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SOME ECONOMIC ASPECTS OF THORIUM BREEDER REACTORS

H. C. Claiborne
M. Tobias

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UNION CARBIDE NUCLEAR COMPANY
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REACTOR EXPERIMENTAL ENGINEERING DIVISION

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Director

SOME ECONOMIC ASPECTS OF THORIUM BREEDER REACTORS

by

H. C. Claiborne and M. Tobias

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SUMMARY

A study of the effects of geometrical and some operational variables on the economics and characteristics of thorium breeder-power reactors has been made as an aid in the selection of design criteria for the TBR program.

No original effort was made to estimate plant investment costs or to introduce new concepts of reactor technology. Plant investment was assumed constant for all systems studied under equal power and temperature conditions. The state of technology and cost factors assumed were those reported by Briggs[3] and Arnold et al[1]. The effect on power cost of core radius, blanket thickness, blanket uranium and thorium concentrations, chemical processing cycle times, poisons and external power density have been investigated using a consistent method of calculation with a standardized set of nuclear constants and cost factors. All results are for a 3-reactor power station delivering 375 Mw of electricity to a power grid.

For both one- and two-region reactors, the unit cost of power is rather insensitive to fairly large changes in nuclear parameters and process variables. This is a direct consequence of plant investment and other fixed charges representing nearly 80% of the power cost.

The results, based on operating and maintenance costs for conventional power and chemical plants, indicate that a two-region reactor station could produce power for 6.2 mills/kwh with a fuel cost of 1.8 mills/kwh. Applying error limits to the items comprising the total cost, a cost range of 5.3 to 8.0 mills/kwh is obtained.

The cost of power from a one-region reactor station was about 0.9 mills/kwh (2.6 mills/kwh fuel cost) higher than for a comparable two-region system if the plant investment and other fixed charges are considered equal

for the two types. It is believed that the fixed charges will be somewhat smaller for the one-region reactor because of simpler construction and operation.

The approximate characteristics of the reactors required for producing power for the above costs are:

	Two-Region	One-Region
Core diameter, ft	5	12
Blanket thickness, ft	2-1/4	--
Core power, Mw	390	481
Blanket power, Mw	91	--
Core power density, Mw	210	19
Thorium conc., gm/liter	1000	260
Blanket uranium conc., gm/kg Th	3	---
Core uranium conc., gm/kg D_2O	8.3	14.5
Core U-235 + U-233 conc., gm/kg D_2O	2.8	6.7
Core Thorex cycle, days	336	450
Blanket Thorex cycle, days	140	--
Hydraulic separator cycle, days	1	--
Average reactor temperature, ^oC	280	280

A comparison of the cost items in mills/kwh for near optimum one- and two-region reactors (assumes equal fixed costs) is shown below.

	Two-Region	One-Region
Plant investment (less chem. proc.)	3.74	3.74
Fuel inventory	0.44	0.84
D_2O inventory	0.52	0.66

	Two-Region	One-Region
Fixed chemical processing	0.76	0.76
Variable chemical processing	0.32	0.18
Operation and maintenance	0.75	0.75
Feed (D_2O and Th)	0.20	0.25
Uranium (233 and 235) credit	0.49	0.05
Net unit cost of power	6.2	7.1

From these results, it is apparent that the net unit cost of power from the two-region reactor is nearly independent of the value of uranium since the fuel inventory charge and the breeding credit are approximately equal. This is not true for the one-region reactor, however. In that case, the breeding credit is small compared to the fuel inventory charge, so that any variation in the latter due to a change in the value of uranium will cause a corresponding change in the cost of power which is virtually uncompensated by the breeding credit.

INTRODUCTION

The feasibility and the technology of aqueous homogeneous reactors have been discussed elsewhere, most recently by Briggs[3]. The present work is concerned with the results of detailed calculations of the effect of the major process variables on the power cost and characteristics of thorium breeder reactors in order to help select design criteria for the TBR. In addition, it was desirable to estimate the possible effect of errors in the nuclear parameters on the cost of power.*

The different reactor systems were compared on the basis of a fixed amount of electrical power (125 Mw per reactor) delivered to a power grid since power is the main product. If power output were not constant, the effect of the process variables would be masked by the effect of power level, the most important factor in unit cost calculations.

An electrical power output of 125 Mw was chosen as standard for one reactor or 375 Mw for a 3-reactor station. This is equivalent to 480.8 Mw of heat for a net station efficiency of 26%. The parameter studies, other than temperature, were made for an average reactor temperature of 280°C.

At the present time, it is impossible to estimate the cost of electricity from nuclear power stations without a fairly large uncertainty. Nevertheless, a study such as this, based as it is upon stated cost factors and a consistent method of calculations, can be used to determine what is, and what is not, of relative economic importance and further provides a rational basis for the selection of most design criteria.

---

* The ORACLE was used to perform the large number of required reactor calculations.

This report consists of two principal parts. The first part is concerned with the two-region thorium breeder reactor and the second with the one-region type. Comparison is made on a common basis insofar as possible.

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TWO-REGION REACTORS

TWO-REGION REACTORS

Methods and Conditions

The program for the study of the two-region reactor has been previously outlined by Briggs and Edlund[4]. The data that were used to get cost factors and process characteristics are given in other publications[3,10], and are discussed in a later section of this report.

A schematic flow diagram of the system studied is shown in Figure 1. The core material will be chemically processed by two methods. The core material is treated in a liquid-solids separation plant utilizing hydraulic separators to remove the precipitated poisons. This procedure is capable of removing 75% of the so-called group-3 poisons (fission product poisons affected by chemical processing). A more complete discussion of this poison removal method is given by Arnold et al[1]. Complete poison removal from the solution carrying the precipitated poisons is effected in the Thorex plant at a rate considerably less than that used for liquid-solid separation. Since the blanket material is a slurry, poisons must be removed from it by the Thorex process only.

In order to produce uranium of high enrichment (about 95% U-233) the blanket stream will have to be partially processed for removal of the excess U-233 (represented by breeding gain) before any mixing of the core and blanket streams in the chemical processing plant. The core enrichment will be only 25-30% U-233. By processing to remove protactinium, uranium composed of nearly 100% U-233 could be produced. For these calculations, however, it was assumed that the uranium product would be that derived from the blanket with all protactinium decayed to U-233 and mixed with the uranium isotopes.

The calculation procedure, which is successively described in the following sections, consists of four main parts:

1) calculation of chemical processing cycle times and uranium isotope concentrations in the blanket and the core by isotope balance equations for the particular blanket power selected (for any set of parameters, calculations were made for three reactor powers);
2) two-group nuclear calculations to determine the critical concentration and the neutron balance which yields in turn the core power and the ratio of resonance to thermal capture in the thorium;
3) unit cost calculations;
4) plot of unit costs versus total reactor power so that the costs at a particular total power can be used for comparison of the systems.

The parameters studied were core diameter, blanket thickness, blanket U-233 concentration, thorium concentration, core poisons, temperature and power density of the system outside the reactor (piping and heat exchangers).

Processing Cycle Times and Uranium Isotopes

For purposes of chemical process calculations, the fission product poisons are considered to be composed of three groups[3]. The first group consists of the noble gases, the second of the high cross-section isotopes and the third of the low cross-section isotopes which transmute by decay or neutron capture into other nuclides of approximately the same low cross

section. The first two groups are virtually unaffected by chemical processing rates required for aqueous homogeneous reactors and their macroscopic cross section is approximated as 1.3% of the fission cross section (0.8% high cross section isotopes and 0.5% residual noble gases). The noble gases are continuously stripped during operation; the high cross section isotopes are rapidly destroyed by neutron capture since their cross section is around 40,000 b. The third group is, however, a function of the chemical processing cycle.

For core processing, two modes of poison removal are employed -- poison precipitation with subsequent liquid-solid separation, followed by Thorex. The precipitation step is capable of removing only some of the atomic species comprising group-3 poisons which will be called subgroup A; the remainder, subgroup B, is not removed by precipitation. Both subgroups are removed by the Thorex process. This is represented by the following equations for equilibrium conditions.

$$gy\left[\Sigma_f(25) + \Sigma_f(23)\right]\ \phi_C - \frac{N(A) - N(o)}{T_{1C}} - \frac{N(o)}{T_{2C}} = 0 \qquad (1)$$

$$(1-g)y\left[\Sigma_f(25) + \Sigma_f(23)\right]\ \phi_C - \frac{N(B)}{T_{2C}} = 0 \qquad (2)$$

and by definition

$$f_3 = \frac{\left[N(A) + N(B)\right]\sigma(3)}{\Sigma_f(25) + \Sigma_f(23)} \qquad (3)$$

$$f_{03} = \frac{\sigma(3)\ N(o)}{\Sigma_f(25) + \Sigma_f(23)} \qquad (4)$$

Solving for T_{2C},

$$T_{2C} = \frac{(f_3 - f_{03}) - y\sigma(3)\ \phi_C\ gT_{1C}}{2y\sigma(3)\ \phi_C\ (1-g)}\left[1 + \sqrt{1 + \frac{4\ f_{03}\ T_{1C}\ y\sigma(3)\ (1-g)\ \phi_C}{(f_3 - f_{03}) - y\sigma(3)\ \phi_C\ gT_{1C}}^2}\right] \qquad (5)$$

This equation actually defines an overall processing cycle for the core. The optimum Thorex cycle time is, of course, that determined by a balance between value of fuel recovered and inventory and chemical processing costs. Another relationship between T_{1c} and T_{2c} for minimum core processing cost could be obtained by utilizing the processing cost equations. For this study, however, the precipitation cycle (T_{1c}) was set constant at one day since the estimated cost[10] of the precipitation process is practically independent of the processing rate for reasonable flow rates. In addition the core processing cost is very small (around 0.08 mills/kwh).

Under the present state of chemical process development, only the Thorex process can be used to treat the blanket material because it is a slurry. The equation for the blanket cycle time is simply

$$T_B = \frac{f_{3B}}{y\ \sigma(3)\ \phi_B} \tag{6}$$

For use in the nuclear calculations, determination of the concentrations of the various isotopes in both core and blanket was necessary. Both core and blanket contain U-233, U-234, U-235 and U-236. In addition, the blanket contains Pa-233 and Th-232. Other isotopes that could be present are neglected since even very small processing losses will prevent the build-up of higher isotopes and the half-lives of Th-233 and Pa-234 are too short to permit significant concentrations to occur.

For the blanket at equilibrium conditions, the following isotope balance equations apply:

$$\sum(02)(1 + \beta)\ \phi_B - \lambda(13)N(13) - \sum(13)\ \phi_B - \frac{N(13)}{T_B} = 0 \tag{7}$$

$$\lambda(13)N(13) - \sum_a(23)\ \phi_B - \frac{N(23)}{T_B} = 0 \tag{8}$$

$$\Sigma_r(23)\,\phi_B + \Sigma(13)\,\phi_B - \Sigma(24)\,\phi_B - \frac{N(24)}{T_B} = 0 \tag{9}$$

$$\Sigma\,(24)\,\phi_B - \Sigma_a(25)\,\phi_B - \frac{N(25)}{T_B} = 0 \tag{10}$$

$$\Sigma_r(25)\,\phi_B - \Sigma(26)\,\phi_B - \frac{N(26)}{T_B} = 0 \tag{11}$$

$$\frac{F(02)}{V_{BT}} - \Sigma(02)\,(1+\beta)\,\phi_B = 0 \tag{12}$$

$$\phi_B = \frac{K\,P_B}{V_{BT}\left[\Sigma_f(23) + \Sigma_f(25)\right]} \tag{13}$$

and

$$V_{BT} = V_B + \frac{P_B \times 10^6}{J_B} \tag{14}$$

$$V_B = \frac{4\pi}{3}\left[R^3 - (a+t)^3\right] \tag{15}$$

Similarly, for the core (neglecting chemical processing losses),

$$q\,\frac{V_{BT}}{V_{CT}}\left[\frac{N(23) + N(13)}{T}\right]_B - \Sigma_a(23)\,\phi_C = 0 \tag{16}$$

$$q\,\frac{V_{BT}}{V_{CT}}\left[\frac{N(24)}{T}\right]_B - \Sigma(24)\,\phi_C + \Sigma_r(23)\,\phi_C = 0 \tag{17}$$

$$q\,\frac{V_{BT}}{V_{CT}}\left[\frac{N(25)}{T}\right]_B - \Sigma_a(25)\,\phi_C + \Sigma(24)\,\phi_C = 0 \tag{18}$$

$$q\,\frac{V_{BT}}{V_{CT}}\left[\frac{N(26)}{T}\right]_B - \Sigma(26)\,\phi_C + \Sigma_r(25)\,\phi_C = 0 \tag{19}$$

$$V_{CT} = \frac{4\pi}{3}\,a^3 + \frac{10^6\,P_C}{J_C} \tag{20}$$

These equations hold only for a breeding ratio of one or greater. For breeding ratios slightly less than one the isotope ratios obtained are

still approximately correct. Actually, except for one isolated case, the breeding ratios were all greater than one.

The method and ease of solution for the set of equations (Eq. 7 through 20) depend on the selection of the independent variables and the availability of automatic computing machinery.

In the present study, the dimensions (R, a and t); blanket power, P_B; blanket U-233 concentration, N(23); poison fraction in the core, f(3C); the thorium concentration, N(02); the external power density and the average reactor temperature were selected as the independent variables.

The ratio resonance to thermal capture in thorium, β, can only be obtained from the nuclear calculation since the fast flux is required to determine it. It was necessary to estimate a value for β, compute the isotope concentrations, compute β from nuclear calculations and then compare the value so obtained with the initial guess. After a little experience, it was possible to estimate an initial value of β that required only two or three iterations.

Nuclear Calculations*

The customary two-group method was employed for obtaining the critical mass and neutron balance for the spherical two-region geometry. The major details of this procedure have been described elsewhere[6, 14]. The only novelty introduced was the use of a "thin shell" approximation[12] to account more adequately for the effect of the zirconium core tank. The nuclear constants used in the work are shown in Appendix I. These values are based on or taken from several publications[2, 7, 13].

