesis to give a systematic and logical approach to the basic problem of when nuclear power will become competitive with conventional power.

The power costs can be broken down into three main categories: fixed charges, fuel, and operation and maintenance. In order to calculate future power costs, each of the categories were considered to be a function of size and time as well as a number of other parameters. The object of the thesis is to write equations relating cost to the various variables and parameters.

Since this study is primarily concerned with nuclear power, results of other surveys are used to calculate costs of conventional power as a function of size. However the prediction of future conventional costs is carried out in detail, relying primarily upon past cost trends.

The future power requirements are predicted by extrapolating past power data into the future. The power generation statistics are extrapolated as an exponential. Recent past power generation has followed this type of increase very closely. However many experts feel that this rate of increase will not continue into the future. It does not seem to be a bad assumption, however, especially for at least the next ten years.

Probably a better criterion to use in predicting future power requirements is power capacity. The past capacity additions do not follow an exponential increase. Therefore total power capacity was plotted as a function of year on log scales. The total capacity was found to be a linear function of time on this plot for all past unit additions except for the depression and war years. This means capacity will not increase as fast as generation which is reasonable to expect since the system load factor will increase as larger units are added.

From the foregoing extrapolations, it is possible to predict new unit additions for the private utilities of Iowa. These utilities are listed in the Appendix. New unit additions are coordinated both with respect to total Iowa system as well as with respect to each individual company. A prediction of future conventional units then will give a basis for comparison with nuclear power plants.

The nuclear power costs are calculated on a basis of the components within the power plant. Here again costs are calculated with respect to fixed charges, fuel, and operation and maintenance.

Fixed charges are calculated as a percentage of the capital costs. The Uniform System of Accounts as prescribed by the Federal Power Commission was used to break up the capital costs with respect to different parts or areas of the power plant. The structures account was further broken down as to individual buildings. The cost of each building was calculated as a function of size. In the reactor plant equipment account the cost of pressure vessel was calculated as a function of vessel size, shielding as a function of reactor vessel diameter, and heat transfer equipment as a function of heat transfer surface area. In the turbine-generator equipment account a detailed set of equations for costs of turbine-generator units as functions of pressure and temperature was derived. These equations allow one to estimate quickly the cost of turbine-generator units. These equations therefore could be used to find optimuim operating conditions for various types of reactors. Cost equations for other parts of the power plant are average values calculated from various studies.

The nuclear power capital costs are broken into conventional capital costs and nuclear capital costs. The conventional capital costs of the nuclear power plant cover equipment similar to that found in a conventional power plant. Therefore yearly factors applied to each of these should be the same. Nuclear capital costs of the nuclear power plant cover reactor equipment as well as the containment structure. A somewhat different yearly factor should be applied to this account since this equipment will decrease in cost as nuclear plant equipment becomes standardized.

Fuel cycle costs are calculated in detail. However due to the many parameters involved assumptions must be made. But in a more detailed study the equations should make it convenient for one to estimate quickly the fuel cycle costs.

Operation and maintenance costs are calculated as average costs for the individual reactors. The purpose for using this method of finding these costs is to insure that the costs are continuous functions of size. In a detailed study of an individual reactor, numbers and types of employees could be estimated as well as their salaries, etc. The future costs of operation and maintenance should decrease at about the same or at a slightly greater rate than the same costs for a conventional power plant. However for the purpose of this study an equal rate will be assumed.

By equating the equations describing the power costs of conventional plants to those describing nuclear plants a locus of size as a function year can be found. On this locus nuclear power costs would be equal to conventional power costs. Therefore if one knew when and how large a power plant should be built, it would be a matter of simply plotting this as a point on the size-time graph. If the point was below the curve conventional power would be cheaper and above the curve nuclear power would be cheaper.

Most equations in this report (outside of fuel cycle cost equations) are functions of x and y. These values refer to plant size in MW and future year respectively unless otherwise stated.

REVIEW OF LITERATURE

Extensive analyses of literature on nuclear power economics are given in References 28 and 8. There are many predictions of when nuclear power will compete with conventional power (11, 5, 9, 1, 3). However predictions are usually based upon one size plant for a particular year e.g. a 200 MW nuclear power plant will compete in 1966 with a conventional plant using $40¢/10^6$ BTU fuel. A method will be developed in this thesis through which a continuous function of time versus size will indicate when nuclear power will compete.

There are many studies conducted by the AEC in the area of economics of nuclear power for utility systems (18). Many of the studies are based on advanced concepts of current operating reactors. However there are many studies on steam cooled reactors (21, 22). These concepts include combination water-steam cooled reactors or separate reactors, one for boiling the water and the other for superheating the steam.

Periodicals are the best source of current information on operating reactors (27, 6). Nucleonics, Electrical World, Power, and Power Engineering are some of the periodicals that include articles on economics of nuclear power.

The Guide to Nuclear Power Evaluation was particularly helpful in furnishing information to calculate cost equations (13, 14, 15, 16, 17). This guide published by the AEC consists of five volumes. Many of the individual cost equations were developed from graphs or tables in this reference. Reference 19 includes a study of the four types of concepts used in this thesis as well as four other concepts.

The Federal Power Commission reports are useful for a study of present operating plants and systems (23, 25). These reports include cost as well as physical data on all major steam power plants in the United States. The Federal Power Commission also publishes a monthly report on power generation statistics (24). This report includes data on an individual state basis.

ELECTRICAL POWER ANALYSIS

The electrical power industry is growing rapidly. The sales of electricity are doubling almost every decade. Industries are growing. Residential areas are requiring more electricity. Air conditioning loads have increased the summer peaks beyond the winter peaks. The modern home is literally full of electrical appliances. The power industry is meeting the challenge and fossil fuels are supplying the demand. However will the fossil fuels last indefinitely? No, but there are still a sufficient supply, it is estimated, to last well into the next century. However there are other sources of power which may become economically competitive with the fossil fuels. One of these sources is nuclear energy.

Iowa Power Statistics

Power generation statistics

The greatest users of electricity in Iowa are the residential customers who consume about 36% of the electricity generated in the state and industry which consumes about 35%. Commercial sources use 25%, and the other 4% is divided among rural and other customers (23).

The sales of electricity for the six major power companies in Iowa are plotted on a semi-log scale in Figure 1. The total steam generation in 1961 by these companies was 6.88 (10^9) KWH from a steam capacity of 1.70 (10^6) KW (23). The state average

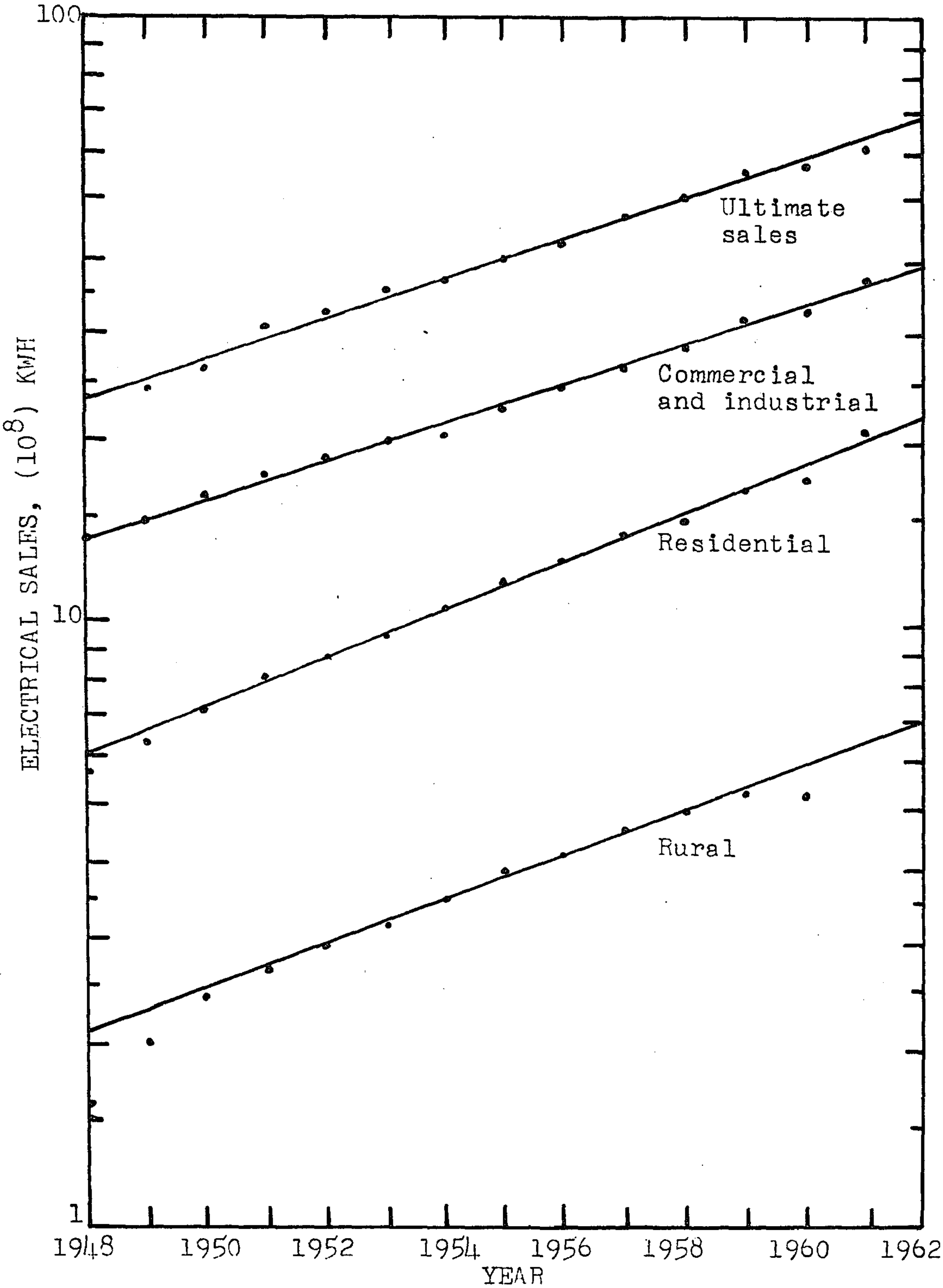

Figure 1. Sales of electrical energy in Iowa

load factor for steam was 46.1%. There are some diesel as well as water driven electrical generators in Iowa which raise the total generation only slightly.

The fuel used by the steam plants in Iowa is about equally divided between coal and gas. Coal is the main fuel in the winter when gas is used for heating, and gas is used mainly in the summer months. The average heating value of coal burned in Iowa power plants is 10,440 BTU/lb and for gas the heating value is 1,030 BTU/ft^3 (25).

Since gas is not available in winter, conventional power plants rely on coal fired units. Therefore future studies are based on coal fired units. Presently the coal-gas fired combination furnaces are very popular and it would seem that these types of units will continue to be popular. However all-coal units should gradually become dominant as gas prices become greater than coal costs.

Power plant cost analysis

Average data for 13 of the most efficient power plants of the private utilities in Iowa are listed in Table 1. The fuel costs for these plants are shown in Figure 2 and the capital costs are shown in Figure 3.

Table 1. Average data for 13 most efficient Iowa steam plants

Average size	104.8 MW
Average generation	467.9 (10^6) KWH
Average number of units	4
Average plant factor	51%
Average capital costs:	
Land and land rights	0.6 $/KW
Structures and improvements	29.1
Equipment	125.0
Total	154.7
Average number of employees per MW	0.55
Average production expenses:	
Operation labor	0.53 mills/KWH
Supplies and expense	0.10
Maintenance	0.31
Fuel	3.28
Total	4.22
Average fixed charges at 13.55%	4.38
Average total generation cost	8.60 mills/KWH

Future Power Predictions

Predictions of future requirements

The electrical power sales for Iowa are plotted on a semi-log plot in Figure 1. The data for the 13 years plotted

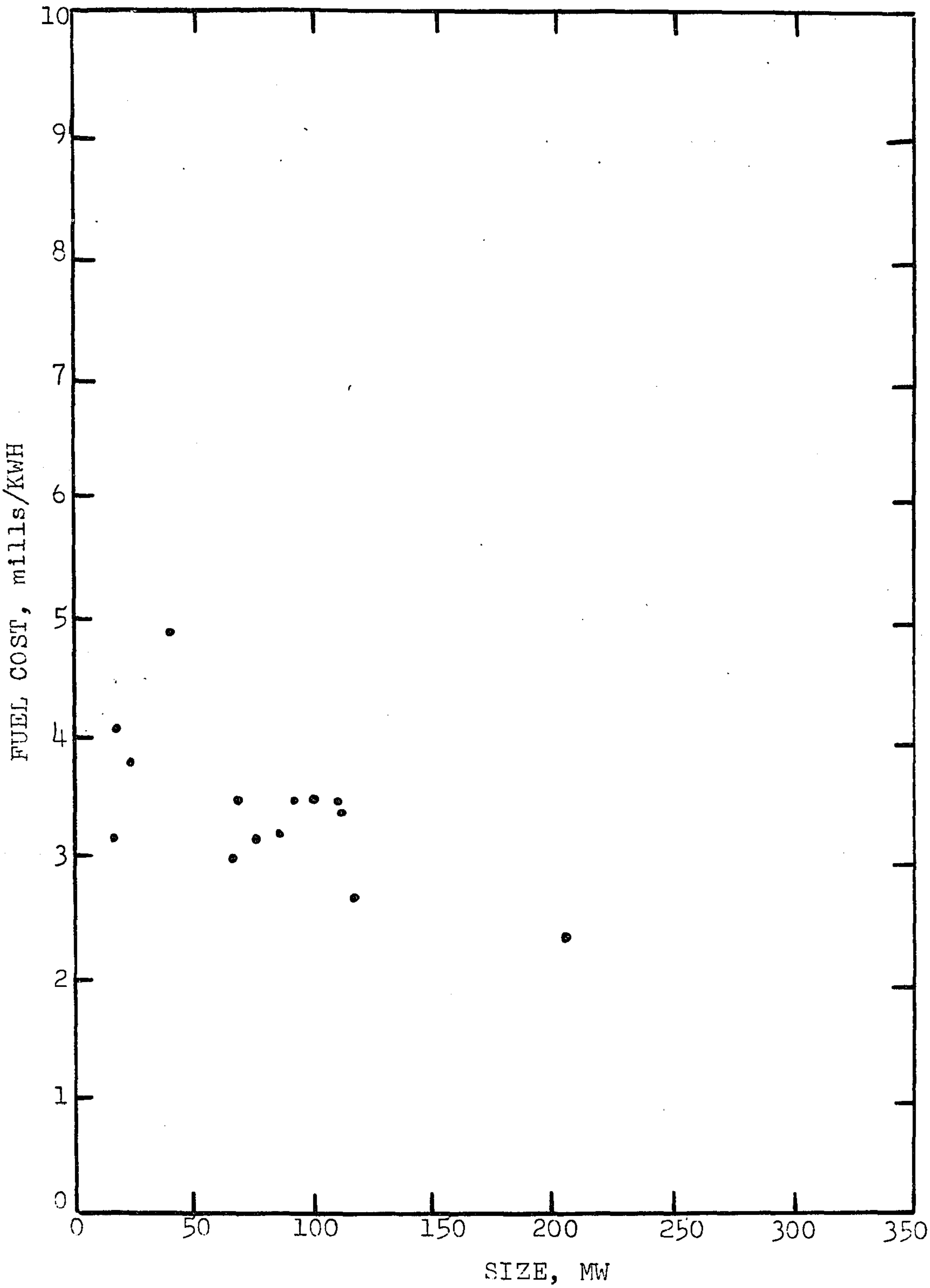

Figure 2. Fuel costs of various steam plants in Iowa (25)

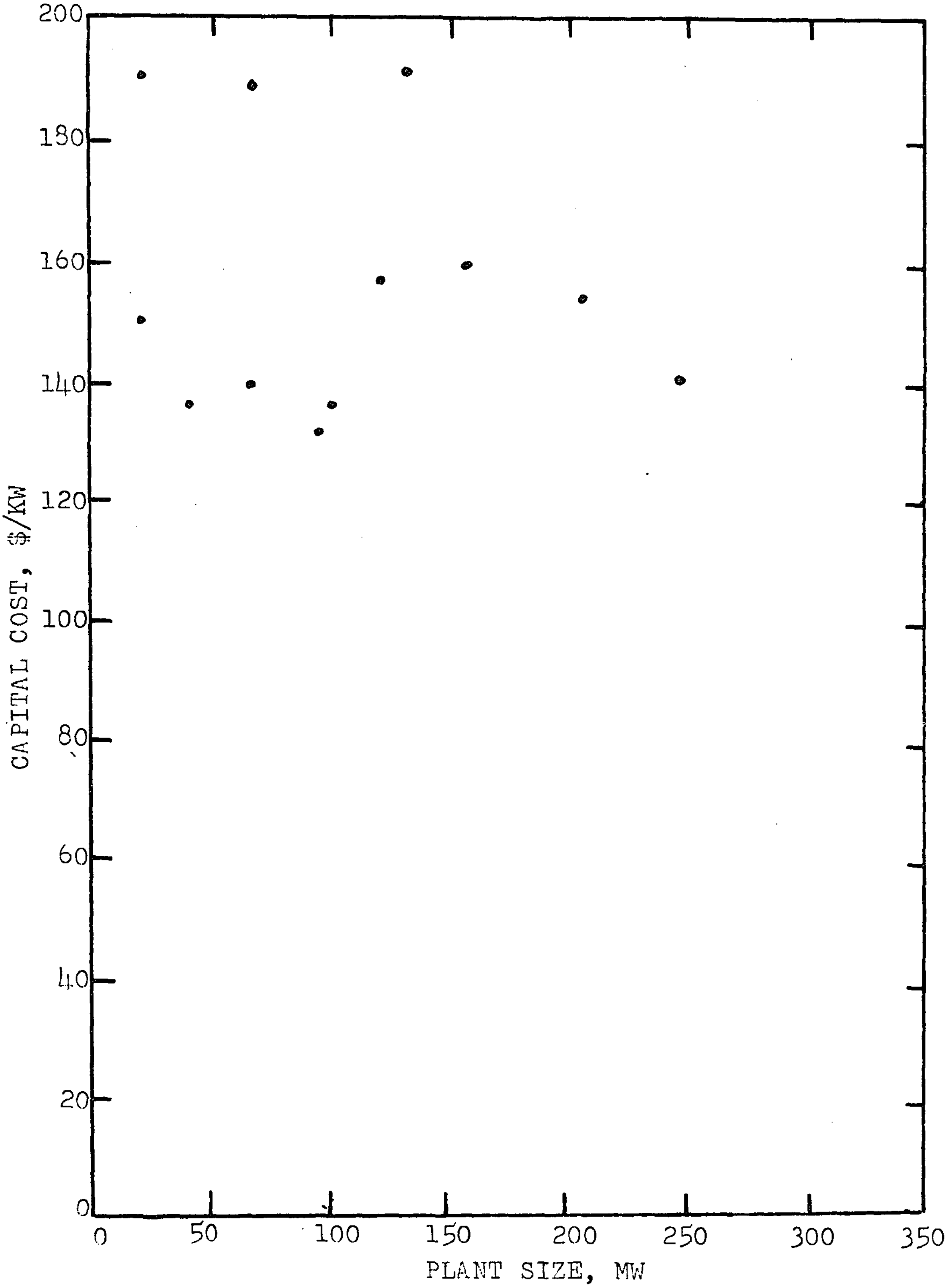

Figure 3. Capital costs of various Iowa steam plants (25)

followed an exponential very closely. The total ultimate sales along with electrical generation are plotted in Figure 4. The generation is somewhat higher due to power losses in transmission. Both of these curves are then extrapolated into the future. There are some power experts that feel the growth will not continue at this rate. However barring unforeseen calamities such as wars or depression the indication seems that the growth will continue at this rate at least for the immediate future.

The equations for the two curves are

$$G \text{ (generation)} = 6.424\ (10^7)\ e^{0.077413y}\ \text{KWH} \qquad (1)$$

$$S \text{ (sales)} = 5.95\ (10^7)\ e^{0.076753y}\ \text{KWH} \qquad (2)$$

where y = year (50 represents 1950, etc.)

