APPLICATION OF THE LEARNING CURVE TECHNIQUE TO NUCLEAR POWER PRODUCTION

by

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I. INTRODUCTION

The important question in the nuclear power industry is no longer when will nuclear power be competitive but what will be the future cost of electrical power produced by nuclear power stations. In this thesis it is shown that for pressurized and boiling water reactors there is a sufficient rate of decrease in costs to allow a prediction to be made for future costs. This prediction can be made if only the cumulative capacity and the proposed size of the reactor is known. Therefore, the required input information for this prediction is quite minimal.

The basic premise of this thesis is that the nuclear industry is similar to many other industries. That is as technological advances are developed, more definite designs are produced, and as experience is gained in the nuclear industry, the total construction cost and the cost of electrical energy which these plants produce will decrease. This premise is based on the concept which goes under many names but the majority of the time is referred to as the manufacturing progress function or the learning curve. The principle on which this concept is based is that the cost required to produce the 2Nth unit is a constant fraction less than the effort required to produce the Nth unit. During a long production run this constant fraction may change and thus for a total production cycle it is possible to obtain a number of constant fractions.

This concept, therefore, is applicable in industry to estimate cost, for example, to be used in contracting. It can also be used by management to view the progress and area deficiency in a production cycle.

In this thesis the economic areas of total construction cost and total power production costs are examined by the learning curve technique with total power production costs being examined in detail. Some of the operating characteristics are also examined. Consideration of burnup and thermal efficiency is very important since they directly effect power costs. Whether these two operating characteristics decrease or increase will have a substantial economic effect on the rapidly growing nuclear industry.

The examination of future fuel costs is also considered since fuel costs have such a great effect on the cost of electrical power. The advent of the high gain breeder into the utility system, for example, will also have an effect on future fuel costs and power costs.

By evaluating all of this information one will see an overall trend of learning in the civilian nuclear power industry. Areas of more rapid decline in cost as well as areas of slower cost decline will also be seen. Some reasons for these trends are also considered and discussed.

II. REVIEW OF LITERATURE

The latest study made on the applicability of the learning curve technique to the nuclear industry appears to have been in 1965 when Merritt (14) applied this technique to the economics of nuclear power. His investigation, however, was quite limited due to the lack of sufficient data.

The learning curve technique up to 1965 was mostly centered around the more conventional mass production type industries. In 1954 Andress (1) published an article on the application of the learning curve to the aircraft industry. In 1959 Conway and Schultz (3) published a more detailed analysis of the learning curve. They presented the application of the learning theory to complex low volume products in addition to its better known application to high volume operations. In 1961 Garg and Milliman (9) published an article which describes the deficiencies which may appear in a given application of the learning technique unless it is modified for design changes as these changes occur. The additional use of the learning curve technique in establishing management goals during a production cycle was discussed by White (28) in 1961. Hirshmann (10) in 1964 discussed the application of this technique to the petroleum processing industry with respect to start up operations. He also describes how different affects such as obsolescence and inflation will effect the prediction made by the learning technique. In 1966 Young (29) published an article which dealt with some of the pitfalls which may come about through the use of the learning curve technique. He explains how many factors which tend to indicate a learning are in effect failures by management due to an overload or surplus of manpower at the start of a production cycle.

Some of the nuclear power cost data came from periodicals such as Nuclear News (19) and the annual nuclear power reports of Electrical World (6, 20). Private communications, however, had to be used in many cases due to the lack of published data. The major sources used to interpret the economic data obtained were AEC publications (21, 22, 23).

The articles published by Nordman, Smith, and Wright (16, 17) were very useful in discussing future fuel costs. These articles contain predictions on when the fast breeder will enter the utility systems and what their effect will be on future fuel requirements. Other items which may effect not only fuel costs, but the total costs of nuclear power are discussed in the report Small Nuclear Power Plants (25). In this report, many areas in nuclear power production where learning is taking place or could possibly take place in the future are explained.

III. THEORY OF THE LEARNING CURVE

The basic theory of the learning curve is simply the graphical or mathematical representation of the skill that an operator gains as he continually repeats his assigned task. This learning or skill that the operator gains will normally increase his efficiency and thus it will take him less time to perform the same given task. With this increase in efficiency, there will be an increase in the number of units a worker will complete within a given amount of labor hours. There also will be a decrease in cost per unit. Therefore, the amount of time required for every doubled quantity, or the 2Nth quantity, will be decreased by a given amount. These results can be used to estimate what the x quantity will cost or how many labor hours will be required per unit for production. The graphical plot of these results are known as performance improvement curves, manufacturing progress functions, learning curves, and other similar titles.

The basic concepts for the learning curve originated in the aircraft industry and were first presented by Dr. T. P. Wright (27). Dr. Wright, in evaluating a particular airplane model, had observed from cost and time studies that the diminishing costs and increasing quantity may be represented by the following mathematical model (27)

$$y = Kx^{-n} \qquad (1)$$

where

y = cumulative average labor hours for x number of like units (total hours required divided by the total units produced)

K = labor hours required for the production of the first unit

x = number of completed whole units

n = a value which gives a measure of rate of reduction

This equation thus describes a constant percentage reduction since each time the cumulative production is increased by a constant percentage, the labor time is decreased by a constant percentage where the rate of production increase is expressed in doubled quantities. The curve can thus be described as a percentage value (27)

$$\text{per cent curve} = \frac{A_{2x}}{A_x} \qquad (2)$$

substituting into equation 1

$$\frac{A_{2x}}{A_x} = \frac{K(2x)^{-n}}{Kx^{-n}} = 2^{-n} \text{ of } \frac{1}{2^n} \qquad (2a)$$

where

A_x = average time per unit for lot size of x units

A_{2x} = average time per unit for lot size of 2x units

Representation of the learning curve, $y = Kx^{-n}$, also may be expressed by

$$\log y = \log K - n \log x \tag{3}$$

If plotted on rectangular graph paper, this equation will describe a linear function with a slope of minus n. The same results will be obtained, however, if the data are plotted directly on logarithmic graph paper. The advantage of utilizing a linear function is that the line may be extrapolated. Cost or labor hours estimates then can be taken directly from the graphs.

There are two basic types of learning curves, the unit cumulative average (UCA) curve and the unit curve (27). They are directly related to each other in that they are parallel and separated only by a constant value of (1-n) except initially when the unit curve approaches the UCA curve (27).

The factors that determine which curve is to be used are convenience and dependability. The unit cumulative average curve is plotted from average labor hours, whereas, the unit curve is plotted from the time required for one particular unit. The unit curve is thus more sensitive to small changes than the UCA curve. The UCA curve, however, is less expensive to maintain since the data requirements are not so extensive.

The learning curve, as indicated, may be represented by a linear function and thus the values or points on the curve are proportional. This proportionality can be mathematically projected and expressed as

$$\frac{Y_a}{Y_b} = \frac{kx_a^{-n}}{Kx_b^{-n}} \qquad (4a)$$

or

$$y_a x_a^n = y_b x_b^n \qquad (4b)$$

If on a 90 per cent curve, the UCA for 10 units is 100 hours, the UCA hours for 20 units can be expressed using equation 4b as follows

$$100 \times 10^{0.152} = y_b 20^{0.152}$$

or

$$y_b = 92.8 \text{ hr.}$$

If the learning curve is assumed to hold for two separate rate portions of a given task, it cannot be assumed to hold for the sum of these tasks unless the separated curves have the same slope (3). In the application to nuclear power production, this non-additative characteristic would normally preclude the addition of the fuel cycle costs curve, the operating charges curve, and the fixed charges curve in order to determine the total rate of cost reduction for total power production costs. This characteristic, however, does not preclude the use of individual points from these curves to give the total power cost at a give cumulative capacity.

To obtain an estimate by use of the learning curve, one needs only to extrapolate the linear function on the graph so it includes the desired information. It is possible, however, for the slope of the curve to change in value during a production cycle (27). This will normally occur when there is a design change or after the initial learning has taken place.

IV. INTRODUCTION OF THE THEORY TO NUCLEAR POWER

Management in every industry is interested in estimating production costs since this information is important for sales contracting purposes. The nuclear industry is certainly not an exception in this area because cost predictions are important not only to the vendors but also to the utilities. The utilities are interested in predictions in order that they may estimate the production costs of the electrical energy from their generating stations. Predictions are also of great interest to the utilities in order that they may plan to meet the requirements of their customers many years in the future. Both the vendors and the utilities are, therefore, interested in a prediction method that requires only a minimum amount of input in order that the cost of prediction studies may be reduced. To apply the learning curve technique to nuclear power, the only required inputs are the cumulative installed capacity committed at that time and the size of the reactor.

The trends to nuclear power as predicted by Felix (8) and presented in Figure 1 are growing quite rapidly. This trend places considerable importance on reactor vendors to remain in competition with their competitors. Establishing management goals is therefore needed and the learning curve technique should apply to the nuclear industry in this area.

The learning curve theory is predominately based on the learning of a worker as he repeats his assigned duties in an

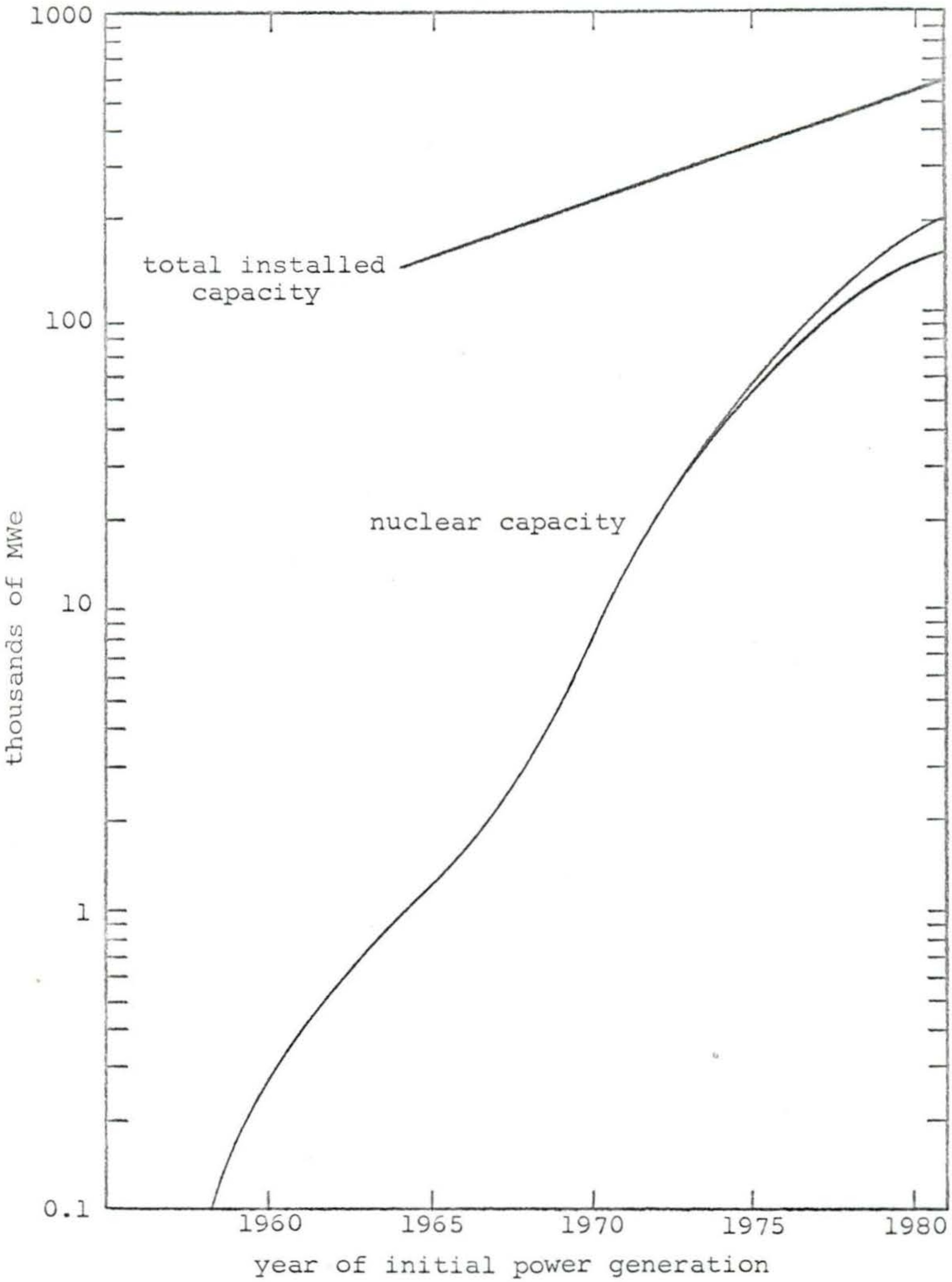

Figure 1. Trends to nuclear generation

assembly line. In nuclear power, however, the learning is based much more on technological improvements as they occur in the nuclear industry. This is true since nuclear reactors are produced only on a semi-mass production basis. It is impossible to produce reactors under a total mass production schedule because they must be constructed on different sites throughout the United States. Some of the common items can be produced, however, in one location and on a mass production schedule. These items would be in the category of common hardware.

In order to apply the learning curve technique to nuclear power production, one must decide upon the areas which he wishes to predict and how these areas will fit into the learning curve equation. The economic areas that will be discussed in this thesis are the total construction costs of a power station, the total power production costs, fuel cycle costs, fixed charges, and operating charges.

The nuclear data on total construction costs will be utilized in the learning curve equation in the following manner:

y = total dollars required for a given unit divided by the net electrical power produced, \$/kw

x = cumulative capacity of megawatts of electricity that have been committed

K = cost in dollars per kilowatt for the production of the first unit

n = the value of the slope which gives a measure of the rate of reduction of total construction costs

The learning curve equation as it will be applied to power production costs is as follows:

y = mills required for total power cost, fuel cycle costs, fixed charges, or operating charges divided by the number of kilowatt hours produced

x = cumulative capacity of megawatts of electricity committed or operating

K = cost required for production of the first unit

n = the value of the slope which gives a measure of the rate of reduction of power costs

Through the use of these equalities, the learning curve technique may be used to estimate nuclear power production costs.

Thermal efficiency and burnup will also be analyzed using this technique since they directly influence the power production costs. Construction times and start up times should also be applicable to the learning curve technique. Presently, the estimates of these times have been quite inaccurate and therefore will not be considered in this thesis.

Light water reactors will be the only reactors considered for analysis using the learning curves since they are the only types which are predominate in the nuclear industry at the present time. Of these reactors, only the ones that are located in the United States will be discussed due to the complications arising from comparison of values that are not based on the same accounting system.

The data as given in the tables are arranged by the year in which the original contracts were awarded and by size within that year. This appears to be the most practical and straight forward approach. The boiling water and pressurized water reactors will be considered jointly since very little price differential exist between these two types of reactors.

V. APPLICATION OF THE LEARNING THEORY

A. Application to Total Construction Costs

The problem is to discover whether there is an orderly decrease in the total construction cost of nuclear power plants and to determine if this decrease has been constant or changing. The term total construction costs, as used here, is intended to include structure, improvements, equipment, interest during construction, additional indirect costs, and contingencies and escalation as described in TID-8531 (21). No adjustments have been made to place interest during construction on a normalized basis. It should be emphasized that totally consistent cost figure are difficult to obtain and that caution is necessary in comparing the costs of different plants.