---

* The ORACLE was used for the large number of calculations required. That part dealing with the nuclear calculations was based on an ORACLE code devised by Willoughby and Fowler[5] for two-region spherical reactors. Calculation, tape handling and punch-out time averaged only 8 minutes for the two-region reactors and 30 seconds for the one-region reactors. If desk computers were used, about 4 to 5 man-days would be required for each case.

Cost Estimation

Selection of proper cost factors is the most difficult part of the evaluation of nuclear power stations since no full-scale plant experience is available. However, reasonable values based on laboratory and pilot plant experience, coupled with normal industrial methods and practice, should produce results with at least sufficient relative accuracy to aid in the selection of design criteria and operating conditions.

No new effort was made to estimate the investment cost for a reactor, turbogenerator plant or chemical processing plant; the estimates by Briggs[3] were used.

Reactor and Turbogenerator Plant Investment

The basis for computing the cost of the reactor with associated equipment and structures was \$11.65[3] per kilowatt of heat for a 450-Mw reactor considered as an integral part of a 3-reactor power station. For power levels different from 450 Mw per reactor, the unit investment cost was corrected by use of Figure 2 (reproduced from ORNL-1642).

The unit investment cost for the turbogenerator plant, which is dependent on the throttle temperature, was obtained from Figure 4 (reproduced from ORNL-1642). The cost of boilers and coal and ash handling equipment is excluded since the reactor plant replaces these items. Since the total reactor power could not be predetermined, a quadratic equation was fitted to the points shown in Figure 2, for purposes of calculation by the ORACLE. Using a plant factor of 80% and a 15% amortization charge, the result is

$$\text{Investment (mills/kwh)} = \frac{1}{E_n}\left(0.3387 - 2.828 \times 10^{-4} P + 1.873 \times 10^{-7} P^2 + 0.02140\, C\, E_G\right) \qquad (21)$$

where P = reactor power, Mw of heat

E_n = net station efficiency

E_G = gross station efficiency

C = turbogenerator plant cost, $/electrical kw

Efficiency

The efficiency of the plant is shown as a function of throttle temperature in Figure 3 (reproduced from ORNL-1642). Estimates were made for the temperature drop from the reactor to throttle. Table I below lists the estimates of the efficiencies used.

Table I

Nuclear Power Plant Efficiencies

Av. Reactor Temp., °C	Throttle Temp. °F	Gross Efficiency	Net Efficiency
320 (608°F)	490	0.315	0.281
300 (572°F)	470	0.304	0.271
280 (536°F)	450	0.292	0.260
250 (482°F)	410	0.274	0.242
200 (392°F)	340	0.240	0.211

Operation and Maintenance

Operating and maintenance charges for the reactor and turbogenerator plants were taken as 3% of the total investment.

Inventories

A 12% charge was assessed against all non-depreciating materials. All fissionable materials were valued at $20/gram. Protactinium was considered a fissionable material only when outside the reactor.

Heavy water was valued at $40/lb. To cover the slight holdup in chemical processing and makeup inventory, the inventory of heavy water was taken as that required to fill the reactor system at room temperature, an amount about 25% greater than necessary at operating temperatures.

Thorium was valued at $5/lb with no appreciable charge for making the ThO_2-D_2O slurry.

The feed stream inventory charges were based on the following holdup times

Spent core fuel	95 days
Spent blanket fuel	
Th + U + 75% of Pa	55 days
25% of Pa	205 days
Thorium feed	30 days

The holdup time associated with the poison removal by the hydraulic separator plant was considered negligible.

Chemical Processing

The estimated cost of the poison precipitation process and the hydraulic separator plant was $210 per day[10] or $70 per day per reactor. This cost was considered independent of the throughput for flow rates of the order of 25,000 liters/day per reactor.

A fixed charge of $ 5,500 per day[3] or $1830 per day per reactor was used for the Thorex plant. The cost includes chemical plant amortization and fixed operating costs. The estimated cost of processing thorium was $3.00 /kg and $0.50 /gram for fissionable material (U-233, U-235 and Pa converted to U-233). In previous studies[3] $1.00/gram was the estimate for processing fissionable uranium; the lower value represents a later estimate[10] by the Chemical Technology Division. Uranium losses were assumed to be 0.1%

of the amount processed through the Thorex plant.

Prior to processing in the Thorex plant, heavy water must be evaporated from the feed streams. A charge of $0.35/liter was used for the recovery of heavy water.[10]

Feed Costs

For breeder reactors (all reactors were breeders, with one exception), only thorium is required and D_2O makeup. As is usual, 5% of D_2O inventory of the reactor system was estimated as the annual makeup requirement.

Results

The results shown in the following tables and graphs are for two-region thorium reactors delivering 125 electrical megawatts to a power grid. The power station is composed of three reactors, three turbogenerators and one chemical processing plant along with some accessory equipment common to the three reactors.

The major results of the study are shown in Figure 5. Results for five typical cases are shown in Table II. It is immediately apparent that the net unit cost is very insensitive to the parameters investigated; only 0.3 mills/kwh separates the highest and lowest cost reactors shown. This is a direct consequence of plant investment and other fixed charges representing nearly 80% of the power cost.

The details of the effects of the individual process variables are discussed below under the heading Major Process Variables. Effects of external power density changes, errors in the group-3 poison cross section and errors in the two-group constants are reported in succeeding sections, followed by discussions of the accuracy of the two-group method and the economics calculations.

Major Process Variables

1) Core Radius -- Variation of the core diameter from 4 to 7 feet results in a power cost change of less than 0.3 mills/kwh. The lowest cost is associated with 4-foot cores, but only a negligible difference of 0.01 mill/kwh exists between 4- and 5-foot cores.

2) Blanket Thickness -- For the blanket concentrations used (500 to 1500 g Th/liter), the unit cost of power varies only about 0.1 mill/kwh for a range of blanket thickness between 1-1/2 and 3 ft. The optimum thickness is about 2 feet for a six-foot core and 2-1/4 feet for a five-foot core.

3) Thorium Concentration -- The lowest unit cost results from using a thorium concentration of 1500 g/liter. However, the cost is only 0.02 mills/kwh less than that for 1000 g/liter. Also, the results indicate that if engineering considerations require the use of thorium concentrations as low as 500 g/liter, the slightly increased unit cost would not preclude possible economic power generation.

Fig. 6 shows the effect of thorium concentration on the breeding ratio and net U-233 production and again indicates that use of thorium concentrations greater than 1000 g/liter leads to a rapidly diminishing improvement in the breeding ratio.

4) Ratio of U-233 Concentration to Thorium Concentration -- About 3 g U-233/kg thorium (see Fig. 8) produces the lowest unit cost for thorium concentrations of 1000 g Th/liter. Here also, only slight changes in unit cost are produced by wide variations in the ratio of U-233 to thorium.

5) Poison Concentration -- The core poisons which are related to the core processing cycle time have little effect on the unit cost in the range 4 - 10% (see Fig. 7). The gross breeding ratio (processing losses neglected) increases almost linearly with reduction in poisons. Below 3% poisons, however, the net U-233 production and net breeding ratio decrease since the highly increased chemical processing rate leads to significant uranium and protactinium losses. In similar fashion, if the blanket U-233 concentration were lowered to small values, the increased chemical processing rate required would likewise cause large fissionable material losses, as well as high chemical processing costs.

6) Temperature -- Under conditions assumed, no optimum temperature was found for the range of average reactor temperatures considered. Lower unit cost is obtained by increasing the temperature, but Fig. 10 indicates that little is to be gained by raising the average temperature appreciably over 280°C. An average reactor temperature of 280°C will probably correspond to an exit temperature of about 300°C.

If engineering considerations preclude core power densities appreciably over 100 kw/liter, it would be necessary to increase the core size or operate with a larger portion of the total power in the blanket. The former course appears economically preferable. The reactors with five- and six-foot cores shown in Table II where typical results for several conditions are shown, have power densities of 210 and 122 kw/liter, respectively. In order to reduce the power density of the five-foot core to 122 kw/liter,

it would be necessary to operate with a U-233 concentration in the blanket of about 12 g/kg of thorium. The cost of power would rise to about 7 mills/kwh, the increase being due primarily to increased inventory charges. The use of a 6-foot core, on the other hand, results in a power cost of 6.45 mills/kwh.

Effect of Group-3 Poison Cross Section Variations

The results of reducing the group-3 poison cross section from 40 to 18 barns at 20°C are shown in Fig. 7. The higher value is a conservative one that has been used in previous studies[3]; the lower value is the latest estimate[10] for thorium-uranium reactors. In general, reducing the poison cross section by over a factor of two reduces the net unit cost by 0.1 mill/kwh and shifts the optimum core poisons from 7 to 6%. The core cycle time is the only result appreciably affected (see Table II). A change greater than a factor of two in the group-3 poison cross section (see Fig. 9) does not appreciably affect the optimum U-233 concentration in the blanket or the optimum blanket thickness of 2 and 2-1/4 feet for the 6-foot and 5-foot cores respectively.

Effect of External Power Density Variations

Other than plant investment the largest single cost is the inventory charge -- nearly one mill/kwh when using values of 20 and 14 kw/liter external power densities (previously used in ORNL-1642 by Briggs) for the core and blanket systems respectively. The effect of increasing these external power densities is shown in Fig. 11. Doubling the core external power density of 20 kw/liter reduces the cost 0.25 mill/kwh, but doubling the blanket external

power density of 14 kw/liter saves only 0.07 mills/kwh. The saving realized from further increases in power density rapidly decrease. A recent design[9] of the TBR indicates that it is possible to achieve external power densities as high as 61 and 55 kw/liter for the core and blanket systems respectively. For this condition the cost is 5.8 mills/kwh, only 0.11 mill/kwh lower than for 40 and 28 kw/liter. For these calculations, it was assumed that no change in capital or operating expense was necessary to achieve higher power densities.

Effect of Errors in the Nuclear Constants

The two group nuclear constants which were estimated for use in the nuclear calculations are probably accurate to within 10-20%. The effect of such errors on the process characteristics and economics was uncertain. Consequently, a study of the effect of substantial changes (± 50%) in the nuclear constants was made for a typical case*.

Although the critical concentration and breeding ratio were changed considerably, the changes in power costs were relatively small being principally confined to altering the amount of credit obtained from excess fuel production. The largest change observed was a difference of about 0.6 mill/kwh between two extreme cases. Where only individual constants were altered, changes in the net cost were less than 0.1 mill/kwh.

Considerable changes in the core uranium concentration do not, however, lead to proportionally large variation in fuel inventory

*The single exception to this procedure was the restriction of $\eta(23)$ to the range 2.28 to 2.36, the approximate limits of accuracy in this quantity cited in BNL 221.

charges since the latter contain contributions of similar magnitude from the blanket system. Thus, for two cases where the uranium concentration differed by a factor of over 4, the fuel inventory charge differed by a factor of 1.4. The effects upon breeding gain are, on the other hand, almost directly converted into changes in credit received for excess fuel production.

It seems reasonable therefore to conclude that errors in the two-group constants are of secondary economic importance since 85% of the power cost is tied up in factors unaffected by such errors.

A summary of the results and constants used is presented in Table III. The most important cost increases were those produced by increases in the quantities τ_B, σa_{13}, p_B, and decreases in η_{23}. Increasing τ_B produces a rise in fast leakage at the expense of resonance capture in thorium, while all other neutron losses remain practically unaffected. Raising σa_{13} causes protactinium absorption to rise at the expense of thorium capture, as well as a change in core isotope ratios leading to higher capture rates in U-234, 235 and 236. An increase in resonance escape probability raises blanket power, increases leakage, depresses resonance capture, and increases thermal capture. A decrease in both resonance and thermal capture in thorium is the principal result of a fall in $\eta(23)$ of 0.04 (1.7%).

The critical concentration was most strongly affected by τ_c, D_{2c}, and, naturally, η. A 50% rise in the first two produced a critical concentration increase of about 30%, while the 1.7% rise in $\eta(23)$ caused a 4.4% decrease in concentration. The breeding ratio was not significantly affected by changing either τ_c or D_{2c}.

None of the quantities investigated had a significant effect upon blanket processing except p_B, for which a decrease of 50% led to a 12% decrease in cycle time. The core thorex cycle was affected mainly by the diffusion constants and τ_c; the greatest effect observed, produced by lowering D_{2c}, was a decrease of cycle time by about 134 days out of 337. However, no significant changes were noted in either core or blanket chemical processing costs.

Accuracy of the Two Group Model and the Calculation of Breeding Ratio

For the large reactors studied, the two group procedure should provide an adequate estimate of the critical mass. The breeding ratio is, however, far more sensitive to inadequacies in the method. For example, difficulty arises in selecting a method of treating thorium resonance captures. In this work, fast neutrons were assumed to slow down without absorption, and captures due to resonance absorption were computed by multiplying the number slowed into the thermal group by (1-p). This treatment overestimates the fast leakage by about a factor of 3. Consequently, the breeding ratio as reported in Table II for a typical case may be low by about 0.02.

A much more serious source of inaccuracy results from uncertainties in η. Errors in the thermal value of η may produce an uncertainty of ± 0.03 in the breeding ratio. Resonance captures in uranium may reduce the breeding ratio by 0.08 if the resonance integral of U-233 is 1500 b and resonance α is as high as unity.

New data concerning the resonance integral of protactinium (650 b) and the thermal cross section (63 b) reported by R. R. Smith[11] have only a slight effect on the breeding gain for the case of a 1000 g Th/liter slurry; the absorptions in protactinium decrease by

only 0.002 absorptions per absorption in U-233.

Uncertainties in the poison cross section may be expected to have little effect since it has been shown in a previous section that poison levels may be varied over a range of 4-10% without appreciable cost variation.

