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Abstract

The effect of thermal efficiency on the individual items of nuclear power cost is considered.

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THE EFFECT OF PLANT THERMAL EFFICIENCY ON THE COST OF NUCLEAR POWER

1.0 INTRODUCTION

It is well known that the cost of nuclear power decreases with increased station thermal efficiency. A specific relationship between cost and efficiency, if available, would be useful in determining how much might be saved by increasing efficiency. Conversely the relationship would also be useful in determining the cost of decreasing plant efficiency. For example, it would help to indicate whether operation with inexpensive, low-temperature fuel cladding material would be feasible.

In the present report, an attempt to determine a specific relationship between nuclear power cost and efficiency is presented. In another report, ORNL-CF-58-7-86, the information developed here is applied to a study of the effect of substituting aluminum alloy for zirconium alloy clad in a boiling water reactor.

Little data are available on which to base a study of the cost vs efficiency relationship. One known factor is that the size of the reactor in terms of heat output is inversely proportional to thermal efficiency. Data are available also on turbine plant cost as a function of steam temperature.²

2.0 SUMMARY

The relationship between nuclear power cost and thermal efficiency developed in this study is shown in Figure 2-1. In this figure, power cost is given relative to the cost for a plant of 25 per cent net thermal efficiency.

[Throughout this report, costs are taken relative to the cost of a 25 per cent net efficiency plant. The reason for choosing this particular efficiency is that it is used in a number of nuclear power cost estimates, and is a fair figure for water-cooled reactors.]

The relationship shown in Figure 2-1 is not limited to any particular reactor type. Rather, it is considered to be generally applicable, for any reactor system in which steam is the working fluid for the turbogenerator, for cost comparisons of reactors of a particular type but of different thermal efficiencies. It is not valid for comparisons between different reactor types.

Fig. 2-1 Effect of Thermal Efficiency on Relative
Total Power Cost

It is risky, in view of the number of assumptions that had to be made, to draw any firm conclusions from this study. It would appear from Figure 2-1, however, that beyond about 30% the incentive to go to higher efficiencies is quite small, and beyond about 35% it is almost non-existent. There are indications that it may be economically feasible to substitute cheap materials for costly materials for fuel cladding even though it means some sacrifice in thermal efficiency. This point is looked into in ORNL-CF-58-7-86.

3.0 RELATION BETWEEN STEAM TEMPERATURE AND THERMAL EFFICIENCY

Modern coal-fired power plants operate at net thermal efficiencies that are about 60 per cent of Carnot efficiency, based on the temperature of the steam at the turbine inlet.² It is reasonable to assume that nuclear plants will do about as well. This relationship was used in the present study wherever it was necessary to convert efficiency to temperature and vice versa. A plot of the relationship is given in Figure 3-1.

4.0 EFFECT OF THERMAL EFFICIENCY ON INDIVIDUAL ITEMS OF POWER COST

Shown in Figure 4-1 is a group of curves relating net thermal efficiency to the relative costs of the individual items that enter into the cost of nuclear power. The manner in which each of these curves was arrived at is discussed below.

4.1 Capital Cost

Capital cost items include the turbine plant, reactor plant, in-pile fuel inventory, and working capital. The latter item consists mainly of the cost of fabricating the first fuel loading; subsequent loadings are regarded as part of the fuel cycle cost.

4.1.1 Turbine Plant

The turbine plant is a convenient point at which to start this discussion, since it provides about the only piece of actual cost data available. Curve D-D, Figure 4-1, shows the relative cost of the turbine plant vs thermal efficiency.²

The portion of the curve to the left of about 30% efficiency reflects the decreasing size of the turbine. To the right of 30%, the increasing relative cost is attributed to the more costly materials needed to withstand the increasing temperature and pressure and to the increasing mass of material in the turbine. These effects outweigh the continuously decreasing turbine size.

Fig. 3-1 Relation Between Steam Temperature and Net Thermal Efficiency

Fig. 4-1 Effect of Thermal Efficiency on Relative
Cost of Individual Power Cost Items

Curve D' is an extension of the portion of the curve lying to the left of the 25% efficiency line. The difference between curves D and D' may be regarded as the incremental cost due to costlier materials.

4.1.2 Reactor Plant

For a given electrical output, the required heat output of the reactor is inversely proportional to thermal efficiency. Curve A-A shows the relation between relative heat output and thermal efficiency. If there were no change in the reactor but size, the reactor cost ratio could be expected to vary about as the 0.6 power of heat output. For efficiencies below 25%, the 0.6 power probably gives values that are fairly realistic. Above 25%, however, the 0.6 power becomes increasingly in error on the low side because it does not reflect the need for costlier materials. To offset this error, it is assumed that above 25% efficiency, the actual cost curve departs from the 0.6 power curve by the same amount that the turbine plant cost D departs from curve D'. The result is represented by curve C-C of Figure 4-1.