The growth rates per year then are

$$G_y = \frac{dG}{dy} = 4.973\ (10^6)\ e^{0.077413y}\ \text{KWH/yr} \qquad (3)$$

$$S_y = \frac{dS}{dy} = 4.567\ (10^6)\ e^{0.076753y}\ \text{KWH/yr} \qquad (4)$$

therefore the growth rates are

$$\frac{Gy}{G}\ (100) = 7.75\%\ /\text{yr} \qquad (5)$$

$$\frac{Sy}{S}\ (100) = 7.67\%\ /\text{yr} \qquad (6)$$

While power generation seems to increase as an exponential, the power capacity seems to increase as a function of time to a power. An investigation has been made of the addition of all the steam generating units of the private utilities. The results of this investigation are plotted in Figure 5 on a log plot. The increase is almost linear on this plot for all years

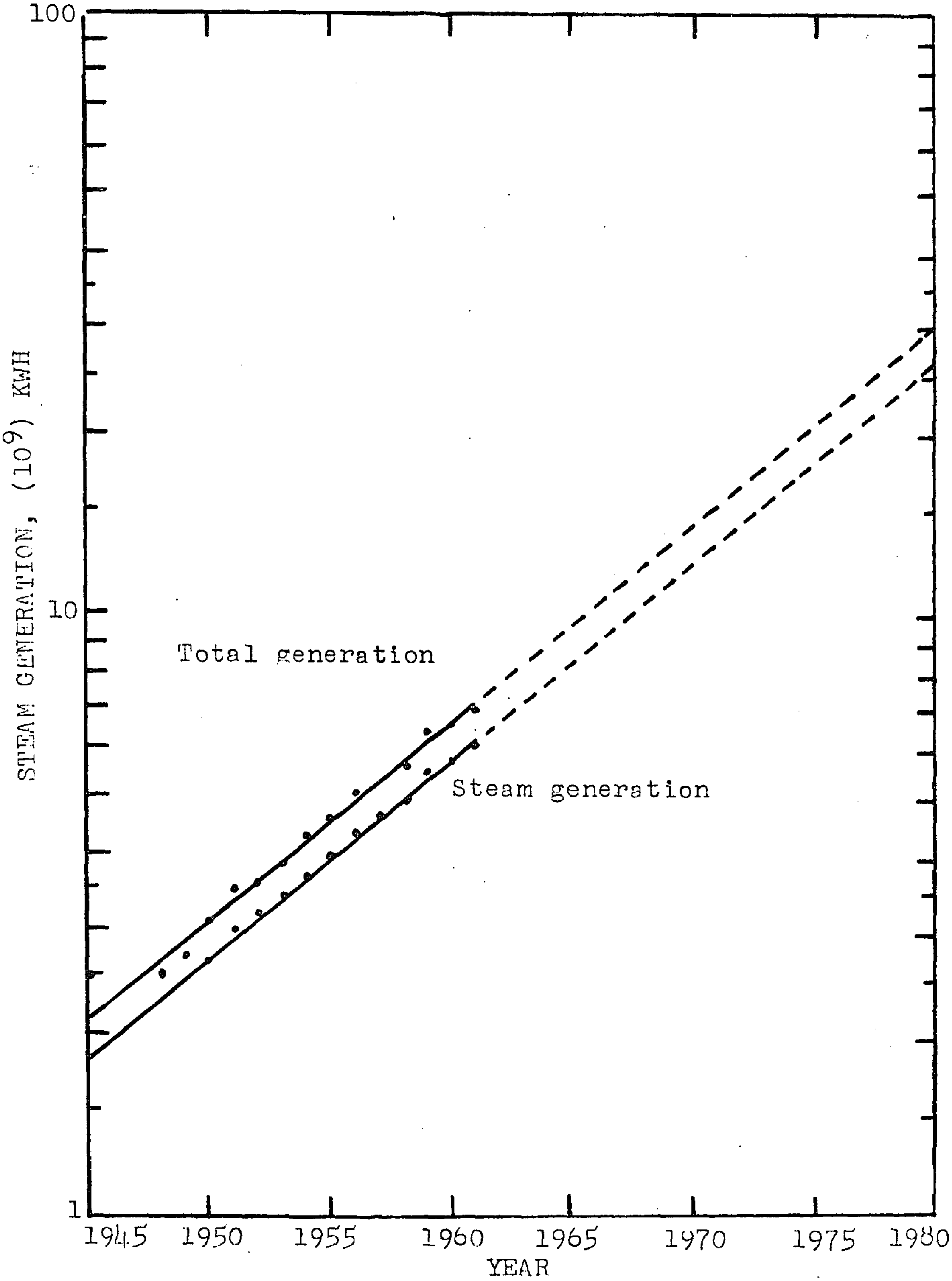

Figure 4. Steam generation by Iowa utilities (23)

except the depression and war years. However the data for the years 1945 to 1961 fell almost along a straight line which in turn was extrapolated into the future. Figure 6 shows results for major steam plants and total capacity of the major private utilities as well as results of a survey conducted by the Iowa Power System. This survey includes the five companies of the system plus Cornbelt Power Company, an REA Company.

The equations of these curves are

$$T \text{ (total capacity)} = 1.29\ (10^{-4})\ y^{4.00}\ \text{MW} \qquad (7)$$

$$S \text{ (steam plants)} = 3.89\ (10^{-6})\ y^{4.83}\ \text{MW} \qquad (8)$$

$$I \text{ (Iowa Power Pool)} = 9.60\ (10^{-6})\ y^{4.59}\ \text{MW} \qquad (9)$$

The increases per year are

$$T_y = \frac{dT}{dy} = 5.16\ (10^{-4})\ y^{3.00}\ \text{MW/yr} \qquad (10)$$

$$S_y = \frac{dS}{dy} = 1.88\ (10^{-5})\ y^{3.83}\ \text{MW/yr} \qquad (11)$$

$$I_y = \frac{dI}{dy} = 4.4\ (10^{-5})\ y^{3.59}\ \text{MW/yr} \qquad (12)$$

The rates of increase per year are

$$\frac{T}{T_y}\ (100) = \frac{400}{y}\ \%/\text{yr} \qquad (13)$$

$$\frac{S}{S_y}\ (100) = \frac{483}{y}\ \%/\text{yr} \qquad (14)$$

$$\frac{I}{I_y}\ (100) = \frac{458}{y}\ \%/\text{yr} \qquad (15)$$

Therefore the per cent increase of capacity added per year decreases with time from about 7% in 1960 to about 5% in 1980. The rate of increase is somewhat smaller than the rate of increase of generation. The difference lies in the fact that as larger units are added the average load factor should increase.

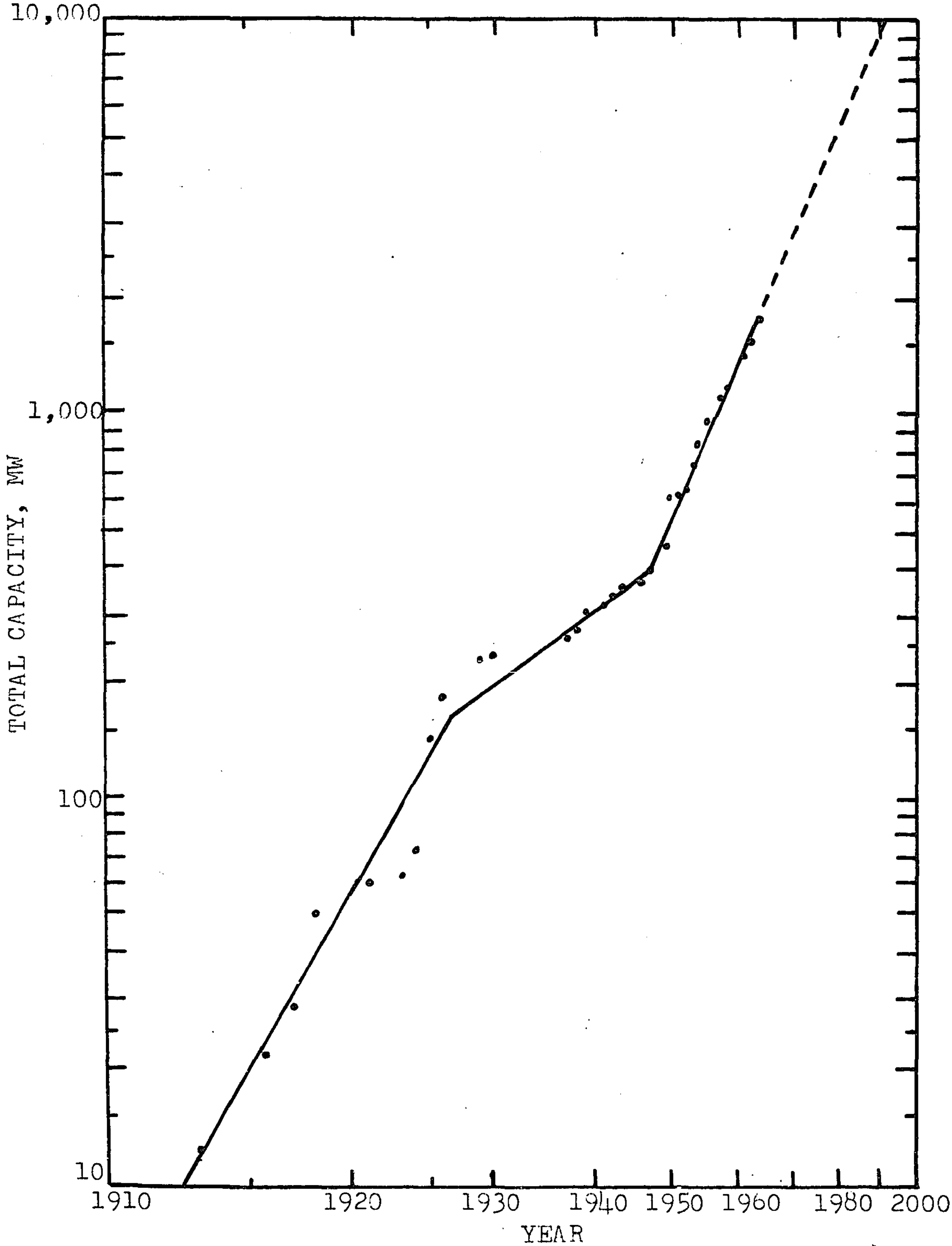

Figure 5. Total steam capacity of private utilities of Iowa

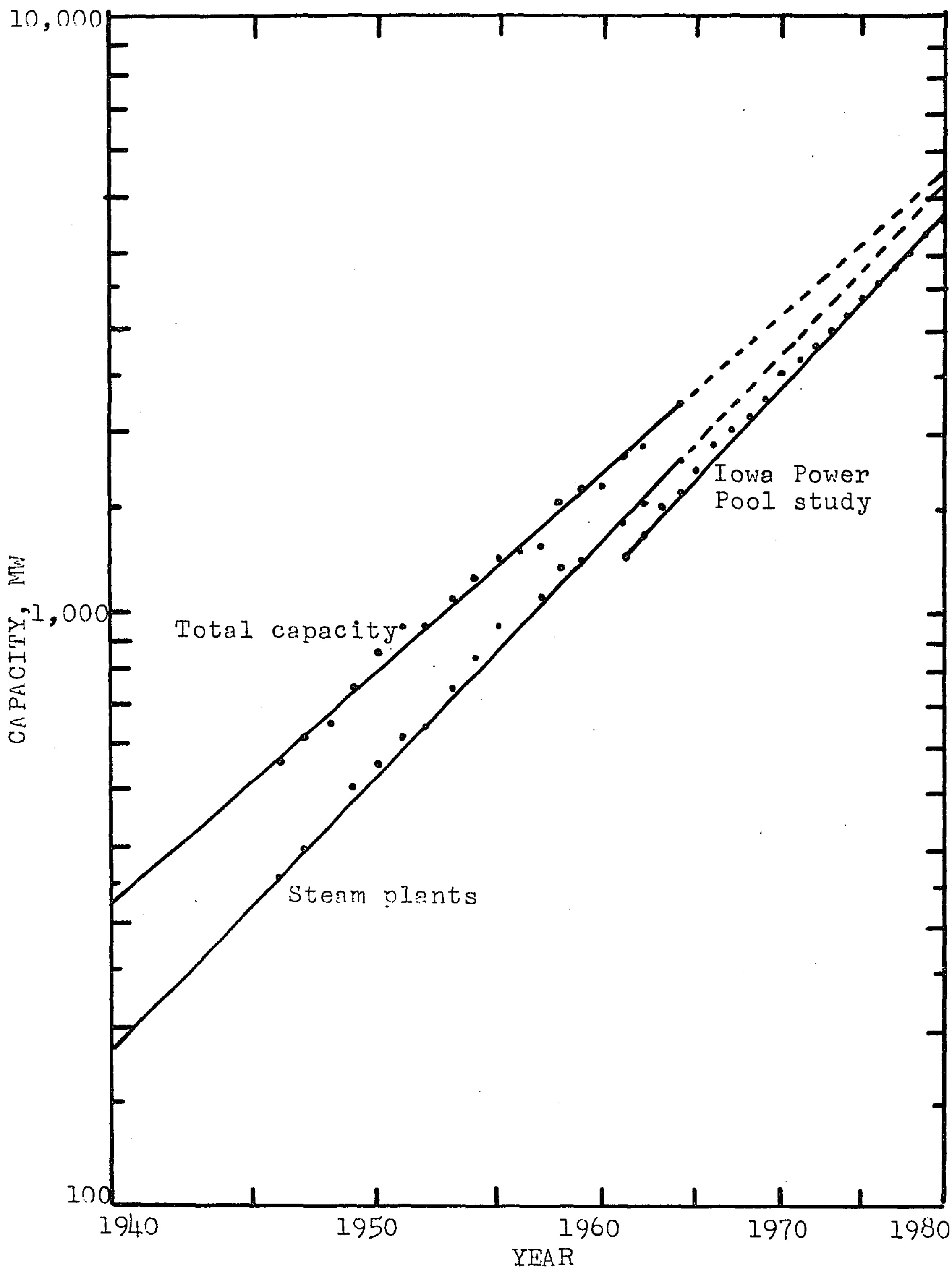

Figure 6. Power plant capacity for power plants of Iowa (25)

Applications of predictions

Once the future capacity requirements can be estimated, the addition of future units can also be estimated. These units should be added to keep the maximum reserve to around 15%. Figure 7 shows the expected future capacity needs and the addition of future units. Each unit added was also coordinated within each individual power company. Table 20 lists the estimated sizes of individual units to be added to the power system and the location of these units. The addition of these units was also coordinated to agree somewhat with plans of powercasting by the Power Development Section of the Iowa Power Pool.

There is also the question of how large a unit a power company can add without jeopardizing its service due to the possible outage of this unit. Figure 8 indicates the ranges in size in which a power company can add a unit without jeopardizing service. The dots are indications of present units or future units to be added for individual Iowa companies. However due to interconnection among the companies it is reasonable to assume that all the private utilities in Iowa can act as one system. Data for all the utilities acting as one system are indicated by cross marks. These are units predicted for future additions. Therefore it can be seen from Figure 8 that the units estimated for the future are well within or below the ranges given in the BWR study (10).

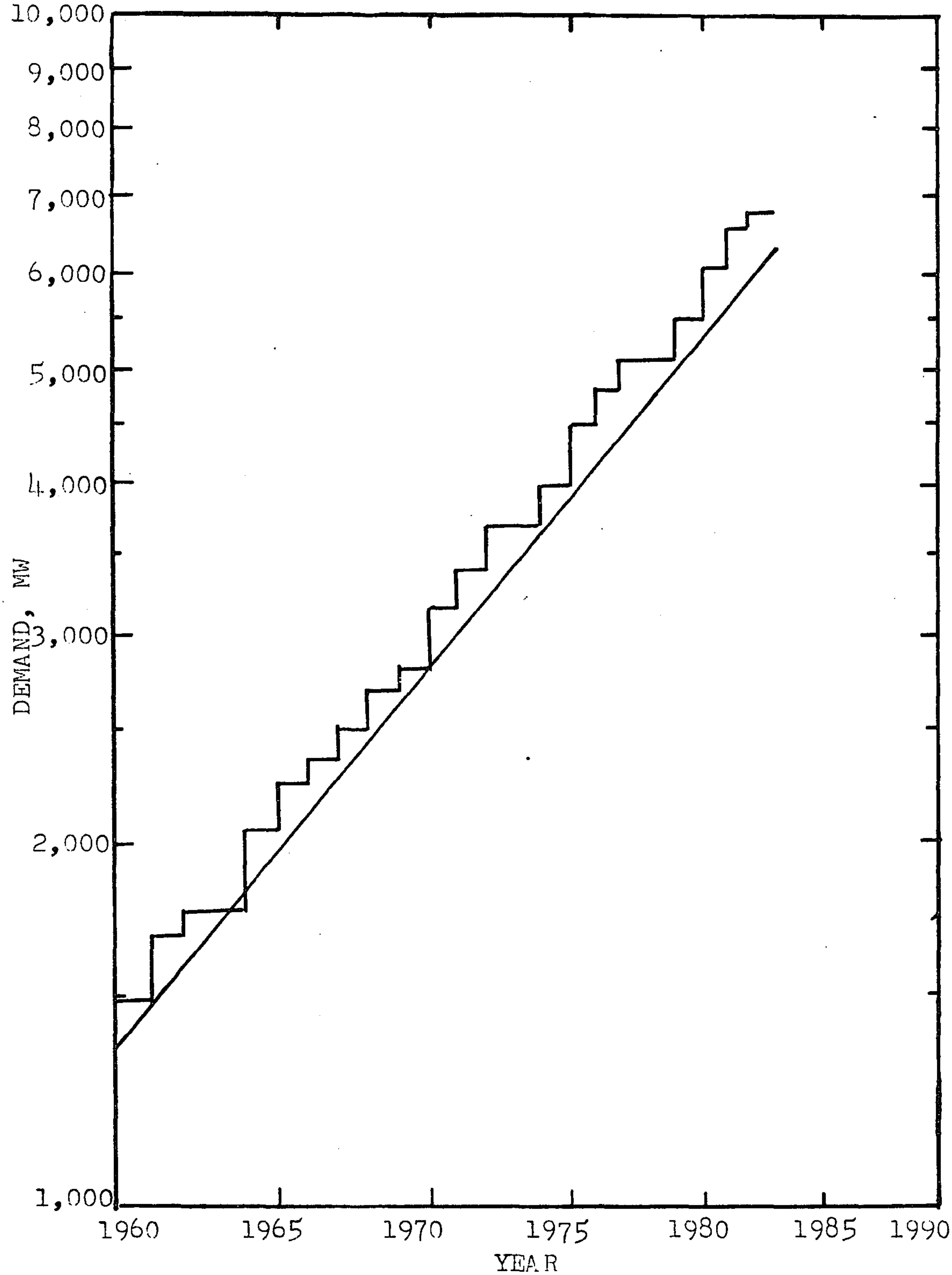

Figure 7. New plant additions for Iowa

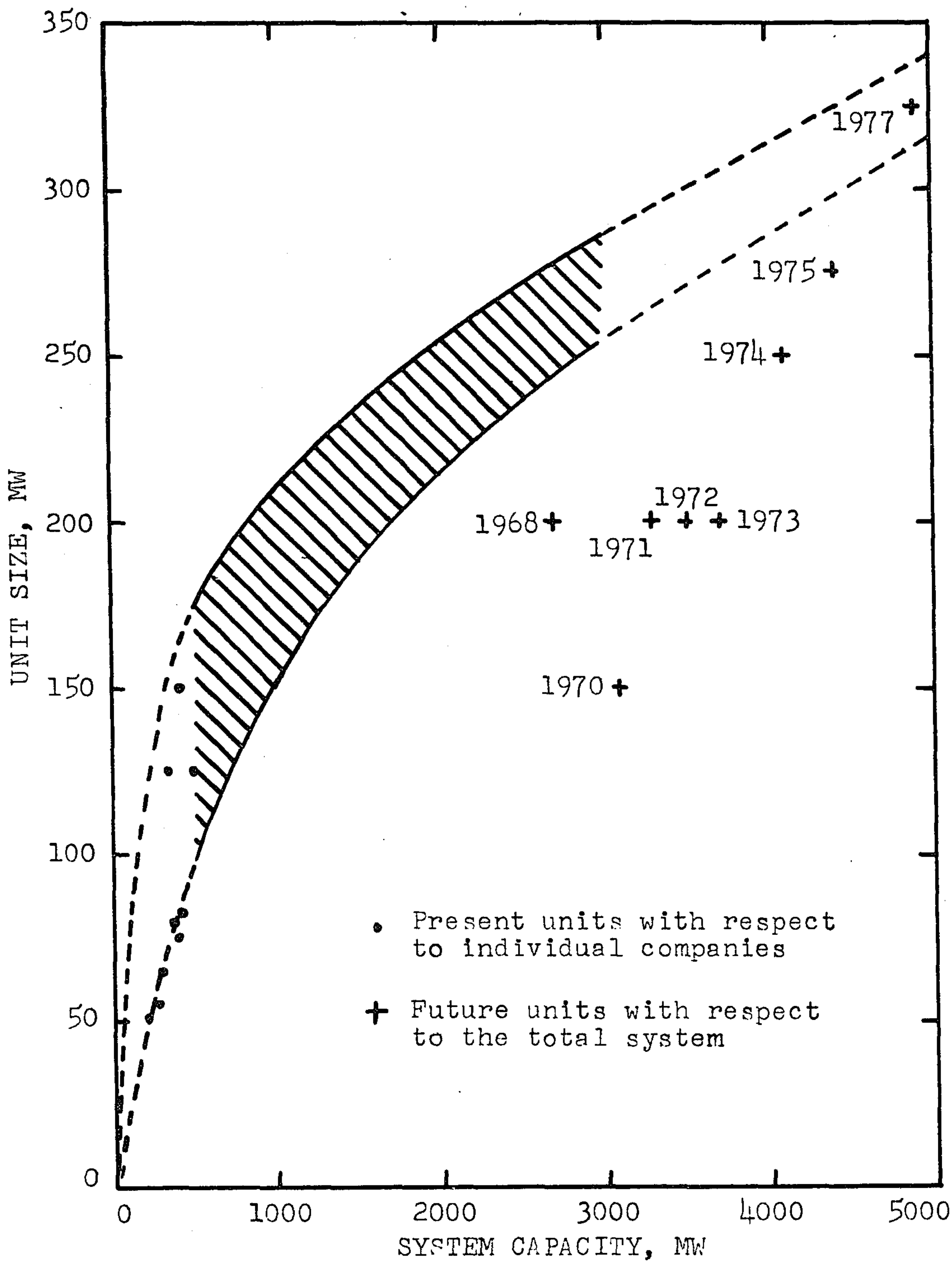

Figure 8. Allowable unit additions as a function of system capacity (10)

CONVENTIONAL POWER PLANT COST ANALYSIS

Fixed Charges

Fixed charges are based on a percentage of capital costs. Capital costs for first, second, and third units are given in Figure 9. Equations representing these costs can be written as

$$C_o = A_1 x + B_1 + \frac{C_1}{x} \quad \$/KW \qquad (16)$$

where x = size of plant in MW

A second order polynomial is used in the derivation of total cost. Therefore the cost per KW is of the form of two linear terms plus a reciprocal x term. The coefficients for the three specific curves in Figure 9 are given in Table 3.