To sum up, the decrease in the breeding ratio produced by the factors discussed above may be expected to be no greater than 0.13. While this number represents an important uncertainty in estimated production of new material, its overall economic significance is slight.

Accuracy of Cost Estimate

The net unit cost of power as determined for two-region reactors near optimum cost (6.2 mills/kwh) is a result that is based on the limited experience available. Obviously, the uncertainty of this result is large enough to span the competitive cost range for a nuclear power industry. An estimate as to the overall accuracy is best made by assessing the accuracy of the individual cost items that comprise the net unit cost of power.

The largest single item is the reactor and turbogenerator plant investment which represents 60% of the total unit cost. Of this cost, 75% is for the turbogenerator plant and 25% is for the reactor and associated equipment. Other cost items are relatively small portions of the total; the largest of these, the inventory charge, is 15% of the net unit cost.

Some of the individual costs comprising the net cost of power have a fairly firm basis and error limits based on experience can be assigned with a fair degree of confidence. These items are capital investment, maintenance and operation for the turbogenerator plant; capital investment for the reactor plant and associated equipment; inventory and

feed costs. Other charges which cannot be assigned error limits with any degree of certainty are maintenance and operation of the reactor plant and chemical processing. Fortunately, the individual costs that rest on a fairly firm basis comprise approximately 80% (based on the total cost without breeding credit) of the cost of power.

The accuracy of the turbogenerator plant investment cost is estimated at ±15%. For such a plant, based on vast industrial experience, the error limit could be narrowed with a definite site selection and the establishment of detailed design criteria (for example, nearly 6% cost reduction could be achieved by installing the turbogenerators outdoors). Briggs[3] sets an error range of 0 to +30% on the estimated cost of the reactor plant since the figures used do not allow for construction contingencies. For maintenance and operation of the turbogenerator plant, a fairly well known quantity, a ±15% assessment of the accuracy should be adequate.

It is difficult to estimate an error limit for the maintenance and operating cost assumed for the reactor plant since a design in which these costs are under control has not yet been visualized. Ultimately, they might be expected to approach the costs for modern, conventional plants. An error of 0 to +100% is assumed because of the unknown factors involved.

The error limits for the fixed chemical processing costs (investment, operation and maintenance) also are difficult to estimate. A value of ±25% is assumed here. Based on various designs and limited data, arguments could be advanced for either raising or lowering the cost used. It is felt that the part of the processing cost that is a function of the throughput is as low as can be expected in the near future; consequently, a 0 to +100% limit is assumed.

The nuclear and isotope calculations are probably accurate to within ±15%. Consequently, cost items (uranium inventory, thorium feed, breeding gains, and, to some extent, processing rates) based on these results have about the same degree of uncertainty if the external power density is assigned approximately the same error range.

Applying the estimated limits of accuracy to the cost items comprising the 6.2 mills/kwh for a near optimum reactor, a cost range of 5.3 to 8.0 mills/kwh is obtained.

The cost of D_2O and the inventory charge (12% and $40/lb used in this study) for non-depreciating items is subject to government control and at present it is difficult to predict the changes in the future. The latest proposed pricing policy by the Atomic Energy Commission lists the cost of D_2O as $28/lb and requires only a 4% inventory or rental charge for non-depreciating items. Applying these proposed costs, the unit cost of power will be in the range of 4.6 to 7.2 mills/kwh.

Table II

Typical Cost Breakdown and Neutron Balances For Two-Region Reactors

Process Characteristics and Costs

Core diameter, ft	5	5	5	5	5
Thorium concentration, g thorium/liter	1000	1000	1000	500	1000
U^{233} concentration in in blanket, g/liter	3	3	3	3	3
Blanket thickness, ft	2-1/4	2-1/4	2-1/4	2	2
Core external power density, kw/liter	20	20	40	20	20
Blanket external power density, kw/liter	14	14	28	14	14
Group-3 poison cross section at 200C, b	40	18	18	40	18
Core poisons, %	7.0	6.0	6.0	7.0	6.0
Blanket poisons, %	4.33	2.67	2.74	5.50	2.72
Blanket power, Mw	89	91	90	89	92
Core power, Mw	392	390	391	392	389
Net unit cost of power, mills/kwh	6.32	6.22	5.91	6.53	6.32
Plant investment (less chemical processing) mills/kwh	3.74	3.74	3.74	3.74	3.74
Fuel inventory, mills/kwh	0.48	0.44	0.35	0.37	0.40
D_2O inventory, mills/kwh	0.52	0.52	0.34	0.49	0.54
Fixed chemical processing mills/kwh	0.76	0.76	0.76	0.76	0.76
Blanket processing, mills/kwh	0.26	0.25	0.24	0.20	0.24
Core processing, mills/kwh	0.09	0.07	0.06	0.09	0.07
Operation and maintenance, mills/kwh	0.75	0.75	0.75	0.75	0.75
Feed cost (D_2O and thorium), mills/kwh	0.20	0.20	0.13	0.19	0.20
Uranium (233 & 235) credit, mills/kwh	0.44	0.49	0.46	0.050	0.38
Gross breeding ratio	1.110	1.121	1.115	1.013	1.096
Net breeding ratio	1.109	1.119	1.114	1.012	1.095
Net U^{233} produced, g/day	59	65	61	7	51
U^{235} in product, wt. fraction	0.0014	0.0013	0.0014	0.0026	0.0014
U^{233} in product, wt. fraction	0.959	0.961	0.958	0.937	0.960
Core system volume, liters	21,400	21,400	11,600	21,400	22,600
Blanket system volume, liters	17,100	17,200	14,000	15,200	18,100
Core concentration, g U^{233}/ kg D_2O	2.53	2.48	2.49	2.44	1.59
Core concentration, g U^{235}/ kg D_2O	0.34	0.30	0.31	0.38	0.19
Core concentration, g uranium/ kg D_2O	9.21	8.30	8.49	9.90	5.34

Table II (Contd)

Reactor (internal & external) inventories, kg					
Thorium	17,100	17,200	14,000	7,600	18,100
U^{233}	97.1	96.2	66.3	66.8	84.3
U^{235}	6.3	5.5	3.2	7.1	3.8
Pa^{233}	18.6	19.0	18.2	14.6	18.8
Feed stream inventories, kg					
Thorium	6,500	6,800	6,400	4,800	6,600
U^{233}(includes Pa^{233})	53.1	45.4	45.9	51.5	44.0
U^{235}	3.0	1.5	1.6	3.4	1.5
Core thorex cycle, days	198	336	182	194	228
Blanket thorex cycle, days	146	140	120	87	150
Net thorium feed, g/day	557	625	621	555	610
Flux at core wall, n/cm^2 sec	1.06×10^{15}	1.10×10^{15}	1.08×10^{15}	1.36×10^{15}	0.84×10^{15}

Neutron Balance

Absorptions in fuel					
U^{233} (core)	0.7957	0.7941	0.7950	0.7928	0.7898
U^{233} (blanket)	0.2043	0.2059	0.2050	0.2072	0.2102
U^{235} (core)	0.1164	0.1035	0.1066	0.1350	0.1039
U^{235} (blanket)	0.0004	0.0004	0.0005	0.0010	0.0004
Neutron losses (other than fuel)					
Core					
Poisons	0.0576	0.0486	0.0487	0.0584	0.0483
U^{234}	0.1153	0.1024	0.1054	0.1328	0.1027
U^{236}	0.0184	0.0163	0.0168	0.0214	0.0163
Sulfur	0.0024	0.0021	0.0022	0.0026	0.0022
Core tank	0.0305	0.0309	0.0308	0.0396	0.0412
D_2O	0.0169	0.0172	0.0172	0.0174	0.0268
Blanket					
Thorium (thermal)	0.8114	0.8171	0.8143	0.8230	0.8348
Thorium (resonance)	0.3297	0.3351	0.3351	0.2264	0.2893
Protactinium	0.0188	0.0192	0.0226	0.0338	0.0186
Poisons	0.0080	0.0050	0.0051	0.0104	0.0052
U^{234}	0.0018	0.0017	0.0019	0.0032	0.0016
U^{236}	3×10^{-7}	3×10^{-7}	4×10^{-7}	8×10^{-7}	3×10^{-7}
D_2O	0.0027	0.0028	0.0027	0.0059	0.0028
Fast leakage	0.0265	0.0264	0.0264	0.0508	0.0336
Slow leakage	0.0075	0.0075	0.0074	0.0423	0.0100
Total absorptions and losses	2.5643	2.5362	2.5437	2.6040	2.5377
Neutrons produced from U^{233}	2.3200	2.3200	2.3200	2.3200	2.3200
Neutrons produced from U^{235}	0.2441	0.2172	0.2238	0.2842	0.2180
Total neutrons	2.5641	2.5372	2.5438	2.6042	2.5380

Table III

Effect of Substantial Changes in the Nuclear Constants[a]

		C_T	C_X	B_R	B(G)	G(U)[b]
Extrapolation distance, in.	7.62	6.257	0.3879	1.097	51.7	8.4
	15.24[c]	6.229	0.4173	1.104	55.5	8.4
15.24	22.86	6.219	0.4294	1.107	59.0	8.4
η of U^{233}	2.28	6.354	0.2896	1.073	38.6	8.8
2.32	2.36	6.109	0.5546	1.135	72.6	8.1
$\sigma_a(13)$	48.4	6.158	0.4965	1.124	66.3	7.8
96.8	145.2	6.299	0.3262	1.086	45.7	9.0
τ_B	106.2	6.136	0.5288	1.131	70.5	8.8
212.4	191.2	6.210	0.4400	1.110	58.6	8.5
	233.6	6.248	0.3943	1.098	52.6	8.4
	318.6	6.324	0.3062	1.077	40.8	8.2
τ_c	109.0	6.217	0.3956	1.099	52.8	6.7
218.0	196.2	6.227	0.4130	1.103	55.1	8.0
	239.8	6.234	0.4210	1.105	56.1	8.8
	327.0	6.259	0.4354	1.109	58.0	10.8
D_{1B}	0.745	6.223	0.4048	1.101	54.0	7.5
1.49	2.24	6.238	0.4235	1.106	56.4	9.0
D_{2B}	0.5865	6.224	0.4249	1.101	57.0	7.5
1.173	1.76	6.256	0.3952	1.099	52.7	8.9
D_{1C}	0.835	6.224	0.4332	1.107	57.1	9.5
1.67	2.505	6.236	0.4097	1.104	50.2	7.8
D_{2C}	0.6152	6.214	0.3797	1.095	50.6	5.1
1.2304	1.846	6.255	0.4300	1.107	57.4	10.8
P_B	0.28	6.181	0.4913	1.122	65.4	8.3
0.56	0.84	6.308	0.3262	1.082	43.5	8.6
Combination case 1 (D's, τ's, p high; extrapolation distance low)		6.692	0.0102	1.004	1.2	15.4
Combination case 2 (D's, τ's, p low; extrapolation distance high)		6.0804	0.5131	1.128	68.42	3.5

Table III (contd)

[a] The following properties were common to all the calculations performed:

Temperature	280°C
Grams of U^{233} per kilogram of thorium	3
Grams of thorium per liter	1000
Poison fraction in core	0.06
Reactor power	480.8 Mw (125 Mw elect. output)
Core diameter	5 ft
Pressure vessel diameter	9 ft
External power densities, kw/liter	
Core system	20
Blanket system	14

[b] The symbols in column headings are defined as follows:

C_T = total power cost, mills/kilowatt-hour

C_X = credit for excess fissionable material produced, mills/kilowatt-hour

B_R = breeding ratio, atoms of fissionable material produced per atom of fuel burned

B(G) = net grams of fissionable material produced per day

G(U) = uranium concentration in core, grams of uranium per kilogram of heavy water

[c] This row gives results for standard case. Underlined numbers are values chosen for parameters in standard case.

[redacted]

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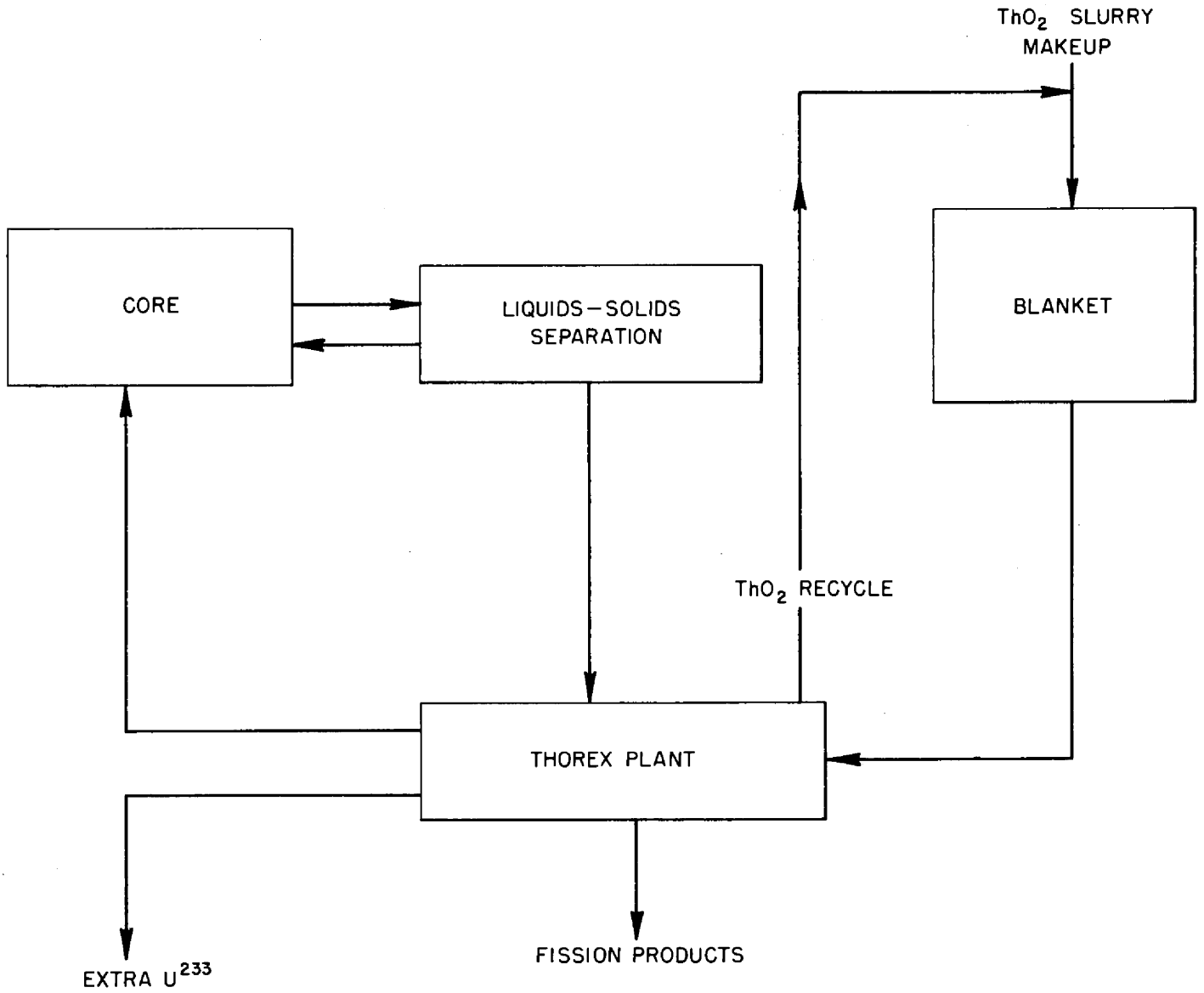

Fig. 1. Schematic Flow Sheet for a Two Region Thorium Breeder Reactor.

