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CONSIDERATION OF NUCLEAR POWER EXPANSION FOR PUERTO RICO, INCLUDING SURPLUS CAPACITY PENALTIES

J. M. Holmes

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J. M. Holmes

DECEMBER 1970

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CONSIDERATION OF NUCLEAR POWER EXPANSION FOR PUERTO RICO, INCLUDING SURPLUS CAPACITY PENALTIES

J. M. Holmes

ABSTRACT

An analysis was made to estimate the optimum time interval for installation of nuclear power plants in Puerto Rico. Data on projected demands for the Puerto Rican system between 1970 and 2000 were used as the basis. The model included effects such as the net penalties for excess capacity, cost-size scaling factors for capital and operating costs, maximum reactor capacity (size) constraints, and salvage values. The optimum capacity expansion interval for an interest rate of 6% and no excess capacity penalty is about 2.5 years. When the price of the excess power sold as nonfirm power was reduced by 0.4 mill/kwhr, the optimum interval did not change. If the penalty for excess capacity is greater than 20% of the capital cost for one year's expansion in capacity, the expansion interval should not be more than one year. The effects of negative penalty costs (net benefits) were also evaluated. If the operating cost savings for nuclear fuel compared with fossil fuel amounted to 0.9 mill/kwhr, the optimum capacity expansion interval would be about 3.9 years. At the current system growth rate this would correspond to a reactor size of about 800 MWe.

INTRODUCTION

Studies have been made of the tradeoffs between plant investments that tend to decrease in unit cost with increase in capacity and the time value of money which favors the postponement of investment and is a function of the prevailing interest rate. Manne[1] developed equations for the optimum size of a plant to be constructed when demand for a product catches up with existing capacity. Demand was assumed to grow linearly with time, so construction of a plant created surplus capacity, which decreased linearly over the period between plant startup dates. The excess capacity function displayed a sawtooth pattern with zero nodes of excess capacity at each startup date when plotted as a function of time. Manne also developed equations for examining the effect of probabilistic growth in demand and the effect of accumulating backlogs in demand on the optimum plant expansion capacity.

Burwell and Ebel[2] performed a similar analysis for desalting plants. They assumed a linear demand growth curve and added the effects of salvage value and fixed operating costs to the analysis. In general, their results indicated that the optimum ratio of plant size to annual growth rate (number of years capacity expansion) was about five. Moyers[3] applied the same general approach used by Burwell and Ebel but considered an exponentially expanding market. He found that optimum sizes of plant expansions were considerably shorter for exponential growth rates than they were for the linear growth curves. For a capacity scaling exponent of 0.8 and an interest rate of 6% over a 30-year horizon, the optimum plant expansion was about three years of capacity expansion. The optimum plant expansion increased to six years when the scaling exponent was decreased to 0.70 from 0.80. Extrapolation of Moyers' results indicates that the optimum plant expansion for a scaling exponent of 0.86 would be approximately two years. Both Moyers and Burwell examined the effect of interest rate on the optimum interval of plant expansions. For a range of interest rates between 3 and 10%, the optimum interval did not shift appreciably.

In the study described here, an attempt was made to determine the optimum capacity expansion for nuclear power plants to be considered for Puerto Rico. A predicted power growth curve prepared by the Puerto Rico Water Resources Authority (PRWRA)[4] was used as the basis for the demand curve. The effect of overcapacity on the optimum capacity expansion was taken into consideration and the magnitude of this effect was treated parametrically.

The results of this study are indicative of the advantages that could be gained by installing one reactor or a multiple reactor plant for more than one year's increase in power demand. The results should not be construed to be a plan for future expansion of the PRWRA system since the model did not include details (e.g., size, age, and operating costs) of the older plants to be placed on standby. Consideration of the benefits to be derived from base loading the nuclear plants, such as lower fuel costs, was included.

BASIC ASSUMPTIONS

The following basic assumptions were made in developing the model for this study:

1. The demand for power in Puerto Rico up to the year 2000 is adequately represented by the predictions developed by PRWRA.

2. A maximum permissible nuclear plant size is specified from either the operating characteristics of the Puerto Rican grid system or the largest reactors available from the vendors during the period under consideration. Information developed by PRWRA was used for this assumption.

3. Each plant capacity expansion is to provide for a constant number of years growth of power demand over the 30-year horizon.

4. The salvage value of a plant at the end of the 30-year horizon and the operating costs not incurred after 30 years (for plants other than the initial plant) are equal to the initial investment plus the present worth of the operating costs times that fraction of the 30-year horizon during which the plant is not operated.

5. The new plants added are operated at full capacity at all times, and a penalty cost is incurred that is proportional to the surplus capacity at any point in time. The unit penalty cost constant is not a function of the surplus capacity, but the program could be modified to take this into account.

6. Both variable and fixed operating costs (not including capital charges) are related to plant size by an exponential function similar to the capital cost function. Plant availability factors are included in operating costs.