Table 2. Coefficients for Equation 16

Unit	A_1	B_1	C_1
First	$-99.3\ (10^{-3})$	167.3	1467
Second	$-59.8\ (10^{-3})$	138.7	967
Third	$-69.6\ (10^{-3})$	147.0	1044
		$75\ MW \leq x \leq 400\ MW$	

To put the cost C_o ($/KW) on a mills per KWH basis one has

$$FC \text{ (fixed charge)} = \frac{10^3 R}{8750 L}\left(Ax + B + \frac{C}{x}\right) \text{ mills/KWH} \qquad (17)$$

where

R = fixed charge rate

L = load factor

8750 = hours per year

These are the fixed charges for the basis year of 1962. In order

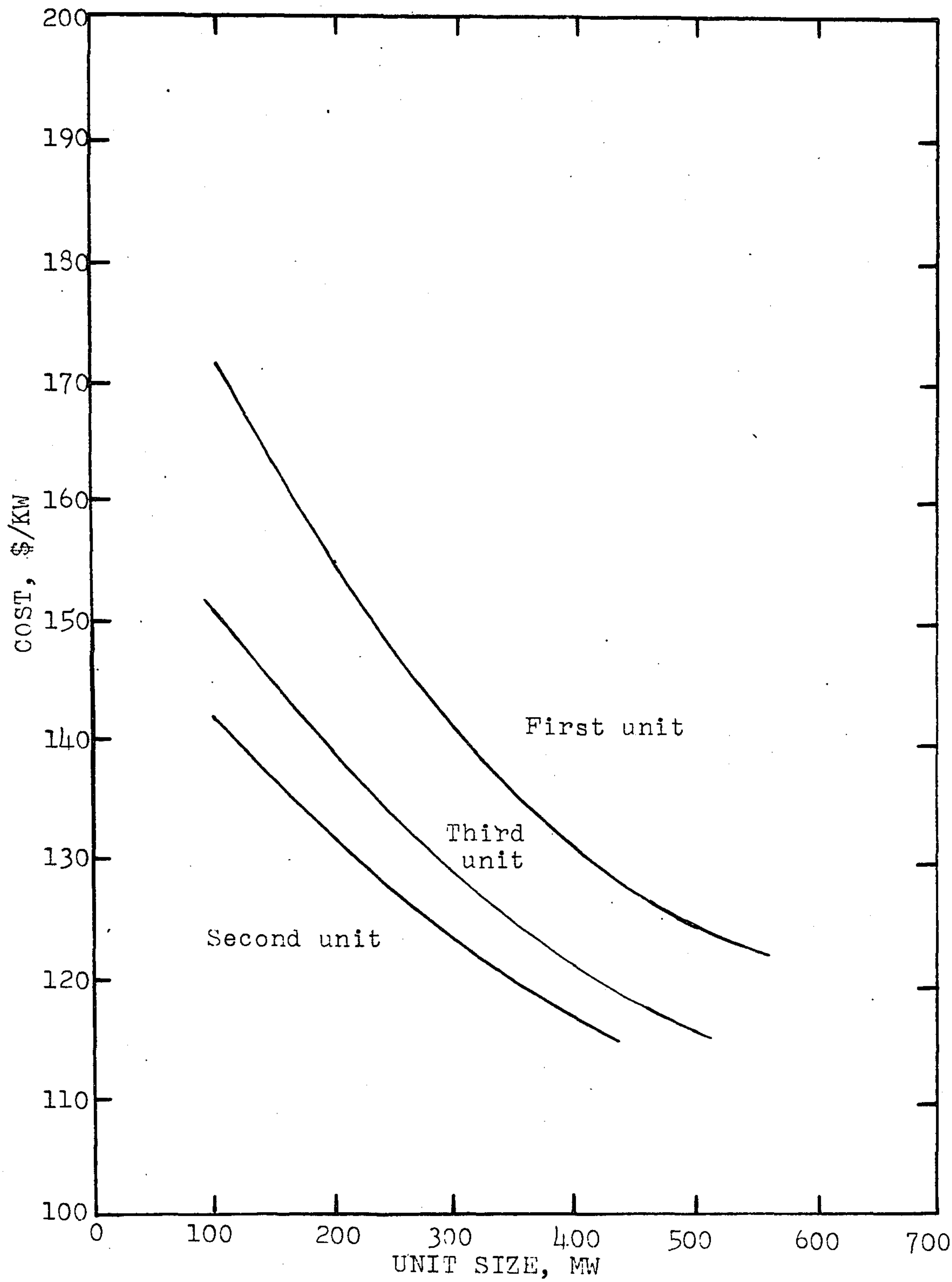

Figure 9. Iowa Pool Study cost per KW of new capacity

to calculate fixed charges for future years, Equation 17 must be multiplied by a factor which is a function of time.

Figure 10 shows the average capital costs of all the power plants of the major private utilities of Iowa. The plot is made as a linear plot. The equation of this curve is

$$Y = 0.4234 + 0.0093y \text{ (normalized to 1962)}$$

Therefore the fixed charges as a function of power plant size and future year are

$$F = \frac{0.1141R}{L}\left(A_1x + B_1 + \frac{C_1}{x}\right)(0.4234 + 0.0093y) \tag{18}$$

Production Costs

The production costs are the expenses of daily plant operation. These costs can be further sub-divided into fuel costs and operation and maintenance costs.

Fuel costs

In calculating fuel costs heat rates are of prime importance. Figure 11 shows heat rate as a function of unit size. The equation of the curve is

$$HR = A_3x + B_3 + \frac{C_3}{x} \tag{19}$$

Table 3. Coefficients of Equation 19

Unit	A_3	B_3	C_3
River	-1.444	9,550.2	49,000
Non-river	-1.300	9,803.0	46,667

$50MW \leq x \leq 450MW$

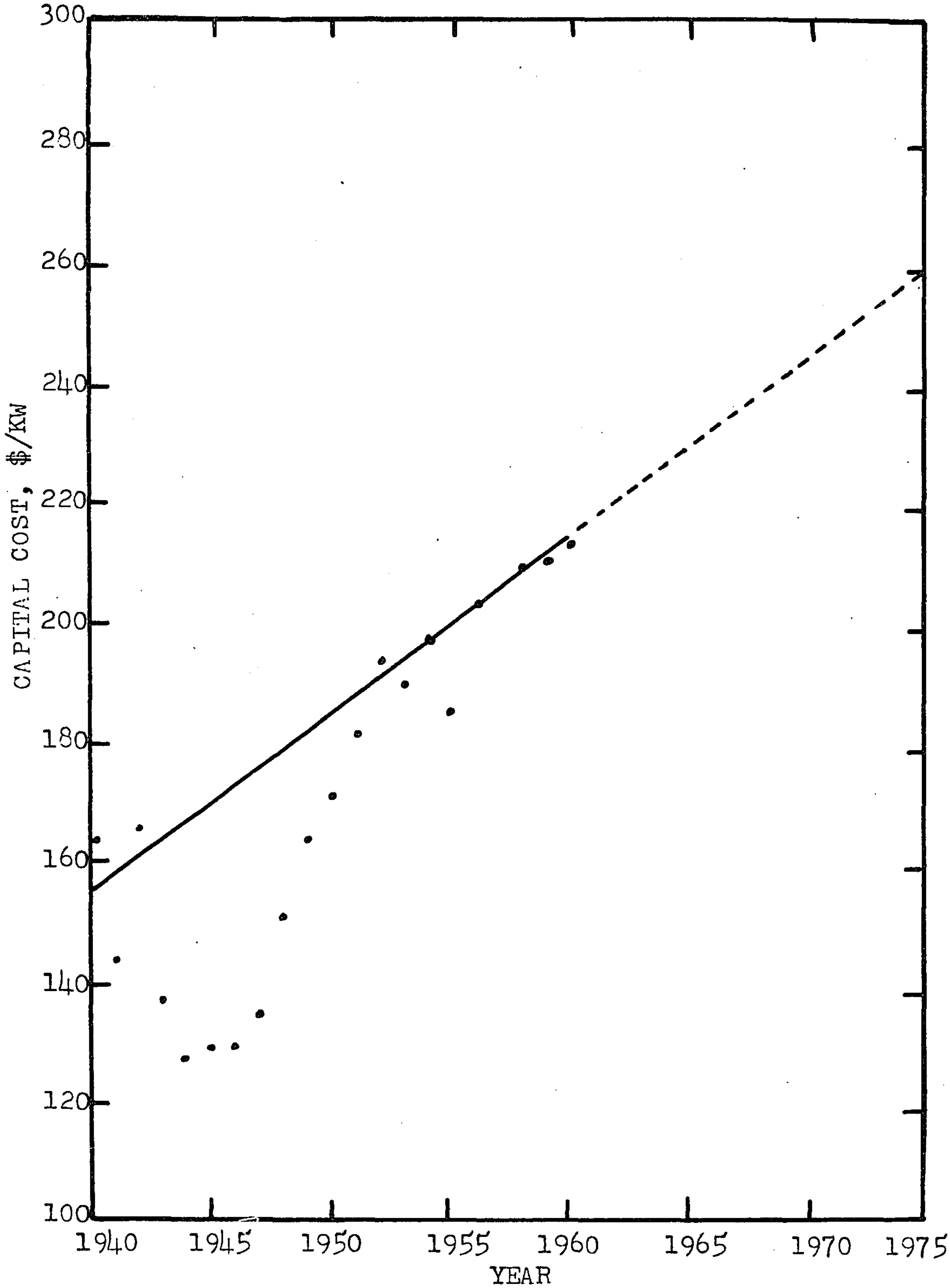

Figure 10. Average capital costs of Iowa power plants

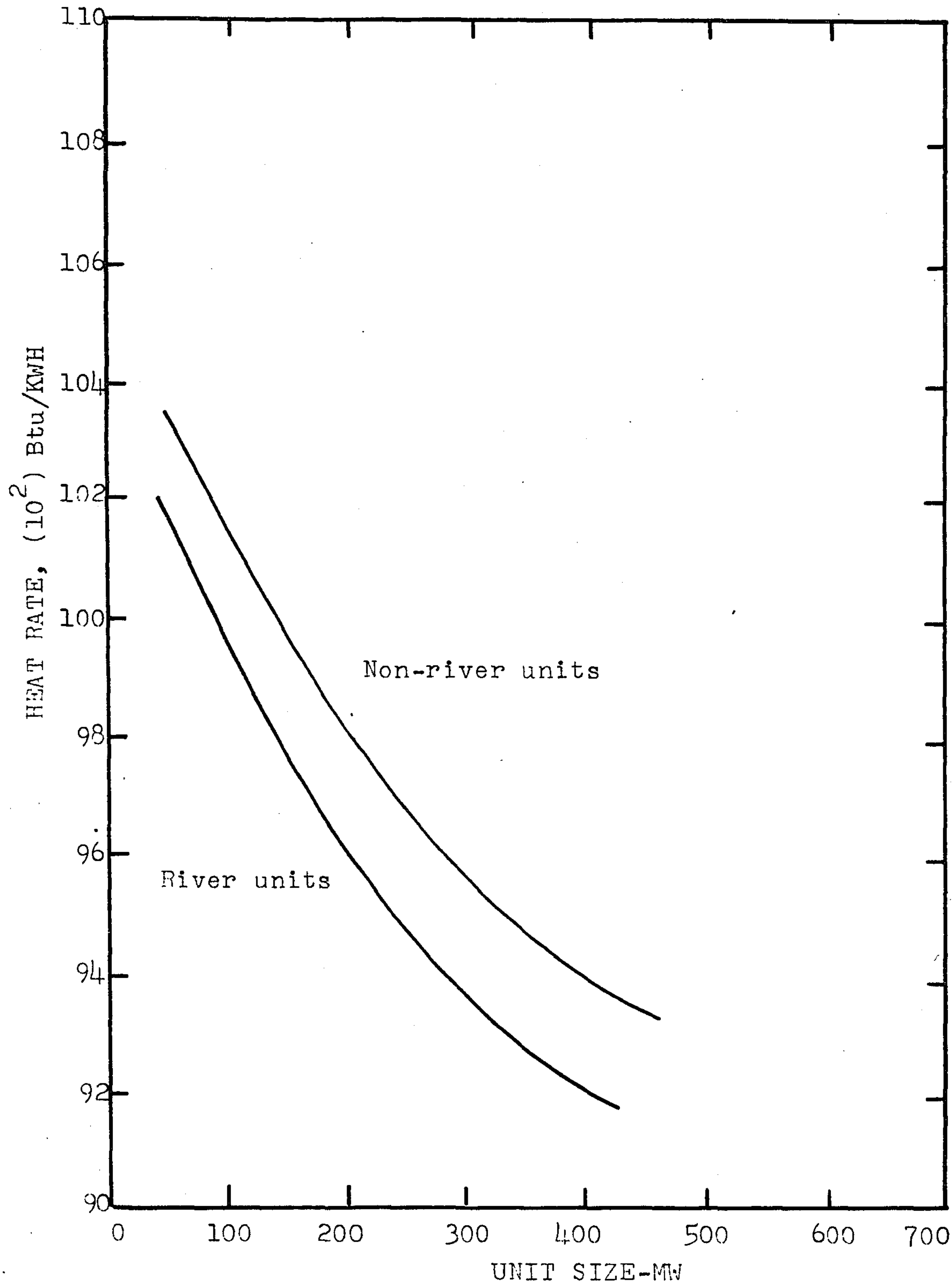

Figure 11. Iowa Pool Study new unit heat rates

The heat rate is expected to decrease approximately exponentially with time (Figure 12). It has become more and more difficult to decrease the heat rate any further. However it does not seem to be unreasonable to expect the heat rates of future units to dip below 7,500 BTU/KWH in the next two decades (29). There are several current units with heat rates below 9,000 BTU/KWH (25). The equation for the exponential in Figure 12 is

$$Y_{HR} = e^{-0.01(y-62)} \text{ (normalized to 1962)} \quad (20)$$

Most units in the Iowa power system burn both coal and gas. However it is expected that in the future gas may be harder to obtain; therefore more units will be switching entirely to coal. This study will consider only coal as the conventional fuel.

Figure 13 shows the expected increase in coal prices for the midwest areas of the United States. Also indicated on this figure is the past coal costs for two major generating stations in Iowa, Riverside and Des Moines #2. The expected linear increase in coal is given by

$$Y_f = 0.512(y-62) + f_o \text{ (normalized to 1962)} \quad (21)$$

where f_o = 1962 coal cost in ¢/10^6 BTU

The conventional fuel cost as a function of size and year is the product of Equations 19, 20, and 21. Therefore one has

$$f = \left(A_3x + B_3 + \frac{C_3}{x}\right) e^{0.01(y-62)} \left[0.512(y-62) + f_o\right] \quad (22)$$

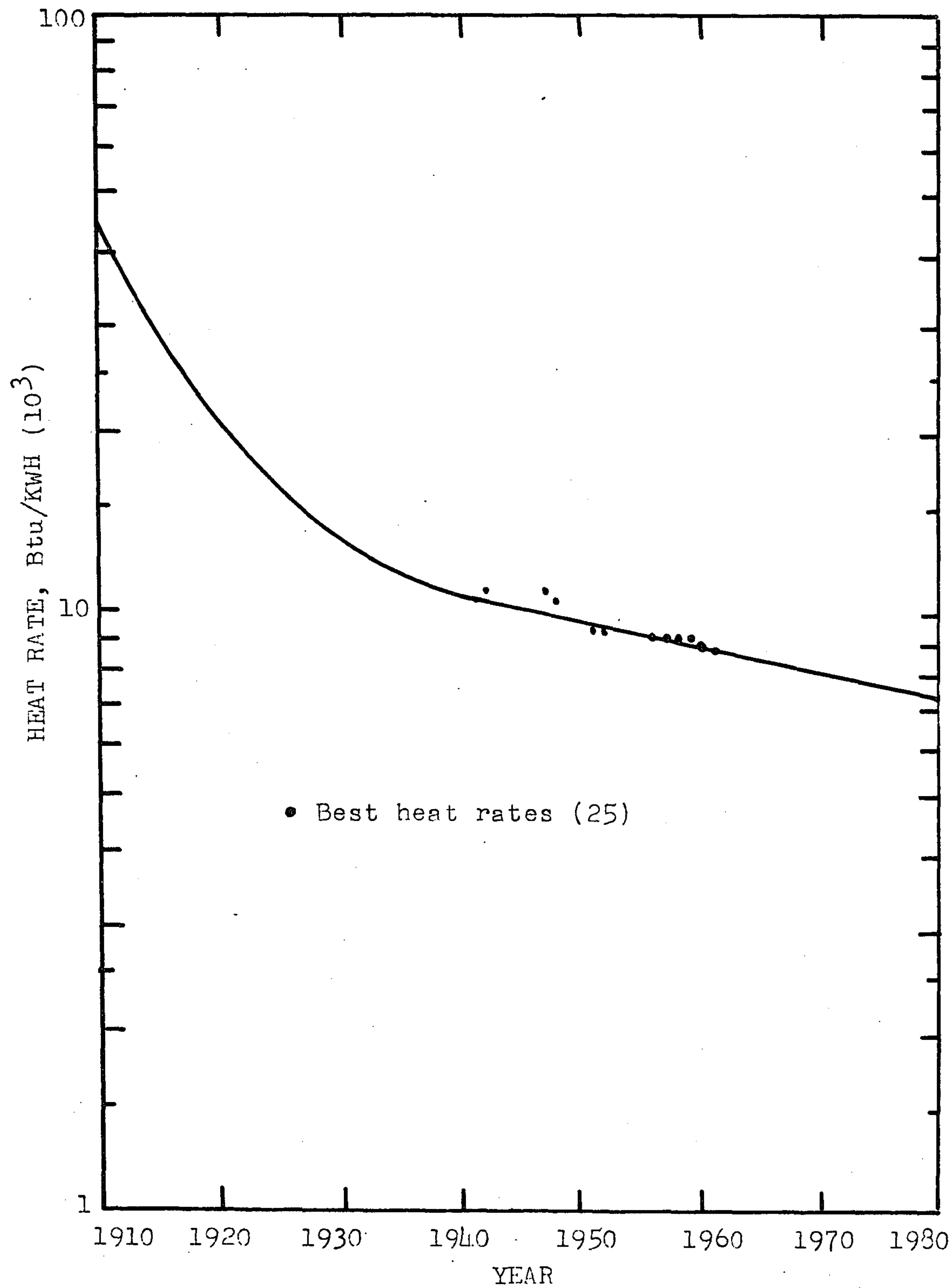

Figure 12. Best heat rates for large units (29)