[redacted]

[redacted]

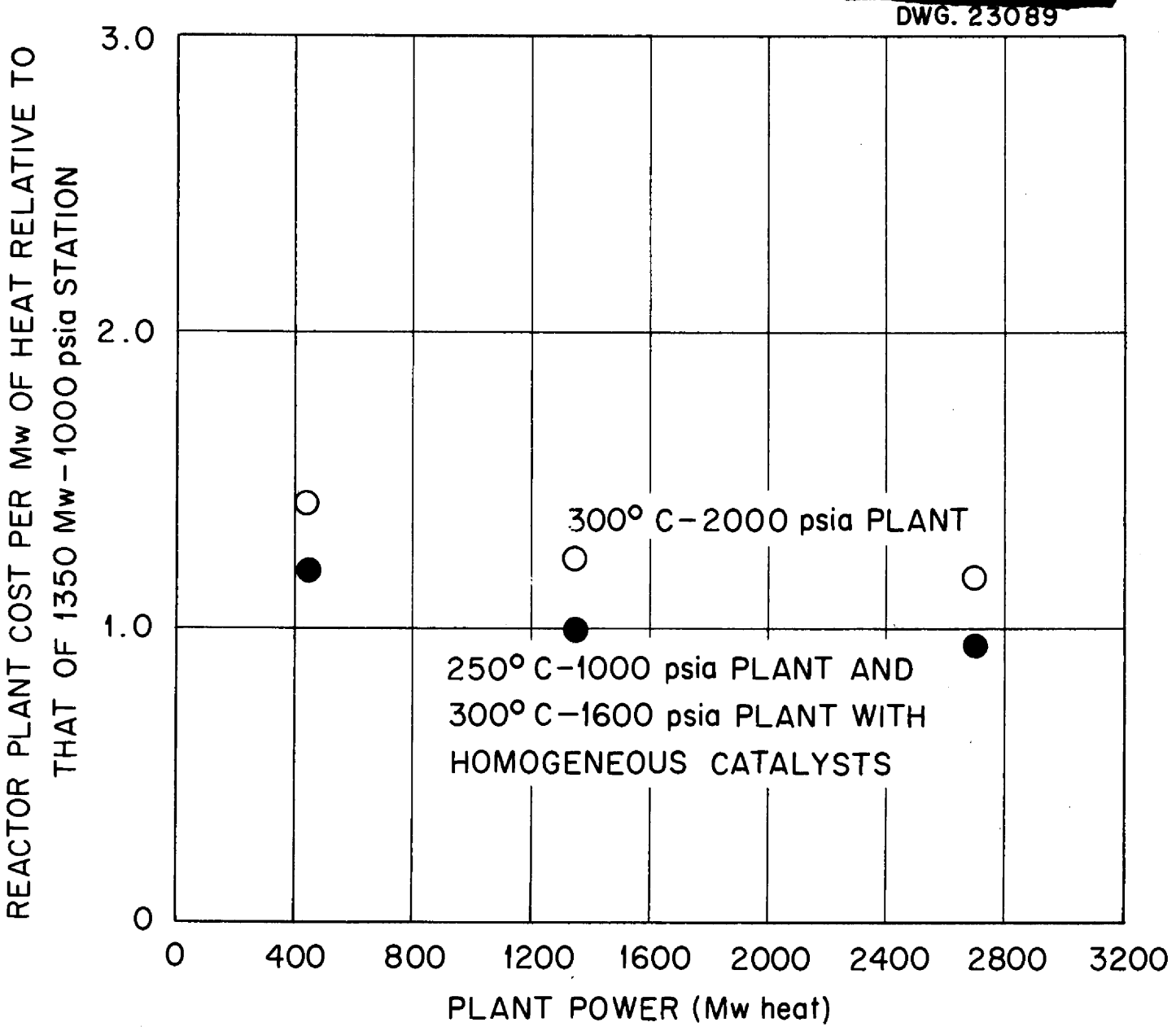

Fig. 2. Effect of Power on Cost of Two-Region Reactor Plant.

[redacted]

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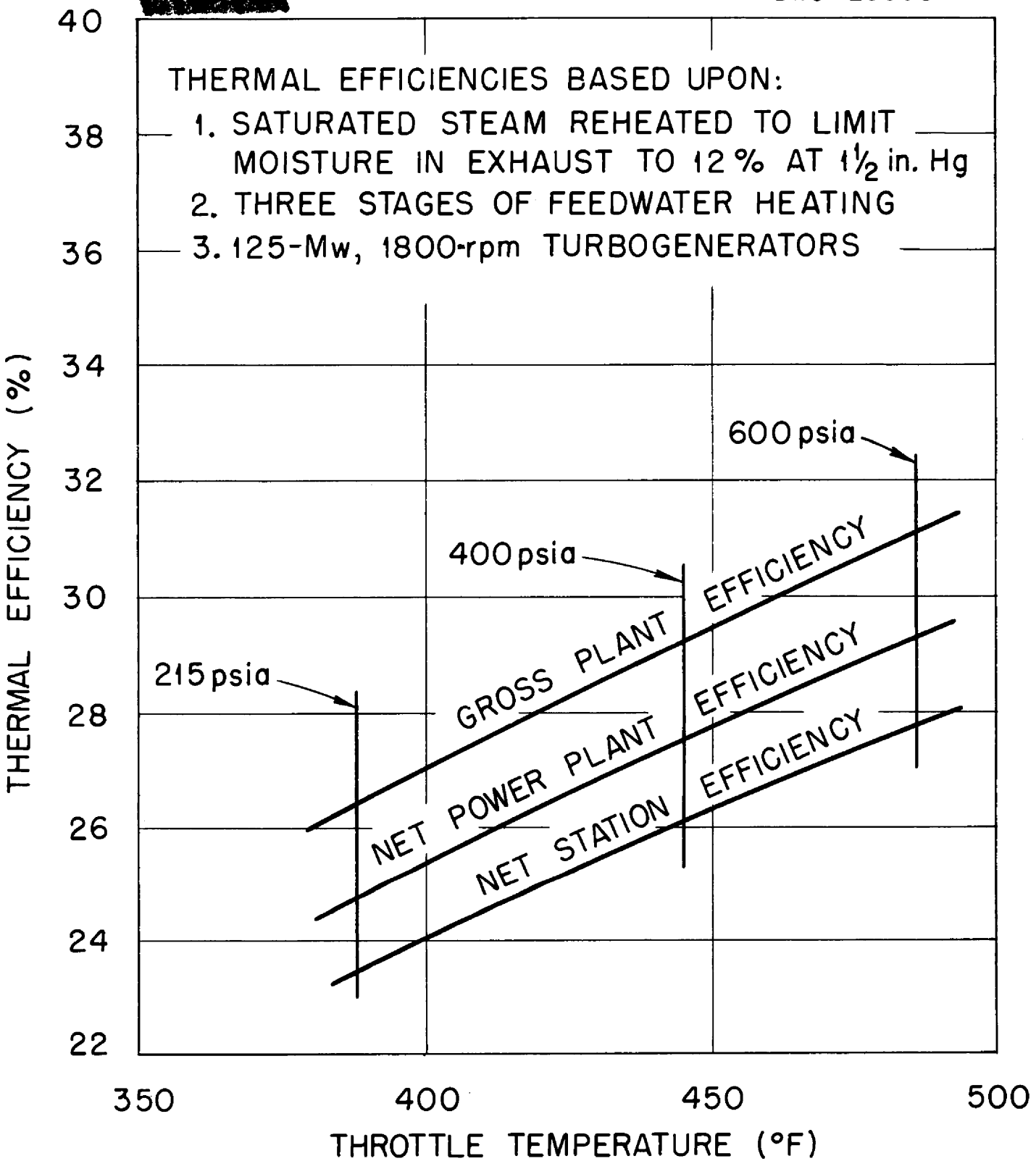


Fig. 3. Effect of Steam Conditions on Turbogenerator Plant Efficiency.

[redacted]

[redacted]

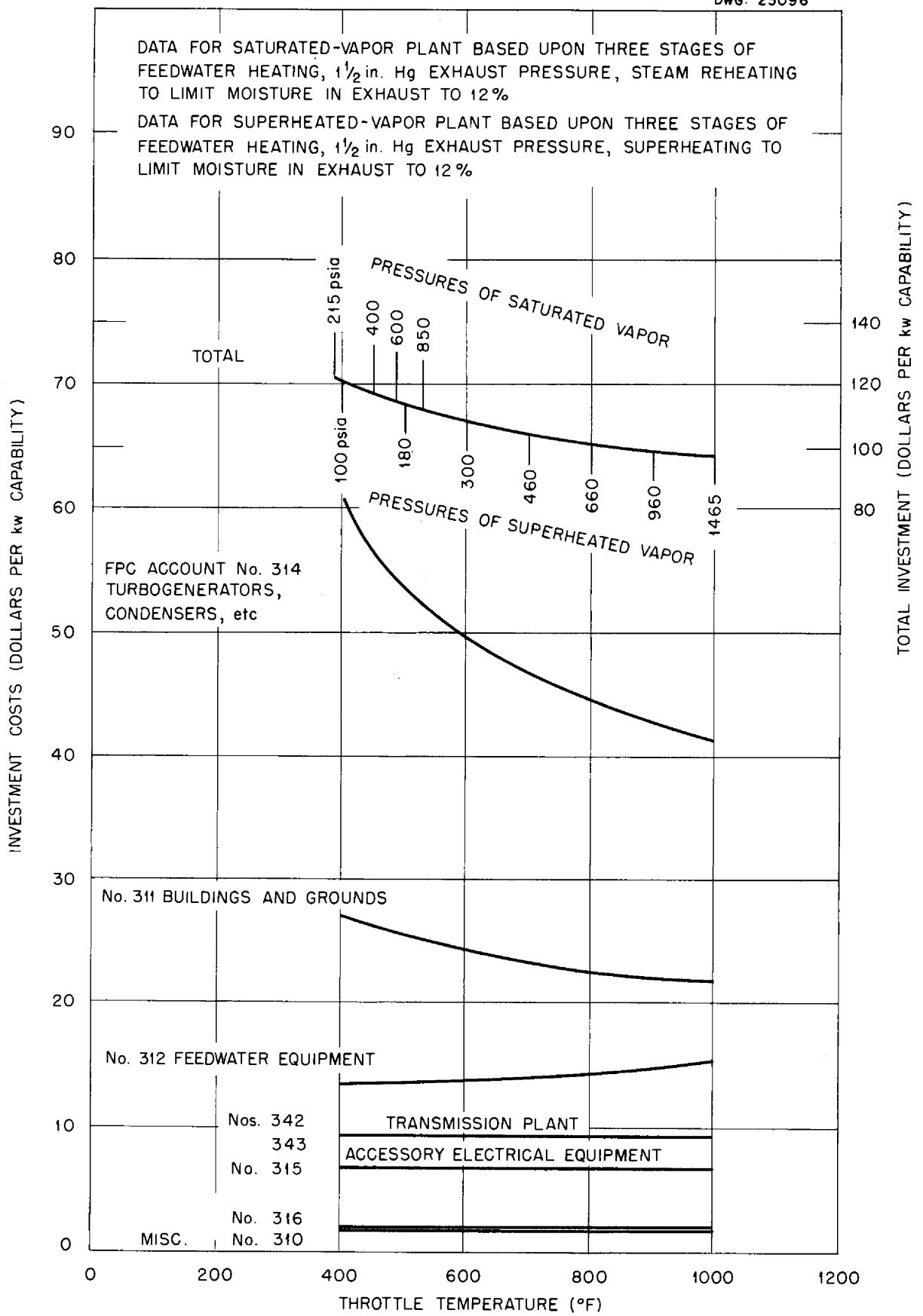


Fig. 4. Effect of Steam Conditions on Power-Plant Cost for 300-Mw Plant.