7. The cost of a multiple plant installation is related to single plants costs in the following manner:

$$\text{Cost} = V3*\left[\begin{array}{c}\text{Number of plants}\\ \text{of size } Z\end{array}\right]^{V2} *(Z)^{V1}$$

where single plant costs are

$$\text{Cost} = V3*Z^{V2}$$

In order to work with continuous functions, it was necessary to allow fractional sized plants when more than one plant was required. Although multiple plants of the same size are probably more desirable, it may be feasible to install a less-than-maximum capacity plant next to a maximum capacity plant if the smaller plant were to be used exclusively to provide energy to an agro-industrial complex. All equations in this report are presented in a semi-computer form to permit transposition back to computer language without extensive modifications.

NOMENCLATURE

X = Number of years capacity expansion or the period between installation of new plants,

J = Plant number,

X*(J-1) = Year when plants are installed in the system,

Z(L) = Maximum reactor capacity during five year periods (L), MW(e),

G(L) = Slope of the demand curve during five year periods (L), MW(e)/yr,

R = Interest rate, %/yr,

MY = Life of a reactor and horizon, years,

V1 = Exponent for multi-plant capital cost,

V2 = Exponent for capital cost equations,

V3 = Coefficient for capital cost equations, $ millions,

V4 = Exponent for multi-plant operating cost,

V5 = Coefficient for operating costs, $ millions,

V6 = Exponent for operating cost equations,

Z2 = Number of years capacity expansion represented by the maximum size reactor, years,

B1 = Number of maximum sized plants to be installed at one time to satisfy the required capacity expansion, X,

C1 = Ratio of the overcapacity penalty cost to the capital cost for a one year expansion, $years^{-2}$,

C2 = Capital cost of capacity expansion, $ millions,

C3 = Operating cost of capacity expansion, $ millions,

C4 = Cost of overcapacity, $ millions,

C6 = Penalty cost for operating plant for one year at a surplus capacity equal to a one year expansion, $ millions/$year^2$,

F = X*(J-1)/30

t = Time in the equations used to derive the overcapacity penalty.

(* Indicates multiplication in all equations)

CAPITAL COST EQUATIONS

The procedure for calculating the total cost during a period when the demand curves are predicted to have an exponential growth rate involved approximating the demand curve by a series of linear functions. Figure 1 shows the results of this approximation where linear segments are shown for five-year increments between 1970 and 2000. The PRWRA data were given up to 1990 so the periods between 1990 and 2000 are projected by linear extrapolation. The slopes of the demand functions for each five-year increment are given in Table 1 along with the maximum desired reactor sizes* for each period. Maximum reactor sizes for 1990-2000 were set at 1200 MW(e) for 1990-1995 and 1500 MW(e) for 1995-2000.

The number of years capacity expansion represented by the maximum size reactor Z(L) is

$$Z2 = \frac{Z(L)}{G(L)} \quad .$$

The number of plants to be installed at time X*(J-1) to satisfy the required capacity expansion X is

$$B1 = \frac{X}{Z2} \quad .$$

The capital cost of a plant for a capacity expansion X which is less than the maximum reactor size Z(L), during period L is

$$C2 = V3*[G(L)*X]^{V2} \quad .$$

If the capacity expansion X requires a plant which is equal to or greater than the maximum allowable reactor size Z(L), the capital cost is

$$C2 = (B1)^{V1}*V3*[Z(L)]^{V2} \qquad B1 \geq 1.0,$$

then

$$C2 = (B1)^{V1}*V3*[Z2*G(L)]^{V2} \qquad B1 \geq 1.0.$$

---

*These reactor sizes are in the vicinity of those recommended by the PRWRA (except for the 1990-2000 periods) based on their present practice of having the largest unit in the system less than 30% of the system peak load.