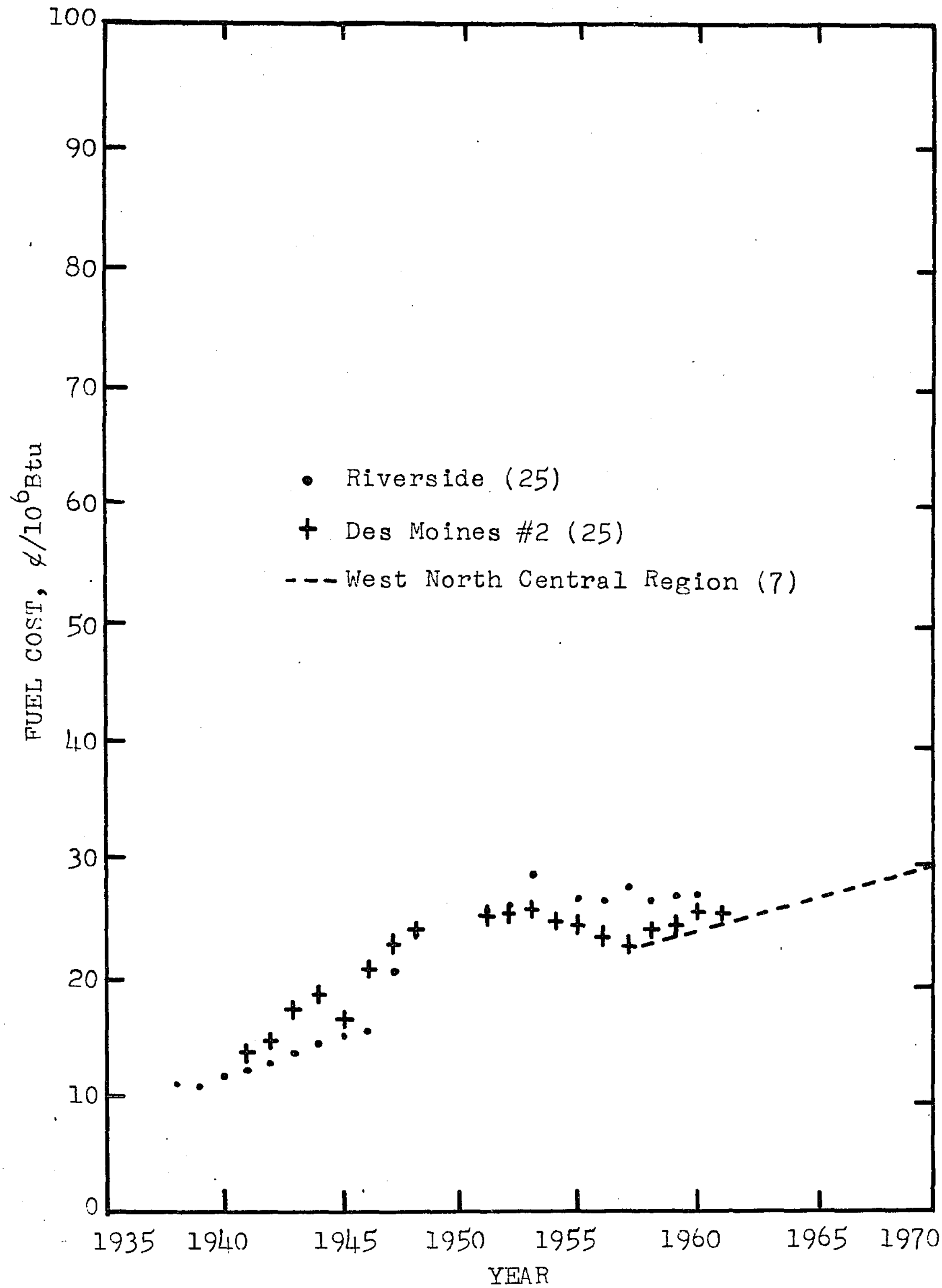

Figure 13. Coal costs

Operation and maintenance

The yearly cost of operation and maintenance for a conventional power plant is indicated in Figure 14. An equation to fit these curves is

$$O_s = A_2 x + B_2 + \frac{C_2}{x} \tag{23}$$

where the constants A_2, B_2, and C_2 are given in Table 4.

Table 4. Coefficients for Equation 23

Unit	A_2	B_2	C_2
First	$-2.67(10^{-3})$	3.60	187
Second	0	1.80	30
	$50\text{ MW} \leq x \leq 400\text{ MW}$		

The average costs of operation and maintenance for all power plants of the private utilities in Iowa are given in Figure 15. An equation, normalized to 1962, to fit the data is

$$Y_o = e^{-0.019(y-62)} \tag{24}$$

Therefore one can write an equation of cost of operation and maintenance as a function of power plant size and year. The equation is

$$O = \frac{1}{8750L}\left(A_2 x + B_2 + \frac{C_2}{x}\right) e^{-0.019(y-62)} \tag{25}$$

where L = load factor

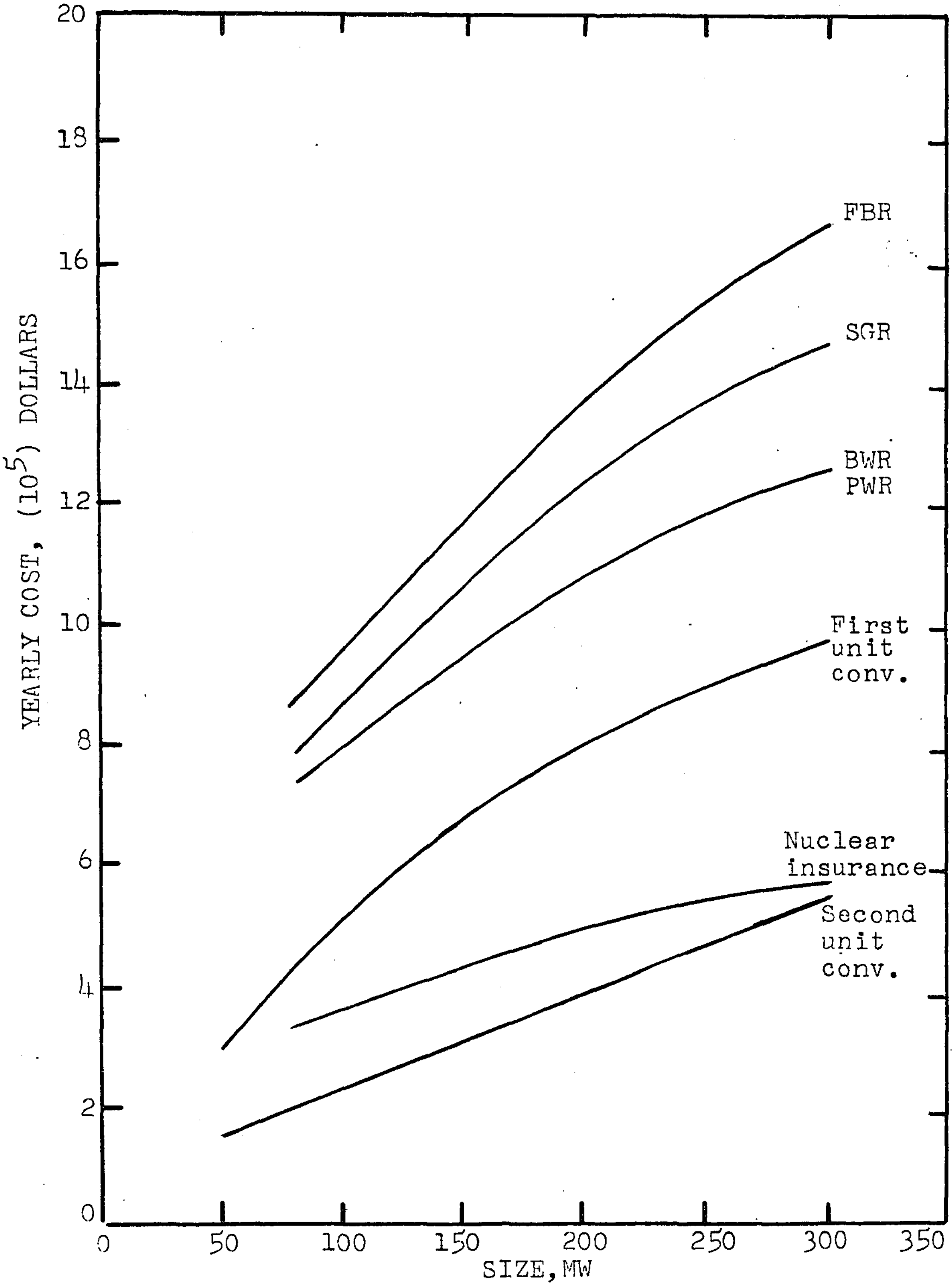

Figure 14. Operation and maintenance costs (19)

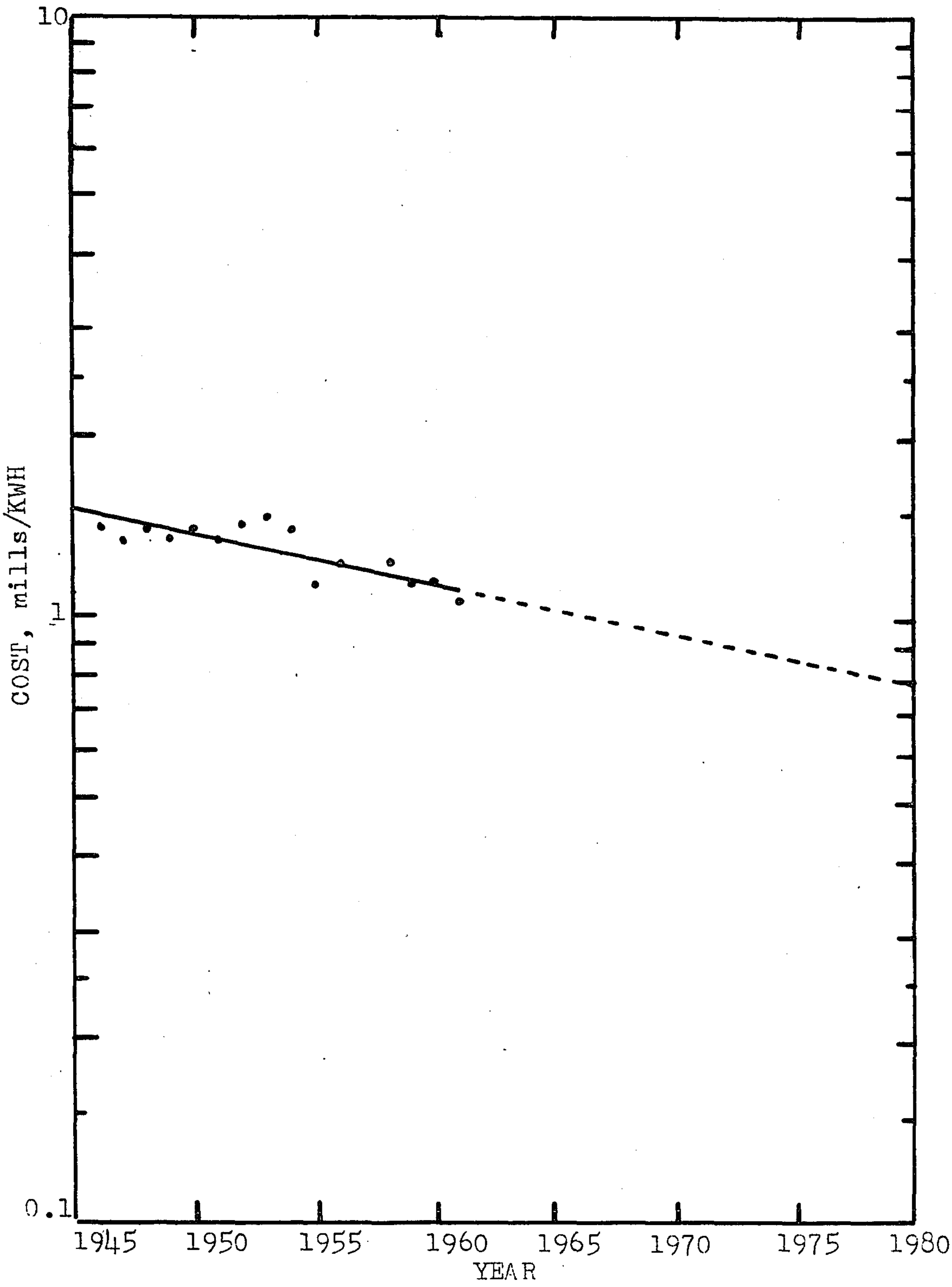

Figure 15. Average operation and maintenance costs for power plants of private Iowa utilities

NUCLEAR POWER PLANT COST ANALYSIS

It may still be a number of years before nuclear power cost estimates can be made accurately. However due to a number of power reactors now operating and others in the planning or building stage, reasonable estimates are possible. There is still much doubt about fuel cycle costs, but systematic studies are being made and as first generation cores are replaced and reprocessed, more information on fuel cycle costs will become available.

Fixed Charges

Fixed charges are based upon the capital costs of the nuclear power plant just as they are in conventional power plants. These costs are a function of load factor and fixed charge rate as well as the capital cost. The capital costs are broken down into individual accounts, each dealing with a certain physical area of the power plant. These accounts are prescribed for public utilities and licensees of the Federal Power Commission. In the report several accounts may be lumped together in order to facilitate calculations.

Land and land rights

The amount of land required for a nuclear power plant depends upon many factors. Population density is of prime importance, although it is not nearly as important today as in the earlier days of nuclear power. Availability of cooling water and climate also influence the location of a nuclear power plant.

A rough estimate for amount of land required for a nuclear power plant would be 1200 acres for a 300 MW plant and 600 acres for a 100 MW plant (13). A linear equation can be used for interpolation between 100 MW and 300 MW.

$$L = 3x + 300 \text{ acres} \tag{26}$$

where x = MW

Assuming land in Iowa would cost $300/acre one has

$$C = 900x + 90{,}000 \text{ dollars} \tag{27}$$

for the cost of land.

Structures and improvements

This account covers the items which principally govern the economics of the specific building under consideration, i.e., excavation, backfill, interior and exterior concrete, and the basic structure complete with the necessary services.

Ground improvements   This sub-account covers the cost of access roads for permanent use, general yard improvements, railroads, and waterfront improvements (14). An equation for this cost as a function of size is

$$C = 0.0333x^3 - 22.5x^2 + 5170x + 400{,}000 \text{ dollars} \tag{28}$$

Buildings   This sub-account includes all the individual building of the power plant. The cost breakdown for each building includes excavation and backfill, bearing piles and caissons, substructure concrete, superstructure, stacks, and building services. Each cost equation is written as a third order polynomial.

$$C = Ax^3 + Bx^2 + Cx + D \tag{29}$$

where the coefficients are given in Table 8.

Table 5. Coefficients for Equation 29 (14)

Building	A	B	C	D
Turbine building	-0.0347	14.5	2293	250,000
Office building	-0.00267	1.65	-18.0	19,000
Services building	-0.00191	0.975	-23.4	11,000
Fuel handling building	-0.00430	1.40	603	110,000
Radioactive waste building	-0.00434	2.00	323.4	100,000
Reactor plant auxiliary building (except SGR)	-0.00334	0.75	691.6	170,000
Miscellaneous building	-0.00128	0.57	55.6	23,300
Reactor building (SGR only)	-0.10	52.7	-1310	600,000
Stack	0	0	50	60,000
Reactor containment structure (except SGR)	-0.1267	67.0	766.7	560,000

Since the sodium cycle in a SGR is operated at pressures very near atmospheric pressure confinement is used rather than containment. Containment is required for reactors operated under pressure such as the water reactors. The FBR is operated at low pressures; however containment is presently being used as an added precaution against excursions.

Reactor plant equipment

This account corresponds to boiler plant equipment in a conventional power plant. The major difference between nuclear power plants and conventional power plants lies in this account. The account includes reactor equipment, heat transfer systems, fuel handling and storage equipment, radioactive waste treatment, instrumentation and control, feed water supply and treatment systems, main piping, and miscellaneous reactor plant equipment.

Reactor equipment   Reactor equipment is further subdivided into reactor vessel, reactor controls, reactor primary shield, reactor auxiliary cooling and heating systems, vapor containers, moderator and reflector and reactor cranes and hoists.

Reactor vessel   The cost per unit volume ($/ft^3) of a PWR pressure vessel is

$$\frac{C}{V} = -47 \left(\frac{H}{D}\right) + 0.16P + 322\$/\text{ft}^3 \qquad (30)$$

where H = vessel height in ft

D = vessel diameter in ft $3.0 \leq \frac{H}{D} \leq 4.5$

P = vessel pressure in psi $1500\text{psi} \leq p \leq 2500$ psi

V = vessel volume in cubic ft

The installation cost is

$$C_I = 36.5V + 63{,}500 \text{ dollars} \qquad (31)$$

An approximation for the volume of the reactor vessel for the PWR is

$$V = 16.85x \text{ ft}^3 \qquad 75 \text{ MW} \leq x \leq 300 \text{ MW} \tag{32}$$

If one assumes an $\frac{H}{D}$ of 3.5 and a pressure of 2,000 psi, we have

$$C + C_I = 8{,}665x + 63{,}500 \text{ dollars} \tag{33}$$

For a BWR one has

$$\frac{C}{V} = -47\left(\frac{H}{D}\right) + 0.16P + 342\$/\text{ft}^3 \tag{34}$$

$$3.0 \leq \frac{H}{D} \leq 4.5 \qquad 750\text{psi} \leq P \leq 1500\text{psi}$$

$$C_I = 40V + 30{,}000 \text{ dollars} \tag{35}$$

$$V = 25.9x \text{ ft}^3 \qquad 75 \leq x \leq 300 \text{ MW} \tag{36}$$

If $\frac{H}{D}$ is assumed as 3.6 and a pressure of 1000 psi, one can write the cost of the BWR pressure vessel as

$$C + C_I = 9{,}745x + 30{,}000 \text{ dollars} \tag{37}$$

A somewhat more subtle approach is needed to write equations for low-pressure vessels. A nomograph is used for calculating the cost of this type vessel (15). The cost is a function of vessel diameter, length, and thickness. The cost can be written as

$$C = (3{,}470D^2 - 14{,}170D + 250{,}000)e^{-0.22M} \tag{38}$$

where $M = \left(\frac{400\ e^{-0.0658T}}{A}\right)^{1/B} \qquad 0 \leq T \leq 80 \text{ ft}, \quad 6\text{ft} \leq D \leq 18 \text{ ft}$

D = vessel diameter in ft

T = vessel tangetial length in ft

A, B = constants given in Table 6

Table 6. Coefficients for Equation 38

Vessel Thickness	A	B
1"	0.053	3.96
$1\frac{1}{2}$"	0.570	3.09
2"	0.918	2.92

If the vessels are made from stainless steel a multiplier of either 4.20 for stainless steel 304 or 4.32 for stainless steel 316 can be used.

For a SGR one can approximate the diameter and tangential length by

$$D = 0.0165x + 17.90 \text{ ft} \qquad 75\text{MW} \leq x \leq 300\text{MW} \tag{39}$$

$$T = 0.01x + 33.0 \text{ ft} \tag{40}$$

The diameter of the SGR is in general greater than 18 ft but Equation 38 can be extrapolated (19). Results for diameters somewhat larger than 18 ft agree well with other previous calculations. For a stainless steel 304 pressure vessel for a SGR the cost can be approximated as

$$C = 3{,}500x + 1{,}330{,}000 \text{ dollars} \tag{41}$$

For the FBR one can approximate the diameter and tangential length as

$$D = 0.005x + 13.5 \text{ ft} \qquad 75\text{MW} \leq x \leq 300\text{MW} \tag{42}$$

$$T = 0.013x + 33.6 \text{ ft} \tag{43}$$

Therefore for a stainless steel 304 vessel one can approximate the cost as

$$C = 1{,}230x + 1{,}313{,}000 \text{ dollars} \tag{44}$$

<u>Control rods</u> There are many different types of control rods and drives. Even a particular type of rod and drive may vary greatly in cost for different reactors. The cost may also vary depending upon whether the rod is a shim rod, regulating rod, or safety rod. Different types of drives are gear and rack, locking hydraulic piston, pneumatic drive, ball-nut and screw, chain and sprocket, magnetic jack, harmonic drive, and others. Rod materials may vary greatly in price also. Materials may be boron, boron steels, cadmium, hafnium, and others. An approximation for the cost is $25,000 per drive plus $60,000 for power supply and position indicators.

$$C = 25{,}000\ N + 60{,}000 \text{ dollars} \tag{45}$$

where N = number of drives required

The number of drives required for a particular reactor can be approximated by

$$N = Ax + B \text{ drives} \qquad (N \text{ to nearest integer}) \tag{46}$$

therefore

$$C = Dx + E \text{ dollars} \qquad 75\text{MW} \leq x \leq 300\text{MW} \tag{47}$$

Table 7. Coefficients for Equations 46 and 47

Reactor	A	B	D	E
BWR	0.23	15	2,500	560,000
PWR	0.1	22	5,750	435,000
SGR	0.04	28	1,000	760,000
FBR	0.03	5	1,500	310,000

Strictly speaking N is an integer but as applied to Equation 46 it is used as a continuous function (19).