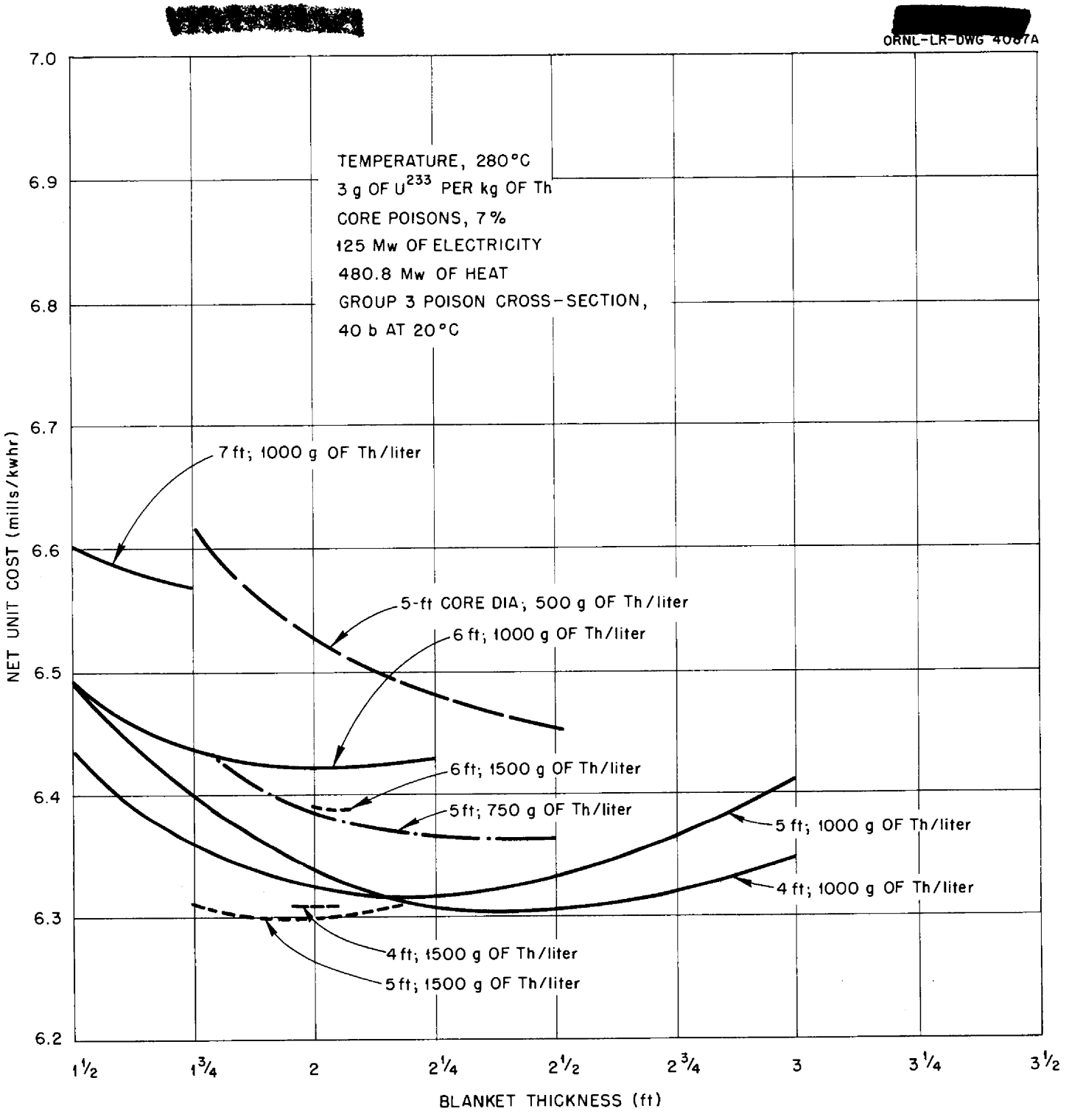


Fig. 5. Effect of Blanket Thickness on Unit Cost.

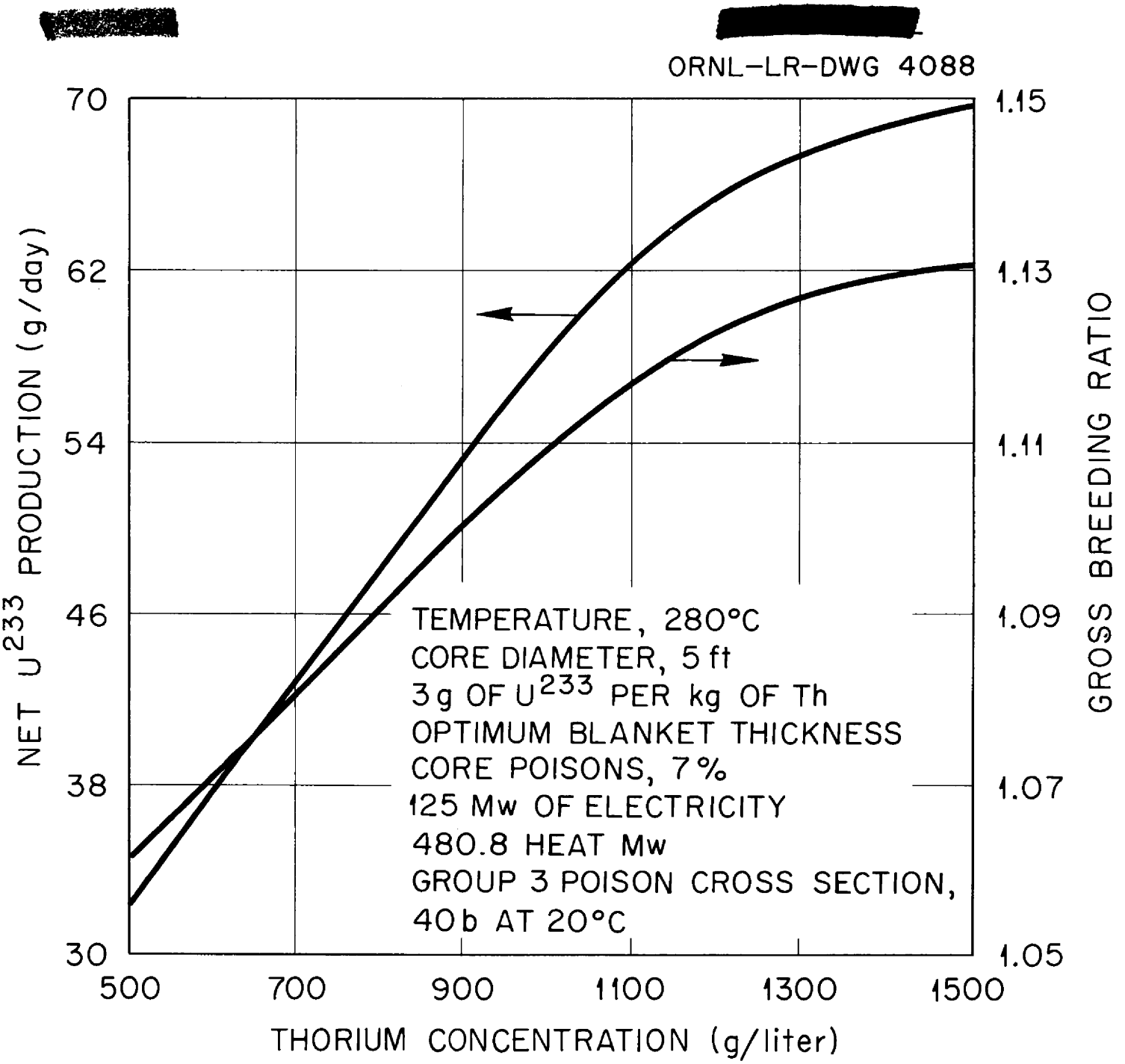


Fig. 6. Effect of Thorium Concentration on Breeding.

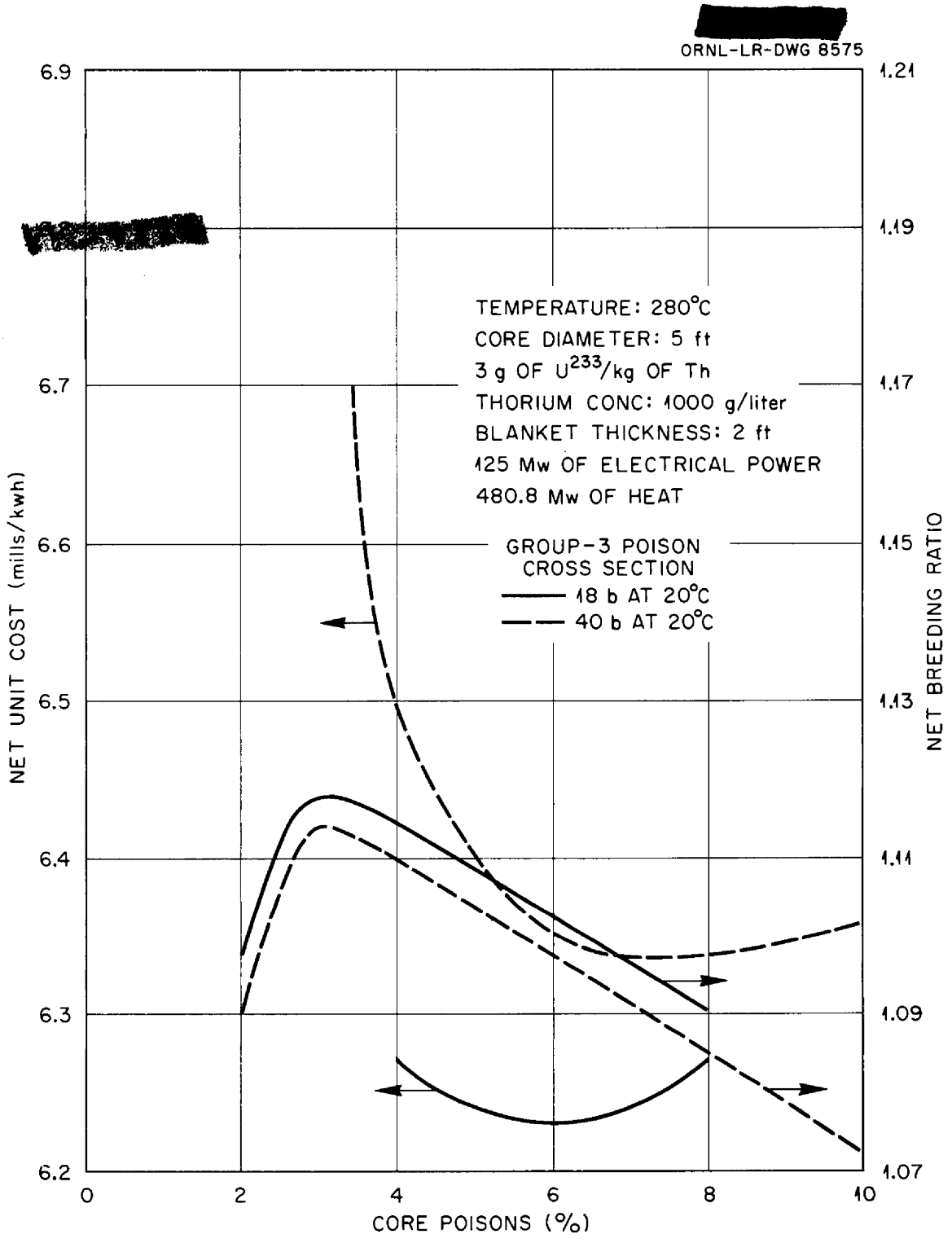


Fig. 7. Effect of Group-3 Poisons on Unit Cost and Breeding Ratio.