4.1.3 In-Pile Inventory

For a given specific power, the in-pile inventory cost is directly proportional to reactor heat rating. Relative inventory cost, therefore, varies with thermal efficiency in accordance with curve A-A of Figure 4-1.

4.1.4 Working Capital

As indicated above, the major item of working capital for a nuclear plant is the cost of fabricating the first fuel loading. Fuel element fabrication is shown by curve B-B in Figure 4-1. A discussion of fuel fabrication is included in section 4.3.

4.2 Operating and Maintenance Costs

The cost of operating a low-efficiency reactor station is not expected to differ significantly from the cost of operating a high-efficiency station. Perhaps because the low-efficiency station has a larger reactor with more fuel to move around and possibly more auxiliaries to run, the operating cost would be slightly higher. It is felt, however, that the difference would be small.

Maintenance costs also are not expected to vary significantly. While the low-efficiency plant has more and larger equipment to maintain, the high-efficiency plant has costlier equipment that may need more frequent maintenance. These factors may balance each other.

For this study, it is assumed that there is no variation in operating and maintenance cost with thermal efficiency (curve E of Figure 4-1).

4.3 Fuel Cost

For a given fuel burnup, the amount of fuel to be reprocessed is directly proportional to reactor heat output, and hence, is inversely proportional to thermal efficiency. Some fuel cost items are directly proportional to the amount processed; others are not. To simplify the cost picture, the various items of cost are divided into categories (1) and (2). Category (1) covers those items for which cost is directly proportional to amount processed; category (2) includes those items for which cost is other than directly proportional to amount processed.

Category (1)

- (a) Fuel burnup (e.g., re-enrichment cost minus plutonium credit)
- (b) Out-of-pile inventory
- (c) Shipping

Category (2)

- (d) Chemical separations
- (e) Chemical conversions (e.g., UNH to UF_6 and UF_6 to UO_2)
- (f) Fuel-element refabrication

The relative costs for items in category (1) follow the curve for relative heat output (curve A-A of Figure 4-1).

Higher throughput (in terms of batch size) at the low-efficiency end should give lower unit costs for the items in category (2). In addition, the cheaper clad and fuel materials that can be used at the low-efficiency end lead to lower unit costs for items (d) and (f). The opposite is true at the high-efficiency end.

The effect of batch size on chemical separations cost can be approximated by means of the AEC chemical reprocessing charge schedule. If a batch size of 20 tons U is assumed for a 25%-efficiency plant, it is found that relative cost varies approximately as the 0.75 power of relative batch size. This relation is shown in curve B-B'. Coincidentally, the same variation is found for conversion of UF_6 to UO_2 , based on figures supplied by Mallinckrodt Chemical Works.⁴ Lacking a better basis, it is assumed that fuel element refabrication cost varies in the same manner. Although a unit price for converting UNH to UF_6 has been fixed by AEC at 5.60/kg U for U of less than 5% enrichment, it will be assumed, for this study, that the unit cost for this conversion varies with throughput in the same way as do the other items in category (2).

The effect of cladding materials on the costs of category (2) items (d) and (f) is difficult to assess. It is assumed that there is no effect for efficiencies below 25% so that the relative cost follows curve B. Above 25%, it is assumed that the actual relative cost curve B departs from the 0.75 power curve B' by about the same amount that curve D departs from curve D'. The chemical conversion operations follow curve B-B'.

5.0 EFFECT OF THERMAL EFFICIENCY ON TOTAL POWER COST

In the foregoing discussion the effect of efficiency on the individual items of power cost was considered. In order to assess the effect on total power cost, it is necessary to make some assumptions regarding the relative weight of the individual items.

5.1 Power Costs for a Plant of 25% Net Thermal Efficiency

The following cases are considered:

<u>Case</u>	<u>Capital Cost</u>	<u>Fuel Cost</u>
I	High	High
II	Low	High
III	High	Low
IV	Low	Low
V	Low	Very Low

To keep the comparison from becoming unduly complex, the following simplifying assumptions are made:

- (a) The reactor fuel is UO_2 of 2% enrichment for each case.
- (b) Fuel burnup is 5,000 Mwd_h /metric ton U for each case except V, for which burnup is 15,000 Mwd_h /metric ton U. For cases I through IV, therefore, the differences between high and low fuel cost lie in the unit costs for the various steps in the fuel reprocessing and refabrication cycle.
- (c) Specific power is 10 Mw_h /ton U for each case.
- (d) Operating and maintenance cost is 1 mill/ kwh_e for each case.
- (e) Writeoff rate for capital (except for in-pile fuel inventory) is 16%/yr; plant load factor is 80%; fuel inventory charge is 4%/yr.