<u>Shielding</u> Shielding is also rather difficult to calculate since there are many different materials and geometries used. However Lane (4) calculated the minimum cost of the biological shield using barytes concrete and optimum combination of iron and water thermal shield. The cost can be approximated by

$$C = 29{,}100 \quad D - 65{,}000 \text{ dollars} \tag{48}$$

where D = core diameter in ft

For the light water reactors the diameter of the core can be approximated by

$$D\ (\text{PWR}) = -0.391(10^{-4})x^2 + 0.0374x + 6.46 \text{ ft} \tag{49}$$

$$D\ (\text{BWR}) = -0.339(10^{-4})x^2 + 0.0324x + 5.60 \text{ ft} \tag{50}$$

$$75 \text{ MW} \leq x \leq 300 \text{ MW}$$

Therefore these reactors have a cost for shielding of

$$C\ (\text{PWR}) = -1.135x^2 + 1{,}085x + 122{,}500 \text{ dollars} \tag{51}$$

$$C\ (\text{BWR}) = -0.985x^2 + 983x + 98{,}000 \text{ dollars} \tag{52}$$

Since the sodium cooled reactors must also have the primary sodium loop enclosed within the biological shielding, the shielding will cost more. A factor that includes the number of primary loops applied to Equation 48 seems to give an approximate value for the cost of shielding for these reactors. Therefore one has an equation

$$C = (1 + L) \quad (29{,}100\ D - 65{,}000) \text{ dollars} \tag{53}$$

where L = number of primary loops

D = core diameter in ft

one can also write

$$L = 0.01x + 1 \qquad 75\text{MW} \leq x \leq 300\text{MW} \tag{54}$$

Here L is treated as a continuous function in order to give a continuous function for the cost (19). For the diameter of the core one can use the approximation

$$D\ (SGR) = 0.0165\ x + 17.9 \text{ ft} \tag{55}$$

$$D\ (FBR) = 0.005\ x + 13.5 \text{ ft} \tag{56}$$

$$75\text{MW} \leq x \leq 300\text{MW}$$

Therefore one can write the cost of shielding for the SGR and the FBR as

$$C\ (SGR) = 4.80x^2 + 5{,}510x + 910{,}000 \text{ dollars} \tag{57}$$

$$C\ (FBR) = 1.45x^2 + 3{,}570x + 656{,}000 \text{ dollars} \tag{58}$$

<u>Other reactor plant equipment</u> This sub-account includes reactor auxiliary cooling and heating systems, vapor containers, moderator and reflector (SGR only), and reactor plant cranes and hoists.

For the light water reactors $500,000 should cover the equipment in this category. For the FBR the cost would be somewhat higher due to the sodium system (19). A cost equation gives

$$C = 3,680x + 650,000 \text{ dollars} \tag{59}$$

This sub-account would have a similar cost equation for the SGR; however the moderator and the reflector must be added (20, 2). A cost equation covering moderator and reflector is

$$C = 2,680x + 1,000,000 \text{ dollars} \tag{60}$$

Heat transfer system The heat transfer system includes primary coolant pumps, secondary coolant pumps, intermediate heat exchangers, steam generators, coolant supply and treatment, and coolant receiving storage.

Coolant pumps Very little cost information is available for pumps for liquid metal reactors. Canned rotor pumps are applicable for water reactors only; however for the purpose of this report the same type of pump is assumed applicable for sodium cooled reactors (15). The cost equation for canned rotor pumps is

$$C = -7.23(10^{-5})g + 12.75g + 43,600 \text{ dollars} \tag{61}$$

$$2,000 \text{ gpm} \leq g \leq 47,000 \text{ gpm}$$

where g = flow rate in gallons per minute

One can estimate the flow rate for the different reactors (19). One has a linear equation

$$g = Ax_{th} = A\frac{x}{\eta} \text{ gpm} \tag{62}$$

where x_{th} = thermal MW

η = plant efficiency

For the reactors in this study, A and η are given in Table 8.

Table 8. Coefficients for Equation 62

Reactor	A	η
BWR	20	28%
PWR	202	28%
SGR	75	30%
FBR	75	30%

It is assumed that 3 pumps are required for each reactor (although this is not in harmony with shielding calculations for SGR and FBR it will give an approximation for pump costs). Therefore using these assumptions one has a pump cost of

$$C = Ax^2 + Bx + C \text{ dollars} \tag{63}$$

where A, B, and C are given in Table 9.

Table 9. Coefficients for Equation 63

Reactor	A	B	C
BWR	-0.128	930	130,800
PWR	-12.4	9,200	130,800
SGR	-1.50	3,187	130,800
FBR	-1.50	3,187	130,800

<u>Main coolant piping and values</u> This sub-account includes all piping and valves between the reactor and heat exchangers and/or steam generators. The cost can be approximated by a linear function (19). For the water cooled reactors the cost is

$$C = 5{,}000x + 100{,}000 \text{ dollars} \tag{64}$$

and for the sodium cooled reactors the cost is

$$C = 7{,}700x + 290{,}000 \text{ dollars} \tag{65}$$

<u>Intermediate heat exchangers</u> This sub-account is only applicable to sodium cooled reactors. The heat transfer area can be approximated by

$$A = 16.2x_{th} = 16.2\frac{x}{\eta} \text{ ft}^2 \tag{66}$$

where x_{th} = thermal MW

η = plant efficiency

Using a value of \$140/sq. ft of heat transfer area one has a cost of

$$C = 7{,}550x \text{ dollars} \tag{67}$$

The installation cost is

$$C_I = -0.033x^2 + 235x + 21{,}600 \text{ dollars} \tag{68}$$

Therefore the total cost is

$$C = -0.033x^2 + 7{,}785x + 21{,}600 \text{ dollars} \tag{69}$$

<u>Steam generators</u> The cost of steam generators is calculated in a manner similar to that of the heat exchangers. The heat transfer area and cost per ft^2 are given in Table 10.

Table 10. Cost of steam generators

Reactor	Heat Transfer Area ft^2	Plant Efficiency %	Cost $\$/ft^2$	Total \$
BWR	29.4 x_{th}	28	63	6,620 x
PWR	58.8 x_{th}	28	63	13,200 x
SGR	16.2 x_{th}	30	80	4,320 x
FBR	16.2 x_{th}	30	80	4,320 x

The installation cost for the BWR is

$$C_I = -0.068x^2 + 192.1x + 14,300 \text{ dollars} \tag{70}$$

for the PWR it is

$$C_I = -0.273x^2 + 384.3x + 14,300 \text{ dollars} \tag{71}$$

and for the sodium cooled reactors it is

$$C_I = -0.040x^2 + 177.4x + 7,900 \text{ dollars} \tag{72}$$

Steam drums   Steam drums are required for BWR type power plants. The cost of steam drums is about \$2 per lb. Therefore the total cost of the drum is

$$C = 128 \text{ mDHt dollars} \tag{73}$$

where m = cost multiplier, 1.0 for steel and 1.3 for stainless steel 304

D = drum diameter, ft

H = drum length, ft

t = drum thickness, in

A 54 ft by 8 ft drum is needed for a 200 MW plant and 78 ft by 8 ft drum is needed for a 300 MW plant (10). By assuming a smooth function of drum volume as a function of plant size one can calculate the total cost of the drum as

$$C = 2{,}500x + 110{,}000 \text{ dollars} \tag{74}$$

$$75\text{MW} \leq x \leq 300\text{MW}$$

Coolant supply and treatment This sub-account can be approximated for a BWR as

$$C = 725x + 109{,}500 \text{ dollars} \tag{75}$$

For the PWR one has

$$C = 725x + 659{,}000 \text{ dollars} \tag{76}$$

plus the cost of a pressurizer (19). The pressurizer is required to maintain the high pressures utilized in the primary cycle. The cost equation is

$$C = -5.63x^2 + 2{,}247x \text{ dollars} \tag{77}$$

plus cost of installation

$$C_I = 0.035x^2 + 3.80x + 12{,}600 \text{ dollars} \tag{78}$$

For the sodium cooled reactors one has also the sub-account coolant receiving and storage facilities. These facilities are needed to handle sodium. The cost equation for sodium cooled reactors is

$$C = 49{,}100x + 1{,}030{,}000 \text{ dollars} \tag{79}$$

Fuel handling and storage facilities This account includes cranes and hoisting equipment, special tools and service equipment, spent fuel cooling and inspection equipment, and shipping casks and cars. One can approximate this account for the BWR, PWR, and SGR by

$$C = 3.55x^2 - 155x + 738{,}000 \text{ dollars} \tag{80}$$

and for the FBR by

$$C = 3.30x^2 + 350x + 1{,}553{,}000 \text{ dollars} \tag{81}$$

This account for the FBR is slightly higher due to the type of fuel handled for a fast breeder reactor (19).

Radioactive waste treatment This account covers the treatment of gaseous, solid, and liquid wastes (19). A cost equation derived for this account is

$$C = 1.75x^2 - 55x + 236{,}000 \text{ dollars} \tag{82}$$

Instrumentation and control This account includes primary plant control system, heat transfer system, reactor safety system, radioactive waste system, radiation monitoring, steam generation controls, and control and instrument piping and tubing (19). A cost equation derived for this account is

$$C = 2{,}650x + 958{,}000 \text{ dollars} \tag{83}$$

Feed water supply and treatment systems This account includes raw water supply systems, purification and treatment system, feed water tanks, feed water heaters, and reactor feed pumps. The cost can be approximated by

$$C = 1.50x^2 + 2{,}690x + 286{,}000 \text{ dollars} \tag{84}$$

for the BWR and

$$C = 4.35x^2 + 305x + 286{,}000 \text{ dollars} \tag{85}$$

for the PWR, SGR, and FBR. The cost is somewhat larger for the BWR because of radioactivity in the main coolant (19).

Steam, condensate, and feed water piping This account includes main steam piping, auxiliary system piping, condensate piping, feedwater piping, and drains and vents. This account can change the total capital costs considerably depending on the amount of stainless steel used in the piping. For a stainless steel system one has a cost equation of

$$C = -14.5x^2 + 24{,}750x + 1{,}270{,}000 \text{ dollars} \tag{86}$$

For an all carbon steel system the cost may be down from the stainless steel system by a factor of 4 or more. Therefore a system of a combination of both types of piping would be somewhere in between these values. However for the purposes of this study the all stainless steel system will be assumed.

Miscellaneous reactor plant equipment This account includes chemical decontamination equipment and reactor plant maintenance equipment (19). A cost equation for this account is

$$C = 385x + 85{,}000 \text{ dollars} \tag{87}$$

Turbo - generator units

This account includes the turbine-generator and related equipment. This equipment is very similar to conventional power plant equipment. The main difference is that current nuclear power plants operate at lower temperatures and pressures than do modern conventional steam plants; therefore steam quality to the turbine is much lower. This may increase the cost somewhat.

Turbine - generators units The costs of the turbine-generators vary greatly depending upon operating temperatures and operating pressures. The base-price cost of non-reheat units is given in Table 11. In addition to the base price there are price differentials due to temperature and pressure which must be considered (19).

Table 11. Base price cost equations for non-reheat condensing turbines

Turbine	Size	Cost Equation
3600 RPM non-reheat condensing		
TCQF-26	$125 \leq x \leq 250$MW	$C = 11{,}040x + 3{,}870{,}000$ dollars
TCQF-23	$125 \leq x \leq 250$MW	$C = 12{,}000x + 3{,}250{,}000$ dollars
TCTF-26	$100 \leq x \leq 200$MW	$C = 11{,}500x + 3{,}000{,}000$ dollars
TCTF-23	$75 \leq x \leq 200$MW	$C = 12{,}320x + 2{,}590{,}000$ dollars
TCDF-26	$60 \leq x \leq 125$MW	$C = 12{,}150x + 2{,}080{,}000$ dollars
TCDF-23	$60 \leq x \leq 125$MW	$C = 13{,}500x + 1{,}650{,}000$ dollars
TCDF-20	$40 \leq x \leq 100$MW	$C = 13{,}900x + 1{,}018{,}000$ dollars
SC-20	$20 \leq x \leq 50$MW	$C = 21{,}170x + 357{,}000$ dollars
1800 RPM non-reheat condensing		
TCQF-43	$250 \leq x \leq 500$MW	$C = 10{,}500x + 8{,}000{,}000$ dollars
TCQF-38	$250 \leq x \leq 500$MW	$C = 10{,}500x + 6{,}950{,}000$ dollars
TCDF-43	$250 \leq x \leq 450$MW	$C = 13{,}000x + 4{,}530{,}000$ dollars
TCDF-38	$200 \leq x \leq 350$MW	$C = 12{,}350x + 4{,}070{,}000$ dollars
TCDF-35	$200 \leq x \leq 350$MW	$C = 12{,}350x + 3{,}740{,}000$ dollars
SC-38	$60 \leq x \leq 150$MW	$C = 12{,}100x + 2{,}460{,}000$ dollars
SC-35	$60 \leq x \leq 150$MW	$C = 12{,}100x + 2{,}210{,}000$ dollars
SC-30	$60 \leq x \leq 100$MW	$C = 14{,}250x + 1{,}725{,}000$ dollars

For a 3600 RPM non-reheat unit add the following cost differential for temperature:

$$C = 0.814\, e^{0.0089T}(x + 1572\, e^{-0.00524T}) \text{ dollars} \tag{88}$$

$$10\text{MW} \leq x \leq 300\text{MW} \qquad 750^{\circ}\text{F} \leq T \leq 1000^{\circ}\text{F}$$

or

$$C = (100 + P)x\left\{e^{\left[5.84(10^{-6})\,P - 0.017\right]T_s}\right\} - (230 + 0.3P)T_s + 92.5P + 26{,}000 \tag{89}$$

$$300\text{psi} \leq P \leq 1450\text{psi} \quad 10\text{MW} \leq x \leq 300\text{MW}$$
$$\text{Saturated} \leq T_s \leq 200^{\circ}\text{F superheat where } T < 750^{\circ}\text{F}$$

For a 3600 RPM non-reheat unit add the following cost differential for pressure:

$$C = 5000\ e^{-0.00375P}(x + 100) \text{ dollars TCTF and TCDF} \tag{90}$$

$$300 \leq P \leq 850\text{psi} \qquad 200 \leq x \leq 250\text{MW}$$

$$C = 1500\ e^{-0.00465P}(x + 100) \text{ dollars TCDF} \tag{91}$$

$$300 \leq P \leq 850\text{psi} \qquad 60 \leq x \leq 125\text{MW}$$

$$C = 4500\ e^{-0.0040P}(x + 100) \text{ dollars} \tag{92}$$

$$300 \leq P \leq 850\text{psi} \qquad \begin{array}{ll} \text{SC, TCSF} & 40 \leq x \leq 50\text{MW} \\ \text{TCTF} & 75 \leq x \leq 175\text{MW} \\ \text{TCQF} & 125 \leq x \leq 175\text{MW} \end{array}$$

$$C = 152x + 14{,}500 \text{ dollars} \tag{93}$$

$$850 \leq P \leq 1450\text{psi} \qquad \text{TCDF} \quad 60 \leq x \leq 125\text{MW}$$

For an 1800 RPM non-reheat unit add the following cost differential for temperature:

$$C = e^{-[9.12(10^{-6})P-0.0078]T_s}\ [2.17Px + 845x + 217P + 84{,}500] \text{ dollars} \tag{94}$$

$$300 \leq P \leq 1450\text{psi} \qquad 60 \leq x \leq 500\text{MW}$$
$$\text{Saturated} \leq T_s \leq 200^\circ\text{F for } T < 750^\circ\text{F superheat}$$

or

$$C = 0.264\ e^{0.00845T}\ (x + 100) \text{ dollars} \tag{95}$$

$$60 \leq x \leq 500\text{MW} \qquad 750^\circ \leq T \leq 1000^\circ\text{F}$$

For an 1800 RPM non-reheat unit add the following cost differential for pressure:

$$C = A\ (x + 100) \text{ dollars} \tag{96}$$

$$\text{where } A = \begin{cases} -4.55(10^{-4})P^2 + 0.0636P + 321.8 & 60 \leq x \leq 125\text{MW} \\ 7.00(10^{-4})P^2 - 1.75P + 1{,}062 & 126 \leq x \leq 500\text{MW} \end{cases}$$

$$300 \leq P \leq 1450\text{psi}$$

The installation cost of the turbine generator is

$$C_I = -0.56x^2 + 1{,}160x \text{ dollars} \qquad 20 \leq x \leq 500\text{MW} \tag{97}$$

The material cost for installation of the concrete pedestal is

$$C_M = 420x \text{ dollars} \qquad 60 \leq x \leq 500\text{MW} \tag{98}$$

The labor cost for installation of the concrete pedestal is

$$C = 230x \text{ dollars} \qquad 60 \leq x \leq 500\text{MW} \tag{99}$$

A similar group of equations can be determined for reheat condensing turbines. However for present studies of nuclear power, temperatures are not high enough to warrant reheat in the power cycle. Sodium cooled reactors show the best promise for reheat cycles.

In order to calculate turbine costs for an individual reactor, assumptions must be made. For the PWR a temperature of 480°F and a pressure of 555psi are assumed. These are saturation conditions. A TCTF-23 3600 RPM turbine is assumed for the range 75-200MW, a TCQF-26 3600 RPM turbine is assumed for the range 125 - 250MW, and a TCDF - 35 1800 RPM turbine is assumed for the range 200 - 300MW. The overlapping regions approximated a linear function. The linear equation for the PWR is

$$C = 23{,}200x + 1{,}920{,}000 \text{ dollars} \tag{100}$$

A temperature of 540°F and a pressure of 950psi are assumed for the BWR. These are saturated conditions. The same types of turbines and ranges were assumed for the BWR as was assumed for the PWR. The resulting equation for the BWR is

$$C = 22{,}660x + 1{,}970{,}000 \text{ dollars} \tag{101}$$

A temperature of 850°F and a pressure of 800 psi are assumed for the sodium cooled reactor. This is a condition of 332°F of superheat. The same types of turbines are assumed for the sodium cooled reactors as were assumed for the water reactors. The resulting cost equation is

$$C = 19{,}640x + 2{,}258{,}000 \text{ dollars} \tag{102}$$

Circulating water system This sub-account includes pumping and regulating equipment, circulating lines, and water treatment system (19). A cost equation is

$$C = 1{,}520x + 170{,}000 \text{ dollars} \tag{103}$$

Condensers The condenser cost can vary depending upon the material used for the tubes. The cost varies from about $\$4.3/ft^2$ for admiralty tubes to $\$7.5/ft^2$ for 70-30 Cupro-Nickel tubes. For purposes of this study a value of $\$5/ft^2$ will be used. It has been estimated that one square ft of condenser surface will condense about 8 lb steam per hour (15). Therefore one has a condenser size of approximately

$$C = 242x_{th} = 242\,\frac{x}{\eta}\ ft^2 \tag{104}$$

This gives a condenser cost of

$$C = 4{,}030x \text{ dollars} \tag{105}$$

where $\eta = 30\%$

The installation cost is approximately \$650/MW (15). Therefore one has a total cost for the condenser of

$$C = 4{,}680x \text{ dollars} \tag{106}$$

Miscellaneous turbo-generator equipment This sub-account covers all other equipment listed under the main account (19). The calculated cost equation is

$$C = 0.25x^2 + 135x + 123{,}000 \text{ dollars} \tag{107}$$

Accessory electric equipment

This account includes switchgear, switchboards, protective equipment, electrical structures, conduits, power and control wiring, and station service equipment. This account would be the same for a nuclear plant as it is for a conventional plant (18). A calculated cost equation for this account is

$$C = 4.00x^2 + 1{,}400x + 720{,}000 \text{ dollars} \tag{108}$$

Miscellaneous power plant equipment

This account includes cranes and hoisting equipment, compressed air and vacuum cleaning equipment, communication systems, fire extinguishing equipment, furniture fixtures, machine tools, laboratory equipment, etc (15). A calculated cost equation for this account is

$$C = -0.10x^2 + 1{,}605x + 275{,}000 \text{ dollars} \tag{109}$$

Indirect construction costs

Indirect construction costs are expenses involved in building a power plant but not included as direct cost of materials and equipment or the labor for the installation of these materials and equipment. These costs are usually calculated as a fixed percentage of direct costs.

General and administrative expenses These costs cover general administration and field superintendence as well as related activities in connection with construction project incurred by the contractor and owner. Costs such as medical, fire protection, insurance during construction, and the fees of the construction contractors are also included.

Engineering, design, and inspection These costs include all engineering, design, and inspection services applicable to construction work, whether incurred directly by the owner, or accrued by the architect-engineer or by the nuclear systems designer.

Start-up costs These expenses are incurred in the start-up and testing of the reactor as well as other power plant equipment. The costs are calculated as 35% of the operating expenses for a year.

Contingencies This is a nominal allowance to provide for unforeseen or unpredicted costs at the time the estimate is prepared.

Interest during construction This account includes the net cost of money used for construction. The interest period is limited to the period of construction which is assumed to be 36 months. The interest rate is assumed to be 6% per annum for investor-owned utilities.

Summary of fixed charges

The total indirect costs for the nuclear plant is calculated to be 37% of the direct costs (19). The indirect costs are added to the direct costs to give total capital costs.