Most of the power plants listed in Table 1 are still in the design or construction stage, and current estimates may differ appreciably from the final costs. Costs to the plant owner that are fixed by contract may also differ from actual expenditures by the contractor. Estimates of the construction costs of specific plants have tended to increase with time and actual costs have in general exceeded the estimates.

Figure 2 presents a graphic representation of the data given in Table 1. From this figure one can see that there was initially a fairly rapid reduction in construction cost. When the cumulative capacity reaches 7,000 MWe, however, the

Table 1. Total construction cost[a]

Plant	Type	Size (MWe-Net)	Est. cost ($ x 10^{-6})	Est. cost ($/kw)	Cumulative capy., MWe	Contract awarded	Commercial operation
Shippingport	PWR	90.0[b]	69.0[b]	767.0	90.0	1953[b]	1957[b]
Indian Point #1	PWR	151.0[b,c]	107.0[b]	404.0	241.0	1955[b]	1963[b]
Dresden #1	BWR	200.0[b]	51.0[b]	180.0	441.0	1955[b]	1960[b]
Yankee	PWR	175.0[b]	39.0[b]	223.0	616.0	1956[b]	1961[b]
Pathfinder	BWR	62.0[d]	25.5[d]	410.0	678.0	1957[b]	1967[b]
Elk River	BWR	22.0[b,e]	14.0[b]	636.0	700.0	1958[b]	1964[b]
Humboldt Bay	BWR	69.0[b]	24.0[b]	348.0	769.0	1958[b]	1963[b]
Big Rock Pt.	BWR	72.8[d]	26.0[d]	358.0	841.8	1959[b]	1963[b]
BONUS	BWR	16.5[d]	17.9[d]	1080.0	858.3	1960[b]	1965[b]
La Crosse	BWR						

[a]Total construction cost. Land, fuel, and transmission plant excluded.

[b]Source (19).

[c]Electric power from reactor only.

[d]Source (24).

[e]Electric power from reactor is 16 MW.

Table 1 (Continued)

Plant	Type	Size (MWe-Net)	Est. cost ($ $\times 10^{-6}$)	Est. cost ($/kw)	Cumulative capy., MWe	Contract awarded	Commercial operation
Conn. Yankee	PWR	462.0[b]	87.0[b]	188.0	1370.3	1962[b]	1968[b]
San Onofre	PWR	430.0[b]	87.0[f]	203.0	1800.3	1963[b]	1967[b]
Malibu	PWR	462.0[b]	83.0[b]	180.0	2262.3	1963[b]	1972[b]
Nine Mile Pt.	BWR	500.0[b]	89.0[b]	178.0	2762.3	1963[b]	1968[b]
Oyster Creek	BWR	515.0[b]	67.0[b]	130.0	3277.3	1963[b]	1968[b]
Robert E. Ginna	PWR	420.0[b]	65.0[b]	155.0	3697.3	1965[b]	1969[b]
Millstone	BWR	549.0[b]	85.0[b]	155.0	4246.3	1965[b]	1969[b]
Pilgrim	BWR	625.0[b]	65.0[b]	104.0	4871.3	1965[b]	1971[b]
Dresden #2	BWR	715.0[b]	79.0[b]	110.0	5586.3	1965[b]	1969[b]
Turkey Pt. #3	PWR	722.0[b]	----	----	308.3	1965[b]	1970[b]
Indian Pt. #2	PWR	873.0[b]	108.0[b]	124.0	7191.3	1965[b]	1969[b]
Fort Calhoun	PWR	455.0[g]	70.0[b]	154.0	7646.3	1966[b]	1971[b]

[f] Source (20).

[g] R. K. Chatfield, Administrative Assistant, Omaha Public Power District, 1623 Harney, Omaha, Nebraska. Economic data on the Fort Calhoun Power Station. Private communication. September, 1967.

Table 1 (Continued)

Plant	Type	Size (MWe-Net)	Est. cost ($ x 10^{-6})	Est. cost ($/kw)	Cumulative capy., MWe	Contract awarded	Commercial operation
Monticello	BWR	472.0[b]	74.0[b]	157.0	8118.3	1966[b]	1970[b]
Point Beach #1	PWR	497.0[h]	61.0[b]	123.0	8615.3	1966[b]	1970[b]
Vermont Yankee	BWR	514.0[b]	88.0[b]	171.0	9129.3	1966[b]	1971[b]
Palisades	PWR	710.0[i]	75.0[b]	106.0	9839.3	1966[b]	1970[b]
Quad Cities #1	BWR	715.0[b]	90.0[b]	126.0	10554.3	1966[b]	1970[b]
Dresden #3	BWR	715.0[b]	81.0[b]	113.0	11269.3	1966[b]	1970[b]
Quad Cities #2	BWR	715.0[b]	77.0[b]	108.0	11984.3	1966[b]	1971[b]
Robinson #2	PWR	730.5[j]	76.0[b]	104.0	12714.8	1966[b]	1970[b]
Easton	BWR	755.0[b]	100.0[b]	132.0	13469.8	1966[b]	1971[b]

[h] C. S. McNeer, Assistant Vice President, Wisconsin Electric Power Company, 231 West Michigan Street, Milwaukee, Wisconsin. Economic data on Point Beach Nuclear Plant. Private communication. November, 1967.

[i] G. S. Keeley, Nuclear Engineer, Consumers Power Company, 212 West Michigan Avenue, Jackson, Michigan. Economic data on the Palisades Plant. Private communication. November, 1967.

[j] R. J. Rutherford, Jr., Director of Information, Carolina Power and Light Company, Raleigh, North Carolina. Economic data on Robinson Unit 2 Nuclear Plant. Private communication. December, 1967.

Table 1 (Continued)

Plant	Type	Size (MWe-Net)	Est. cost ($ x 10^{-6})	Est. cost ($/kw)	Cumulative capy., MWe	Contract awarded	Commercial operation
Surry #1	PWR	783.0[b]	130.0[b]	166.0	14252.8	1966[b]	1971[b]
Surry #2	PWR	783.0[b]	108.0[b]	138.0	15035.8	1966[b]	1972[b]
Three Mile Island	PWR	831.0[b]	116.0[b]	140.0	15866.8	1966[b]	1971[b]
Oconee #1	PWR	874.0[b]	86.0[b]	98.5	16740.8	1966[b]	1971[b]
Oconee #2	PWR	874.0[b]	86.0[b]	98.5	17614.8	1966[b]	1972[b]
Burlington #1	PWR	999.0[b]	139.0[b]	139.0	18613.8	1966[b]	1971[b]
El Diablo	PWR	1060.0[b]	154.0[b]	145.0	19673.8	1966[b]	1971[b]
Peach Bottom #2	BWR	1065.0[b]	138.0[b]	130.0	20738.8	1966[b]	1971[b]
Peach Bottom #3	BWR	1065.0[b]	125.0[b]	118.0	21803.8	1966[b]	1973[b]
Browns Ferry #1	BWR	1065.0[b]	----	----	22868.8	1966[b]	1970[b]
Browns Ferry #2	BWR	1065.0[b]	----	----	23933.8	1966[b]	1971[b]
Point Beach #2	PWR	455.0[b]	57.0[b]	128.0	24388.8	1967[b]	1971[b]
Bailly	BWR	515.0[b]	91.0[b]	177.0	24903.8	1967[b]	1973[b]
Kewaunee	PWR	527.0[b]	85.0[b]	161.0	25430.8	1967[b]	1972[b]
Shoreham	BWR	540.0[b]	105.0[b]	194.0	25970.8	1967[b]	1973[b]

Table 1 (Continued)

Plant	Type	Size (MWe-Net)	Est. cost ($\$ \times 10^{-6}$)	Est. cost (\$/kw)	Cumulative capy., MWe	Contract awarded	Commercial operation
Prairie Is. #1	PWR	550.0[b]	100.0[b]	182.0	26520.8	1967[b]	1972[b]
Prairie Is. #2	PWR	550.0[b]	98.0[b]	178.0	27070.8	1967[b]	1974[b]
Turkey Pt. #4	PWR	722.0[b]	----	----	27792.8	1967[b]	1971[b]
Cooper	BWR	778.0[b]	125.0[b]	161.0	28570.8	1967[b]	1973[b]
Ark. Pwr. Lt. Co.	PWR	800.0[b]	140.0[b]	180.0	29370.8	1967[b]	1973[b]
Jersey Central Pwr. Lt.	PWR	800.0[b]	100.0[b]	125.0	30170.8	1967[b]	1973[b]
Maine Yankee	PWR	800.0[b]	100.0[b]	125.0	30970.8	1967[b]	1972[b]
Va. El. Power	PWR	800.0[b]	----	----	31770.8	1967[b]	1974[b]
Shippingport #2	PWR	800.0[b]	----	----	32570.0	1967[b]	1973[b]
Crystal Rvr. #3	PWR	825.0[b]	110.0[b]	133.0	33395.8	1967[b]	1972[b]
Milliken	BWR	829.0[b]	130.0[b]	157.0	34224.8	1967[b]	1973[b]
Rancho Seco	PWR	841.0[k]	142.0[b]	168.0	35065.8	1967[b]	1973[b]

[k] J. J. Mattimoe, Assistant Chief Engineer, Sacramento Municipal Utility District, 6201 S Street, Sacramento, California. Economic data on the Rancho Seco Nuclear Generating Station. Private communication. November, 1967.

Table 1 (Continued)

Plant	Type	Size (MWe-Net)	Est. cost ($ x 10^{-6})	Est. cost ($/kw)	Cumulative capy., MWe	Contract awarded	Commercial operation
Calvert Cliffs #1	PWR	848.0[b]	118.0[b]	139.0	35913.8	1967[b]	1973[b]
Calvert Cliffs #2	PWR	848.0[b]	105.0[b]	124.0	36761.8	1967[b]	1975[b]
Oconee #3	PWR	874.0[b]	92.0	105.0	37635.8	1967[b]	1973[b]
Indian Pt. #3	PWR	965.0[b]	159.0[b]	165.0	38600.8	1967[b]	1971[b]
Burlington #2	PWR	993.0[b]	121.0[b]	122.0	39593.8	1967[b]	1973[b]
Zion #1	PWR	1050.0[b]	164.0[b]	151.0	40643.8	1967[b]	1972[b]
Zion #2	PWR	1050.0[b]	153.0[b]	146.0	41693.8	1967[b]	1973[b]
Browns Ferry	BWR	1065.0[b]	115.0[b]	108.0	42758.8	1967[b]	1972[b]
Phila Electric #1	BWR	1065.0[b]	----	----	43923.8	1967[b]	1976[b]
Phila Electric #2	BWR	1065.0[b]	----	----	44988.8	1967[b]	1976[b]
Bridgman #1	PWR	1100.0[b]	----	----	46088.8	1967[b]	1972[b]
Bridgman #2	PWR	1100.0[b]	----	----	47188.8	1967[b]	1973[b]

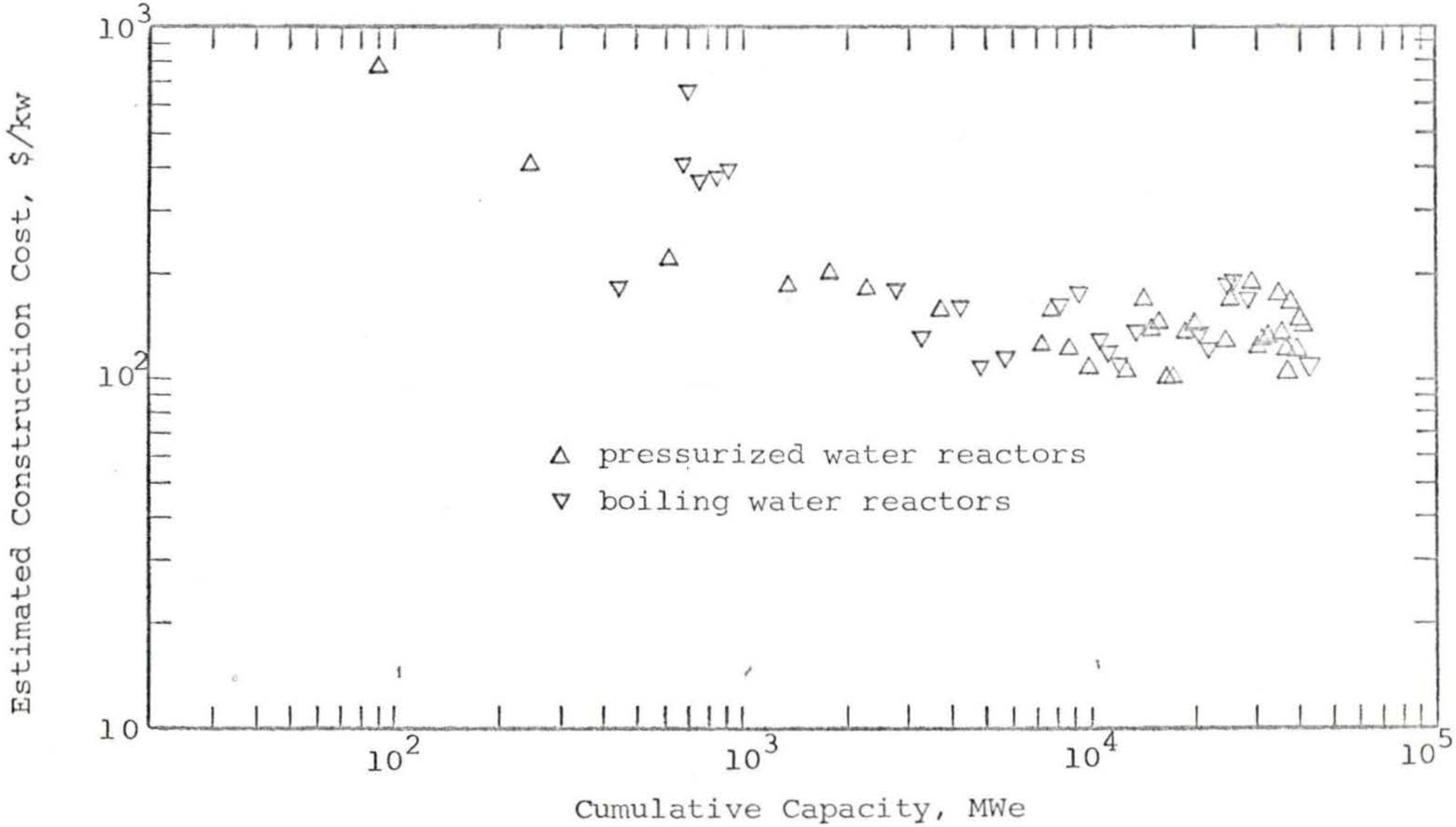

Figure 2. Estimated total construction costs

total construction costs tend to show a leveling off period. The actual learning curves were not plotted in Figure 2 due to the scatter of the data but a definite trend in construction costs can be seen.

The rapid decrease in dollars per kilowatt which appears initially in Figure 2 can be partially attributed to the increasing plant sizes as the nuclear industry began to expand. Figure 3 presents this decrease in cost versus the size of the plants. It can be seen from Figure 3 that the size of the plant has a definite effect on construction cost up to the 400 MWe size range. After that size range has been reached, the effect is still present but on a much more minimal basis. Chittenden's (2) predictions for construction costs of plants becoming operational in 1970 also indicates this same size versus cost dependence. Other factors which caused this initial decrease are due to technological advances and experience gained in the relatively new industry.