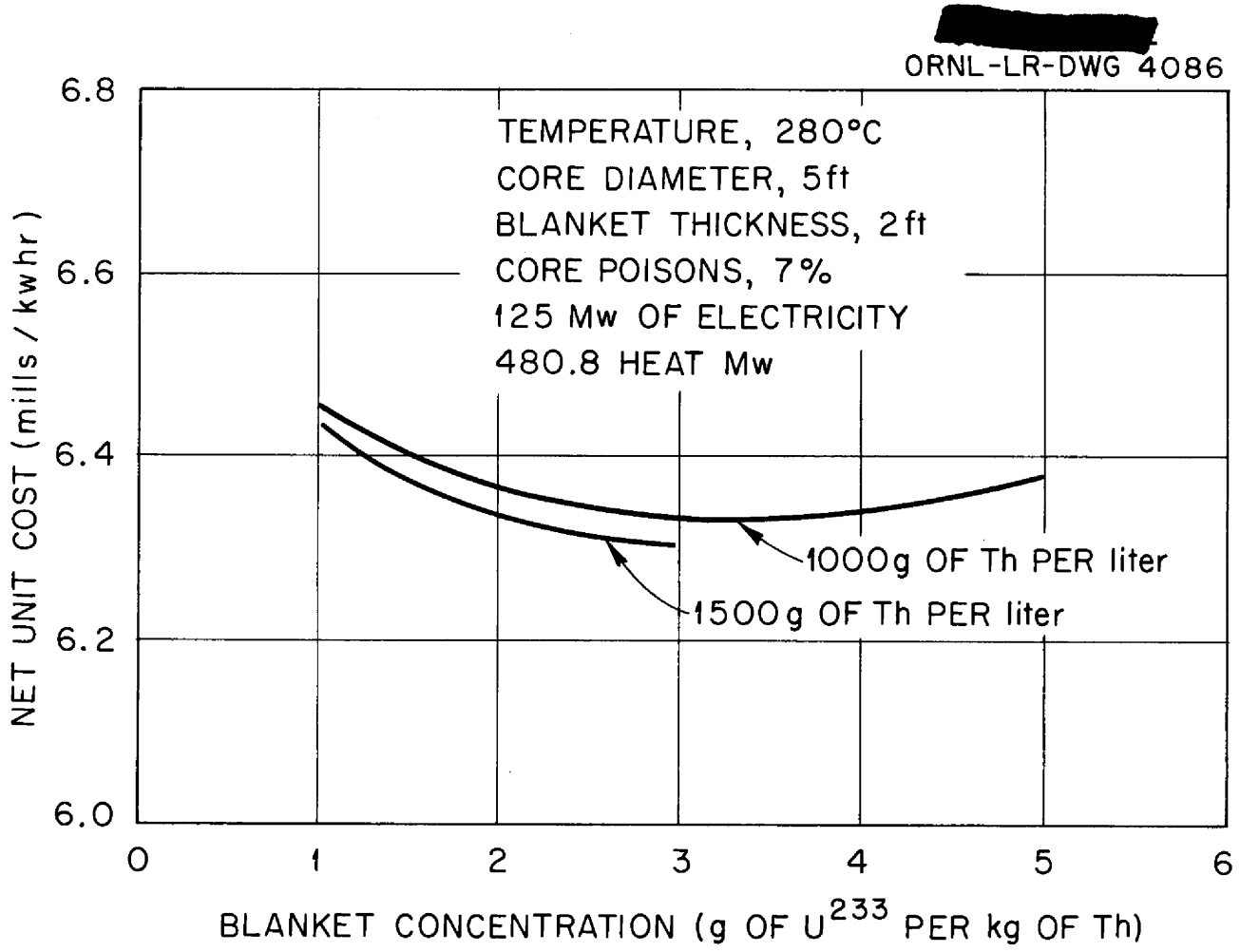
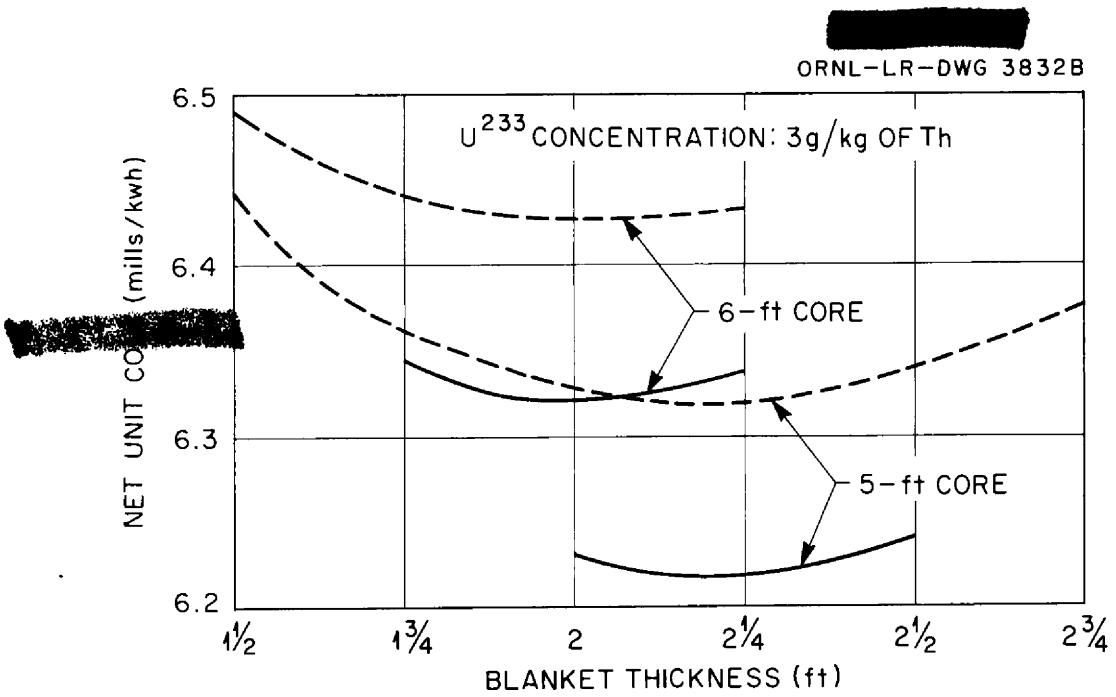


Fig. 8. Effect of Blanket Uranium Concentration on Unit Cost.



TEMPERATURE: 280°C
THORIUM CONCENTRATION: 1000 g/liter
CORE POISONS: 6%
ELECTRICAL POWER: 125 Mw
HEAT: 480.8 Mw
——— GROUP-3 POISONS: 18 barns AT 20°C
– – – – GROUP-3 POISONS: 40 barns AT 20°C

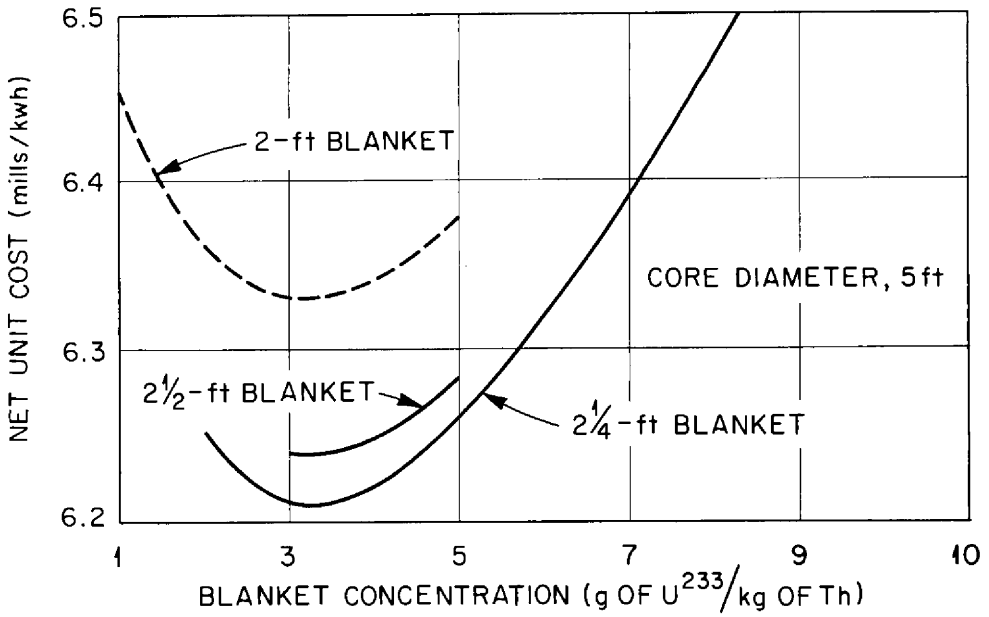


Fig. 9. Effect of Group 3 Poison Cross Section on Unit Cost.

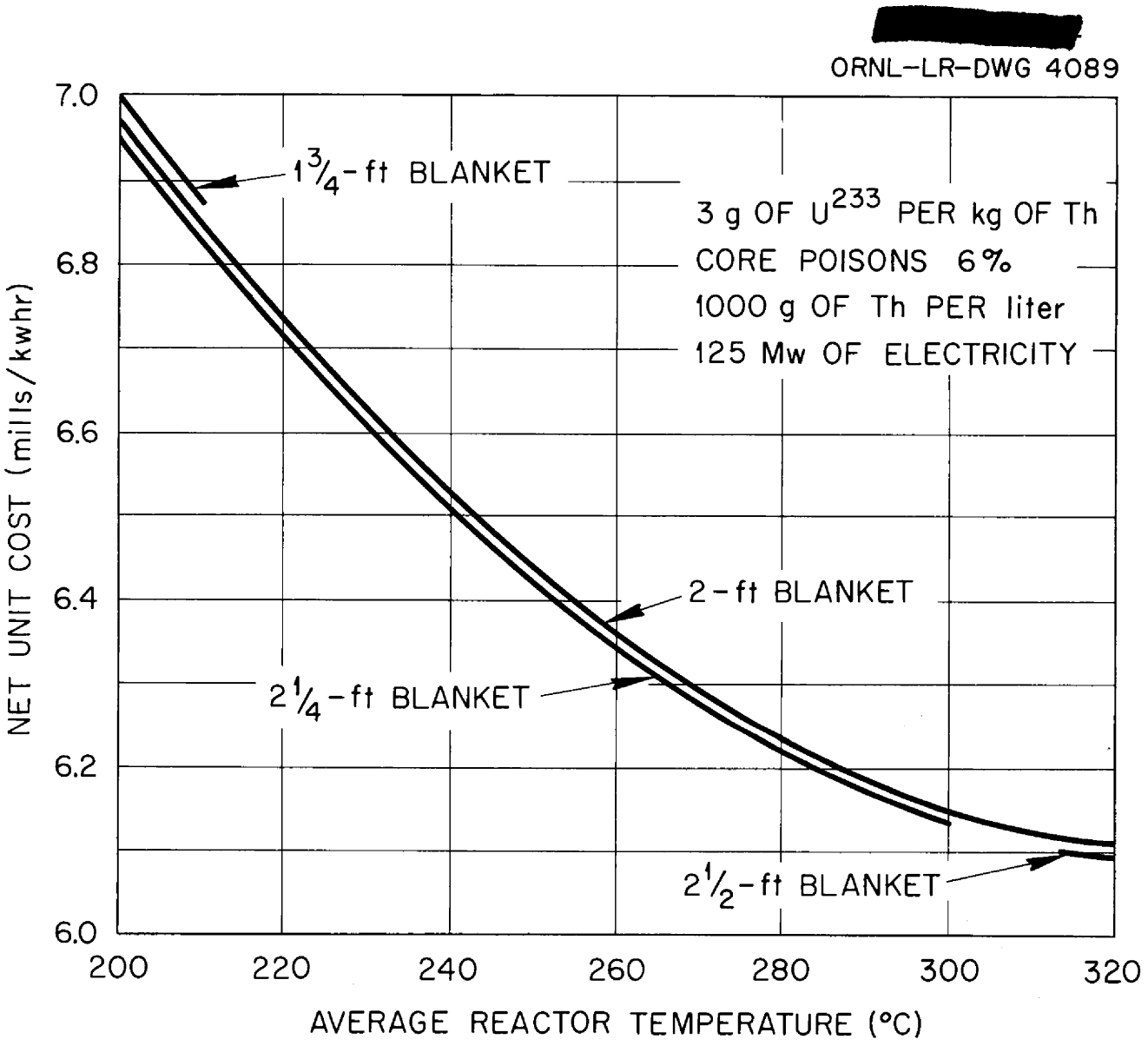


Fig. 10. Effect of Temperature on Unit Cost.

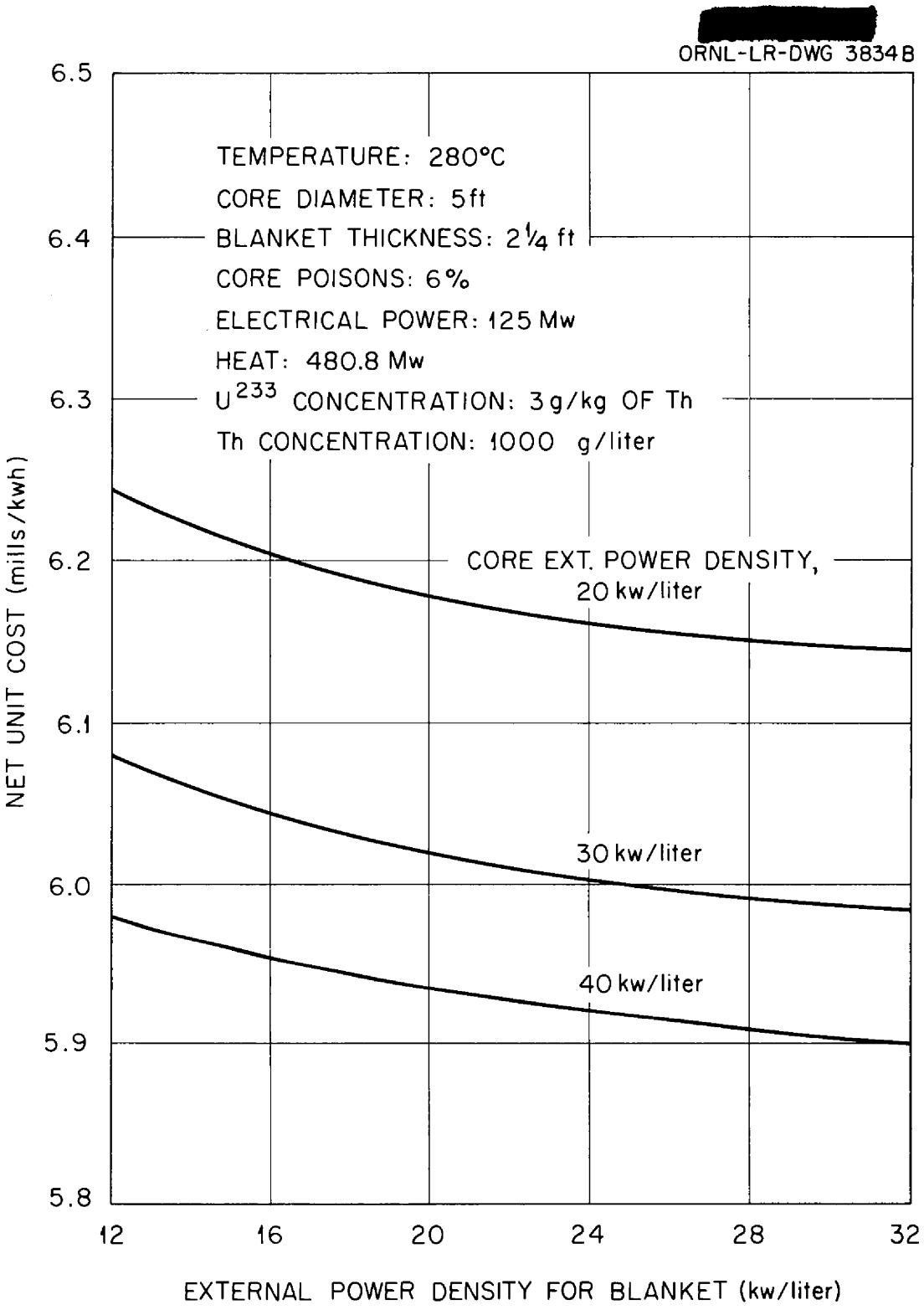


Fig. 11. Effect of External Power Densities on Unit Cost

ONE-REGION REACTORS

ONE-REGION REACTORS

Methods and Conditions

Use of slurry in the one-region reactor system precludes hydraulic separation as a method of poison removal. All poison removal must be done in the more expensive Thorex plant. It was assumed that the fuel would be in the form of a UO_3-ThO_2 slurry in D_2O.