The direct costs of a nuclear power plant can be split into nuclear direct costs and conventional direct costs. The conventional direct costs include the accounts in the nuclear power that are the same as the accounts in a conventional power plant. The nuclear direct costs include the reactor plant and containment structure. By adding the coefficients of all the equations of all the fixed charges accounts one obtains an equation of

$$C = Ax^3 + Bx^2 + Cx + D \tag{110}$$

where the coefficients are given in Table 12.

Table 12. Coefficients of Equation 110

Reactor	A	B	C	D
Conventional direct costs				
BWR	-0.0212	3.50	42,050	4,491,000
PWR	-0.0212	3.48	42,650	4,491,000
SGR	-0.1192	56.15	37,780	5,379,000
FBR	-0.0212	3.47	39,090	4,779,000
Nuclear direct costs				
BWR	-0.1267	56.1	64,030	5,425,000
PWR	-0.1267	40.9	72,000	6,096,000
SGR	0	-3.38	116,800	9,467,000
FBR	-0.1267	60.0	111,400	11,120,000

By applying the indirect cost factor and dividing Equation 107 by the size of plant one obtains capital cost on a basis of \$/KW as a function of plant size in MW. Therefore one has

$$C = Dx^2 + Ex + F + \frac{G}{x} \tag{111}$$

where the coefficients are given in Table 13.

Table 13. Coefficients of Equation 111

Reactor	D	E	F	G
Conventional capital costs:				
BWR	$-2.90(10^{-5})$	0.00480	57.60	6,153
PWR	$-2.90(10^{-5})$	0.00477	58.43	6,153
SGR	$-16.33(10^{-5})$	0.07693	41.71	7,369
FBR	$2.90(10^{-5})$	0.00475	53.55	6,547
Nuclear capital costs:				
BWR	$-17.36(10^{-5})$	0.0769	87.73	7,432
PWR	$-17.36(10^{-5})$	0.0560	98.64	8,352
SGR	0	-0.00463	160.00	12,970
FBR	$-17.36(10^{-5})$	0.0822	152.56	15,236

Production Costs

Production costs include all costs for day to day operation of the power plant. These costs include fuel costs, maintenance costs, supplies, and labor.

Fuel cycle costs

The fuel cycle cost can be broken down according to location of the core, that is in fabrication, in the reactor, or in chemical reprocessing. Each of these can be further sub-divided as is indicated in Table 14.

Table 14. Sub-division of fuel cycle accounts (16)

	Processing	Shipping	Use Charge	U Loss or Consumption	Pu Loss or Consumption
Fabrication					
Transit to conversion site	--	F_{21}	F_{31}	--	--
Conversion and fabrication	F_{12}	--	F_{32}	F_{42}	--
Transit to reactor and recycle	--	F_{23}	F_{33}	--	--
Reactor					
Pre-irradiation inventory	--	--	R_{31}	--	--
Irradiation	--	--	R_{32}	R_{42}	R_{52}
Decay	--	--	R_{33}	--	--
Chemical Processing					
Transit to process site	--	P_{21}	P_{31}	--	--
Separation	P_{12}	--	P_{32}	P_{42}	P_{52}
Uranium conversion	P_{13}	--	P_{33}	P_{43}	--
Plutonium conversion	P_{14}	--	--	--	P_{54}
Transit to receiving point	--	P_{24}	--	--	--

In Table 14 the symbols represent different expenses in \$/KgU through the fuel cycle. Therefore the total fuel cycle cost will be

$$\sum_{i=1}^{5} \sum_{j=1}^{5} (F_{ij} + R_{ij} + P_{ij}) \ \$/\text{KgU} \tag{112}$$

The blank spaces in Table 14 indicate there are no fuel cycle costs in these areas. Each of the cost parameters in Table 14 is a function of parameters listed in Table 15.

Table 15. Fuel cost data (16)

Design Parameters	Units	Values
a. Fuel composition, fuel element size		
b. Cladding material		
c. Fuel enrichment when charged to reactor	%	
d. Fuel enrichment when discharged from reactor	%	
e. Average fuel exposure	MWD/T	
f. Plutonium concentration in discharged fuel	gm/kg U	
g. Rated gross power level	MWt	
h. Rated net power level	MWe	
i. Reactor fuel loading, initial	MTU	
j. Total fuel discharged per initial fuel loading	MTU	
k. Description of fuel management program		

Table 15 continued

Operating Parameters, Set by Industry	Units	Values
A. KgU charged/KgU charged		1.00
B. Predicted plant operating factor	%	
C. Shipping time, AEC to fabricator	days	20
D. Shipping time, fabricator to reactor	days	20
E. Shipping time, recycle scrap to AEC	days	20
F. Shipping time, reactor to chemical processing site	days	20
G. Conversion and fabrication plant throughput rate	MTU/month	4.0
H. Time interval between delivery of fuel batch to reactor site and charging to reactor	days	30
I. Spare fuel maintained on hand at all times, exclusive of discrete charging batches (average)	MTU	2.0
J. Batch size charged to reactor per refueling	MTU	ki
K. Batch size discharged from reactor per refueling	MTU	kj
L. Number of discharge batches accumulated for chemical processing campaign		one
M. Irrecoverable losses during conversion of UF_6 to UO_2	%	1.0
N. Irrecoverable losses during fabrication	%	1.0
O. Conversion and fabrication, recycle to AEC	%	10.0

Table 15 continued

Operating Parameters, Set by AEC		Units	Values
P.	Minimum decay cooling period for irradiated fuel	days	120
Q.	Irrecoverable loss during chemical separation, U	%	1.0
R.	Irrecoverable loss during chemical separation, Pu	%	1.0
S.	Irrecoverable loss during conversion, U	%	0.3
T.	Irrecoverable loss during conversion, Pu	%	1.0
U.	Chemical separation plant processing rate	MTU/day	Figure 19
V.	Chemical conversion plant processing rate	MTU/day	1000 d ≤ 5% 150 d > 5%
W.	Reprocessing losses	%	1.0
Economic Parameters, Set by Industry			
m.	Conversion processing cost	$/kg U	Figure 16
n.	Fabrication processing cost	$/kg U	Figure 17
o.	Shipping charge, AEC to fabricator	$/kg U	1.50
p.	Shipping charge fabricator to reactor	$/kg U	1.50
q.	Shipping charge, reactor to chemical processing site	$/kg U	16
Economic Parameters, Set by AEC			
r.	Use charge rate	%/year	4.75
s.	Uranium price at enrichment prior to irradiation (as UF_6)	$/kg U	Figure 18

Table 15 continued

Economic Parameters, Set by AEC	Units	Values
t. Uranium price at discharge enrichment (as UF_6)	\$/kg U	Figure 18
u. Conversion charge, UNH to UF_6	\$/kg U	5.60 $d \leq 5\%$ 32.00 $d > 5\%$
v. Conversion charge, Pu nitrate to Pu metal	\$/gm	1.50
w. Pu price (credit)	\$/gm	9.50
x. Shipping charge, chemical process site to AEC receiving plants (U and Pu)	\$/kg U	1.0
y. Separations plant daily charge	\$/day	17,800
z. Turnaround time	days	2 $\quad \frac{K}{U} < 2$ $\frac{K}{U} \quad 2 \leq \frac{K}{U} \leq 8$ 8 $\quad \frac{K}{U} > 8$

The following equations are parameters for Table 14 calculated as functions of the parameters in Table 15. All parameters are in terms of \$/kg Uranium charged to the reactor.

$$F_{12} = (m + n) \tag{113}$$

$$F_{21} = (A + M + N + O)o \tag{114}$$

$$F_{23} = (A + O)p \tag{115}$$

$$F_{31} = (A + M + N + O)\left(\frac{rcs}{365}\right) \tag{116}$$

$$F_{32} = (A + M + N + O)\left(\frac{Jrs}{365G/H}\right) \tag{117}$$

$$F_{33} = (DA + EO)rs\left(\frac{1}{365}\right) \tag{118}$$

$$F_{42} = (M + N)As \tag{119}$$

$$R_{31} = \left(\frac{ArsH}{365}\right) + \left(\frac{Irs}{i}\right)\left[\frac{e}{365B(g/i)}\right] \qquad (120)$$

$$R_{32} = \left(\frac{Ar}{2}\right)\left[s + \left(\frac{j}{i}\right)t\right]\left[\frac{e}{365B(g/i)}\right] \qquad (121)$$

$$R_{33} = \left(\frac{j}{i}\right)\left(\frac{rtP}{365}\right) \qquad (122)$$

$$R_{42} = As - \left(\frac{j}{i}\right) t \qquad (123)$$

$$R_{52} = - f \left(\frac{j}{i}\right) w \qquad (124)$$

$$P_{12} = \left(\frac{j}{i}\right)\left[\frac{y}{(10^3)K}\right]\left[\left(\frac{K}{U}\right) + z\right] \qquad (125)$$

$$P_{13} = \left(\frac{j}{i}\right)(1.00 - x)a \qquad (126)$$

$$P_{14} = \left(\frac{j}{i}\right)(1.00 - W)fu \qquad (127)$$

$$P_{21} = \left(\frac{j}{i}\right)q \qquad (128)$$

$$P_{24} = \left(\frac{j}{i}\right)(1.00 - W)(1.00 - S)x \qquad (129)$$

$$P_{31} = \left(\frac{j}{i}\right)\left(\frac{trF}{365}\right) \qquad (130)$$

$$P_{32} = \left(\frac{j}{i}\right) tr \left[\left(\frac{K}{U}\right) + 30\right]\left(\frac{1}{365}\right) \qquad (131)$$

$$P_{33} = \left(\frac{j}{i}\right)(1.00 - W)\ tr\ (1.00 - W)\left[\left(\frac{K}{V}\right) + 5\right]\left(\frac{1}{365}\right) \qquad (132)$$

$$P_{42} = uQ\left(\frac{j}{i}\right) \qquad (133)$$

$$P_{43} = S(1.00 - W)\left(\frac{j}{i}\right) u \qquad (134)$$

$$P_{52} = Rf\left(\frac{j}{i}\right)(w - u) \qquad (135)$$

$$P_{54} = T\ (1.00 - W)\ f\left(\frac{j}{i}\right)(w - u) \qquad (136)$$

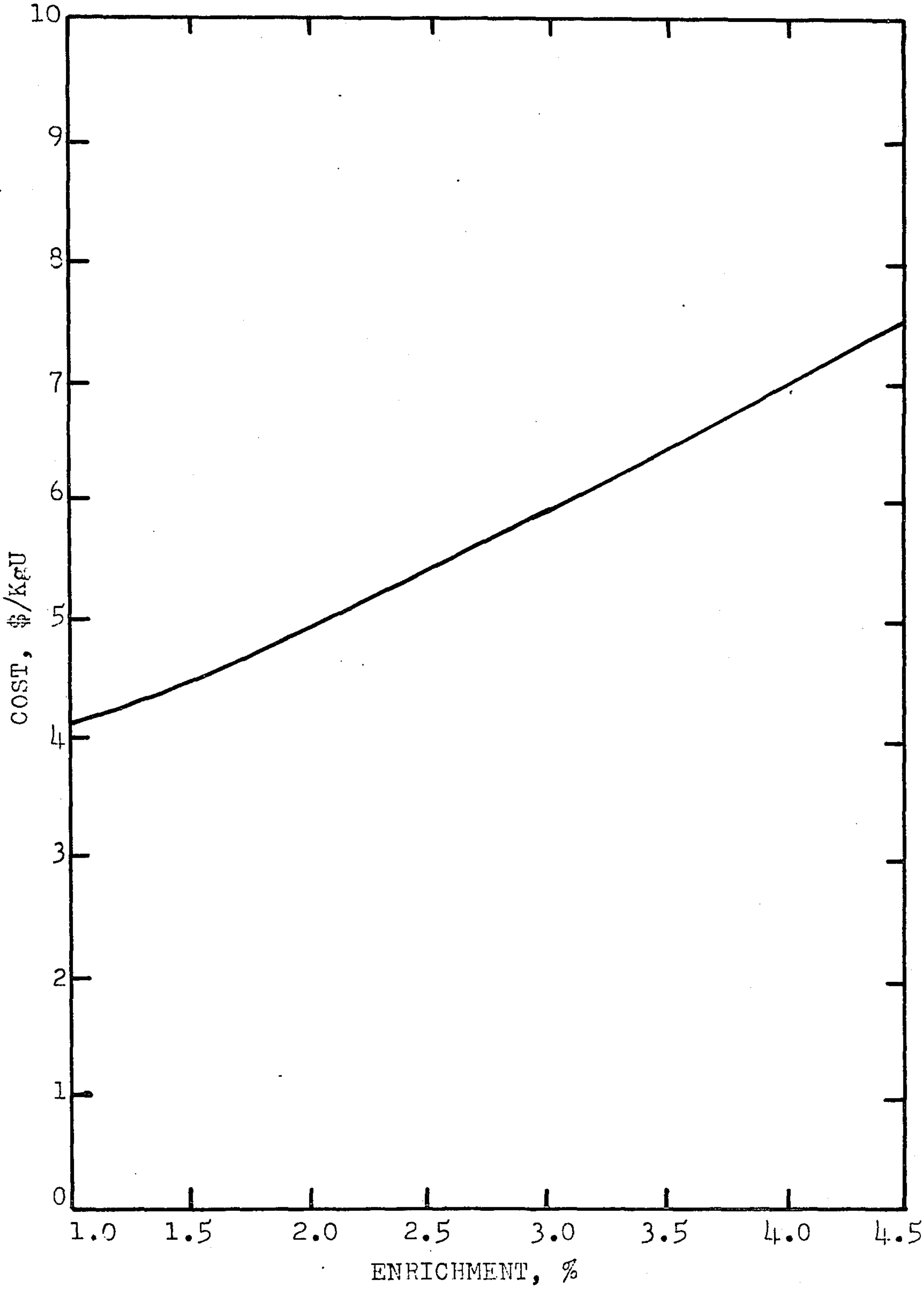

Figure 16. Average conversion cost for UF_6 to UO_2 powder(16)

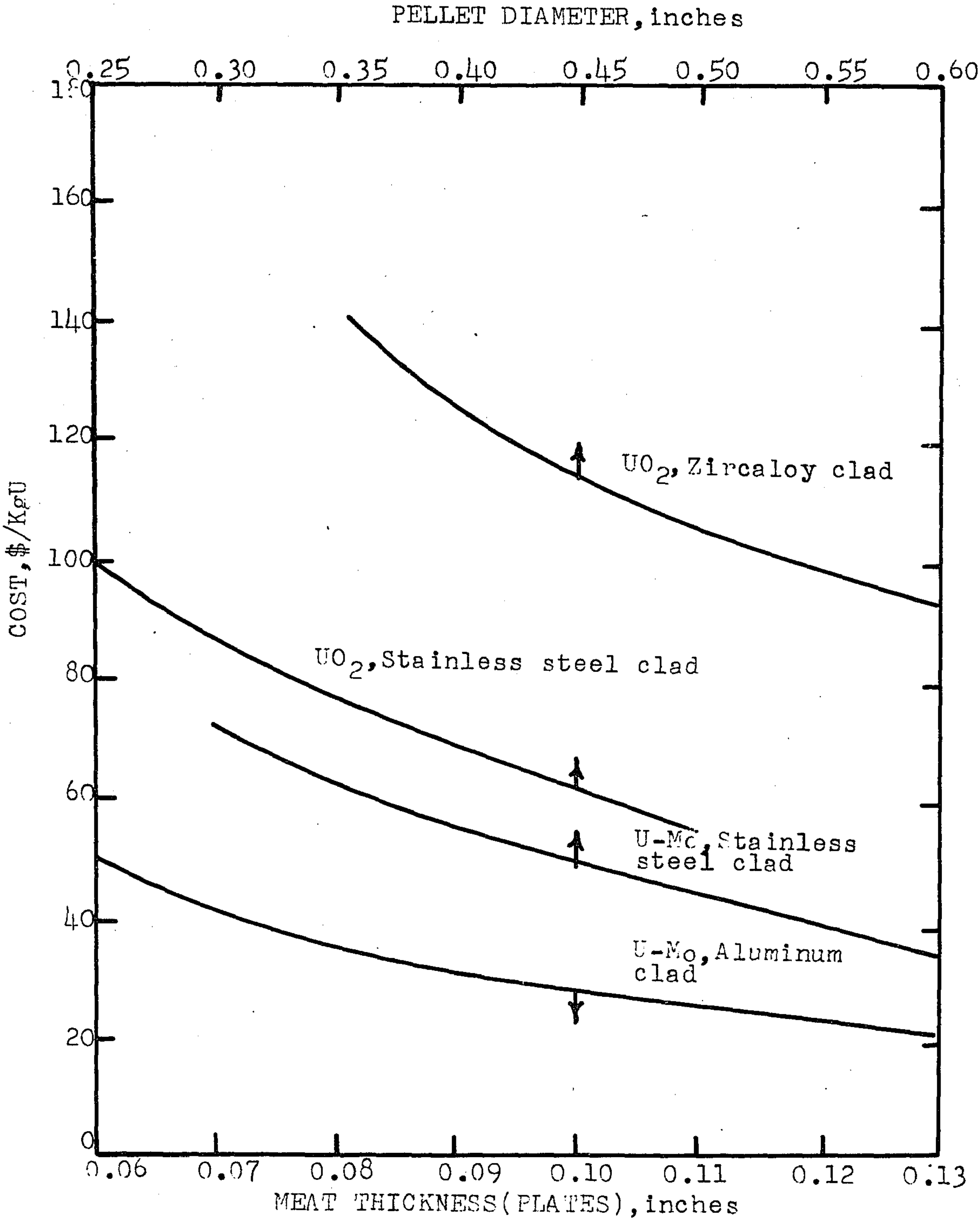

Figure 17. Average fabrication costs

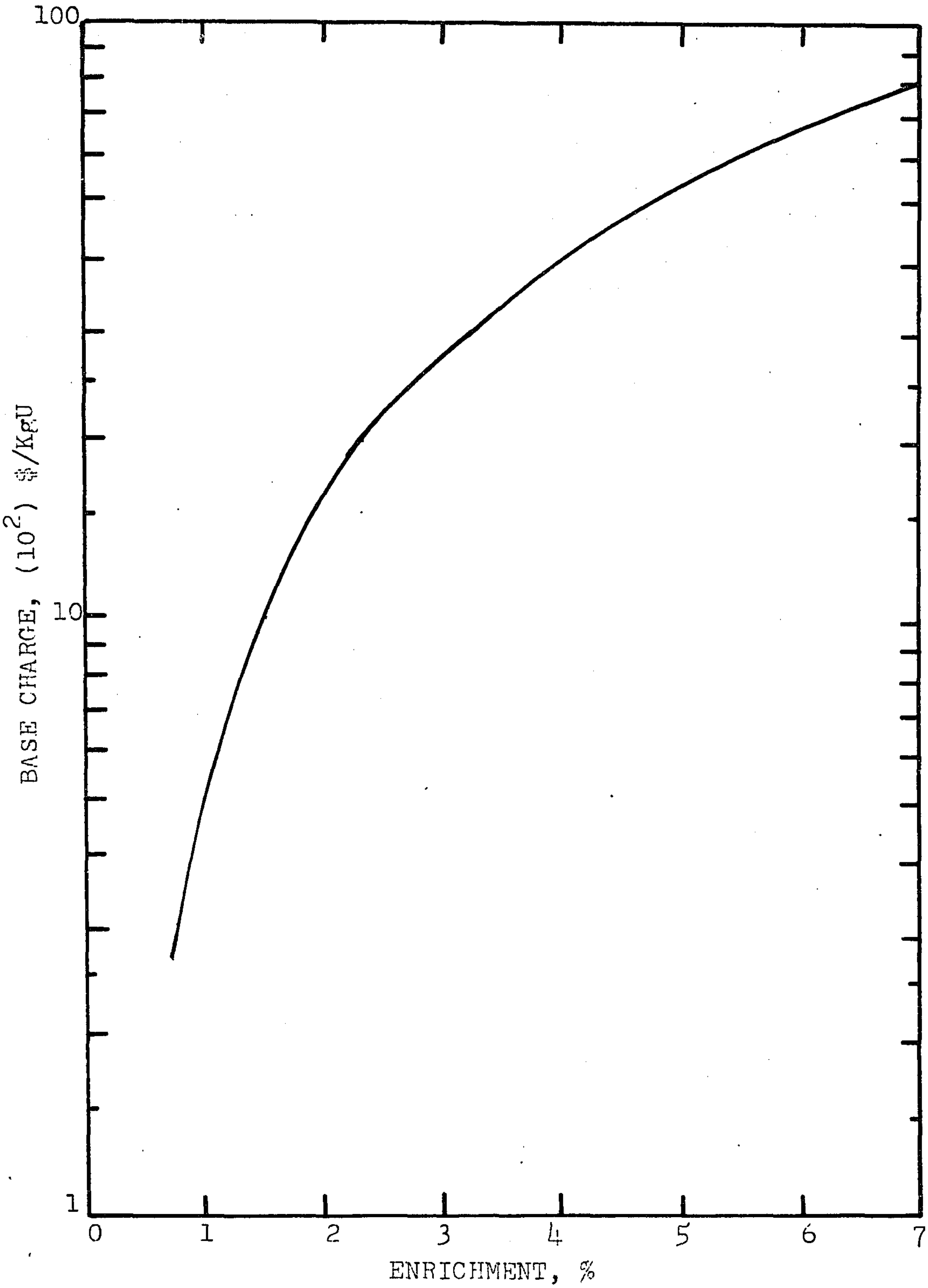

Figure 18. Base charges for enriched uranium, as UF_6 (16)