The fluctuations in the points as seen in Figure 2 can be attributed to many different factors. One of these factors is the location where the plant was constructed. This factor causes a fluctuation in labor costs, cost of materials, transportation costs, and other geographical effects such as climate. Other factors which cause fluctuations are the time when the plant was built and the number of units to be constructed at a given site. Since it is known that many

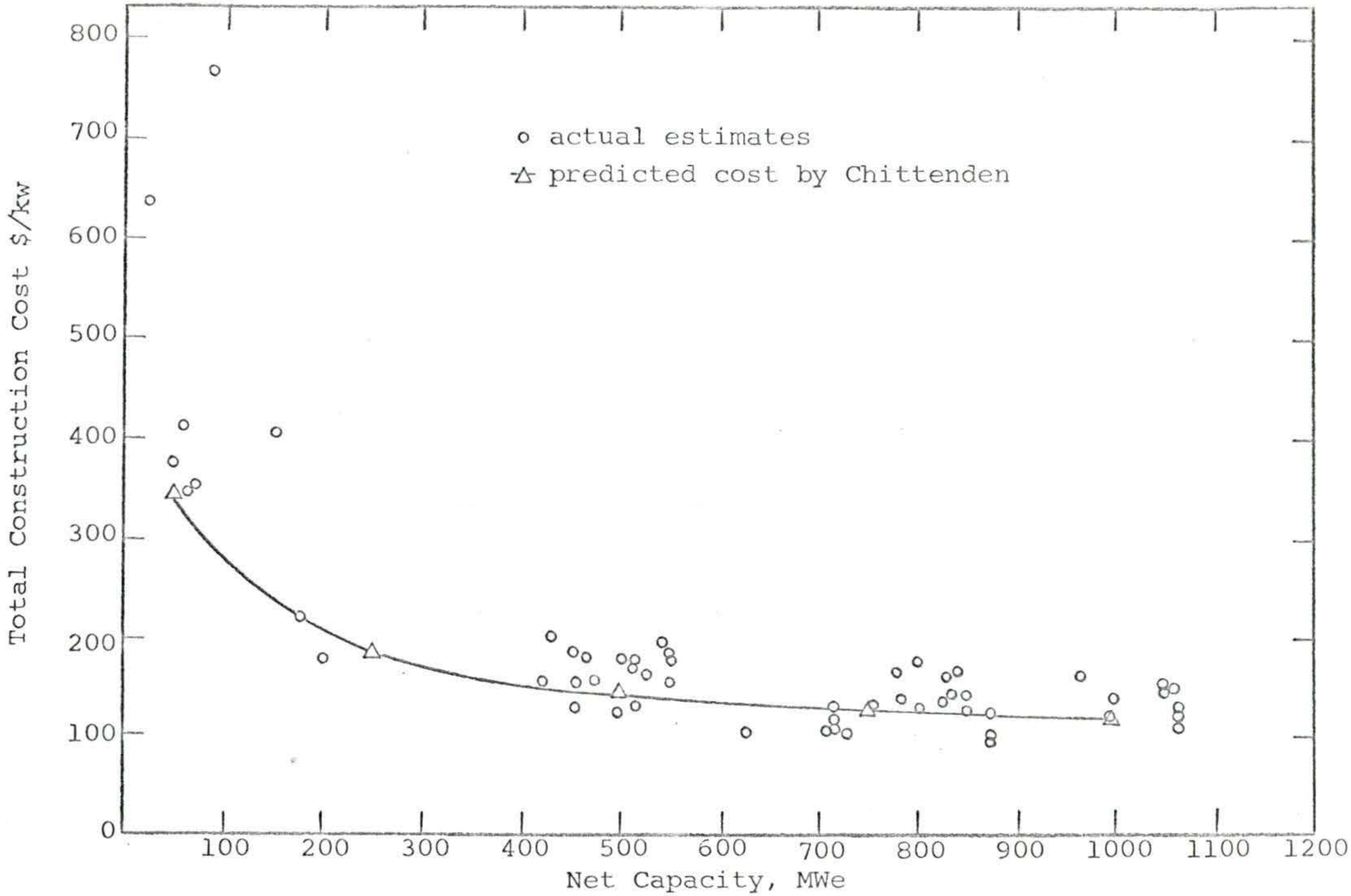

Figure 3. Total construction cost of water reactors

estimates do not agree with the final cost of a plant, the validity and reason for a given estimate may also cause fluctuation in construction costs of different plants.

A greater decrease in cost can be anticipated in the near future for nuclear power stations. This trend should come about as more multiple sites are built as well as through joint operations.

B. Application to Total Power Production Costs

In this section, the total power production costs will be analyzed through the use of the learning curve technique. In Table 2, the production costs that are available on light water reactors are listed. These costs are graphically represented in Figure 4. It can be seen from this figure that there are two different measured rates of decrease for total power cost. Initially in the industry, a fairly steep decline is noted followed by a leveling off period accompanied by only a slight decline in costs. In order to determine the reduction factors for the curves in Figure 4 and subsequent figures, use was made of equation 2a

$$\frac{A_2}{A_1} = \left(\frac{x_2}{x_1}\right)^{-n}$$

where

A_1 = the cost of the reference unit

A_2 = the cost of the subsequent unit

Table 2. Power production costs[a]

Plant	Fuel cycle costs	Operating charges	Fixed charges	Total cost
Shippingport	10.39[b]	18.84[b]	30.92[b]	60.15[b,c]
Indian Point #1	5.80[b]	1.90[b]	10.00[b]	17.70[b]
Dresden #1	4.35[d]	---	---	9.00[d,e]
Yankee	2.80[d]	2.50[d]	4.60[d]	9.90[d,f]
Pathfinder	4.32[g]	1.23[g]	8.61[g]	14.16[g]
Elk River	3.86[g]	3.14[g]	7.13[g]	14.13[g,h]
Humboldt Bay	4.07[g]	1.44[g]	6.30[g]	11.78[g]
Big Rock Point	2.70[g]	1.80[g]	7.50[g]	12.00[g]
BONUS	6.00[g]	4.30[g]	14.60[g]	24.90[g]
La Crosse	3.10[g]	1.72[g]	3.63[g]	8.45[g]
Conn. Yankee	2.10[i]	0.68[i]	3.25[i]	6.03[i]

[a]All costs and charges are in mills per kilowatt hour.

[b]Source (6).

[c]Energy data based on core 1.

[d]Source (14).

[e]Second core estimated at 8.0 mills/kwhr.

[f]Based on 175 MWe, 80% plant factor, 20 year depreciation.

[g]Source (24).

[h]All energy costs are based on an average value.

[i]Source (26).

Table 2 (Continued)

Plant	Fuel cycle costs	Operating charges	Fixed charges	Total cost
San Onofre	1.99[d]	0.42[d]	3.98[d]	6.39[d]
Malibu	1.80[j]	0.50[j]	2.40[j]	4.70[j,k]
Nine Mile Point	2.17[l]	0.61[l]	3.89[l]	6.67[l]
Oyster Creek	1.66[m]	0.55[m]	2.04[m]	4.25[m]
Millstone	1.70[n]	0.50[n]	2.20[n]	4.40[n]
Indian Point #2	1.63[b]	0.36[b]	2.04[b]	4.03[b]
Fort Calhoun	1.38[o,p]	0.67[o]	1.48[o,q]	3.53[o]

[j]W. A. Sells, Engineer of Design and Construction Department of Water and Power, The City of Los Angeles, 111 Hope Street, Los Angeles, California. Economic data on Malibu Nuclear Plant. Private communication. November, 1967

[k]Energy costs are based on a 70% plant factor.

[l]R. F. Prieto, Technical Writer, Niagara Mohawk Power Corporation, Buffalo, New York. Economic data on Nine Mile Point Power Station. Private communication. November, 1967.

[m]Source (12).

[n]H. R. Nims, Project Manager, The Millstone Point Company, Hartford, Connecticut. Economic data on Millstone Point Power Station. Private communication. November, 1967.

[o]R. H. Chatfield, Administrative Assistant, Omaha Public Power District, 1623 Harney, Omaha, Nebraska. Economic data on the Fort Calhoun Power Station. Private communication. September, 1967.

[p]The actual value may be slightly lower than this estimate.

[q]The actual value may be slightly higher than this estimate.

Table 2 (Continued)

Plant	Fuel cycle costs	Operating charges	Fixed charges	Total cost
Point Beach #1	1.79[r]	0.47[r]	2.70[r]	4.96[r]
Robinson #2	1.78[s]	0.35[s]	2.71[s]	4.84[s]
El Diablo	1.67[t]	0.32[t]	2.39[t]	4.38[t,u]
Shoreham	1.71[v]	0.31[v]	3.41[v]	5.43[v]
Rancho Seco	1.34[w]	0.59[w]	2.22[w]	4.15[w]

[r]C. S. McNeer, Assistant Vice President, Wisconsin Electric Power Company, 231 West Michigan Street, Milwaukee, Wisconsin. Economic data on Point Beach Nuclear Plant. Private communication. November, 1967.

[s]R. J. Rutherford, Jr., Director of Information, Carolina Power and Light Company, Raleigh, North Carolina. Economic data on H. B. Robinson Unit 2 Plant. Private communication. December, 1967.

[t]D. V. Kelly, Chief Mechanical Engineer, Pacific Gas and Electric Company, 245 Market Street, San Francisco, California. Economic data on Diablo Canyon Plant. Private communication. November, 1967.

[u]Computed for an 80% plant factor.

[v]J. I. Martone, Manager, Nuclear Engineering Division, Long Island Lighting Company, Hicksville, New York. Economic data on Shoreman Nuclear Power Station. Private communication. November, 1967.

[w]J. J. Mattimoe, Assistant Chief Engineer, Sacramento Municipal Utility District, 6201 S Street, Sacramento, California. Economic data on the Rancho Seco Nuclear Generating Station. Private communication. November, 1967.

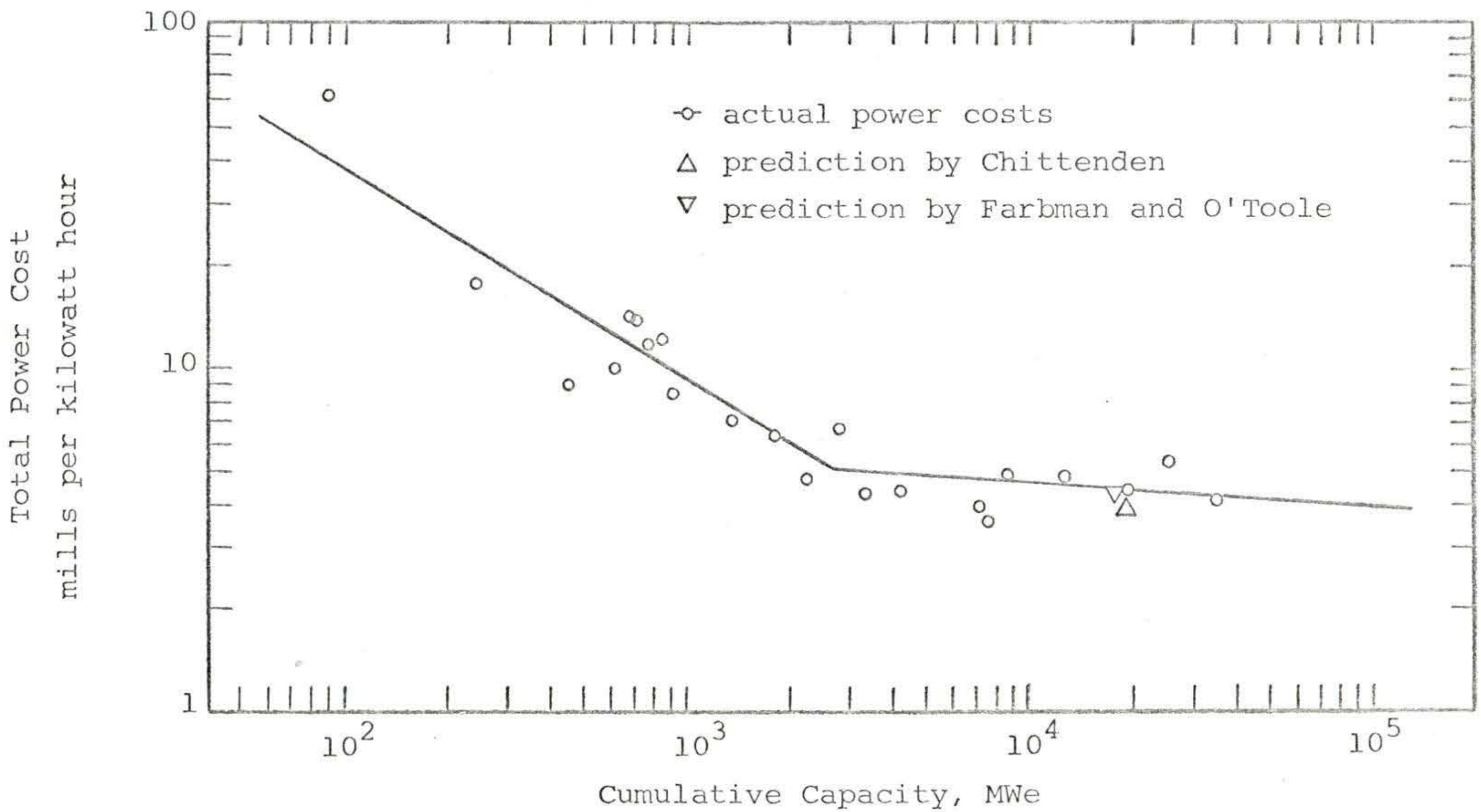

Figure 4. Total power cost

x_1 = the cumulative capacity location of the reference unit

x_2 = the cumulative capacity location of the subsequent unit

n = the measure rate change

From the graph of total power cost versus cumulative capacity in Figure 4, the slope, n, of the initial part of the curve was found to be 0.61. The reduction rate between doubled quantities is

$$\frac{A_{2x}}{A_x} = \frac{1}{2^n} = 2^{-0.61}$$

$$2^{-0.61} = 0.655$$

and which corresponds to a reduction rate of 34.5%. The slope, n, for the later part of the curve was found to be 0.0742 which corresponds to a reduction rate of 5% in cost in mills per kilowatt hour. Thus one can see that the rate of change between doubled quantities in the industry at this time can be expressed as a 5% decrease in total power production costs.