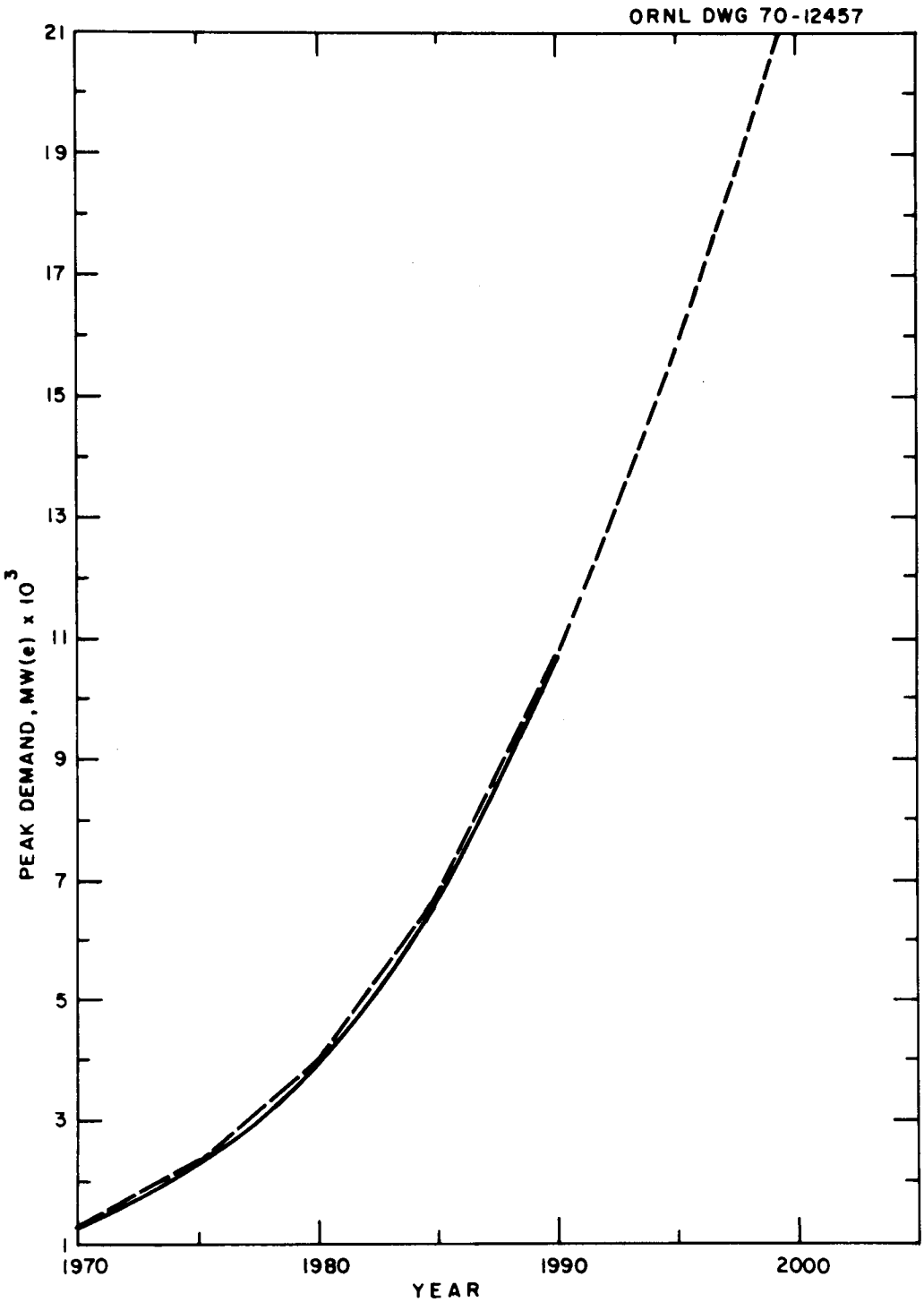

Fig. 1. Puerto Rican Power System Peak Power Demand

Table 1. Power Demand and Maximum Plant Sizes for Puerto Rico

Time Period	Average Increase In Peak Demand [MW(e)/yr]	Maximum Reactor Capacity [MW(e)]
1970-75	204	500
1975-80	330	600
1980-85	525	800
1985-90	820	1000
1990-95	1000[a]	1200[a]
1995-2000	1200[a]	1500[a]

[a]Estimated.

OPERATING COST EQUATIONS

In a similar manner, the operating cost for a plant where $B1 < 1.0$ is

$$C3 = V5*[G(L)*X]^{V6} ;$$

for $B1 \geq 1.0$

$$C3 = (B1)^{V4}*V5*[G(L)*Z2]^{V6}$$

since operating costs were also assumed to scale in a multiplant operation.

OVERCAPACITY PENALTY COSTS

The model used for developing the penalty cost equation is illustrated in Figure 2. At time X*(J-1), when the new plant is placed on stream, the excess capacity is equal to the plant capacity X. Excess capacity is expressed in terms of years of capacity expansion at the time the plant is built. For example, if a one-year expansion in demand equals 200 MW(e) when a plant is installed, but in fact a 600 MW(e) plant is built, the excess capacity at startup would be X = 3.0 years. The excess capacity decreases linearly until year X*J when it reaches zero and then goes to X as a new reactor is brought on stream. Therefore, the excess power that could be generated at any time t is