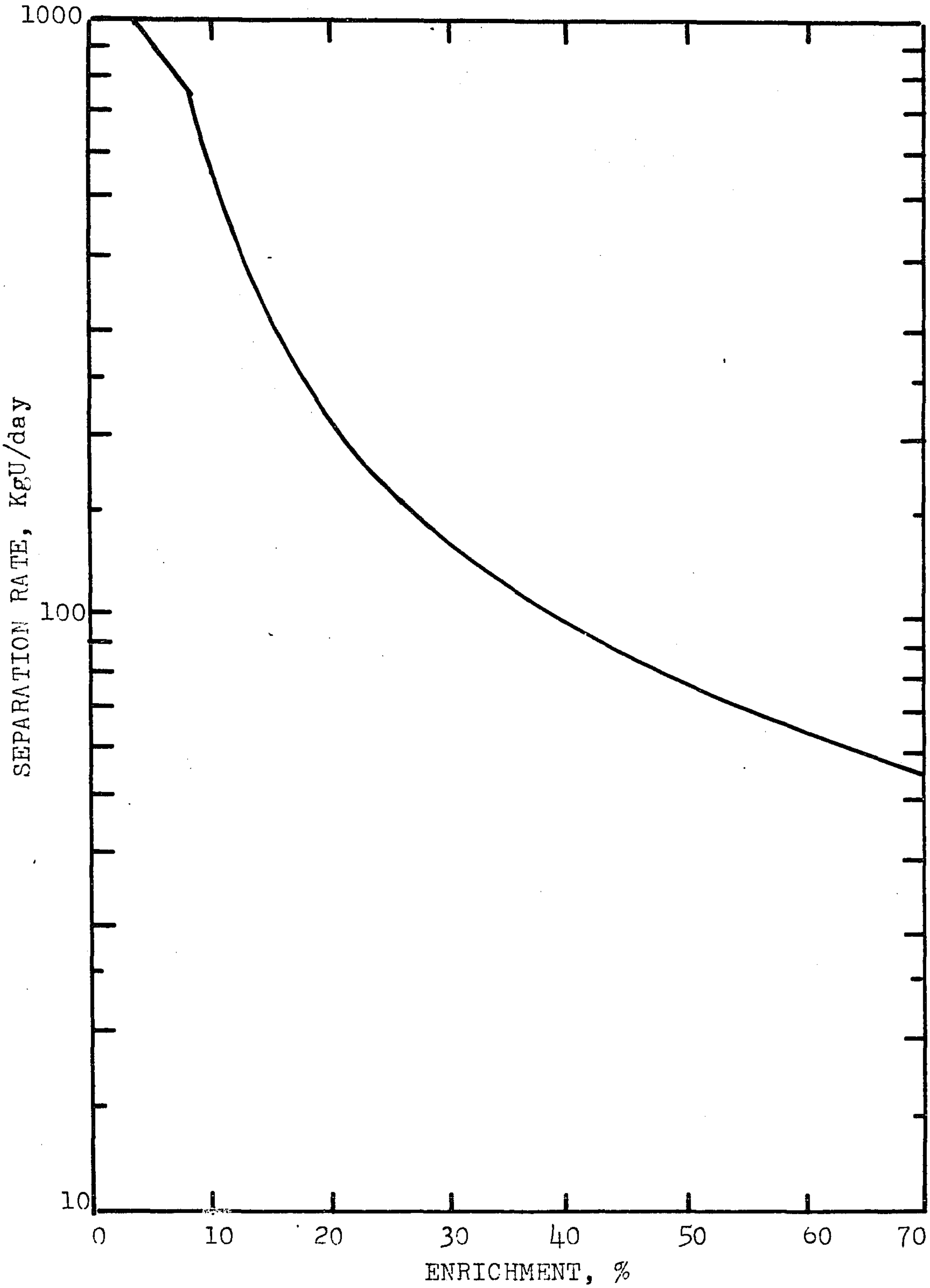

Figure 19. Separation plant capacity (16)

The chemical separation plant processing rate and the base charges for enriched uranium and UF_6 are given in Figures 19 and 20 respectively (16).

Assumed values for various parameters are listed under the values column in Table 15. Many of the assumed values are averages of quantities for present nuclear plants or educated guesses by the AEC and industry. In a more detailed study each of the assumptions could be calculated. Bringing together Equations 113 - 136 according to each second subscript and using the assumed values of Table 15 one has in \$/Kg U

$$F_1 = m + n \tag{137}$$

$$F_2 = 3.33 \tag{138}$$

$$F_3 = 1.3(10^{-4}) s \; (44.4 + 8.4 \; ki) \tag{139}$$

$$F_3 = 0.02 \; s \tag{140}$$

$$R_3 = 1.3(10^{-4}) \left\{ 30 \; s + 120 \left(\frac{j}{i}\right) t + \left[\frac{ie}{2gB} \left(\frac{4}{i} + 1\right) s + \left(\frac{j}{i}\right) t\right]\right\} \tag{141}$$

$$R_4 = s - \left(\frac{j}{i}\right) t \tag{142}$$

$$R_5 = -9.5 \left(\frac{j}{i}\right) f \tag{143}$$

$$P_1 = \left(\frac{j}{i}\right)\left[\left(\frac{17.75}{U}\right) + 5.55 + 1.48f\right] + \left(\frac{17.75z}{ik}\right) \tag{144}$$

$$P_2 = 16.99\left(\frac{j}{i}\right) \tag{145}$$

$$P_3 = 1.3(10^{-4}) \left(\frac{j}{i}\right) s \left[55 + ik \left(\frac{1}{U} + \frac{0.98}{V}\right)\right] \tag{146}$$

$$P_4 = 1.3(10^{-2}) \left(\frac{j}{i}\right) t \tag{147}$$

$$P_5 = 0.19\left(\frac{j}{i}\right)^f \quad (148)$$

If one defines

$$U_{oo} = \sum_{j=1}^{5} \sum_{c=1}^{5} (F_{ij} + R_{ij} + P_{ij}) \quad (149)$$

one can obtain a fuel cost of mills/KWH

$$U_o = \frac{U_{oo}}{24e\left(\frac{h}{g}\right)} \text{ mills/KWH} \quad (150)$$

In order to calculate fuel costs for specific nuclear reactors still other assumptions must be made. These assumptions listed in Table 16 are taken from Reference 19.

Table 16. Fuel parameters for specific reactors (19)

Description	PWR	BWR	SGR	FBR
Fuel composition	UO_2	UO_2	U-10Mo	U-10Mo
Diameter of fuel element, in	0.3	0.5	0.58	0.158
Cladding material	ss	Zr	ss	Zr
Fuel enrichment charged, %	3.1	2.0	3.0	21.0
Fuel enrichment discharged, %	2.1	1.0	2.5	19.5
Average burnup, MWD/T	15,000	15,000	11,000	16,550[1]
Plutonium concentration in discharge, gm/KgU	7.0	5.3	1.7	27.4[2]
Fuel management	1/3	1/3	1/2	1
Power plant efficiency, %	28	28	30	30

[1]Equivalent MWD/T for core

[2]Plutonium generated in blanket

In order to calculate fuel cycle costs the initial core loading must be known. This loading will vary greatly with individual reactors. However for purposes of this study calculations of core loading as a function of plant size were made (19). These equations are

$$i\ (PWR) = 0.236x\ MTU \tag{151}$$

$$i\ (BWR) = -5.78(10^{-4})x^2 + 0.36x\ MTU \tag{152}$$

$$i\ (SGR) = -3.25(10^{-4})x^2 + 0.202x + 20\ MTU \tag{153}$$

$$i\ (FBR) = 0.054x + 43\ MTU\ (blanket) \tag{154}$$

$$i\ (FBR) = 0.0215x + 5.3\ MTU\ (core) \tag{155}$$

$$75MW \leq x \leq 300MW$$

Using the assumptions listed in Table 16, final fuel cycle cost equations can be derived. The equations have the form

$$Uo = F_3 + \frac{G_3}{x} + E_3x + H_3 \tag{156}$$

where these constants are listed in Table 17.

Table 17. Constants for Equation 156

	F_3	G_3	E_3	H_3
BWR	2.33	$1.91(7.05 + \frac{1}{B})$	$3.6(10^{-4})\ (0.304 - \frac{1}{B})$	$\frac{0.224}{B}$
PWR	2.38	$3.04(6.23 + \frac{1}{B})$	---	$\frac{0.315}{B}$
SGR	2.03	$3.36(1.48 + \frac{1}{B})$	$4.82(10^{-4})(0.045 - \frac{1}{B})$	$\frac{0.30}{B}$
FBR	7.24	7.15	$4.80(10^{-3})$	0.21

Operation and maintenance, nuclear insurance

Operation and maintenance cost estimates include supervision and engineering, station labor plus 20% fringe benefits, operating supplies and maintenance materials and services. Nuclear insurance premium include all risk property insurance, nuclear liability insurance, and government indemnity. Operation and maintenance costs as well as nuclear insurance are shown in Figure 13. The equations for operation and maintenance and nuclear insurance are of the form

$$0 = E_2 x + F_2 + \frac{G_2}{x} \tag{157}$$

where the constants are given in Table 18.

Table 18. Coefficients for Equation 157

Reactor	E_2	F_2	G_2
BWR	$-8.0(10^{-3})$	7.20	380
PWR	$-8.0(10^{-3})$	7.20	380
SGR	$-7.5(10^{-3})$	7.75	390
FBR	$-8.0(10^{-3})$	8.60	380

ECONOMIC ANALYSIS

Simplication of Cost Equations

For nuclear plants four basic equations were derived for each type of power plant. Future nuclear costs are rather difficult to estimate. Walsh (28) uses a learning curve method to estimate future nuclear power costs. Figure 18 of that reference lists a series of curves to determine future nuclear power costs. An equation fitting the data in that figure was calculated; however an adjustment was made because the curves were derived on a fixed dollar basis. Since in this report extrapolations are used from past cost data, current dollar basis is used. The adjusted curve is

$$Y = (10^{-3})\ y^2 - 0.1652\ \ y + 7.4 \text{ (normalized to 1962)} \quad (158)$$

This curve is applied to both nuclear capital costs as well as nuclear fuel costs.

The same yearly factor that was applied to the conventional capital costs was applied to the conventional portion of the nuclear capital costs. Similarly the same yearly factor that was applied to the conventional power plant was applied to the operation and maintenance expenses of a nuclear power plant. The operation costs in a nuclear power plant are somewhat higher than those in a conventional power plant. However it is reasonable to expect that the ratio of the two costs should remain relatively constant.

The yearly cost factors used for conventional plants are of an exponential form which is a rather difficult form to handle in this economic analysis. Therefore the exponentials are approximated by linear functions as follows:

$$e^{-0.01(y-62)} \approx 1.62 - 0.01y \qquad (159)$$

$$e^{-0.019(y-62)} \approx 2.178 - 0.019y \qquad (160)$$

The errors in these approximations are 2% and 7.5% in the year 1980, the maximum year for this study. It would seem that 7.5% error would be somewhat high; however the points in Figure 14 are fairly scattered. This yearly factor is applied to operation and maintenance costs which are small. Therefore the error in the final analysis will be small.

Using the above factors we arrive at the following basic cost equations.

fuel: $f_c = (1.62-0.01y)\,[0.512(y-62)+f_o]\left[A_3x + B_3 + \frac{C_1}{x}\right](10^{-5}) \qquad (161)$

fixed charges: $F_c = \frac{0.1141R}{I}\,(0.4234 + 0.0093x)\left[A_1x + B_1 + \frac{C_1}{x}\right] \qquad (162)$

operation and maintenance: $O_c = \frac{0.1141}{I}\,(2.178 - 0.019y)\left[A_2x + B_2 + \frac{C_2}{x}\right] \qquad (163)$

where

f_o = 1962 conventional coal cost

R = fixed charge rate

I = load factor

A_3, B_3, and C_3 are given in Table 3

A_1, B_1, and C_1 are given in Table 2

A_2, B_2, and C_2 are given in Table 4 nuclear power

fuel: $$f_N = \left[(10^{-3})y^2 - 0.1652y + 7.4\right]\left[E_3x + F_3 + H_3 + \frac{G_3}{x}\right] \quad (164)$$

fixed charges, conventional:

$$F_{NC} = \frac{0.1141R}{I}\,(0.4234 + 0.0093Y)\left[D_c x^2 + E_c + F_c + \frac{G_c}{x}\right] \quad (165)$$

fixed charges, nuclear:

$$F_{NM} = \frac{0.1141R}{I}\left[(10^{-3})y^2 - 0.1652y + 7.4\right]\left[D_n x^2 + E_n x + F_n + \frac{G_n}{x}\right] \quad (166)$$

operation and maintenance:

$$O_N = \frac{0.1141}{I}\,(2.178 - 0.019y)\left(E_2x + F_2 + \frac{G_2}{x}\right) \quad (167)$$

where I = load factor

E_3, F_3, H_3, and G_3 are listed in Table 20

D_c, E_c, F_c, and G_c are listed in Table 13

D_n, E_n, F_n, and G_n are listed in Table 13

E_2, F_2, and G_2 are listed in Table 21

Solution of Equations

To get an equation of plant size versus year i.e. a locus of points that nuclear power will be economically competitive with conventional power, one sets

$$f_c + F_c + O_c = f_N + F_{NC} + F_{NN} + O_N$$

where I and f_o are parameters. The equation is of second order in terms of the year; therefore the equation can be solved for y in terms of x.

$$y = \frac{-\nu + \sqrt{\nu^2 - 4\mu\omega}}{2\mu} \quad (168)$$

where $\mu = -5.12(10^{-8})\ x_{3c} - 1.083(10^{-3})\epsilon$

$$\nu = (1.147 - 0.01f_o)10^{-5}\ x_{3c} + 9.3(10^{-3})\beta - 0.019\,\delta + 0.181\epsilon$$

$$\omega = (1.62f_o - 51.43)10^{-5}\ x_{3c} + 0.4234\beta + 2.178\,\delta - 8.05\epsilon$$

$$\alpha = \frac{0.1141R}{I}$$

$$\beta = (x_{1c} - x_{Nc})$$

$$\delta = \frac{0.1141}{I}(x_{2c} - x_{2N})$$

$$\epsilon = (x_{3N} + \alpha x_{NN})$$

R = fixed charge rate (14% used in this study)

I = load factor

f_o = 1962 coal cost in ¢/10^6BTU

$$x_{1c} = A_1x + B_1 + \frac{C_1}{x}$$

$$x_{2c} = A_2x + B_2 + \frac{C_2}{x}$$

$$x_{3c} = A_3x + B_3 + \frac{C_3}{x}$$

$$x_{NC} = D_cx^2 + E_cx + F_c + \frac{G_c}{x}$$

$$x_{NN} = D_Nx^2 + E_Nx + F_N + \frac{G_N}{x}$$

$$x_{2N} = E_2x + F_2 + \frac{G_2}{x}$$

$$x_{3N} = E_3x + F_3 + H_3 + \frac{G_3}{x}$$

Five different sizes of units 100, 150, 200, 250, and 300 MW were used in solving for the year. These points were then joined by a smooth curve.

The solutions of Equation 168 for various values of the parameters are shown in Figures 20, 21, 22, and 23. The solutions of Equation 168 for both light water reactors are very nearly the same; therefore no distinction will be made between the two types of reactors. Only one curve is shown for the SGR since it probably will not be competitive until the middle of the next decade. The FBR, which has tremendous future promise, should not be economically competitive with conventional power in the next two decades.

For the light water reactors three load factors and three conventional costs were applied each for first and second unit conventional plants. Therefore there are 18 curves describing the light water reactors. It is assumed that third and subsequent units will be at or near the cost of a second unit.

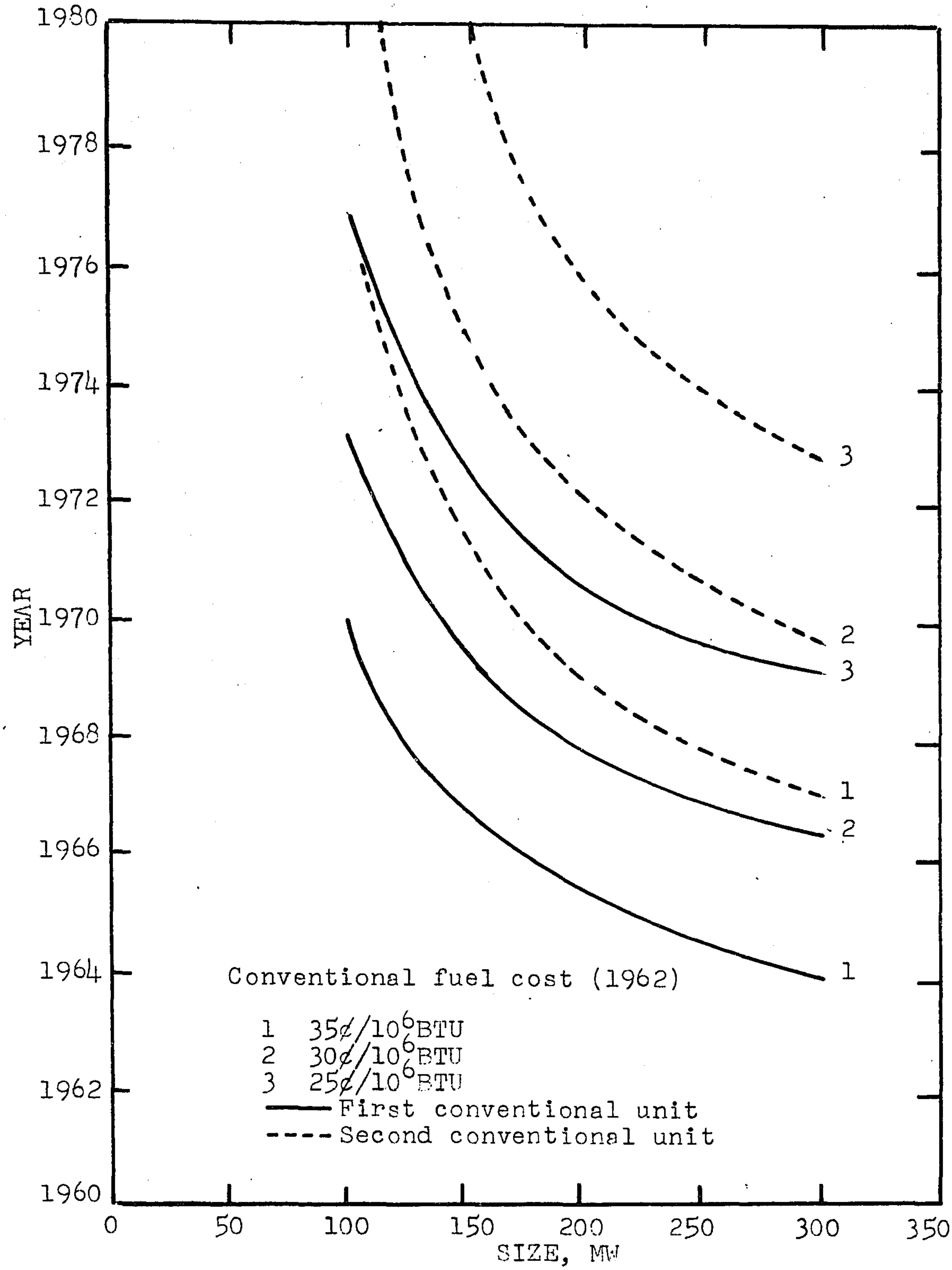

Figure 20. Curves for economic nuclear power, 90% load factor light water moderated reactors