The initial curve in Figure 4 exemplifies the rapidly changing technology of the newly established nuclear industry and also the contribution of decreasing cost due to larger generating stations. The dependence of total power costs on size is analogous to that of total construction costs as is shown in Figure 5. Chittenden's (2) predictions also shows

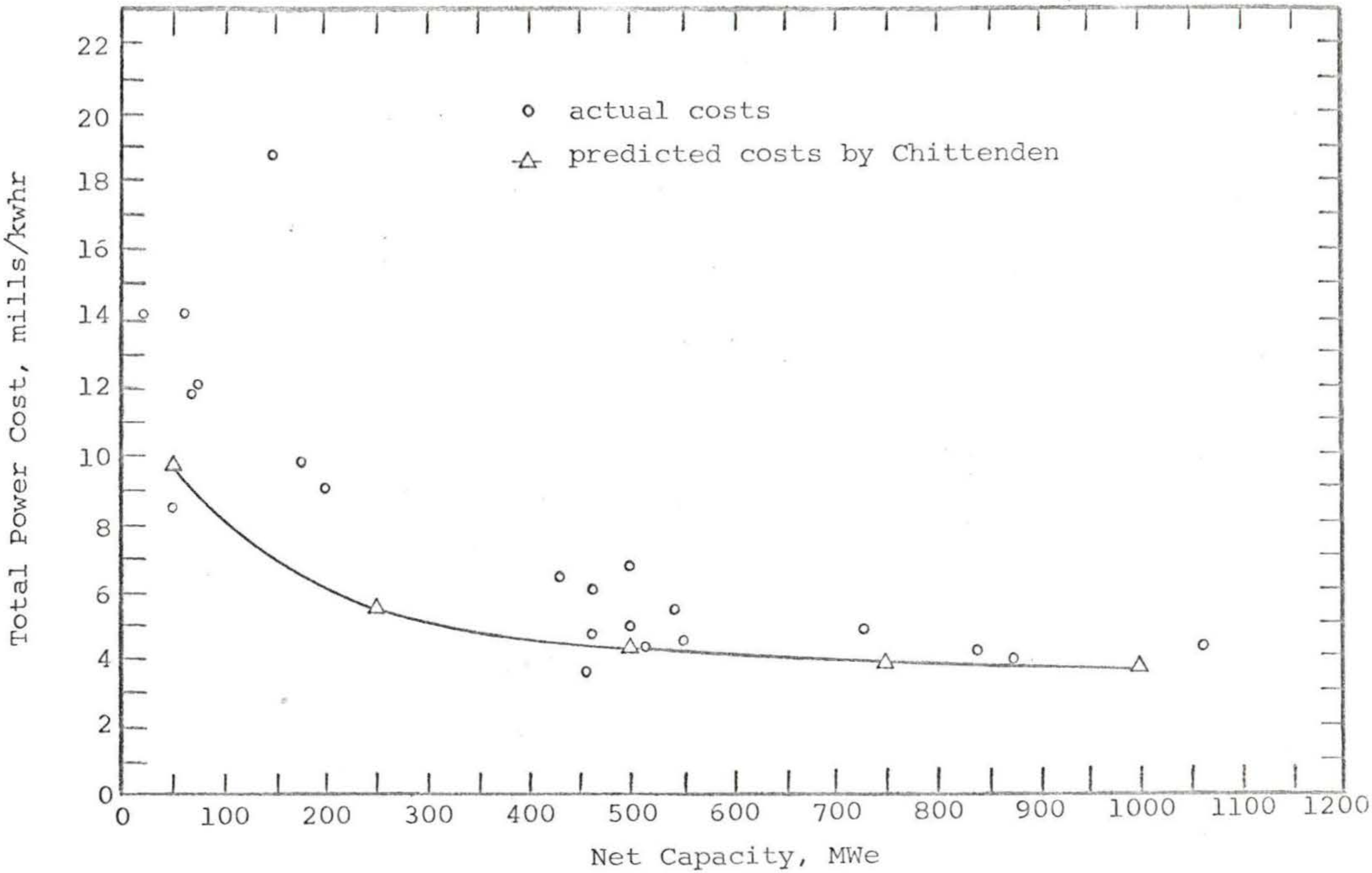

Figure 5. Total power cost versus size for water reactors

this great reduction in cost versus size for the smaller capacity power stations. It can be seen that the predictions by Chittenden (2) for a 750 MWe plant and Farbman and O'Toole's (7) predictions for a 625 MWe plant fall very close to predictions developed by the learning curve technique as shown in Figure 4. The plot of the data, however, is accompanied by some fluctuation. These fluctuations again can be attributed to the location, size, and other items as mentioned in the discussion of total construction costs.

C. Application to Fixed Charges

The largest single factor in the total production costs of electricity from nuclear stations is the fixed charges arising from the high construction costs. The fixed charges as discussed here include the cost of money, depreciation, interim replacements, property damage insurance, nuclear liability insurance, and federal, state, and local taxes as defined in TID-7025 (23).

To compute the contribution of annual fixed charges to the unit cost of electrical energy, one must estimate the number of kilowatt hours to be generated by a given plant each year (21). This can be determined by the product of the average power level of the plant during operation and the time during which the plant is operating. When the resulting value is expressed as a percentage of the energy that could be generated, it is called the plant factor (21). This factor is thus determined by the capacity of the plant and also by the demand for electrical energy from the plant.

Fixed charges also depend upon the type of utility that owns the generating station. The cost of money will vary between private utilities, municipalities, and rural co-operatives. The latter two being reduced since they are publicly financed.

The above mentioned price of money coupled with the different plant factors for different power stations will cause a fluctuation in fixed charges from plant to plant as shown in Figure 6. Again plant size, location, and other elements also cause some fluctuation.

Application of the learning theory to the data in Figure 6 again will result in two separate learning curves as indicated. The steeper slope indicating again a new industry with vast technological improvements accompanied by cost decreases due to increasing plant size. The initial curve represents a reduction factor of 39.3%, whereas, the latter curve represents a reduction factor of 3.4%.

D. Application to Fuel Cycle Costs

The next area of total production cost to be considered is fuel cycle costs. Included in fuel cycle costs are the

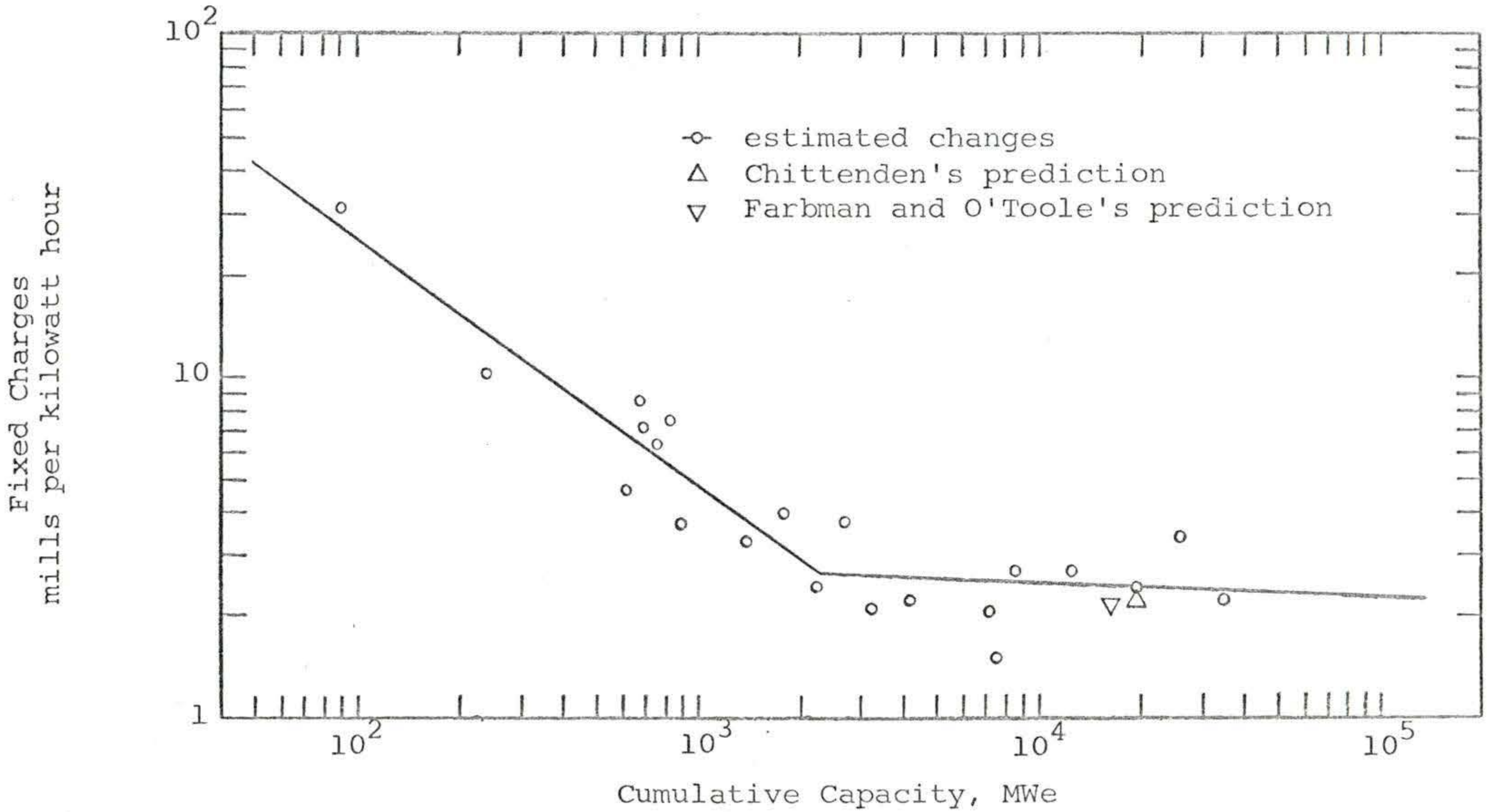

Figure 6. Fixed charges

cost of fabricating the fuel elements, the cost of chemical processing of irradiated fuel and chemical conversion of the special nuclear materials recovered, the use charge of the leased fuel, the cost of fuel consumption, and the credit for plutonium and U-233 produced (21).

Many items may cause slight fluctuations in fuel cycle costs from one reactor to another as can be seen in Figure 7. Cost of fuel element fabrication may vary due to design, size, dimensional tolerances, enrichment of the uranium, the kind of alloying and cladding material, and other items depending upon the specific reactor. Transportation costs may vary due to insurance rates, cooling time prior to shipment, the weight of the shipment, and carrier rates. The greatest cause for variation in transportation costs is the type of material to be shipped. Irradiated fuel elements are, perhaps, the greatest challenge of any radioactive material to the transportation business. Normally the irradiated fuel is capable of criticality as well as being highly radioactive. The heat of radioactive decay also presents some problems. The transportation of all materials gives rise to fairly high transportation costs due to the precautions that must be taken in case of fire or accident in order that the release of fission products and radioactive contamination can be avoided. This requires that almost every type material have a particular type of a shipping cask. Each of the other

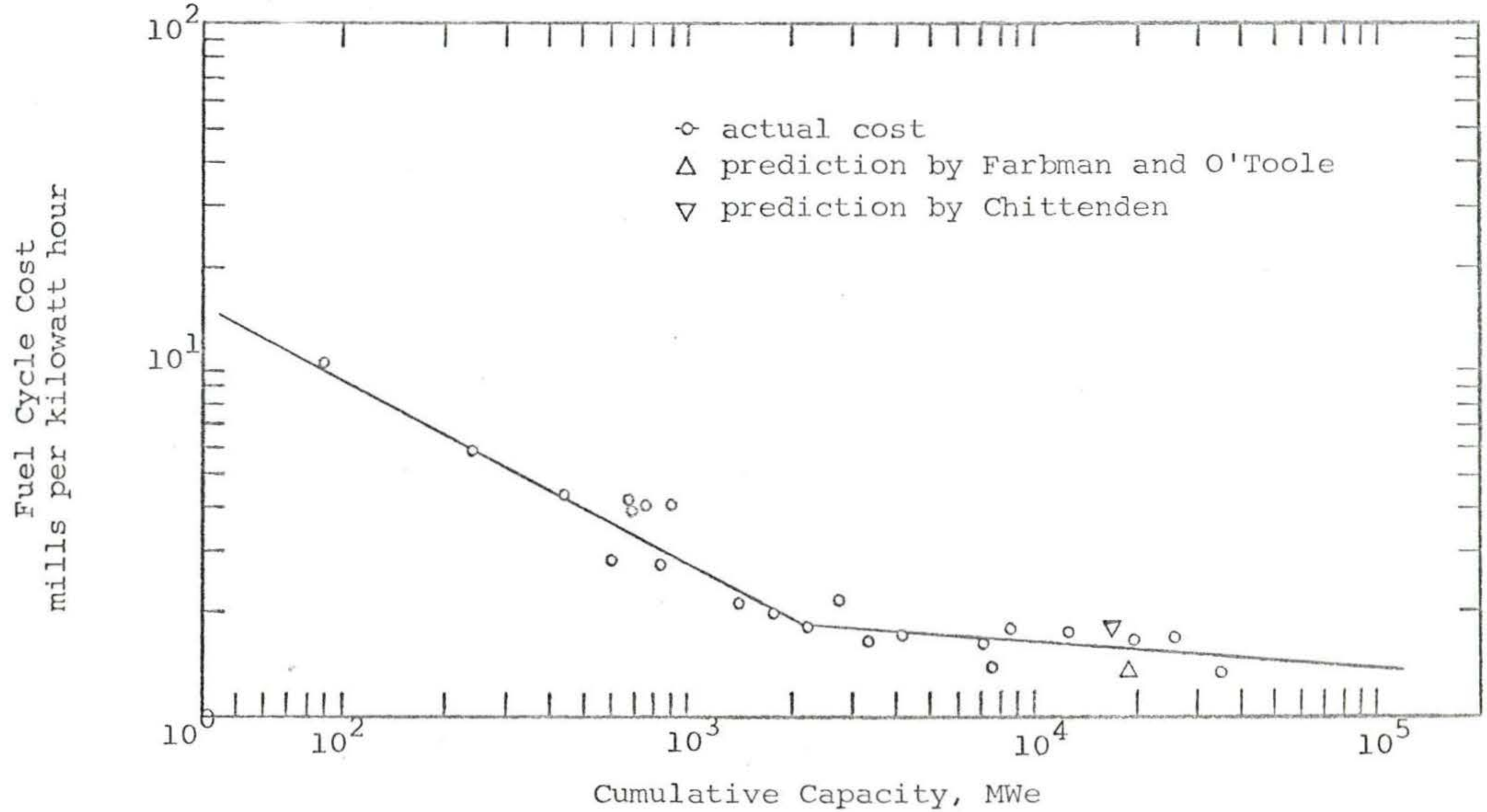

Figure 7. Fuel cycle cost

areas included in fuel cycle costs will also tend to have slight fluctuations between generating stations. These fluctuations will produce the spread in data as observed in Figure 7.

An important aspect of fuel cycle costs is also the plutonium price and its effect on the economics of recycling plutonium as a reactor fuel. This effect will change in the future, however, since the value of plutonium will be determined by supply and demand.

If one applies the learning techniques to the data in Figure 7, the appearance of two learning curves as was seen in fixed charges will again be seen. The reduction factors for the two curves are 30.2% and 5.5% respectively. Again this indicates a rapid decrease in a new industry followed by a leveling off period.

E. Application to Operating Charges

The final item to be considered under total power production costs is operating charges. This cost includes the areas of operation, maintenance, and moderator and coolant make up (21). A large amount of this cost results from the salaries for the operation, maintenance, engineering, and supervisory personnel.

The operating charges also will depend upon the design of the nuclear plant and on the arrangement of equipment. These items have a great effect on the ease and speed with which maintenance and refueling can be performed. Therefore, these items will cause some of the fluctuations present in Figure 8. The cost of training personnel is also considered under the heading of operating charges. Training is a fairly large expense initially in the operation of a power station. The cost of moderator and coolant make up is only slightly important in this analysis since light water reactors are the only reactors being considered.

The learning curves obtained from the data on operating charges are presented in Figure 8. The initial curve represents a reduction factor of 49.2% followed by a reduction factor of 6.7%. This indicates that operating charges when compared to the other production costs have had the greatest decrease in cost initially and also at the present time.

F. Application to Burnup and Thermal Efficiency

Both burnup and thermal efficiency affect the total power production cost of the electrical energy produced by nuclear power stations. These operating characteristics, therefore, are worthy of mention in an economic analysis of this type since they have some effect on the fluctuations which were previously discussed. Equilibrium and first core burnup and thermal efficiency for some of the light water reactors are tabulated in Table 3.