$$= (X-t)*dt.$$

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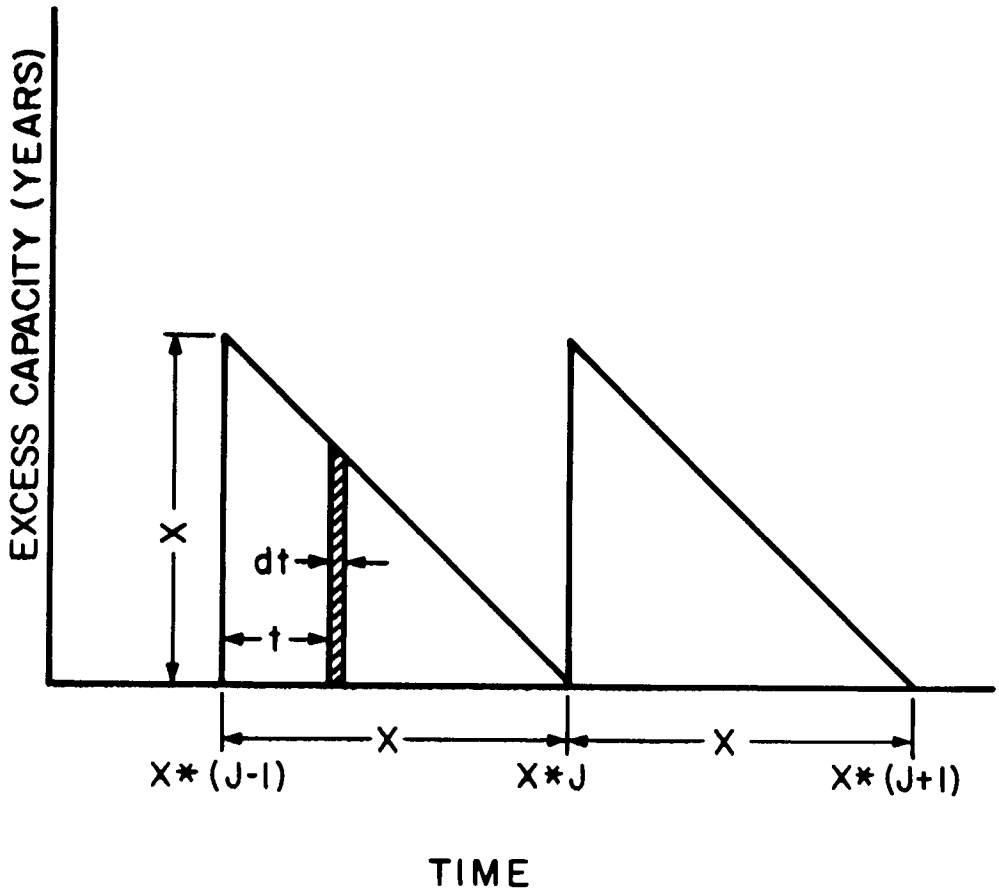

Fig. 2. Overcapacity Penalties

The cost of this excess power present-worthed to the time when the plant was brought on stream is

$$= C6*(X-t)*\exp(-R*t)*dt$$

and the total cost for period X is

$$= C6*\int_0^X (X-t)*\exp(-R*t)*dt.$$

The solution to this equation is

$$= \frac{C_6}{R^2}*[\exp(-R*X)-1 + X*R]$$

where $X \geq 0$.

SALVAGE VALUE AND OPERATING COSTS NOT INCURRED

The salvage value of a reactor and the operating costs not incurred after the 30-year horizon were assumed to be proportional to that fraction of the horizon during which the plant is not operated or $X*(J-1)/30$. For the first installation, this fraction would be zero since $J = 1$; for the second installation it would $= X/30$, etc. Therefore, the total for salvage value plus operating costs not incurred at the end of the horizon would be

$$= X*(J-1)*\frac{(C2 + C3)}{30} .$$

TOTAL PLANT COSTS

The total plant cost is equal to the sum of the capital cost, operating costs, and penalty costs less the salvage value and operating costs not incurred. All of these costs must be present worthed to the initial year of the horizon as follows:

$$\text{Present Worth of Total Cost (PWTC)} = \frac{C2 + C3 + C4}{(1 + R)^{X*(J-1)}} - \frac{F*C2 + F*C3}{(1 + R)^{30}} .$$

For capacity expansions which are less than the maximum plant size during period L, ($B1 < 1.0$), this becomes

$$\frac{PWTC}{V3*[G(L)]^{V2}} = \frac{X^{V2} + \frac{V5*[G(L)*X]^{V6}}{V3*[G(L)]^{V2}} + C1*\frac{[\exp(-R*X) + X*R - 1]}{R^2}}{(1 + R)^{X*(J-1)}} - \frac{F*X^{V2} + \frac{F*V5*[G(L)*X]^{V6}}{V3*[G(L)]^{V2}}}{(1 + R)^{30}}$$

where

$$F = X*(J - 1)/30$$

$$C1 = \frac{C6}{V3*[G(L)]^{V2}} \quad .$$

Note that both sides of the equation have been divided by the capital cost of a plant (to satisfy a year's expansion during any period L) and the penalty cost is expressed as a fraction of this capital cost.

For capacity expansions which are greater than or equal to the maximum plant size during period L ($B1 \leq 1.0$), the equation is

$$\frac{PWTC}{V3*[G(L)]^{V2}} = \frac{(B1)^{V1}*(Z2)^{V2} + \frac{(B1)^{V4}*V5*[G(L)*Z2]^{V6}}{V3*[G(L)]^{V2}} + C1*\frac{[\exp(-R*X) - 1 + X*R]}{R^2}}{(1 + R)^{X*(J-1)}} - \frac{F*(B1)^{V1}*(Z2)^{V2} + \frac{F*(B1)^{V4}*V5*[G(L)*Z2]^{V6}}{V3*[G(L)]^{V2}}}{(1 + R)^{30}} \quad .$$