Assumed unit capital costs are shown in Table 5-1. Costs for turbine plant and reactor plant are those given by Lane.¹ Assumed unit fuel costs, shown in Table 5-2, are based on figures arrived at by a panel of experts.³

Table 5-1

Unit Capital Costs

<u>Item</u>	<u>High</u>		<u>Low</u>	
	<u>\$/kw</u>	<u>mills/kwh_e</u>	<u>\$/kw</u>	<u>mills/kwh_e</u>
Turbine	130	3.0	95	2.2
Reactor Plant	220	5.0	100	2.3
In-Pile Fuel Inventory	22	0.1	22	0.1
Working Capital	9	0.2	2	-
Total	381	8.3	219	4.6

Table 5-2

Unit Fuel Costs

Item	High ^a		Low ^a		Very Low ^b	
	\$/kg U	mills/kwh _e	\$/kg U	mills/kwh _e	\$/kg U	mills/kwh _e
Shipping	10	0.3	8	0.3	8	0.1
Chemical Processing	21	0.7	13	0.4	13	0.2
UNH to UF ₆	12	0.4	3	0.1	3	0.1
Pu(NO ₃) ₄ to metal ^c	4	0.1	2	0.1	5	0.1
Burnup	57 ^d	1.8	8 ^e	0.3	27 ^e	0.3
UF ₆ to UO ₂	30	1.0	10	0.3	10	0.1
Fabrication	90	3.0	15	0.5	15	0.2
Out-of-pile Inventory	-	0.2 ^f	-	0.1 ^g	-	0.1
Total ^h	224	7.5	59	2.1	81	1.1

a. Burnup = 5000 Mwd/ton U.

b. Burnup = 15,000 Mwd/ton U.

c. Based on 1.7 g Pu/kg U at 5000 Mwd/ton U and 5.3 g Pu/kg U at 15,000 Mwd/ton U.

d. Pu at \$12/g metal.

e. Pu at \$30/g metal.

f. Out-of-pile inventory = 2 x in-pile inventory

g. Out-of-pile inventory = in-pile inventory.

h. Figures for \$/kg U do not include out-of-pile inventory; mills/kwh figures do include it.

Total power costs for each case for the 25%-efficiency plant are shown in Table 5-3. These include 1 mill/kwh_e for operation and maintenance.

Table 5-3

Total Power Cost for Plant of 25% Net Thermal Efficiency

Case	Cost, mills/kwh
I - High Cap, High Fuel	16.8
II - Low Cap, High Fuel	13.1
III - High Cap, Low Fuel	11.4
IV - Low Cap, Low Fuel	7.7
V - Low Cap, Very Low Fuel	6.7

5.2 Power Costs for Plants of 15 to 40% Net Thermal Efficiency

Application of the relative costs plotted in Figure 4-1 to the unit cost figures given in Table 5-1 and Table 5-2 gives total costs for plants of 15 to 40% efficiency. These totals are plotted in Figure 5-1. The same information is plotted vs steam temperature in Figure 5-2.

Fig. 5-1 Relation Between Thermal Efficiency and Total Power Cost

Fig. 5-2 Relation Between Steam Temperature and Total Power Cost

Relative fuel, capital, and total costs are shown in Table 5-3, and are plotted in Figure 2-1.

Table 5-3

Relative Costs for Plants of 15 to 40% Thermal Efficiency

Case	Thermal Efficiency, %					
	15	20	25	30	35	40
High Cap	1.28	1.11	1.00	0.94	0.93	0.93
Low Cap	1.25	1.10	1.00	0.95	0.93	0.95
High Fuel	1.52	1.20	1.00	0.87	0.79	0.73
Low Fuel	1.50	1.19	1.00	0.87	0.79	0.74
Very Low Fuel	1.54	1.21	1.00	0.86	0.77	0.72
I High Cap + High Fuel	1.37	1.15	1.00	0.91	0.87	0.85
II Low Cap + High Fuel	1.39	1.15	1.00	0.91	0.86	0.83
III High Cap + Low Fuel	1.30	1.12	1.00	0.94	0.91	0.90
IV Low Cap + Low Fuel	1.29	1.11	1.00	0.94	0.91	0.90
V Low Cap + Very Low Fuel	1.27	1.10	1.00	0.94	0.92	0.92

Figures 2-1 and 5-1 show the expected drop in power cost with increasing thermal efficiency. They indicate that the incentive to increase thermal efficiency above 30% is quite small and is almost non-existent above 35%. Parenthetically, it may be noted that to increase thermal efficiency from 30 to 35% it is necessary to increase the steam temperature by more than 200°F (Figure 3-1).

Figure 2-1 shows that fuel cost is affected more strongly by thermal efficiency than is capital cost. This figure and Figure 5-1 also show that when capital cost is the major part of total cost (i.e., fuel cost is low), the point at which total cost begins to level off is much lower than when fuel cost is high.

By the way of comparison, studies by TVA indicate that for its conditions, power cost for coal-fired stations is lowest at a thermal efficiency of about 38%.

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