The irradiation level or burnup is expressed in terms of

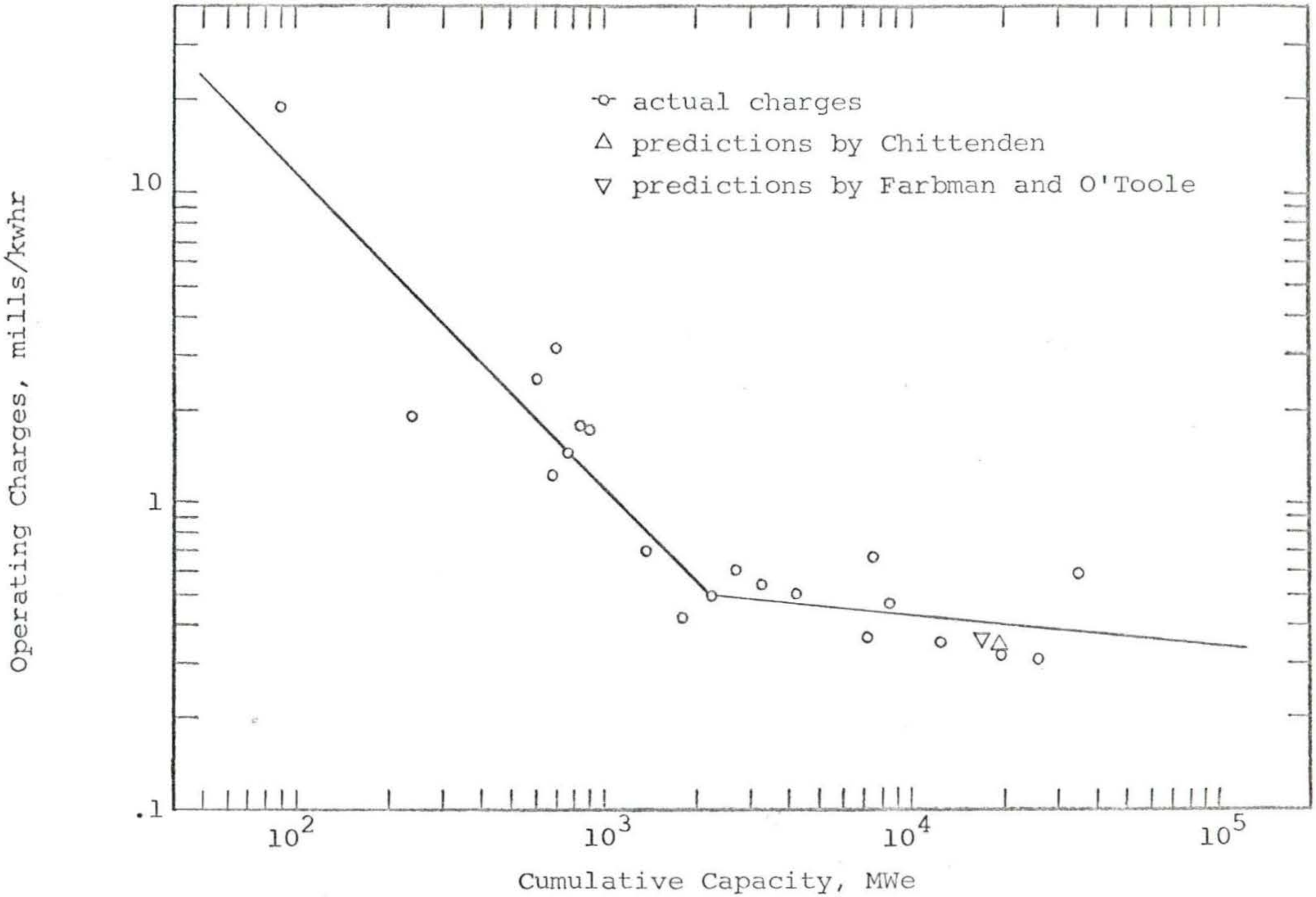

Figure 8. Operating charges of light water reactors

Table 3. Thermal efficiency and burnup data

Plant	Thermal efficiency (%)	1st core burnup (MWD/T)	Equilibrium core burnup (MWD/T)
Shippingport	29.7[a]	11,000[a]	----
Indian Point #1	30.0[a]	14,800[a,b]	20,000[b,c]
Dresden #1	29.3[a]	10,000[c]	12,000[c]
Yankee	29.0[a]	6,300[c]	14,000[c]
Pathfinder	31.5[c]	7,800[c]	10,000[c]
Elk River	31.4[c]	9,500[d]	----
Humboldt Bay	30.4[e]	11,000[d]	14,000[c]
Big Rock Point	33.0[a]	16,500[d]	----
BONUS	33.0[a]	11,000[d]	----
La Crosse	30.3[c]	14,000[d]	16,000[c]
Conn. Yankee	31.4[c]	20,000[c]	24,000[c]
San Onofre	33.4[a]	24,000[a]	24,000[c]
Malibu	31.0[f]	12,000[f]	24,000[c]

[a]Source (20).

[b]Per tonne of uranium and thorium.

[c]Source (14).

[d]Source (24).

[e]Source (6).

[f]W. A. Sells, Engineer of Design and Construction, Department of Water and Power, The City of Los Angeles, 111 Hope Street, Los Angeles, California. Economic data on Malibu Nuclear Plant. Private communication. November, 1967.

Table 3 (Continued)

Plant	Thermal efficiency (%)	1st core burnup (MWD/T)	Equilibrium core burnup (MWD/T)
Nine Mile Point	33.0[g]	15,000[g]	22,000[c]
Oyster Creek	32.3[a]	16,500[a]	22,000[c]
Millstone	31.4[h]	15,000[h]	----
Dresden #2	31.0[a]	20,000[a]	----
Indian Point #2	31.7[e]	----	27,000[e]
Fort Calhoun	33.9[i]	18,240[i]	27,360[i]
Monticello	30.0[j]	18,000[j]	----
Point Beach #1	32.5[k]	----	27,000[k]

[g]F. R. Prieto, Technical Writer, Niagara Mohawk Power Corporation, Buffalo, New York. Economic data on Nine Mile Point and Easton Power Station. Private communication. November, 1967.

[h]H. R. Nims, Project Manager, The Millstone Point Company, Hartford, Connecticut. Economic data on Millstone Point Power Station. Private communication. November, 1967.

[i]R. H. Chatfield, Administrative Assistant, Omaha Public Power District, 1623 Harney, Omaha, Nebraska. Economic data on the Fort Calhoun Power Station. Private communication. September, 1967.

[j]A. V. Dienhart, Manager of Engineering, Northern States Power Company, 414 Nicollet Avenue, Minneapolis, Minnesota. Economic data on Monticello Nuclear Generating Plant. Private communication. January, 1968.

[k]C. S. McNeer, Assistant Vice President, Wisconsin Electric Power Company, 231 West Michigan Street, Milwaukee, Wisconsin. Economic data on Point Beach Nuclear Plant. Private communication. November, 1967.

Table 3 (Continued)

Plant	Thermal efficiency (%)	1st core burnup (MWD/T)	Equilibrium core burnup (MWD/T)
Palisades	32.0[l]	24,000[l]	----
Dresden #3	----	15,000[e]	----
Robinson #2	30.0[m]	14,000[m]	27,000[m]
Easton	33.0[g]	19,000[g]	----
Oconee #1	34.0[n]	----	----
Burlington #1	32.0[o]	21,800[o]	32,000[o]
El Diablo	32.6[p]	----	----

[l]G. S. Kelly, Nuclear Engineer, Consumers Power Company, 212 West Michigan Avenue, Jackson, Michigan. Economic data on the Palisades Plant. Private communication. November, 1967.

[m]R. J. Rutherford, Jr., Director of Information, Carolina Power and Light Company, Raleigh, North Carolina. Economic data on H. B. Robinson Unit 2 Plant. Private communication. December, 1967.

[n]W. S. Lee, Duke Power Company, Power Building, Box 2178, Charlotte, North Carolina. Economic data on Oconee Nuclear Station No. 1. Private communication. November, 1967.

[o]R. M. Eckert, Chief Engineer, Electric Engineering Department, Public Service Electric and Gas Company, 80 Park Place, Newark, New Jersey. Economic data on Burlington Nuclear Power Plant. Private communication. November, 1967.

[p]D. V. Kelly, Chief Mechanical Engineer, Pacific Gas and Electric Company, 245 Market Street, San Francisco, California. Economic data on Diablo Canyon Plant. Private communication. November, 1967.

Table 3 (Continued)

Plant	Thermal efficiency (%)	1st core burnup (MWD/T)	Equilibrium core burnup (MWD/T)
Shoreman	32.8[q]	18,900[q]	----
Rancho Seco	32.5[r]	----	28,200[r]

[q]J. I. Martone, Manager, Nuclear Engineering Division, Long Island Lighting Company, Hicksville, New York. Economic data on Shoreman Nuclear Power Station. Private communication. November, 1967.

[r]J. J. Mattimoe, Assistant Chief Engineer, Sacramento Municipal Utility District, 6201 S Street, Sacramento, California. Economic data on the Rancho Seco Nuclear Generating Station. Private communication. November, 1967.

the megawatt days of heat generated per ton of uranium in the reactor and is abbreviated MWD/T_m (21). The peak irradiation level will normally occur in the center of the reactor core and may be several times greater than the average irradiation level for the core. If fuel management techniques are utilized, it is possible to increase the average level of burnup for the core. This increase in burnup will reduce the annual throughput of the fuel and the annual cost of fabricating, shipping, and processing of fuel elements. Accompanying the higher irradiation levels, however, must be the development of fuel elements to withstand this increase which, in turn leads to the possibility of higher fabrication and processing costs. Moreover, the fuel enrichment may have to be increased with the result that use and burnup charges are increased (21).

As experience and technology have been obtained, burnup levels have increased. This trend is indicated in Figures 9 and 10. The learning curves for equilibrium and first core burnups initially represent a rate of increase of 54% and 88% respectively. This trend is followed by the final learning curves that indicate a rate of increase of 3.4% for first core burnup and a 6.5% increase for the equilibrium core. In Figures 9 and 10, one can see that technology and experience are still being slowly obtained. It is anticipated that for pressurized water reactors, burnups in the range of 30,000 to 40,000 MWD/T can be obtained (7). If the development of fuel elements that can withstand this increase can be fabricated at lower costs, it will have an important effect on reducing fuel cycle costs.

Thermal efficiency also is an important operating characteristic which affects the construction costs and fuel cycle costs. It can be expressed as the ratio of the net electrical power over the net thermal power produced. The nuclear industry has utilized the technological improvements made throughout the years in conventional plants and thus it did not start from a completely new concept. This is probably why, as seen in Figure 11, there was not a rapid increase in