RESULTS FOR PUERTO RICAN SYSTEM

To solve these equations, a computer program named CAPEX was developed which calculated the present worth of the total costs over the range of $0.5 \leq X \geq 10.0$ using C1 as a parameter. Minimum costs for each value of C1 ($0 \leq C1 \geq 0.50$) were identified. Figure 3 shows a plot of the results for $0 \leq C1 \leq 0.5$ and Table 2 presents the values for the optimum capacity

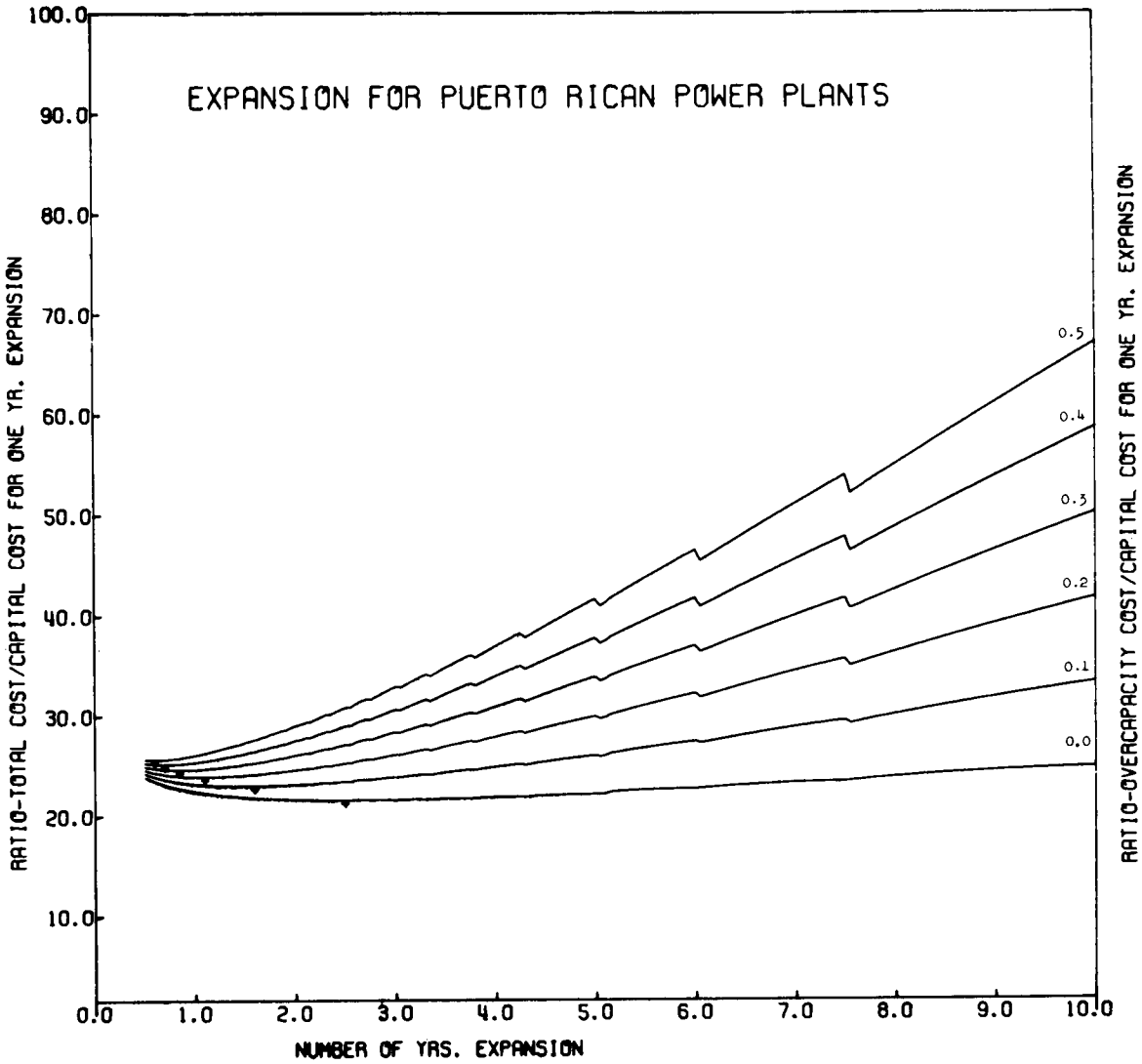

Fig. 3. Expansion for Puerto Rican Power Plants

Table 2. Optimum Capacity Expansions For Puerto Rico Power Plants

Penalty Cost Ratio[a]	Minimum Cost Capacity Expansion (years)
0.0	2.5
0.01	2.5
0.02	2.5
0.03	2.3
0.04	2.0
0.05	1.9
0.06	1.7
0.07	1.7
0.08	1.7
0.09	1.7
0.10	1.7
0.20	1.1
0.30	0.85
0.40	0.70
0.50	0.60

[a]Ratio of overcapacity penalty cost to capital cost of one year's expansion.

expansions as a function of C1. Table 3 summarizes the results of this calculation for values of C1 of 0.0 and 0.1. Reactor operating and capital costs for these calculations were developed by Spiewak[5] for a 6% interest rate which is comparable to an 8% fixed charge rate. A 6% interest rate was used throughout the program. Capital costs were increased by 10% to cover the higher construction costs experienced by contractors in Puerto Rico. Values for the constants used in the capital and operating cost equations are given in Table 4.