The calculations for the one-region reactor were considerably easier than for the two-region reactors. No iteration is required to determine the resonance to thermal absorption in the thorium. Therefore, it is possible to write a set of equations covering the isotope concentrations and the nuclear calculations which could be solved simultaneously by a simple iterative procedure.

The independent variables were reactor size, thorium concentration, process cycle time and external power density.

It is to be noted that the basic configuration of a three-reactor power station has been preserved here in order to provide as close a comparison as possible of the two systems. It may be argued that such a scheme places the one-region system at an initial disadvantage because of the much lower power density which results. The underlying philosophy of the three-reactor station was to limit the individual power sources to the order of 100 Mw of electricity because of network considerations. Possibly 375 Mw of electrical power from a two-reactor station composed of one-region reactors would be more economical.

Fission Product Poisons

The fission product poisons were handled in the same fashion as the two-region reactor. Since only the Thorex process is used, the equation for the processing cycle time is similar to equation (6).

$$T = \frac{f_3}{y\,\sigma_3\,\phi} \tag{22}$$

Isotope Concentrations and Critical Equation

As in the two-region calculation, the higher isotopes of thorium and of uranium beyond U-236 need not be considered. In addition, the effect of the U-238 added with the enriched feed (93.5% U-235, 2.0% U-234, and 4.5% U-238) for the non-breeders was neglected because of the small quantity and small cross section. The critical equation is simply

$$p\left[\eta(25)\,\Sigma_a(25) + \eta(23)\,\Sigma_a(23)\right] = (1 + \tau B^2)\,(\Sigma_T + D_2 B^2) \tag{23}$$

and the relationship for the resonance to thermal absorption can easily be shown to be

$$\beta_{02} = \frac{(1 - p)}{p}\,\frac{(D_2 B^2 + \Sigma_T)}{\Sigma(02)} \tag{24}$$

For a one-region reactor under equilibrium conditions,

$$\left[1 + \beta(02)\right]\Sigma(02)\,\phi - \lambda(13)\,N(13) - \Sigma(13)\,\phi - \frac{N(13)}{T} = 0 \tag{25}$$

$$\lambda(13)\,N(13) + q\left[\frac{N(13) + N(23)}{T}\right] - \Sigma_a(23)\,\phi - \frac{N(23)}{T} = 0 \tag{26}$$

$$\frac{F(24)}{V_T} + \Sigma_r(23)\,\phi - \Sigma(24)\,\phi + \Sigma(13)\,\phi - (1-q)\,\frac{N(24)}{T} = 0 \tag{27}$$

$$\frac{F(25)}{V_T} + \Sigma(24)\,\phi - \Sigma_a(25)\,\phi - (1-q)\,\frac{N(25)}{T} = 0 \tag{28}$$

$$\sum_r(25)\,\phi - \sum(26)\,\phi - (1-q)\,\frac{N(26)}{T} = 0 \qquad (29)$$

$$\phi = \frac{3.38 \times 10^{16}\ P/V_T}{\Sigma_f(23) + \Sigma_f(25)} \qquad (30)$$

For breeder reactors the set of equations shown above (22 through 30) was solved simultaneously by iterative methods with the feed of U-235 (F25) set equal to zero. However, to handle the case of breeders and non-breeders with the same general method, another equation is used that relates the gross breeding ratio (no chemical losses), chemical processing losses (0.1% used for all reactors) and the U-235 feed for the non-breeders. Obviously just enough U-235 must be added to make the net breeding ratio equal to one. Therefore by a direct material balance (or by combining equations 25, 26, and 28 and assigning a processing loss),

$$(B_R-1) + \frac{F(25)/\phi\ V_T}{\Sigma_a(25) + \Sigma_a(23)} - \frac{0.001\left[N(13) + N(23) + N(25)\right]}{\left[\Sigma_a(25) + \Sigma_a(23)\right]\phi T} = 0 \qquad (31)$$

In brief the calculation was performed in the following manner. For a particular value of power (P), reactor diameter (for a sphere $B = \frac{\pi}{R}$) process cycle time (T) and thorium concentration (N(02)), the critical equation (eq. 22) was used to calculate the concentration of U-233 with no poisons, Pa or higher isotopes of uranium. The other isotopes were then calculated with F(25) = 0 for the first iteration. Then equation (28) was used to compute F(25). If F(25) was minus, the reactor was a breeder and the iteration with F(25) = 0 was continued until the desired accuracy (≥0.01%) was attained. If the reactor was a non-breeder, the percentage recycle, q, was set equal to 0.999 (all recycled minus the 0.1% processing loss) and the value

of F(25) computed from equation (31) was used in each successive iteration until sufficient convergence occurred. Hand calculations of this nature would be quite laborious, requiring several hours of computation for each reactor. All the required instructions and equations, however, were easily coded and the ORACLE averaged only around 15 seconds per reactor calculation.

Cost Estimation

No attempt was made to estimate the investment cost of the one-region plant. For initial comparison purposes, it can be assumed that this cost is comparable to that of the two-region plant.

All other cost factors are the same as used for the two-region study.

Results

All results are for 125 Mw of electrical power delivered to a power grid for a one-region reactor operating at an average temperature of 280°C (equivalent to 480.8 Mw of heat with a net station efficiency of 26%). An external power density of 20 kw/liter was used in all cases.

The unit cost of power is shown as a net partial cost in the following table and graphs. This cost is the sum of the inventory charges, feed (thorium and for non-breeders U-235), D_2O makeup and chemical processing charges that are a function of throughput minus the credit for breeding gain, if any. Costs not included are the fixed charges on the plant investment (reactor, turbogenerator and chemical processing), fixed operating costs for the chemical processing plant

and operating and maintenance which is usually taken as a percentage of the plant investment (3% in the two-region study). The comparable fixed cost for the two-region reactors is 5.25 mills/kwh. Consequently, for initial comparison, the total unit cost can be obtained by adding the fixed cost of 5.25 mills/kwh to the net partial unit costs shown.

The results for 5 reactor sizes of interest at near optimum conditions are presented in Table IV. It is immediately apparent that for one-region reactors near the optimum cost conditions large breeding gains cannot be obtained and high isotopic purity ($\sim$95%) U-233 cannot be produced without a protactinium recovery process. This would involve separation of protactinium from the uranium isotope mixture as soon as practical after discharge from the reactor. Such a procedure would not ordinarily be required for the two-region reactor since a product of about 95% purity is expected.

The effect of the chemical processing cycle (determines the fission poison level) is shown in Figures 12, 13, and 14 for the reactor diameters from 10 to 16 ft. In general the optimum cycle time increases with increase in thorium concentration and reactor diameter; the optimum cycle time for the reactors near optimum cost appear to be about twice as large as for a two-region machine. For non-breeders it was assumed that a 30-day supply of U-235 feed was on hand, but no reserve supply of fissionable material was assumed for breeders. Thus the loss in credit from the breeding gain and the additional inventory charge caused the abrupt changes in slope that appear in the graphs at the point of change from breeder to non-breeder.

The net partial cost as a function of diameter and thorium concentration at optimum cycle time (determined from Figures 12, 13, and 14)

is shown in Figure 15. It is apparent that, for the reactor sizes of interest, the optimum thorium concentrations are between 200 and 300 g/liter.

The effect of reactor diameter (determined from Figure 15) on the partial unit cost of power for optimum process cycle times and thorium concentrations is shown in Figure 16. The minimum partial unit cost of 1.88 mills/kwh occurs for a reactor size of 12 ft with a thorium concentration of 260 g/liter. From a cost viewpoint there is little variation in the range of reactor sizes from 10 to 14 ft, the maximum difference being only 0.12 mills/kwh.

The comparable minimum partial cost for the two-region reactor is 0.97 mills/kwh. Therefore, a cost differential of 0.9 mills/kwh seems to exist in favor of the two-region reactor provided that the fixed costs for the two reactor types are equal. This difference is, of course, uncertain because of possible unforeseen engineering difficulties which may arise in the course of construction and operation of either type reactor. It is not unreasonable to suppose, for instance, that fixed costs may be somewhat smaller for the one-region reactor because of simpler construction. Clearly, questions such as these can be resolved only by comparison of the performance of actual reactors.

Table IV

Cost Breakdowns and Neutron Balances for Several One-Region Reactors Near Optimum Conditions*

Process Characteristics and Costs

Reactor diameter, ft	10	11	12	13	14
Thorium concentration, g/liter	300	300	250	250	200
Process cycle time, days	450	400	400	500	450
Net partial cost of power, mills/kwh	2.00	1.92	1.88	1.93	2.01
Uranium (U^{233} and U^{235}) credit mills/kwh	0	0.04	0.057	0.15	0.11
Chemical processing (less fixed costs), mills/kwh	0.17	0.20	0.18	0.16	0.16
Feed costs (Th, D_2O, U) mills/kwh	0.40	0.22	0.25	0.28	0.32
D_2O inventory, mills/kwh	0.52	0.58	0.66	0.75	0.86
Uranium inventory, mills/kwh	0.92	0.96	0.84	0.89	0.77
Total system volume, liters	38,900	43,800	49,700	56,600	64,700
Power density in reactor, kw/liter	32.4	24.1	18.8	14.8	11.8
Gross breeding ratio	0.957	1.011	1.012	1.035	1.025
Net breeding ratio	0.956	1.009	1.010	1.034	1.024
Net breeding gain (U^{233} and U^{235}) g/day	0	5.79	6.3	20.4	14.3
Critical concentration, g U^{233}/kg D_2O	7.99	7.62	5.82	5.60	4.15
Critical concentration, g U^{235}/kg D_2O	1.18	0.71	0.56	0.46	0.37
Uranium concentration, g U/kg D_2O	26.08	17.60	13.42	10.68	8.50
Reactor (internal & external) inventories, kg					
Thorium	11,700	13,100	12,400	14,200	12,900
U^{233}	251.9	270.9	236.0	258.8	220.4
U^{235}	37.4	25.3	22.5	21.2	19.7
Pa^{233}	18.9	19.8	19.9	20.9	20.4
Feed stream inventories, kg					
Thorium	1,400	1,800	1,700	1,600	1,600
U^{233} (includes Pa)	34.7	41.8	37.0	32.4	31.1
U^{235}	5.4	3.5	3.1	2.3	2.4
U^{233} in product, wt. fraction	0.306	0.433	0.434	0.524	0.487
U^{235} in product, wt. fraction	0.042	0.038	0.038	0.040	0.040
Thorium feed, g/day	528	560	561	580	572
U^{235} feed, g/day	26.7	0	0	0	0
Reactor poisons, %	5.49	4.93	5.46	6.10	6.34

Table IV (Contd)

Neutron Balances

Absorptions and losses					
Pa^{233}	0.0191	0.0186	0.0214	0.0206	0.0235
U^{233}	1.0000	1.0000	1.0000	1.0000	1.0000
U^{234}	0.1090	1.1019	0.1040	0.0910	0.0986
U^{235}	0.1599	0.1009	0.1029	0.0883	0.0966
U^{236}	0.0235	0.0095	0.0095	0.0044	0.0061
D_2O	0.0070	0.0073	0.0095	0.0099	0.0133
Poisons	0.0573	0.0491	0.0545	0.0601	0.0629
Th^{232} (thermal)	0.5516	0.5775	0.6269	0.6516	0.6998
Th^{232} (resonance)	0.4687	0.4520	0.4063	0.4043	0.3488
Fast leakage	0.1873	0.1518	0.1309	0.1123	0.0993
Slow leakage	0.07081	0.0623	0.0694	0.0622	0.0730
Total neutrons absorbed and lost	2.6541	2.5309	2.5351	2.5046	2.5218
Production					
Neutrons from U^{233}	2.3200	2.3200	2.3200	2.3200	2.3200
Neutrons from U^{235}	0.3341	0.2109	0.2151	0.1846	0.2018
Total neutrons produced	2.6541	2.5309	2.5351	2.5046	2.5218

* 125 Mw of electricity, 480.8 Mw of heat. Average temperature 280°C, external power density, 20 kw/liter.