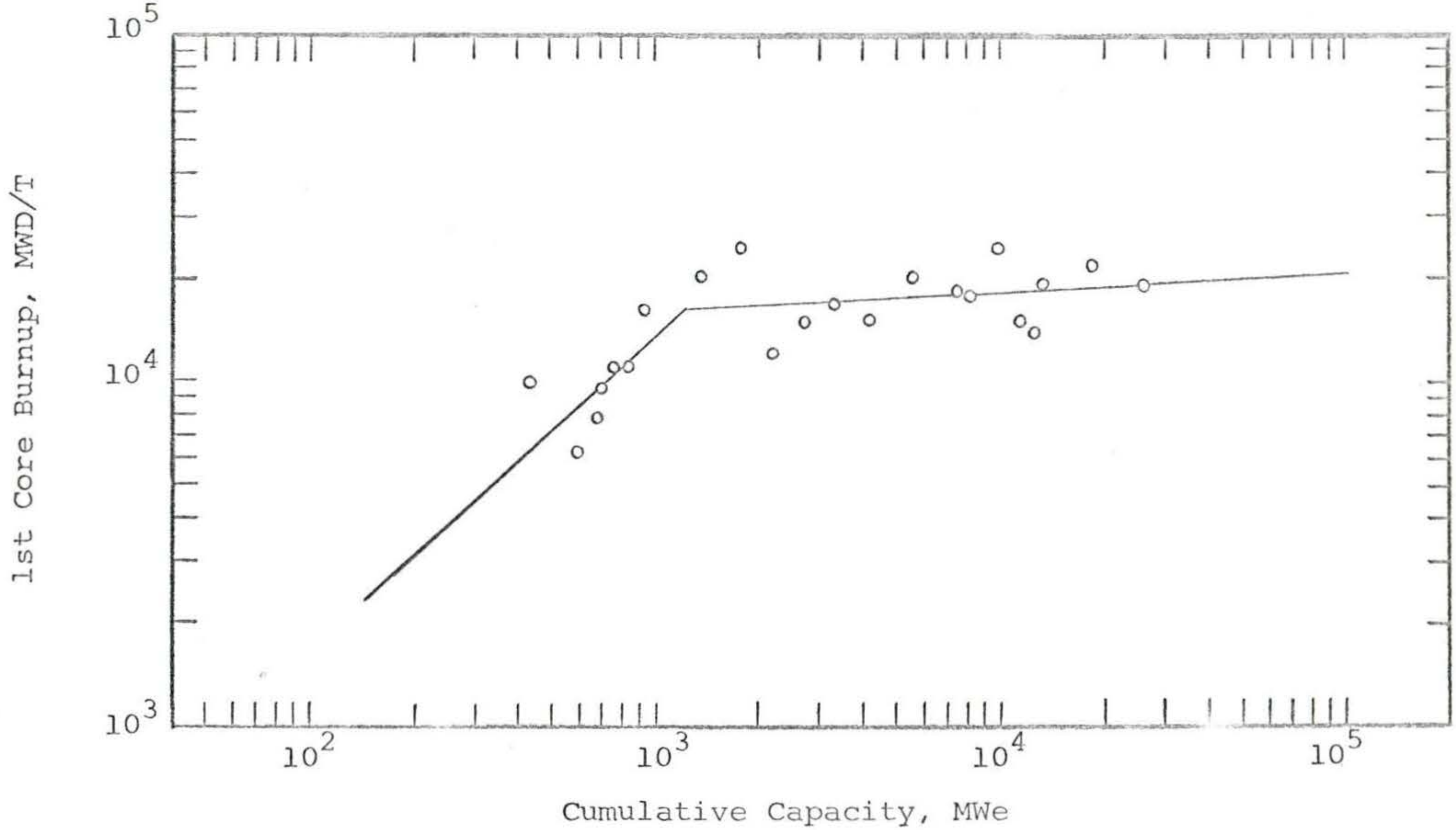

Figure 9. 1st core burnup for light water reactors

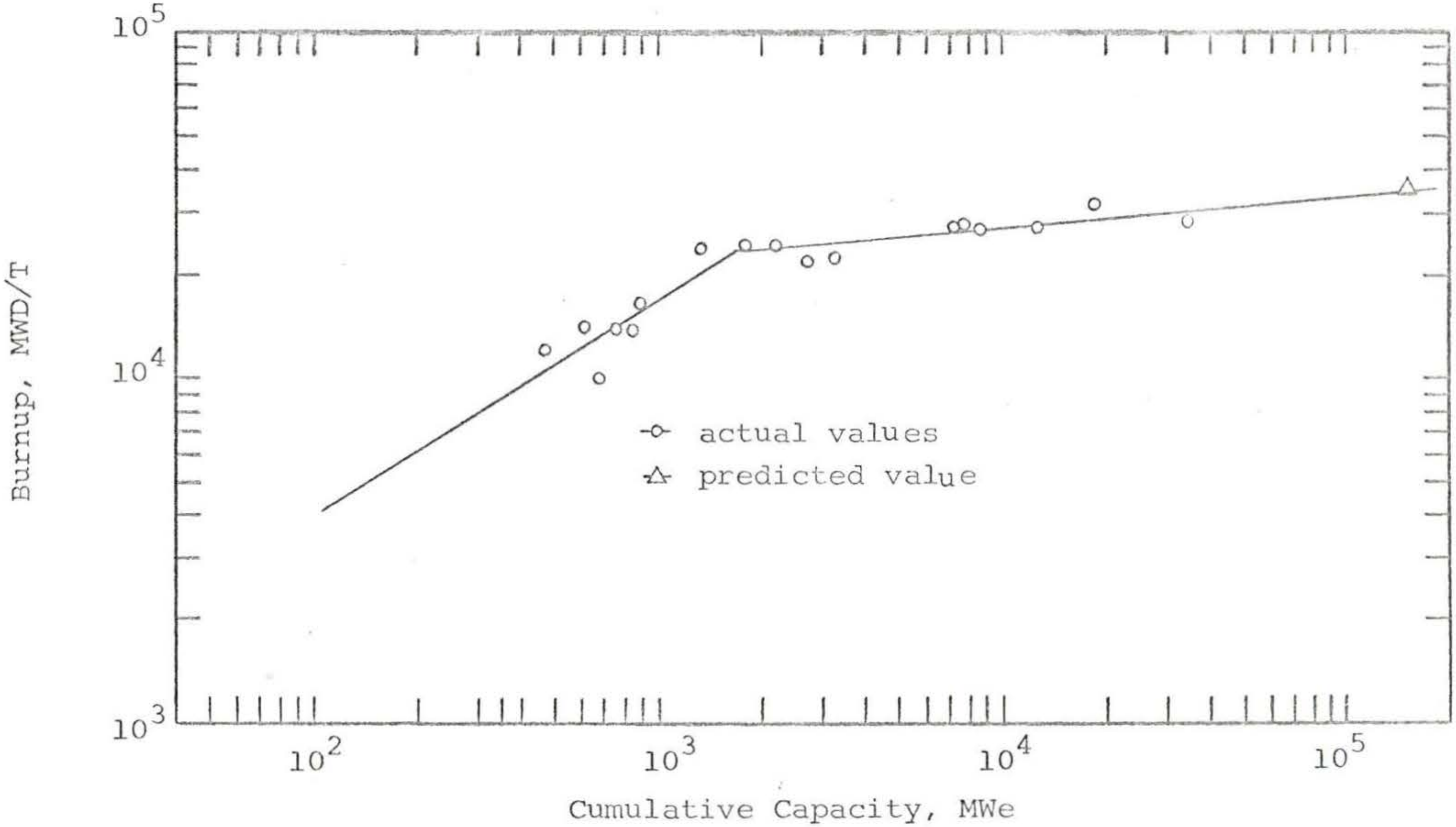

Figure 10. Equilibrium burnup for light water reactors

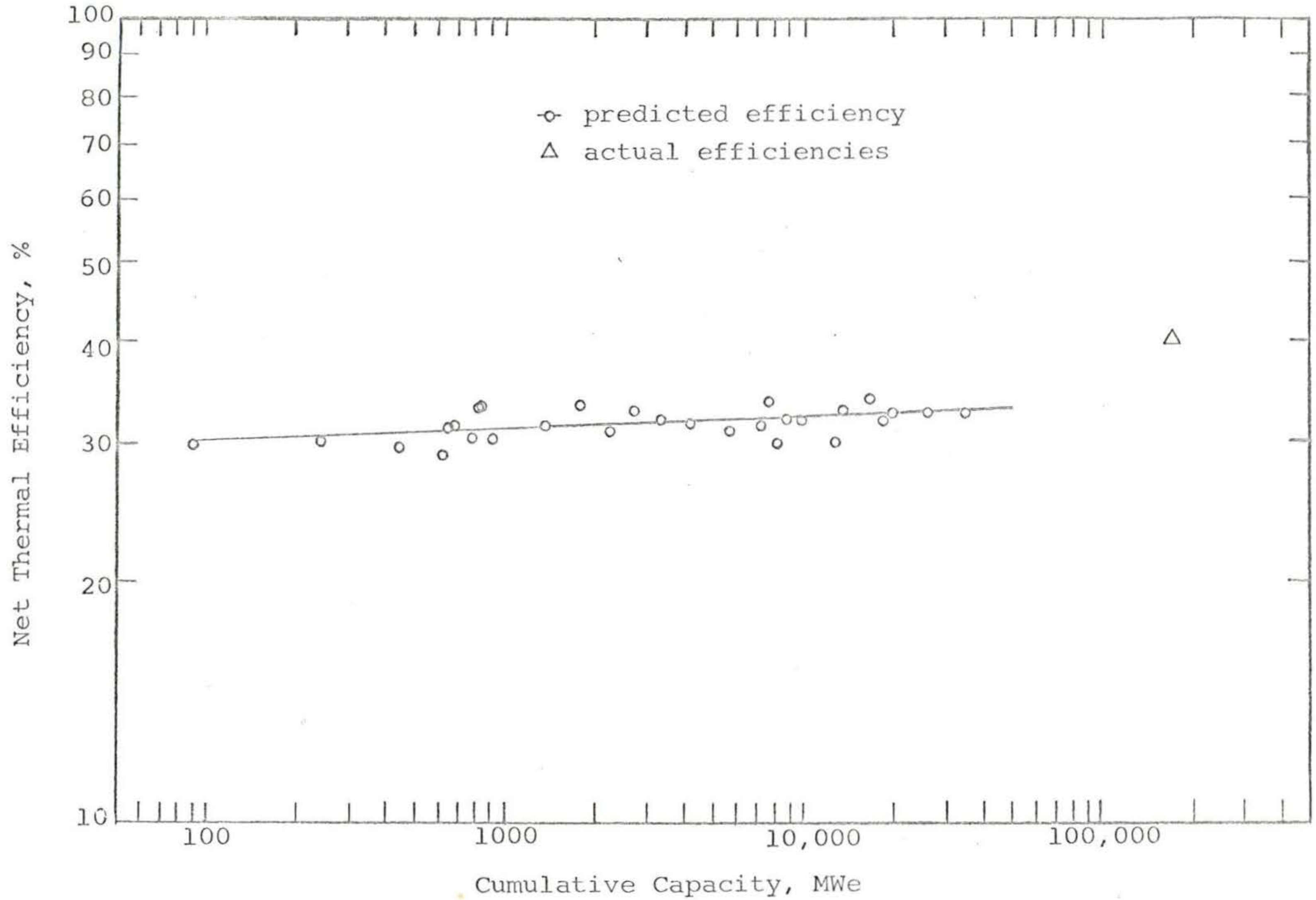

Figure 11. Thermal efficiencies of light water reactors

thermal efficiency like there was in other areas in the nuclear industry. Several items, however, have limited the use of conventional technology such as the necessity of conserving neutrons, protecting fuel while it is being burned, and confining fission products (20). These items have required that the nuclear industry develop cladding, structural, and alloying materials which will withstand thermal and corrosive effects plus perform well under neutron irradiation.

Through the development of these materials and other technological advances, it has been predicted that by 1980 efficiencies may reach 40% (4). Thus with the possible increase in thermal efficiency and burnup, the total construction costs and fuel cycle costs for nuclear generating stations should be reduced. The efficiencies for some of the operating plants that are listed in Table 3 are based on the original designs of the plants. Some of these thermal efficiencies have increased due to operating experience. These increases, however, have not been reflected in this thesis.

VI. FUEL COSTS IN THE FUTURE

When predicting the cost of nuclear power, one must consider the current supply of fuel available for use in the nuclear power stations as well as the quantity of fuel which will be available in the future. This will have a great effect on power costs since roughly half of the cost of power is fuel cycle cost. It is also possible during the life of a plant that about two and one half times its original cost could be spent for fuel. Power costs are predicted to be fairly low for the generating plants now being built. However, as fuel becomes more difficult to produce at the purity level required, the cost of fuel will increase and thus cause an increase in total power costs. This will definitely have an effect upon the predicted cost of power produced by nuclear stations.

The problem of minimizing the increase in fuel cost may be attacked in three different ways. The first approach would be to develop a less costly means of mining and processing the uranium ore. The second approach is to develop better and less expensive techniques to conserve fuel. The last approach is to utilize advanced nuclear reactors in the utility systems. All of these approaches will be discussed briefly in this chapter with special emphasis on the use of advanced reactors.

In considering future fuel costs from the aspect of mining and processing, the availability of uranium ore becomes very important. The outstanding success of the light water portion of the nuclear power program has resulted in commitments (end of 1967) of nuclear plants with a cumulative capacity of more than 47,000 MWe in the United States (19). It has been estimated by Dietrich (5) that nuclear plants with a cumulative capacity of 25,000 MWe and operating at an average plant factor of 75 per cent will require over their 30 year lives some 145,000 tons of natural U_3O_8 as fuel. The domestic reserves of the United States are currently estimated by the United States Atomic Energy Commission at about 145,000 tons of U_3O_8 which can be processed at less than ten dollars per ton (11). Thus the commitments for nuclear power stations in the United States of more than 47,000 MWe cumulative capacity are no longer small relative to the estimated reserves.

The Atomic Energy Commission's current estimate of 95,000 MWe committed by 1980 appears to be somewhat conservative (11). The lifetime fuel requirements for this capacity would approach 475,000 tons of U_3O_8, an amount which certainly could not be produced from the current estimates for domestic reserves (11). The Atomic Energy Commission estimated additional reserves of U_3O_8 at 325,000 tons whereas the United States Geological Survey has a more optimistic estimate of these reserves at 650,000 tons (11). It has been estimated by Hoveke (11) that the cumulative requirements through 1980 will be approximately 170,000 tons of U_3O_8 with an annual requirement of approximately 28,000 tons. Unless this rapidly increasing cumulative capacity of nuclear power stations is accompanied by the discovery of more domestic reserves, these reserves will certainly be depleted by 1980.

To supply the nuclear power plants which have already been committed, major expansion in the areas of processing and production of nuclear fuels must occur before many years. With this expansion, new techniques should be developed in these areas which will lead to a reduction in cost. Current estimates of fuel cost for a large water reactor which would become operational in the 1970's are about 1.8 mills per kilowatt hour (11). The fuel cost is anticipated to be about 25 percent lower by 1980 assuming that mining and processing techniques are improved.

The capacity of the gaseous diffusion plants must also be considered when one discusses the processing and production of fuel. By the end of 1968, it is estimated that the three gaseous diffusion plants will be operating at about one third of peak capacity (11). Hence there seems to be sufficient enrichment capacity for future power reactor fuels. Thus it appears that if normal technological improvements accompany expansion, future fuel costs will not be increased by mining and processing cost but possibly by the lack of uranium reserves.

As more nuclear power plants are being built and the nuclear industry continues to grow, the full significance of spent fuel reprocessing becomes quite apparent. This spent fuel contains plutonium as well as 30 to 50 percent of the original uranium 235 (13). With adequate reprocessing, this plutonium and uranium can be recovered and recycled to power reactors, thereby achieving a greater utilization of the uranium reserves and enhancing the economics of nuclear power production.

Standard charges for reprocessing fuels of the Yankee or Dresden type reactors are approximately $32,000 per metric ton of uranium, subject to cost escalation for material and labor in accordance with government indicies (13). The total cost of reprocessing spent fuel is in the area of about 12 percent of the fuel cycle cost for any reactor operating under equilibrium conditions (13).

Very difficult hurdles have had to be overcome to bring the processing of spent fuel to its present state of development. A few of these hurdles have been the development of processing technology, pioneering work in licensing and contracting, pricing the services and developing the first completely funded continuous care of highly radioactive waste.

Lower reprocessing charges accompanied by reasonable profits appear to hinge on increasing the throughput per dollar of capital (13). Additional price reductions may result from the recovery and sale of such isotopes as cesium, strontium, and neptunium (13). Some of these isotopes are in extremely short supply and recovering them from spent power reactor fuel appears to be the most economical source.

Lower reprocessing cost first appeared to demand that large plants with high throughput and capacity be built. Preliminary studies, however, indicate that a two metric ton uranium capacity per day plant is about the largest desirable for reprocessing low enrichment, high burnup, power reactor fuels (13). These studies also indicated that several such plants should be regionally located to best serve the power industry (13).

Thus one of the major objectives of the reprocessing industry appears to be keeping reprocessing prices at a reasonable cost. This, of course, will definitely benefit the nuclear industry. The utilization of spent fuel will also reduce the annual requirement for newly mined uranium ore and therefore help in holding fuel cost at a low level in addition to reducing the depletion of uranium reserves.

The ultimate goal for nuclear power is to achieve complete self-sufficiency in the area of fuel supply. This attitude comes, in part, from the fear that the available uranium reserves will be depleted due to inefficient thermal reactors and thus leave many countries without a natural source of fissile material. The solution, then, is to introduce reactors into the utility systems which will breed more fissile material than they consume and thus provide fuel for refueling themselves and other nuclear power reactors. Ideally, this breeding rate should be high enough to accommodate the growth in electrical power usage. In the United States, this growth has been doubling approximately every ten years (18).

The future trends of nuclear power can be divided into five time periods. The first period will be the continual construction of thermal reactors with the water reactors predominating in the production of electrical power. In the second period, the construction and electrical production by the breeder reactors will start having a significant effect on the industry. The third period will occur when the number of high gain breeders operating is sufficient to closely approach complete self-sufficiency of fuel supply within the nuclear power production industry. The fourth period which has been suggested by Neef and Jones (15) is a period when plutonium production will exceed demand. During this period, the thermal reactor will recycle as much plutonium as possible accompanied by the availability of plutonium for other uses. The final period will come possibly around the year 2055 when all thermal reactors have been phased out of the utility systems leaving only the high gain breeders producing electrical power (5).

The important question which effects the nuclear industry then is when will the breeder start limiting the need for uranium? The earliest data as estimated by Nordman, Smith and Wright (17) is the early 1980's, with a more predominate effect by 1985. Figure 12 graphically presents the effects of high gain breeders on requirements for uranium. In it is presented the effects of the high gain breeders if they are developed and introduced by 1980, 1985, or if no high gain breeders enter the nuclear power production picture by 2005. As can be seen in Figure 12, the ultimate requirement for uranium metal, which will effect the price of fuel to be used in reactors, will largely depend upon when the breeders become effective in the nuclear power industry. Another important factor in the reduction of uranium ore requirements is due to low, medium or high gain breeder reactors. High gain breeders as indicated in the figures of this chapter are breeders with a doubling time of about seven years (16).