The cost-versus-number of reactors scaling factor for both the capital and operating costs (V1 and V4, respectively) was assumed to be 0.9. This is based on information given in ORNL-4290 concerning the costs of multiple reactor installations. However, the data in this report were developed in 1967-68 so the factors used should probably be updated when the costs of recent multiple-reactor stations such as Brown's Ferry become available.

Penalty costs were treated parametrically in this study because it was difficult to obtain data on the actual costs of excess capacity. A few examples of costs that might be incurred because of overcapacity are:

(1) Loss of income from sales of excess capacity as nonfirm power to large power consumers. The reduction in price of this power could be considered a penalty cost.

(2) If the new plant is base loaded and older plants are shut down or placed on standby, the cost of maintaining and starting up the older plants as the demand increases could be considered a penalty cost.

(3) Benefits that accrue through the installation of nuclear power plants can be regarded as negative penalty costs. For example, if older, less efficient, fossil fuel plants are placed on standby because the nuclear plant is base loaded, fuel cost savings should be considered and would be negative penalty costs. These savings would be proportional to the system overcapacity at any point in time and would decrease as the fossil plants are placed on line in order to meet the system demand.

Table 3. Schedule of Optimum Reactor Installations

Time Period	Average Increase In Peak Demand [MW(e)]	Penalty Cost Ratio, C1			
		0.0		0.10	
		Power Capacity[a] [MW(e)]		Power Capacity[a] [MW(e)]	
1970-75	204	510	(1.0)	347	(0.7)
1975-80	330	825	(1.4)	561	(0.9)
1980-85	528	1320	(1.7)	898	(1.1)
1985-90	820	2050	(2.0)	1394	(1.4)
1990-95	1000	2500	(2.1)	1700	(1.4)
1995-2000	1200	3000	(2.0)	2040	(1.4)

[a]Values in parenthesis are the number of maximum sized reactors for the required expansion (see Table 1).

Table 4. Capital and Operating Cost Equation Constants

Constant	Value
V1	0.9
V2	0.8670
V3	0.5229
V4	0.9
V5	0.3767
V6	0.8980
R	0.060
MY	30.0

(4) If all the surplus power could not be marketed and the nuclear plants are not base loaded, the variable operating cost per unit of power generated might be somewhat greater since the reactor would not be operating at its design capacity and the efficiency of the system would be lower.

(5) Outage rates for reactors tend to increase with reactor size. Data[6] on projected nuclear plants indicate that the initial outage rates increase from 10.5 to 14.8% as the reactor size is increased from 570 to 1045 MW(e). Therefore, a penalty should be included if a reactor larger than that required to meet the system demand is installed.

EXAMPLES OF PENALTY COSTS

An estimate of the penalty cost ratio has been made for the case where the excess capacity is sold as nonfirm power. Results of this estimated ratio are given in Table 5. The penalty cost was assumed to be 0.4-mill/kwhr which was used as a differential rate; therefore, the penalty cost constant, C6, is equal to the value of the power produced for a year's expansion in demand at a 0.4-mill/kwhr rate. This unit of production must be used

Table 5. Estimated Value of Penalty Cost Ratio For a 0.4-mill/kwhr Nonfirm Power Price Differential

Time Period	Reactor Size For One Year Increase In Demand [MW(e)]	(a) Overcapacity Penalty ($ millions)	(b) Reactor Cost ($ millions)	Penalty Cost Ratio (a/b)
1970-75	204	0.61	49.38	.0124
1975-80	330	0.98	75.15	.0130
1980-85	528	1.57	113.27	.0139
1985-90	820	2.44	166.34	.0147
1990-95	1000	2.97	197.81	.0150
1995-2000	1200	3.56	231.94	.0153
			Average	.0141

because the surplus capacity is expressed in terms of the number of years of capacity expansion. The units of constant C6 are $/millions per year per year of capacity expansion. The C1 ratio is obtained when constant C6 is divided by the capital cost of a year's capacity expansion. Table 5 shows that this ratio will change very little between 1970 and 2000 and has an average value of about 0.014 for the 0.4-mill/kwhr rate differential. Table 2 indicated that the optimum capacity expansion would be about 2.5 years for a C1 value of 0.014, which is the same as the value for no overcapacity penalty.

The effect of negative penalty costs (net benefits) on the optimum capacity expansion is shown in Figure 4. For values of C1 less than −0.015, the optimum capacity expansions increase quite rapidly. An example may be used to demonstrate this effect. If the operating cost savings for nuclear over fossil fuel amounted to 0.9 mill/kwhr, the value of C1 would be equal to −0.032 and the optimum capacity expansion would be about 3.9 years. This compares with the 2.5 year optimum expansion for C1 = 0.0 which is an increase of 1.4 years. For the 1970-75 period, this increase would recommend that an additional 286 MW(e) of capacity be installed [the total capacity increment would be 796 MW(e)]. However, the costs of maintaining the fossil fueled plants on standby should also be considered, so the optimum expansion would probably be between 2.5 and 3.9 years. Detailed cost data would be required to establish a realistic value for this penalty.