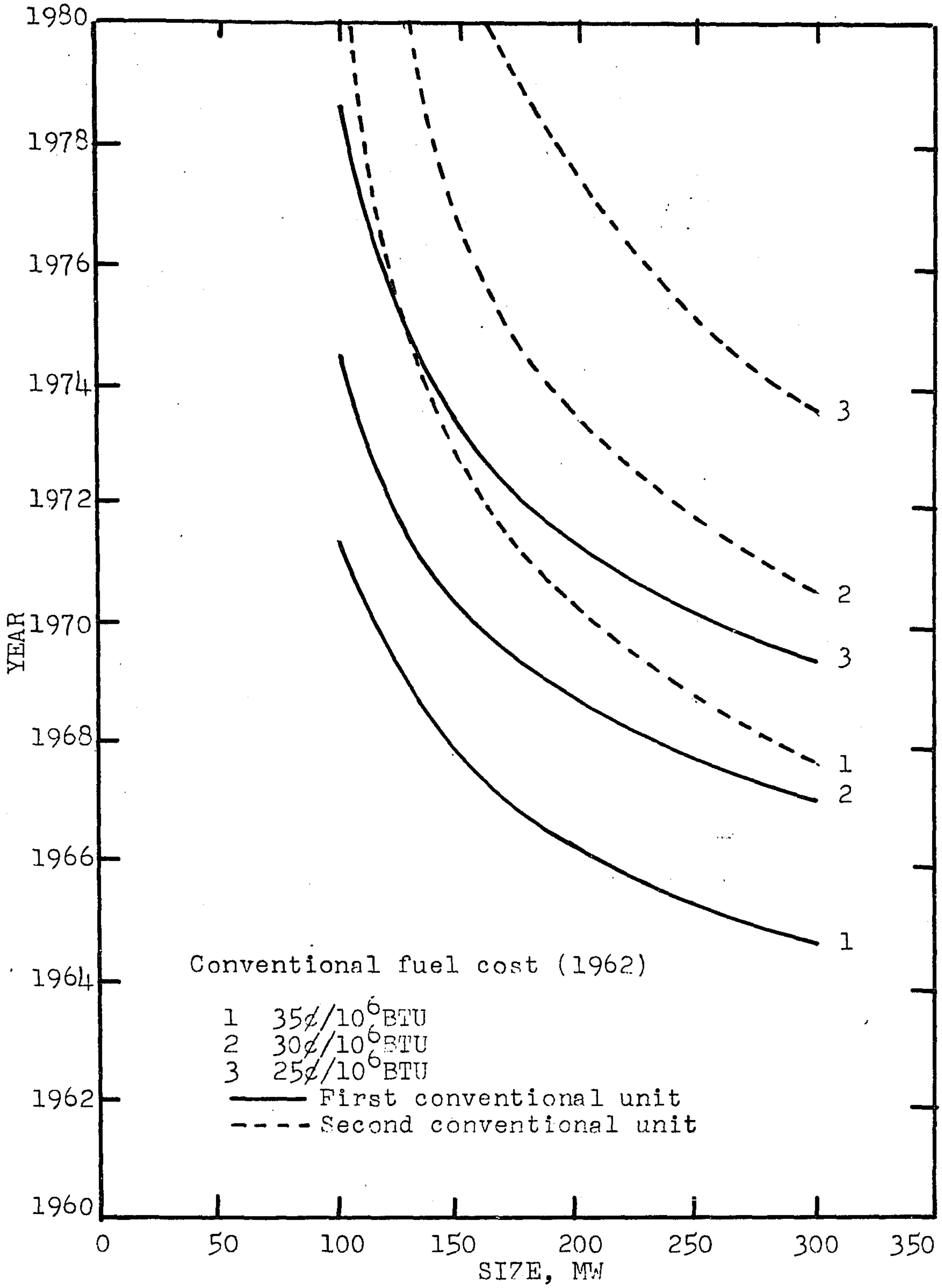

Figure 21. Curves for economic nuclear power, 80% load factor light water moderated reactors

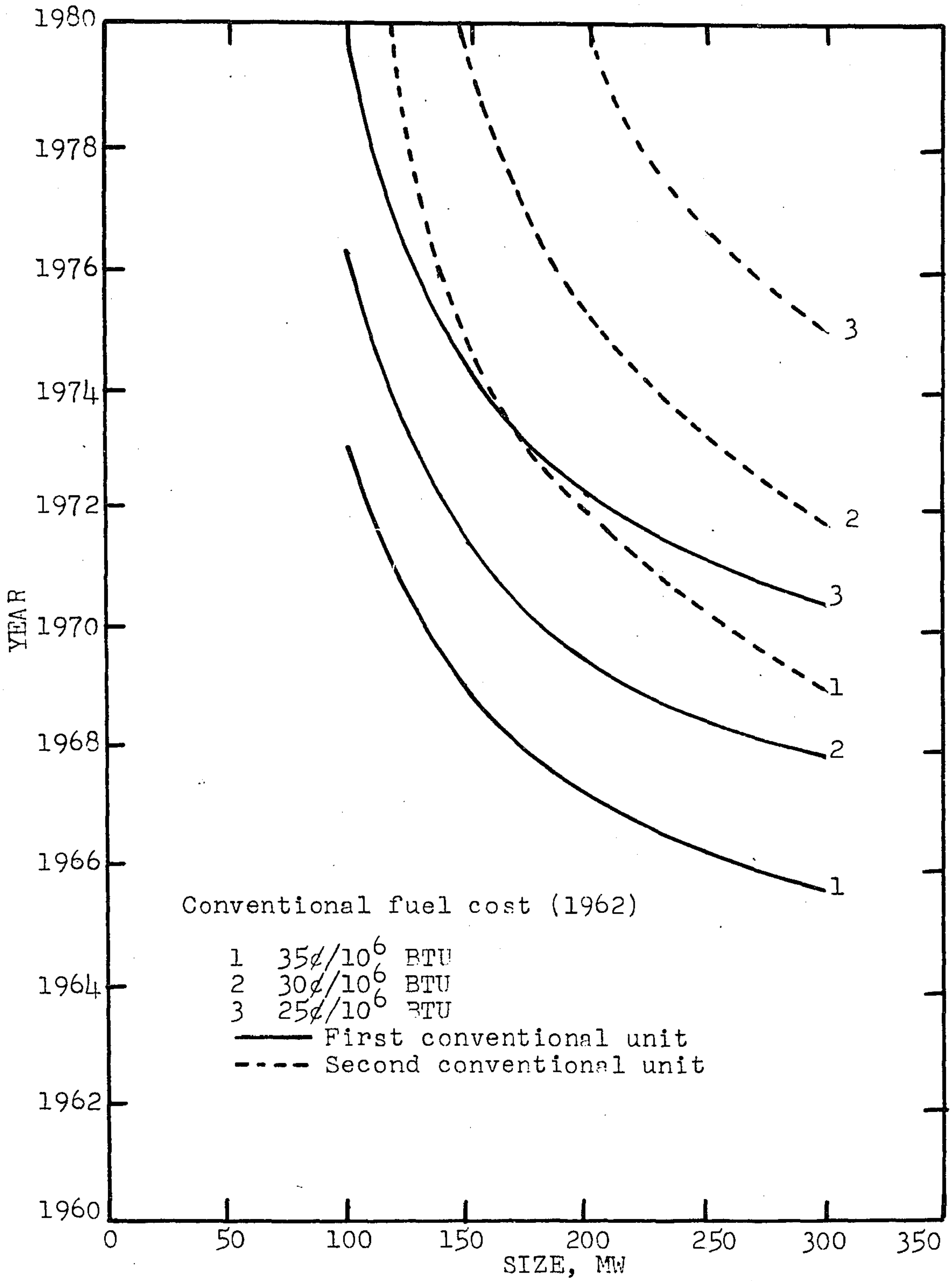

Figure 22. Curves for economic nuclear power, 70% load factor light water moderated reactors

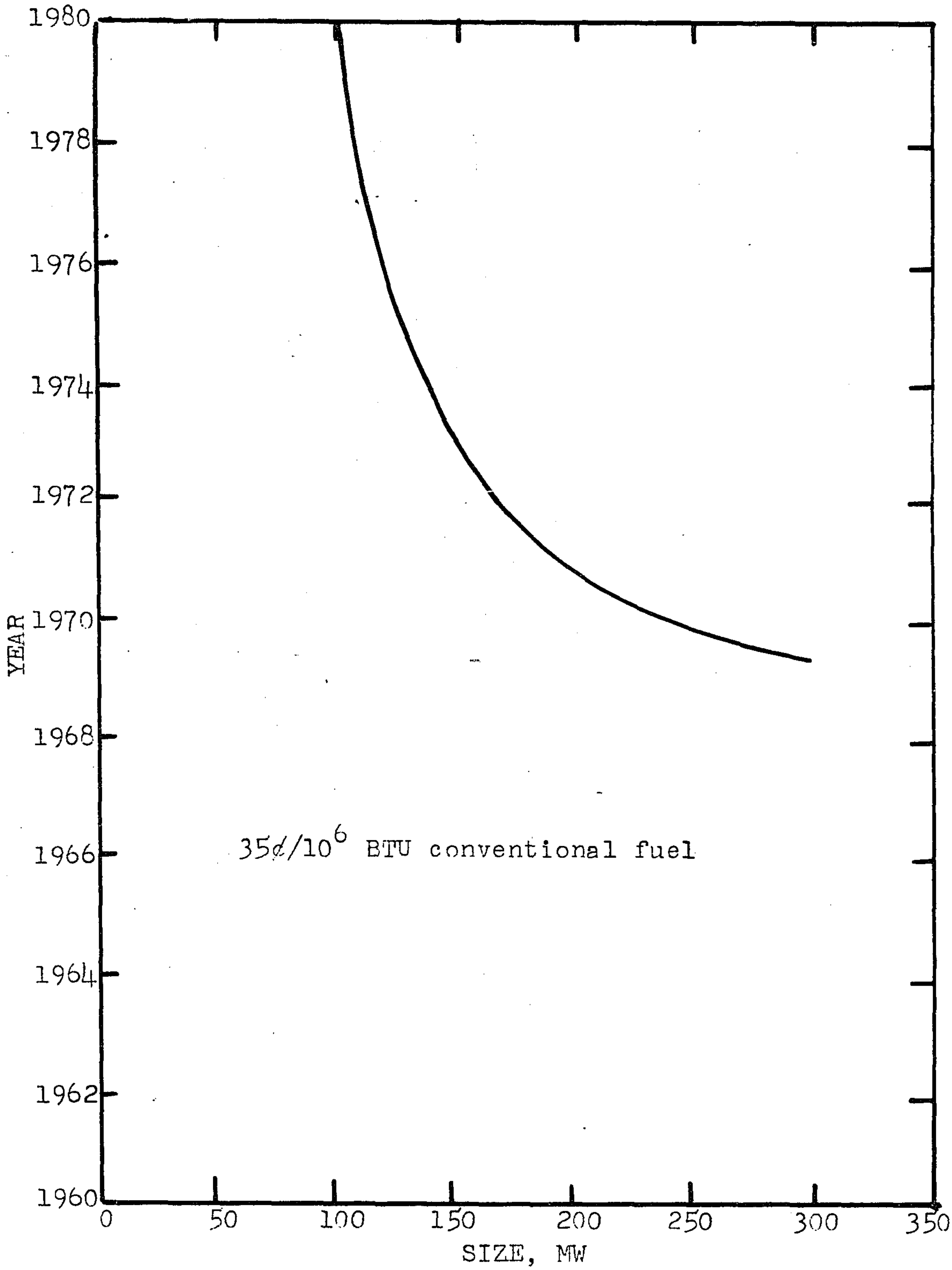

Figure 23. Curves for economic nuclear power, 90% load factor, SGR

DISCUSSION OF RESULTS

The application of these results should help to determine the economic feasibility of building a nuclear power plant rather than a conventional coal fired plant. Table 19 lists predicted locations and sizes of future units for the private utilities of Iowa.

By checking each unit against Figures 21, 22, and 23 one can predict the economic feasibility of building a nuclear power plant rather than a conventional power plant. The method of analysis is to take the conventional plant size and date of completion and locate that point on the figure of proper load factor. Then locate the curve (or extrapolated curve) of constant 1962 coal cost. If the point is below the curve the conventional plant is cheaper, but if the point is above the curve the nuclear plant is cheaper.

In most AEC studies a load factor of 80% and a fixed charge rate of 14% are assumed. Therefore using these values a comparison is made of the predicted plants in Table 19. The first nuclear power plant to be competitive in Iowa should be a 150 MW unit at Charles City in 1970. It is marginal whether a 150 MW one should be competitive at Cedar Rapids in 1970. The next one to be competitive should be a 200 MW nuclear unit replacing the second unit at Lansing in 1973. After 1975 water moderated nuclear plants should be competitive with all conventional coal plants but one.

Table 19. Predicted future power plants

Plant	Co.	Instal-lation Year	Unit	MW	1962 Fuel Cost ¢/10^6BTU	Most Economic Unit*
Riverside	IIG	1961		125	26	
Sutherland	IEL	1961		82	27½	
Fox Lake	IPC	1962		75	38	
Des Moines	IPL	1964	2	125	26	
Neal	IPS	1964	1	150	30	
Bridgeport	ISU	1965	2	56	23	C
Prairie Creek	IEL	1965	3	140	30	C
Riverside	IIG	1966	2	150	26	C
Dubuque	IPC	1967	2	150	27	C
N. Des Moines	IPL	1968	1	200	26	C
Burlington	ISU	1969	1	120	24	C
Charles City	IPS	1970	1	150	34	N
Cedar Rapids	IEL	1970	1	200	32	C or N
Davenport	IIG	1971	1	200	25	C
Council Bluffs	IPL	1972	3	200	28	C
Lansing	IPC	1973	2	225	27	N
Sutherland	IEP	1974	2	250	27½	C or N
Neal	IPS	1974	2	175	30	C or N
N. Des Moines	IPL	1975	2	275	26	N
Bridgeport	ISU	1976	3	150	23	C
Davenport	IIG	1977	2	350	25	N
Fox Lake	IPC	1978	2	225	38	N
Des Moines	IPL	1979	1	375	26	N
Waterloo	IPS	1979	1	200	28	N
Cedar Rapids	IEL	1980	2	250	32	N
Davenport	IIG	1981	3	350	25	N
Dubuque	IPC	1982	2	250	27	N
Bridgeport	ISU	1982	1	150	23	N

*C - Conventional N - Nuclear

SUMMARY

The purpose of this thesis was two-fold. It is the author's hope that a detailed cost analysis of a nuclear power plant will help cost estimators make a quick and accurate estimate of any major part of a nuclear plant. Equations should help in minimizing costs in those areas where the equations are functions of physical quantities.

The fuel cycle cost breakdown should help anyone make a quick and reasonably accurate estimate of the fuel costs for various nuclear reactors. These equations could be useful in optimizing reactor parameters especially where digital computers are used. Therefore a large number of variables can be handled.

The second purpose of the thesis was to predict with reasonable accuracy the future of nuclear power with respect to an economic viewpoint. The final results seem to be in agreement with other estimates (11).

Possible future studies could include computer studies using many parameters such as temperature, pressure, basic reactor parameters, fixed charge rate, etc., as well as load factor and conventional fuel cost. Future studies also could include an analysis of conventional power plants. Thus if one equated the cost of similar equipment in each type of power plant, the final analysis due to fixed charges would only include a comparison between boiler plant equipment and reactor plant equipment.

LITERATURE CITED

1. Budge, W. L. and Lloyd, B. L. Economic atomic power - when? American Power Conference Proceeding. 22: 106-117. 1960.

2. Corcoran, W. P. Core parameter study for a 300 MW sodium graphite reactor. U. S. Atomic Energy Report NAA-SR-Memo-4486. [North American Aviation, Inc., Downey, Calif.]. 1959.

3. IAEA examines reactor costs. Nuclear Power. 5, No. 54: 87. October, 1960.

4. Lane, J. A. How to design reactor shields for lowest cost. Nucleonics. 13, No. 6: 56-58. June, 1955.

5. Lewis, W. B. Outlook for competitive nuclear power - interview. Nucleonics. 18, No. 1: 68-72. January, 1960.

6. Nuclear power plants; the long view. Nucleonics. 21, No. 6: 59-82. June, 1963.

7. Report on fuel outlook I. Electrical World. 149, No. 21: 101-104. May 26, 1958.

8. Rohach, A. F. Economics of nuclear power. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. Ames, Iowa. 1961.

9. See 8,000 MW atomic capacity by '66. Electrical World. 154, No. 20: 65. November 14, 1962.

10. U. S. Atomic Energy Commission. Boiling water reactor study. I. 306 MW power reactor conceptual design. U. S. Atomic Energy Commission Report TID-8500. [Technical Information Service Extension, AEC]. July, 1959.

11. __________. Civilian nuclear power appendices to a report to the President-1962. U. S. Atomic Energy Commission. Washington, D.C. 1962.

12. __________. Civilian power reactor program. I. Summary of technical and economic states as of 1959. U. S. Atomic Energy Commission Report TID-8516. [Technical Information Service Extension, AEC]. 1960.

13. __________. Guide to nuclear power cost evaluation. I. Reference data and standards. U. S. Atomic Energy Commission Report TID-7025. [Technical Information Service Extension, AEC]. March, 1962.

14. __________. Guide to nuclear power cost evaluation. II. Land, improvements, building, and structures. U. S. Atomic Energy Commission Report TID-7025. [Technical Information Service Extension, AEC]. March, 1962.

15. __________. Guide to nuclear power cost evaluation. III. Equipment costs. U. S. Atomic Energy Commission Report TID-7025. [Technical Information Service Extension, AEC]. March, 1962.

16. __________. Guide to nuclear power cost evaluation. IV. Fuel cycle costs. U. S. Atomic Energy Commission Report TID-7025. [Technical Information Service Extension, AEC]. March, 1962.

17. __________. Guide to nuclear power cost evaluation. V. Production costs. U. S. Atomic Energy Commission Report TID-7025. [Technical Information Service Extension, AEC]. March, 1962.

18. __________. Nuclear power and utility systems. U. S. Atomic Energy Commission Report TID-15329. [Technical Information Service Extension, AEC]. April, 1962.

19. __________. Power cost normalization studies civilian power reactor program-1959. U. S. Atomic Energy Commission Report SL-1674. [Sargent and Lundy, Chicago]. January, 1960.

20. __________. Status report for sodium graphite reactors. U. S. Atomic Energy Report NAA-SR-Memo-4156. [North American Aviation, Inc., Downey, Calif.]. 1959.

21. __________. Steam-cooled power-reactor evaluation. U. S. Atomic Energy Commission Report TID-8536. [Technical Information Service Extension, AEC]. April, 1961.

22. __________. Steam cooled power reactor evaluation capital and power generation costs. U. S. Atomic Energy Commission Report TID-12747. [Technical Information Service Extension, AEC]. March, 1961.

23. U. S. Federal Power Commission. Statistics of electric utilities in the United States, 1961. U. S. Federal Power Commission Report FPC-S-155. 1961.

24. __________. Electric power statistics. U. S. Federal Power Commission Report. Washington, D.C. 1962.

25. __________. Steam-electric plant construction cost and annual supplement, 1961. U. S. Federal Power Commission Report. Washington, D.C. 1961.

26. U. S. National Archives. Federal Register. 26, No. 103: 4765-4766. May 31, 1961.

27. U. S. power reactor report progress. Nucleonics. 21, No. 1: 22-23. January, 1963.

28. Walsh, E. M. Economics of nuclear power for Iowa. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology, Ames, Iowa. 1963.

29. What may be ahead in power production. Mechanical Engineering. 82, No. 5: 61-65. May, 1960.

ACKNOWLEDGEMENTS

The author wishes to acknowledge his gratitude to Dr. Glenn Murphy, Head of the Department of Nuclear Engineering, for his interest and encouragement throughout this study.

Gratitude is expressed to the Iowa Power and Light Company for making the study possible and particularly to Mr. J. W. Hummer for obtaining information on current Iowa Power Pool studies.

APPENDIX

Abbreviations used in text:

BTU	British Thermal Unit
ft	feet
gm	gram
gpm	gallons per minute
in	inches
kg	kilogram
KW	kilowatt
KWH	kilowatt hour
lb	pound
MTU	metric tons of uranium
MW	megawatt
MWD/T	megawatt day per metric ton of uranium
MWE	megawatts, electrical
MWT	megawatts, thermal
psi	pounds per square inch
RPM	revolutions per minute

Reactors:

BWR	Boiling Water Reactor
PWR	Pressurized Water Reactor
SGR	Sodium Graphite Reactor
FBR	Fast Breeder Reactor

Turbines:

SC	Single Casing Unit
TCSF	Tandem Compound single flow
TCDF	Tandem Compound double flow
TCTF	Tandem Compound triple flow
TCQF	Tandem Compound quadruple flow

Private Utilities in Iowa:

IEL	Iowa Electric Light and Power Company
IIG	Iowa and Illinois Gas and Electric Company
IPC	Interstate Power Company
IPL	Iowa Power and Light Company
IPS	Iowa Public Service
ISU	Iowa Southern Utilities

Steam Stations of Iowa Private Utilities (1961 data):

Plant	Co.	MW
Beaver Channel	IPC	17.3
Big Sioux	IPS	41.0
Bridgeport	ISU	66.0
Council Bluffs	IPL	130.6
Des Moines	IPL	211.0
Dubuque	IPC	93.8
Fox Lake	IPC	23.0
Lansing	IPC	66.3
Maynard Street	IPS	117.4
Moline	IIG	99.1
Prairie Creek	IEL*	96.0

Plant	Co.	MW
Riverside	IIG	244.5
Sutherland	IEL	156.6

*Owned by Central Iowa Power Cooperative but operated by IEL.