Other estimates and economic analysis have been made pertaining to the advent of the fast breeder. One of these estimates is by Dietrich (5) in which it has been estimated that the breeder fraction of the total nuclear capacity begins in 1985. In this analysis, two different doubling times are considered as shown in Figure 13. The upper curve, which represents breeder reactors with a doubling time of twenty

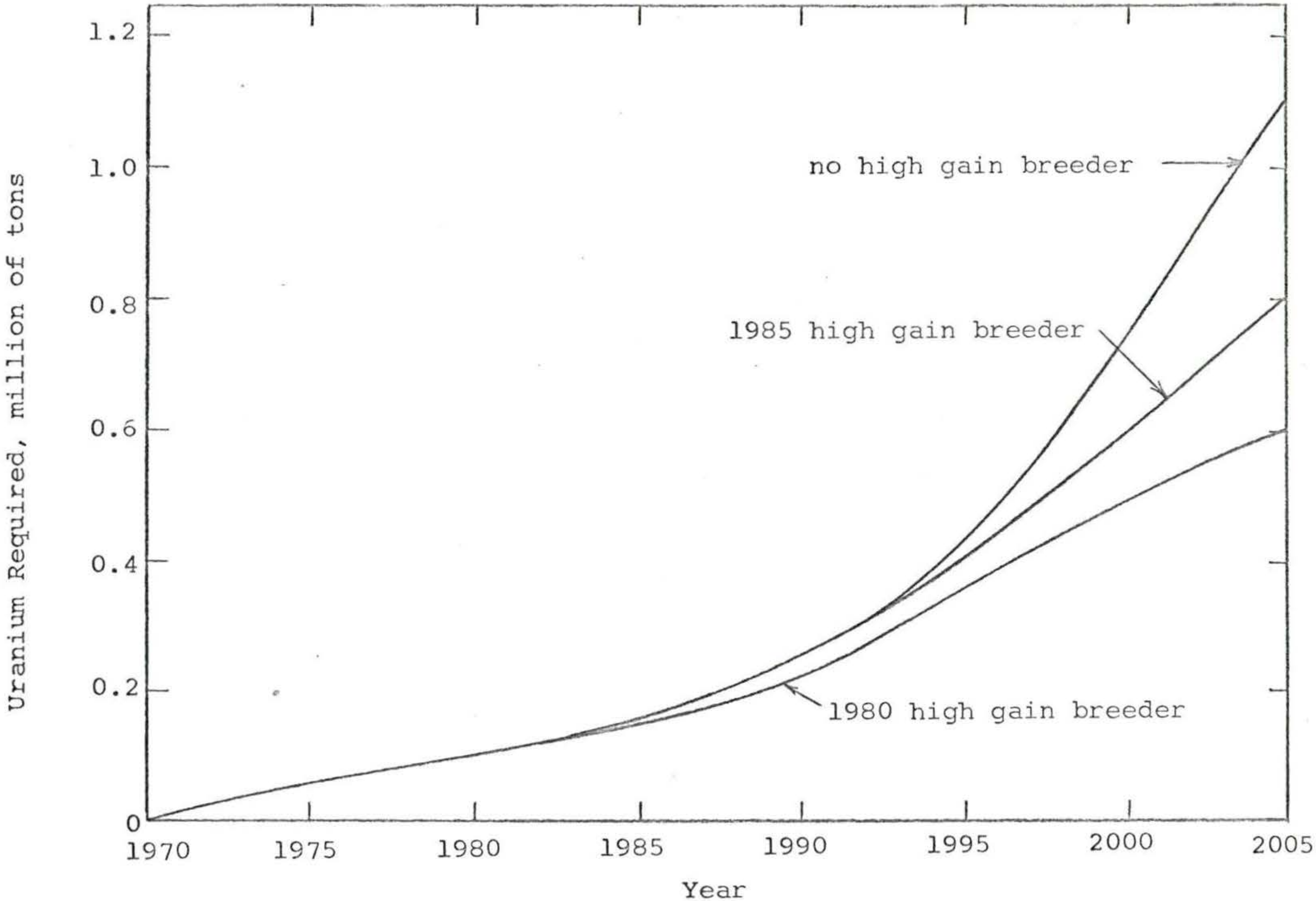

Figure 12. Effect of high gain breeder on uranium requirements (17)

year, levels off at about 2055 which indicated a zero requirement for uranium ore. Chronologically it is estimated that by about 2020 the fast breeder capacity will have surpassed converter capacity and by approximately 2030 the converter capacity will begin to decline (5). From the lower curve of Figure 13 it can be seen that the total requirements for ore can be markedly reduced if minimum doubling time breeders are available. The leveling off of both curves indicates that the demand for plutonium produced by converters is no longer required and the installed converter capacity drops to zero (5). Upon the withdrawal of all thermal reactors from the utility systems, all new power demands will be supplied from the fast breeders which will receive fuel from other operating breeders. The cumulative ore requirements as presented in Figure 13 represents uranium used for inventory in the converters existing at that time but does not include the burnup or uranium ore prior to 1985 (5).

A recent estimate of the cost of exploiting United States uranium reserves is shown in Figure 14. The reserves are measured in metric tons of contained uranium metal. The possible total reserves contain the reasonably assured resources which are in known ore deposits plus possible additional resources which may be economically exploitable (17). The reasonably assured reserves are assumed to be profitably removable through the use of presently known technology.

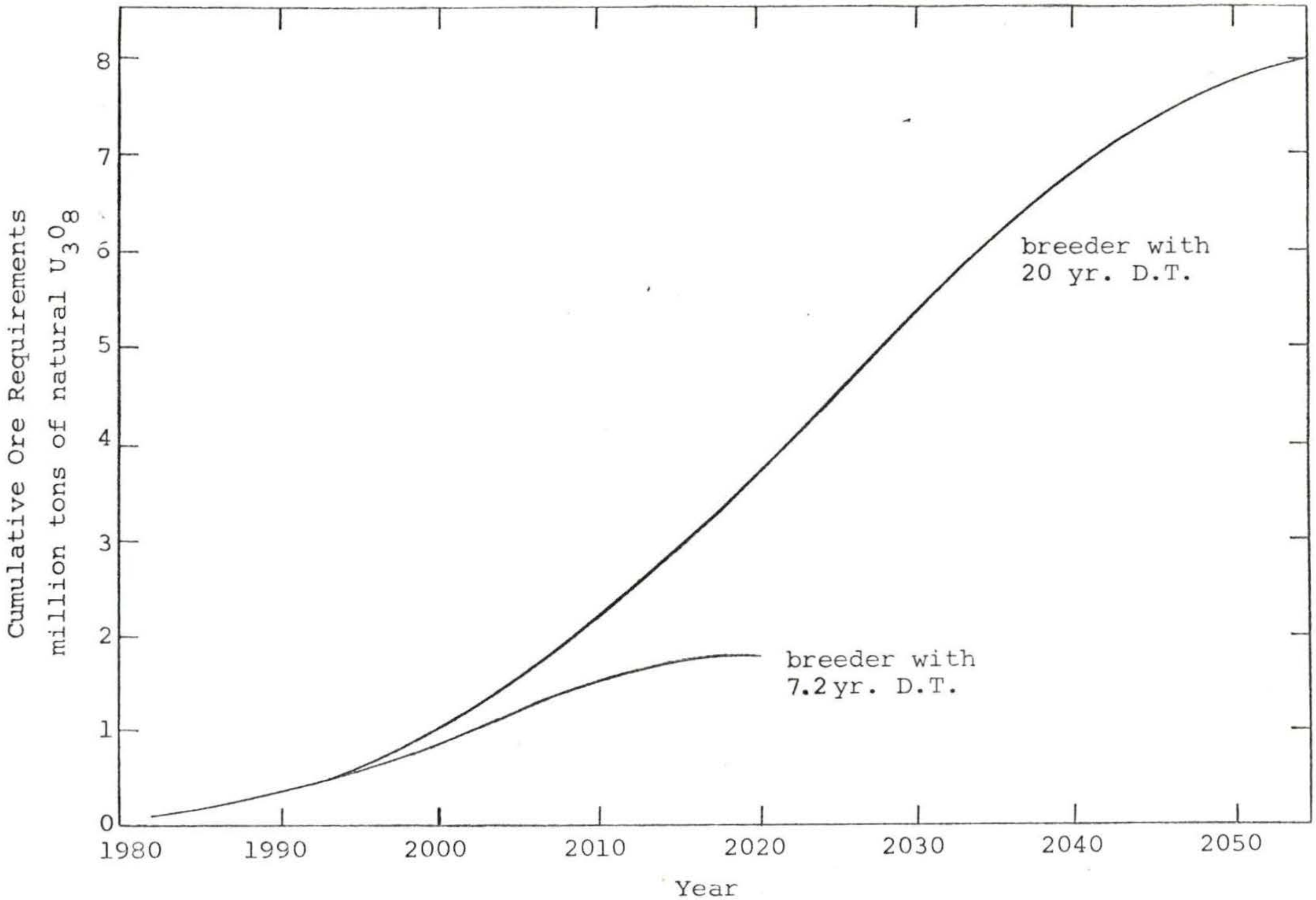

Figure 13. Ore requirements to 2055 (5)

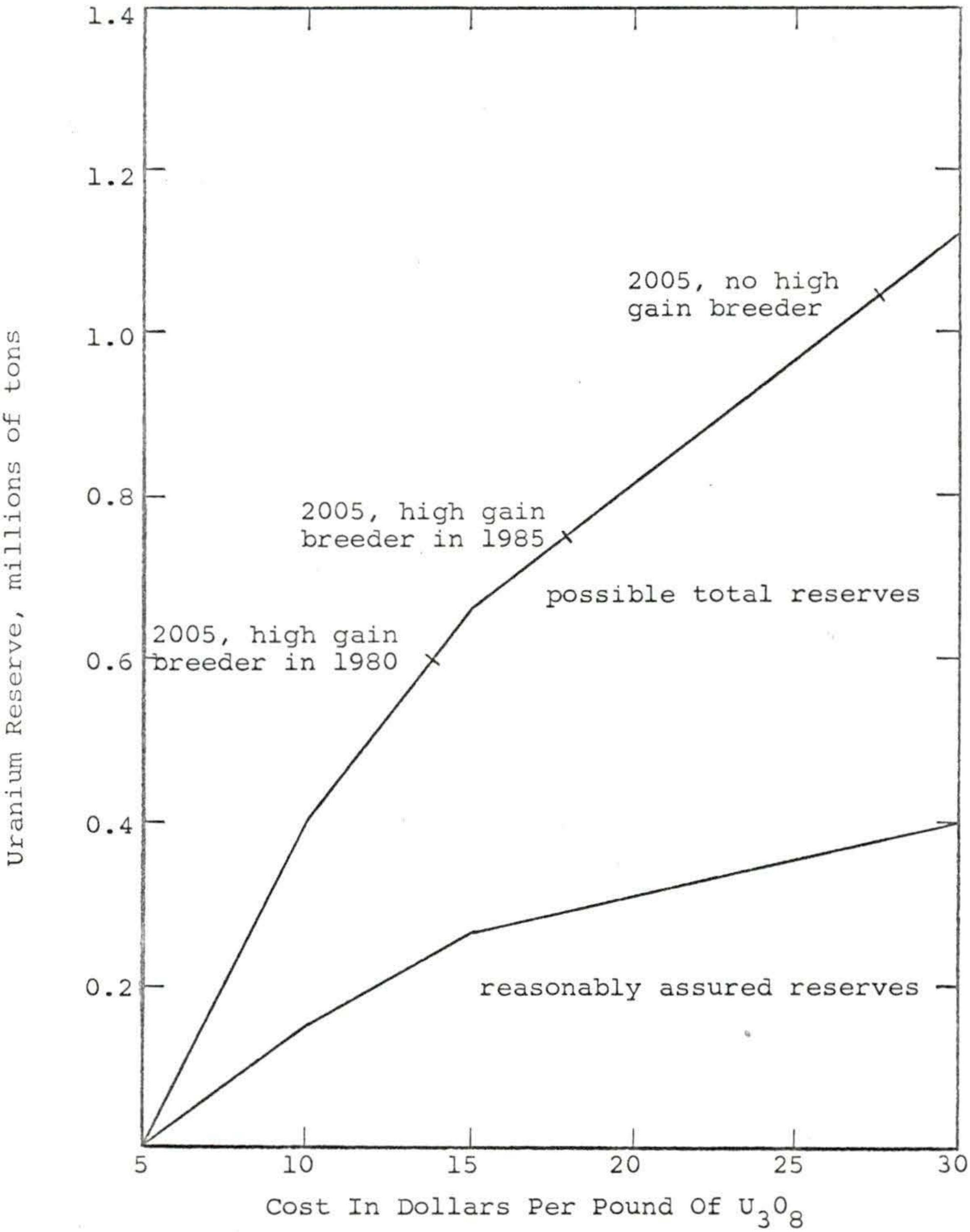

Figure 14. Costs of exploiting U.S. uranium reserves (17)

From Figure 14 it can be seen that the total reserves available will last much longer if the high gain breeder is established at the earliest possible date. One can also see from Figure 14 that the cost of exploiting the uranium reserves will increase much more rapidly if there is no, or a late, advent of the breeder reactor.

The effects of rising ore cost on fuel cycle cost can readily be seen from Figure 15. Once again the importance of rapid development of high gain breeders in order to maintain nuclear power at a competitive and reasonable cost can be seen. Since a market for plutonium produced by the thermal reactors would be provided by the high gain breeders, this market would decrease or at least dampen the overall effects of rising ore costs. Where no breeders are constructed, a much greater rise in fuel cycle cost will occur from the following effect. There will be increased uranium needs accompanied by higher costs plus the lower value received from the plutonium produced in the thermal reactors.

All three categories, mining and processing, reprocessing, and the construction of advanced nuclear reactors, will have a considerable effect on nuclear power cost from civilian reactors. Each of these categories must be advanced with changing times in order to maintain power costs at a minimum. Especially important will be the introduction of the high gain breeders. These will conserve on the uranium

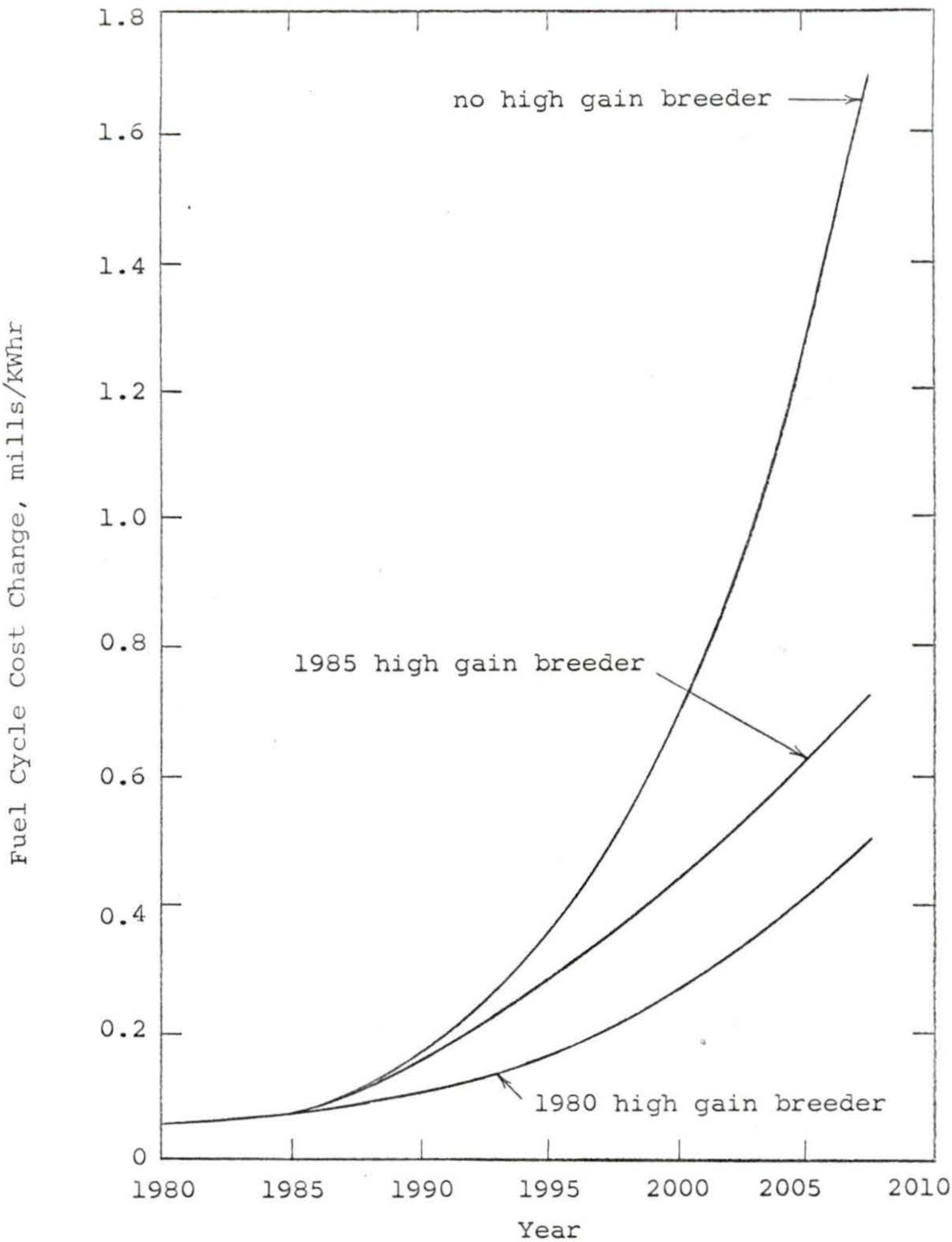

Figure 15. Affects of rising ore cost on fuel cycle cost (5)

reserves of the United States plus reduce the total fuel cost by providing a premium market for thermal reactor produced plutonium.