Note that for a penalty cost ratio greater than 0.2 (see Fig. 3), the optimum capacity expansion is close to or less than one year's increase in demand. Therefore, it appears that annual additions to capacity are to be preferred if the annual penalty costs for overcapacity are greater than 20% of the capital cost for one year's capacity expansion. Also, for $0 \leq C1 \leq 0.10$ the curves are quite shallow indicating that costs do not change significantly over a wide range of plant capacity expansions.

The results of this analysis are indicative of the advantages that could be gained by installing one reactor or a multiple reactor plant for more than one year's increase in power demand. However, since the model could not take into account details of the PRWRA system, such as the size and age of the older plants to be placed on standby, the results should not

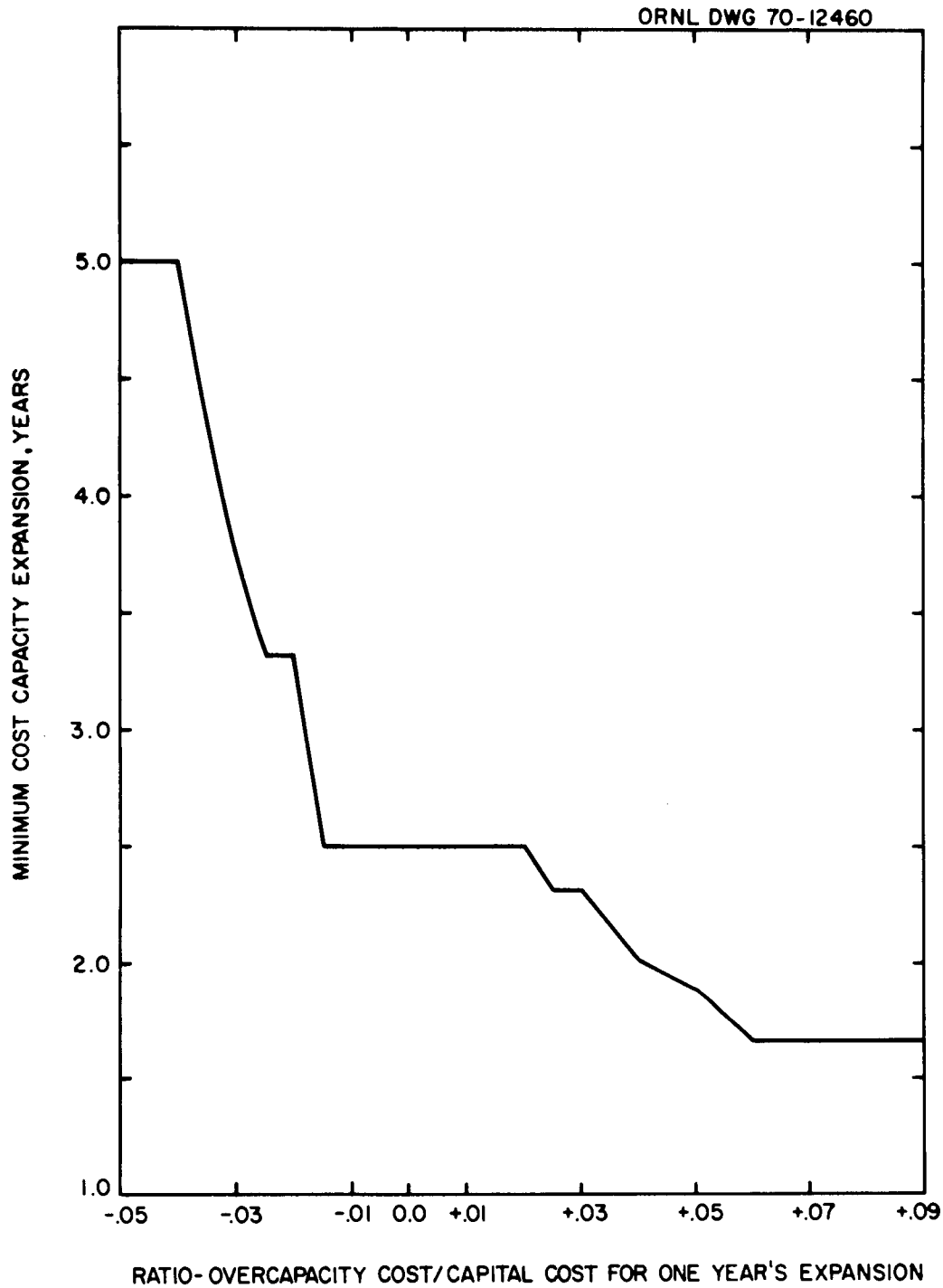

Fig. 4. The Effect of Overcapacity Penalty Cost Ratio on the Optimum Capacity Expansion for Puerto Rico Power Plants

be construed as a plan for future expansion. Only through a detailed analysis of the system including all of the pertinent penalties can a firm basis for future expansion be established.

RESULTS FOR MAXIMUM REACTOR CAPACITIES AVAILABLE FROM MANUFACTURERS

A case was examined where the maximum reactor capacities that are predicted to be available from the manufacturers during each time period are used instead of the maximum capacities given in Table 1. Projections of available capacities were made by Lane[7] and are given in Table 6.

Figure 5 shows the results of this calculation. The only result that changed significantly was for a zero overcapacity penalty, and here the optimum capacity increased to 3.0 years. All of the other optimum capacities are the same as for the smaller maximum reactor capacities projected by PRWRA (see Table 1). For C1 = 0, each plant capacity in the schedule given in Table 3 would be increased by about 20% and only one reactor would be installed during each expansion.

Table 6. Predicted Maximum Reactor Capacities

Time Period	Maximum Single Reactor Capacity [MW(e)]
1970-75	1030
1975-80	1400
1980-85	2000
1985-90	2500
1990-95	3000
1995-2000	4000

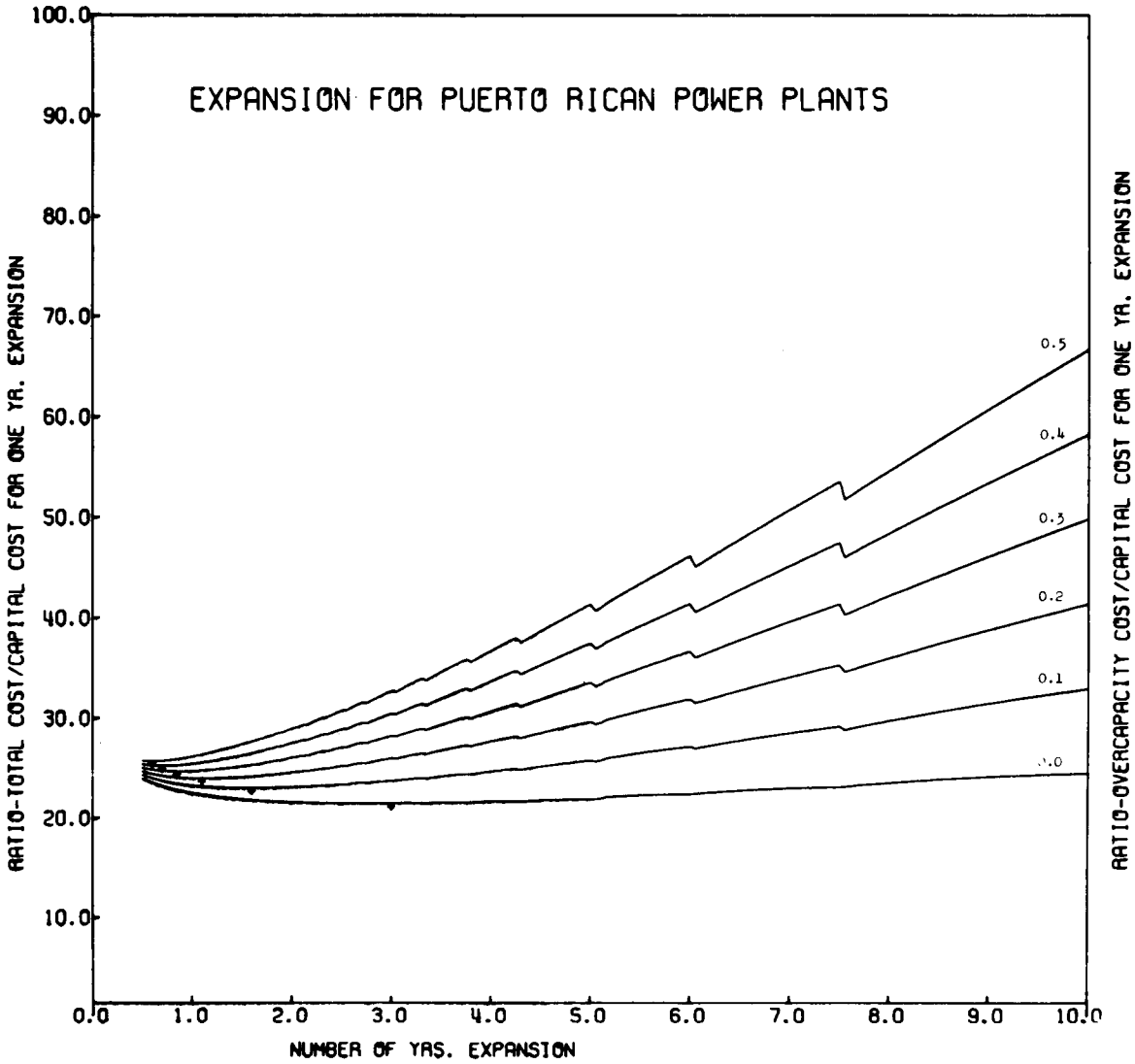

Fig. 5. Expansion for Puerto Rican Power Plants

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