VII. AREAS OF COST REDUCTION IN NUCLEAR POWER

When applying the learning curve technique to nuclear power production, it is important to note the areas where cost reductions are possible. It has been shown that as the net electrical size of nuclear power plants increases the cost of electrical power decreases. There are, however, definite areas where actual or potential cost reduction through learning may develop. These areas will be discussed in the following sections.

A. Cost Reduction through Joint Action

If utilities were to jointly purchase several identical nuclear power plants and jointly perform some of the special functions required for nuclear plants, it could result in a substantial cost reduction. This reduction would result from spreading the size independent costs associated with nuclear power over many units. In order to consider this area, it must be hypothesized that the interested utilities would first form a group or committee from which the joint participation could be accomplished. Utilizing this joint committee, the utilities could contract jointly for the same or very similar power stations. The group could represent all participating utilities in dealing with the Atomic Energy Commission and other regulatory agencies. It could also coordinate and monitor radiation protection, secure consulting services, and arrange for joint purchasing of nuclear fuel elements and associated fuel cycle services.

Joint action can be broken down into two time periods, joint action before operation and joint action during operation. Joint action before operation may include such items as joint reactor purchase, joint fuel element purchase, joint licensing and safeguards, and personnel training. Joint action during operation would include items pertaining to waste disposal, fuel cycle management, and radiation protection.

Joint purchasing could result in the greatest potential cost reduction through the use of joint action. This reduction comes about through the purchase of more than one identical or near identical nuclear power plant. The vendor can sell the reactors at a reduced cost due to multiple orders, reduced nuclear engineering and project management costs, and reduced architectural engineering costs since orders are identical.

Nuclear fuel costs could also be reduced through joint fuel element purchase. The reduction would be brought about because of lower fabrication costs which in turn results from the increased scale of operation. Cost reduction could also result from decreases in reprocessing costs by combining spent fuel batches from the participating utilities.

Joint licensing and safeguards could result in savings if the group would order identical reactor plants, radioactive waste disposal building, and contaminated storage vaults. Under these conditions, the Atomic Energy Commission would be approving one safety analysis report instead of a number of individual reports. The individual utilities could then deal separately with the Atomic Energy Commission on the rest of the site and the balance of the plant. It is not expected, however, that say for two plants, the cost of licensing would be the same as for one plant. It is anticipated, however, that the application for pre-licensing would receive closer scrutiny with more questions being raised than would be the case for just a single plant. There has been estimates made that the licensing and compliance costs would be reduced by one half if five identical units were procured by a group of five utilities (25). This estimate does not take into consideration any simplification in regulatory requirements. If both multiple unit procurement and regulatory simplification were present, the savings should be greater but not necessarily in proportion to the number of units.

Savings could also result from joint action in the area of personnel training. A major portion of training costs are made up of transportation, salaries, and the expenses of employees during the training period (25). Utilization of the group would allow the assigning of key personnel from one utility to another. This would allow the key personnel from all the utilities to start training and gain experience as soon as the first reactor in the group goes into operation. Then when their own reactor becomes operational, the personnel will already have had some operating experience. The savings through joint operation in personnel training has been estimated at 10% of the total personnel training costs (25).

Joint action during operation includes joint use of waste disposal facilities, radiation protection facilities, and fuel element purchases. On site facilities provide for the collection, processing, and storage or disposal of radioactive wastes. Temporary on site storage is provided for the low level solid wastes generated during normal operation of a nuclear power plant. At this time, the Atomic Energy Commission requires that this low level waste be buried on state or federal owned land by licensed private firms (25). It has been estimated that through possible negotiation by the group to set up joint collections, the savings might amount to 15% of the annual cost of solid waste disposal (25).

Each plant organization for a nuclear power station normally includes a health physicist or radiation protection engineer plus a health physics technician. It is quite possible, that through joint action, the health physicist could possibly be eliminated from each plant organization by utilizing one health consultant for the group. The consultant would be available for consulting at all times and would make scheduled periodic visits to each utility in the group. The savings in this area would be approximately $6,000.000 annually (25).

The largest savings brought about by the group in the area of fuel cycle management would be through coordination in purchasing fuel elements. It might also be possible to have a reduction in fuel inventory for each individual utility.

B. Cost Reduction through Technological Improvements

Technological improvements normally lag the reactors by about four years since it takes approximately four years for the design, fabrication, construction, and start up of a nuclear power plant. The next generation of reactors, however, can then utilize what has been learned in the previous generation. These improvements could be the result of the development of improved instrumentation and control systems and elimination of certain standby systems. An actual example is the development of the jet recirculation pump (25). Some improvements, such as a decrease in fuel or operating and maintenance costs, can be incorporated into an operating plant. Technological improvements are definite learning affects that can be interpreted from the learning curve technique.

C. Cost Reduction through Decrease in Fuel Cost

One area where it is anticipated that learning will result during operation of a nuclear plant and thus bring about a reduction in cost is in the fuel area. The predicted savings will come about through technological improvements, cost reduction due to large scale operations, long term cost trends for uranium ore, and the reimbursement for the plutonium produced. At the present time, some of the technological improvements have been the result of the development of uranium oxide fuel materials, the development of fabrication techniques which permit long fuel exposures without loss of structural integrity, the use of zirconium alloys for fuel cladding, and the development of new fuel cycle manage-schemes (25). All of these technological improvements allow for a more uniform power distribution and a longer reactivity lifetime for the fuel.

With the increase in the number of nuclear power plants, fuel cost savings should be increased due to the increased scale in fuel fabrication and reprocessing. It has been estimated by some firms who are engaged in fuel fabrication that a ten-fold increase in annual throughput of a fuel fabrication plant would lead to a reduction of up to $50/Kg in the cost of fabrication of fuel assemblies (25). This reduction would definitely cause a fair decrease in fuel cycle costs of an operating reactor. This decrease is approximately equivalent to 0.35 mill/kwhr for fuel with a 20,000 MWD/ton burnup (25). Lower reprocessing cost should also accompany this increased fuel use.

Other possible areas of cost reduction in fuel could be in the areas of uranium ore costs and the value of the plutonium produced in a reactor. These areas, however, are very speculative and it would be impossible to make any accurate predictions. These areas will eventually be determined by the law of supply and demand.

D. Cost Reduction through Regulatory Simplification

Regulatory simplification is also a category where the cost of power could be reduced. A reduction in this category would effect two cost areas of a nuclear power plant. First the capital cost of the plant would be reduced due to the lower cost of obtaining the construction permit and operating license for the facility. The second reduction would be in the area of operating expenses. The cost of satisfying the Division of Compliance of the AEC that the plant is being operated in a safe manner is an operating expense (25).

In 1965, the Atomic Energy Commission appointed a seven man panel to review the Commission's licensing and regulation responsibility (25). It has been estimated, if the recommendations they put forth were placed into effect, that the minimum time required to obtain a construction permit could possibly be reduced from one year to six months (25).

E. Cost Reduction due to Stretch

Nuclear power stations in operation have demonstrated the capability of achieving appreciably higher power densities and greater power outputs than their initial net rating. This capability has been called "stretch". It results from the margin which the designer provides between the design prints and the actual rating. After operating over a period of time, the coolant flow and neutron flux distribution have been more accurately measured and determined. Experience has shown that the designer is much more conservative in accounting for these distributions than those which are observed during actual operations. Due to stretch, it has been possible to increase the core output and thus increase the net power output of the nuclear power station. This, of course, reduces the cost per unit of the power being produced.

All of the preceding areas of cost reduction may have a considerable effect on the cost of power produced by a nuclear power plant. The total effects can be seen from estimates by the U.S. Atomic Energy Commission as shown in Figure 16 (25). It can be seen from the graph that these areas will especially

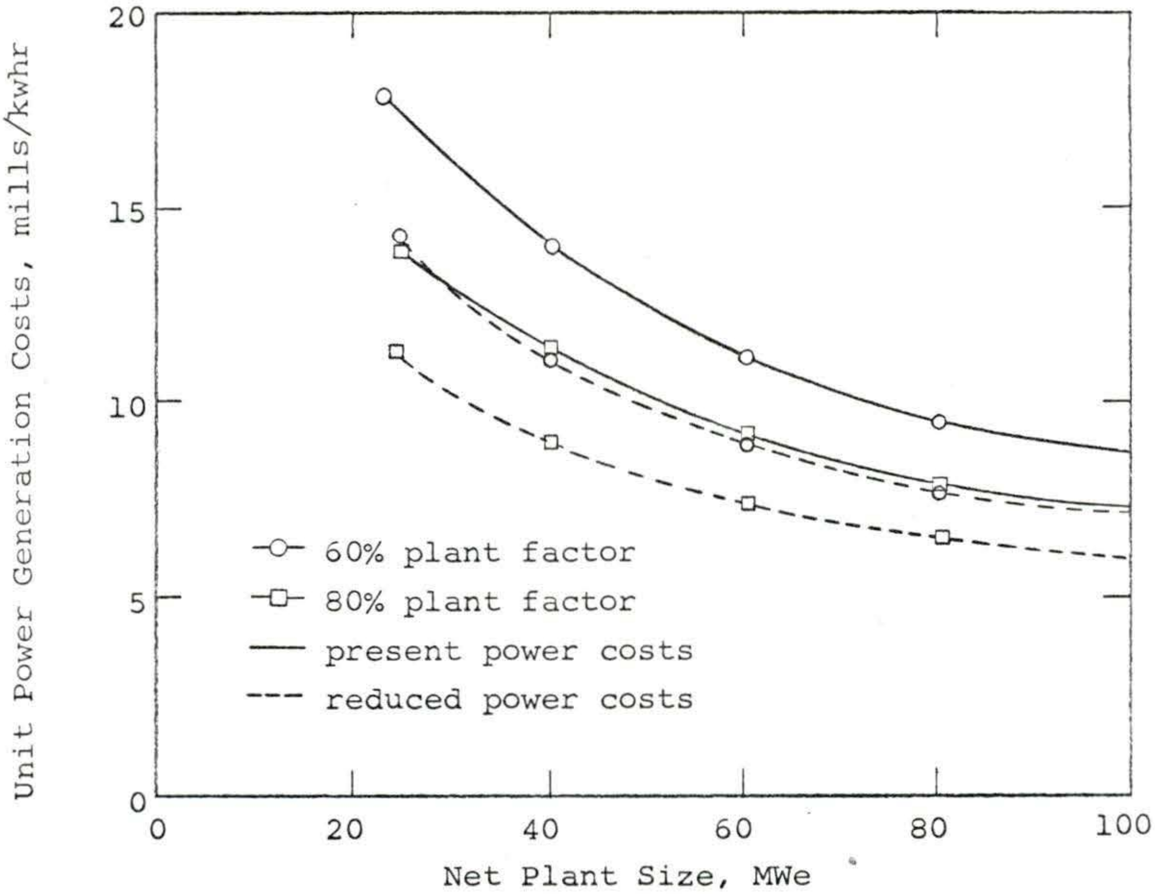

Figure 16. Energy costs from nuclear power plants

reduce the cost of power produced from nuclear power plants with 300 MWe net capacity or lower. On plants larger than 300 MWe, the reduction is spread over a larger net capacity and thus it requires a much greater savings in dollars to show a very sizeable reduction in power cost. The cost reduction areas discussed in this chapter will, however, result in lower power costs irregardless of the size of the power station.

VIII. SUMMARY AND CONCLUSIONS

Virtually every industry should be capable of producing products at a lower cost after experience in the field has been gained. It seems that if continuous effort and management goals are extended to do a task better, then this goal will be continuously achieved. Many of the industries in which an improvement of this type has been found to occur may be described by the learning curve technique. In this thesis the nuclear industry was found to submit to this technique for (1) total power production costs, (2) fixed charges, (3) fuel cycle costs, (4) operating charges, (5) first core and equilibrium burnup, and (6) station thermal efficiency. The reduction factors obtained for the final curves in the production cost areas were 5%, 3.4%, 5.57% and 6.7% respectively. The final factors for first core and equilibrium burnup were an increase of 3.4% and 6.5% respectively, whereas, the factor for thermal efficiency was a constant 1% increase.

This method of predicting future costs of operating characteristics should be very useful to the nuclear industry and to the utility companies as long as no major changes in either the goals of the industry of the national economy appears. This technique will be more accurate when no major changes are experienced other than experience being gained and a more stable industry is developed. The vendors can use this information for establishing management goals and for sales contracting. The utility companies should find these predictions or this prediction method very useful, because they have to plan for the future in order to meet the continually increasing demands of their customers for electrical energy.

It appears that with the information available the learning curve technique has been advanced about as far as possible in its application to the nuclear power industry unless curves for operations other than those proposed in this thesis are treated. Of course, the ultimate goal for this type of analysis is to be able to construct the type of curves drawn here for only one size of reactor and thus eliminate the size dependence of the smaller power stations.

It would be very interesting as a future study using this technique to analyze the fast breeder reactors as the data become available. One would think that an appreciable amount of the technological improvements gained from the thermal reactors could be utilized and thus the initial slopes for the fast breeders should show a much less rapid decline.

The analysis from the available data on boiling water and pressurized water reactors leads to the conclusion that there is a decrease in costs and an increase in some operating characteristics taking place in the nuclear power industry at the present time. The decreases in costs are in the areas of total production costs with the highest rate of reduction associated with operating charges. The greatest increase in operating characteristics being in the area of equilibrium core burnup. But it is also concluded that the learning curve technique is only applicable for nuclear power stations with a net capacity greater than 400 MWe due to the size dependence of the smaller plants.

Also one must conclude that if the fast breeders are not introduced into the utility systems at the earliest possible date, the fuel costs associated with nuclear generating stations will increase quite rapidly due to the dwindling uranium ore reserves.

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