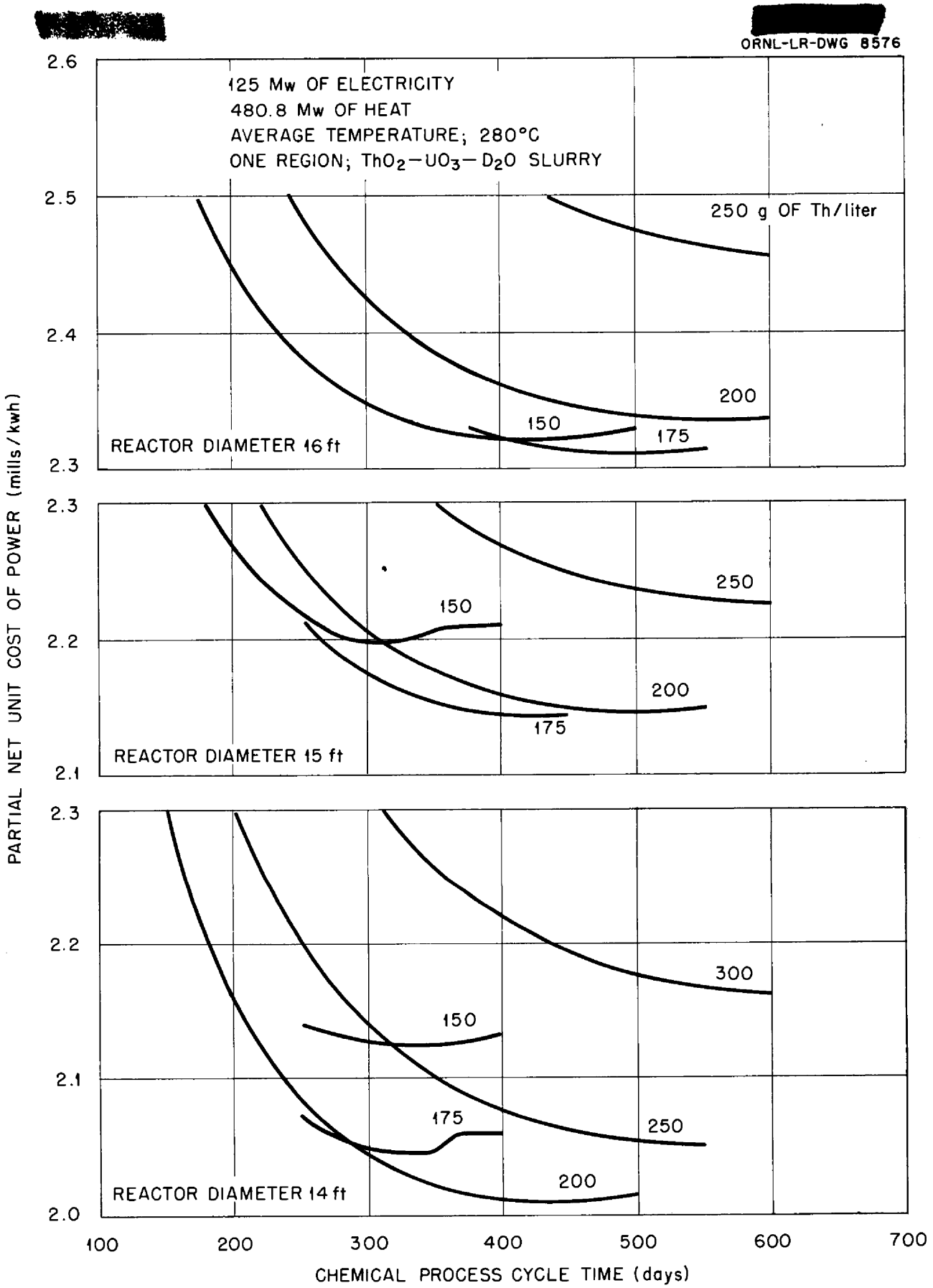


Fig. 12. Effect of Process Cycle Time on Unit Cost.

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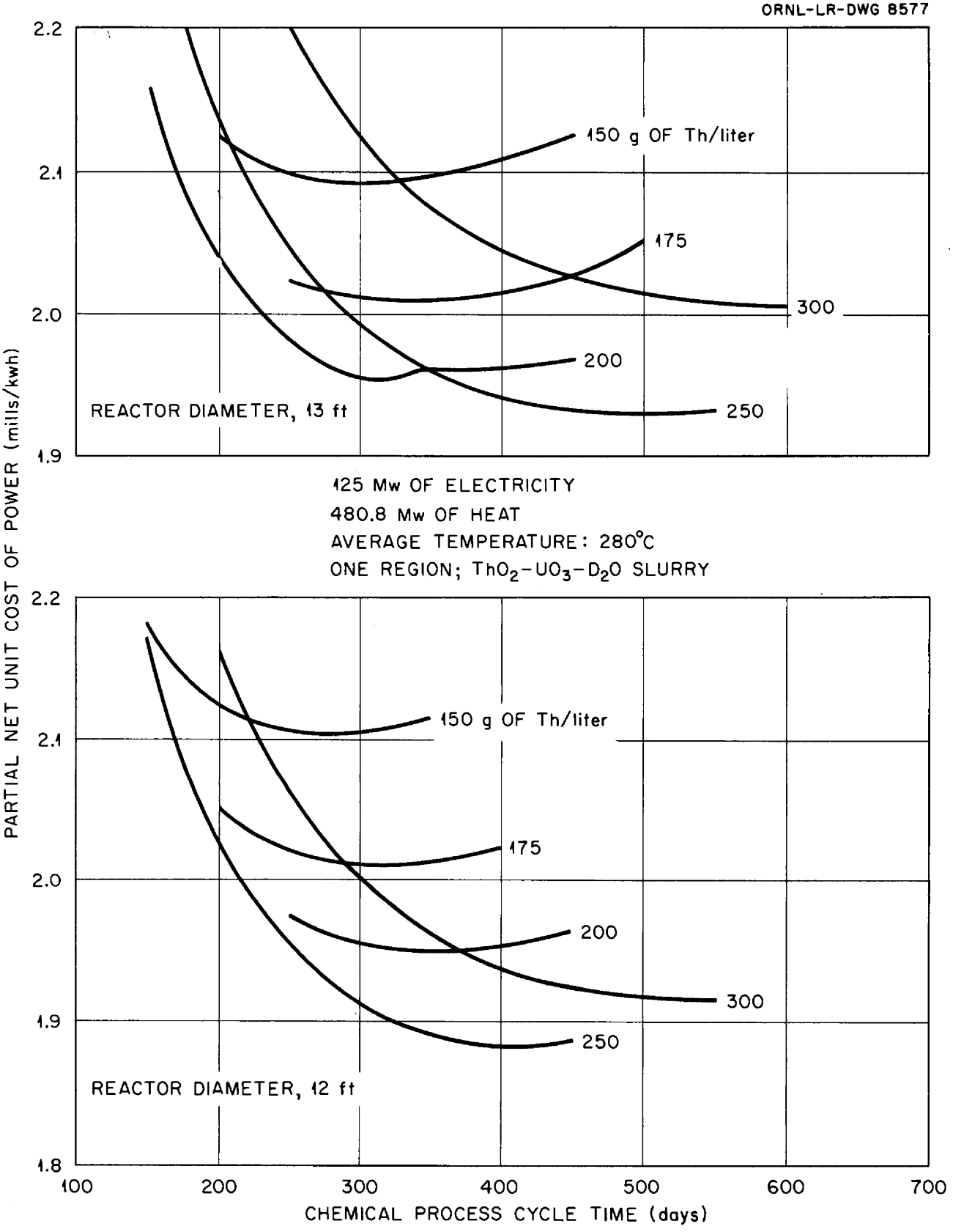

Fig. 13. Effect of Process Cycle Time on Unit Cost.

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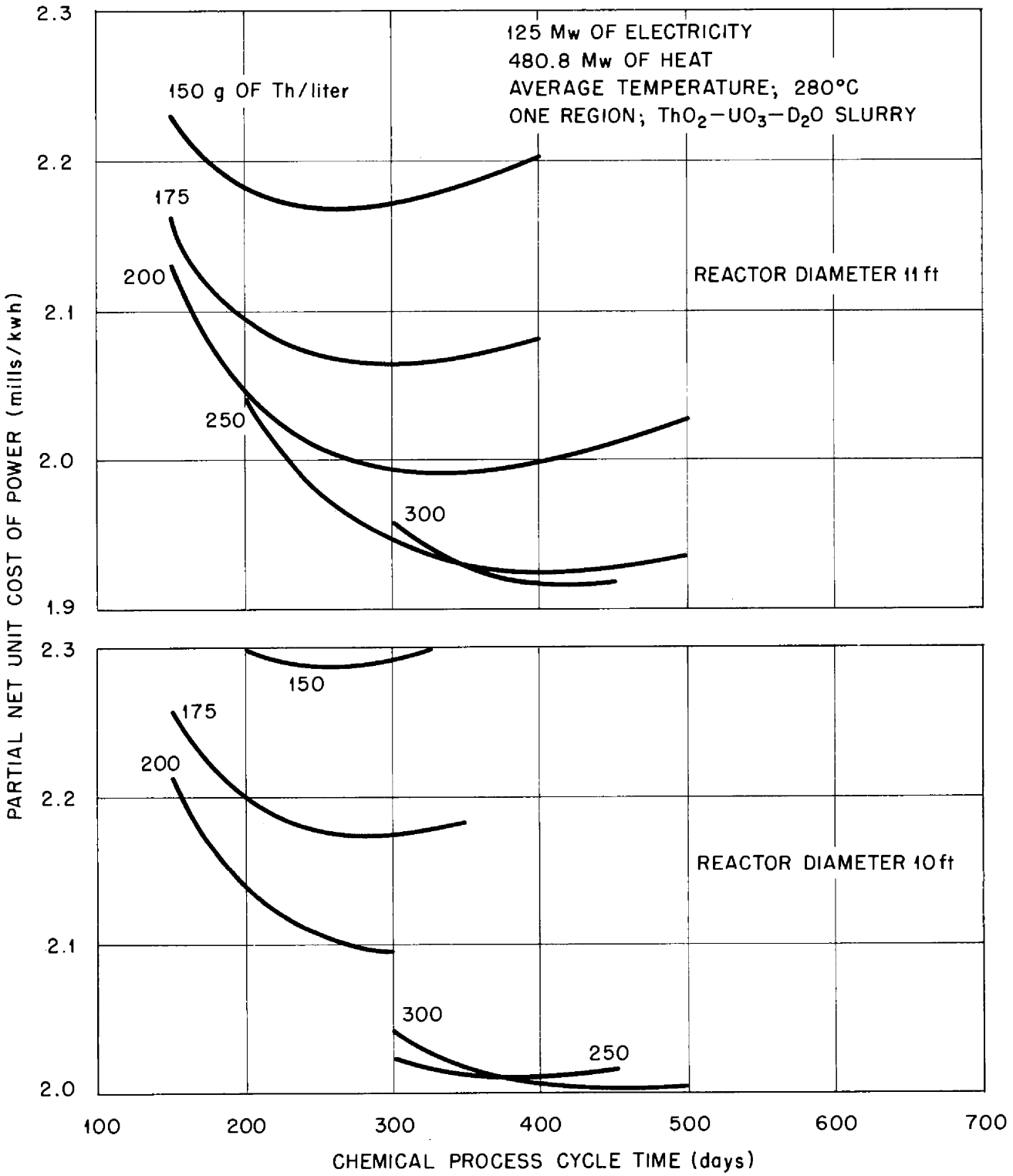

Fig. 14. Effect of Process Cycle Time on Unit Cost.

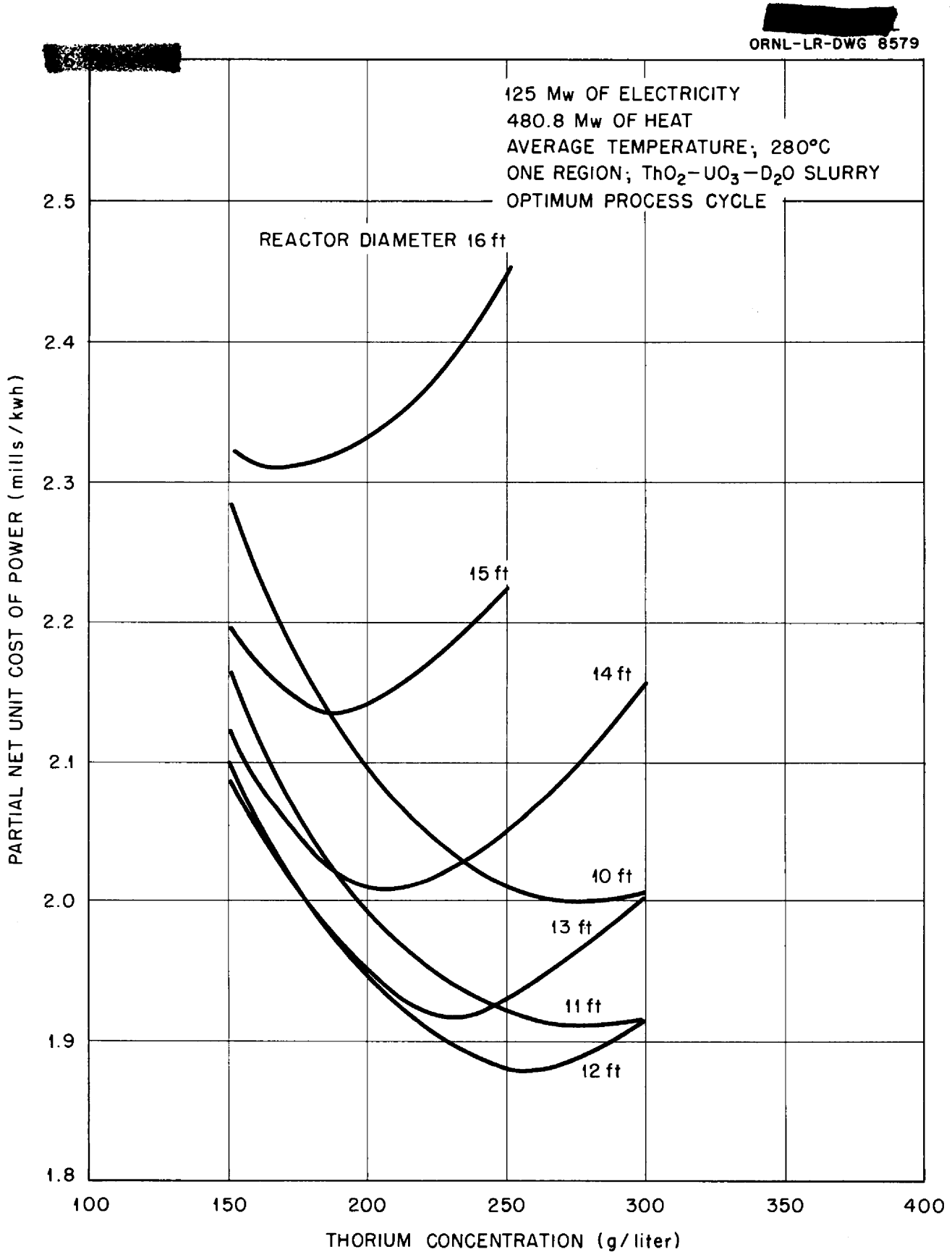

Fig. 15. Effect of Thorium Concentration on Unit Cost.

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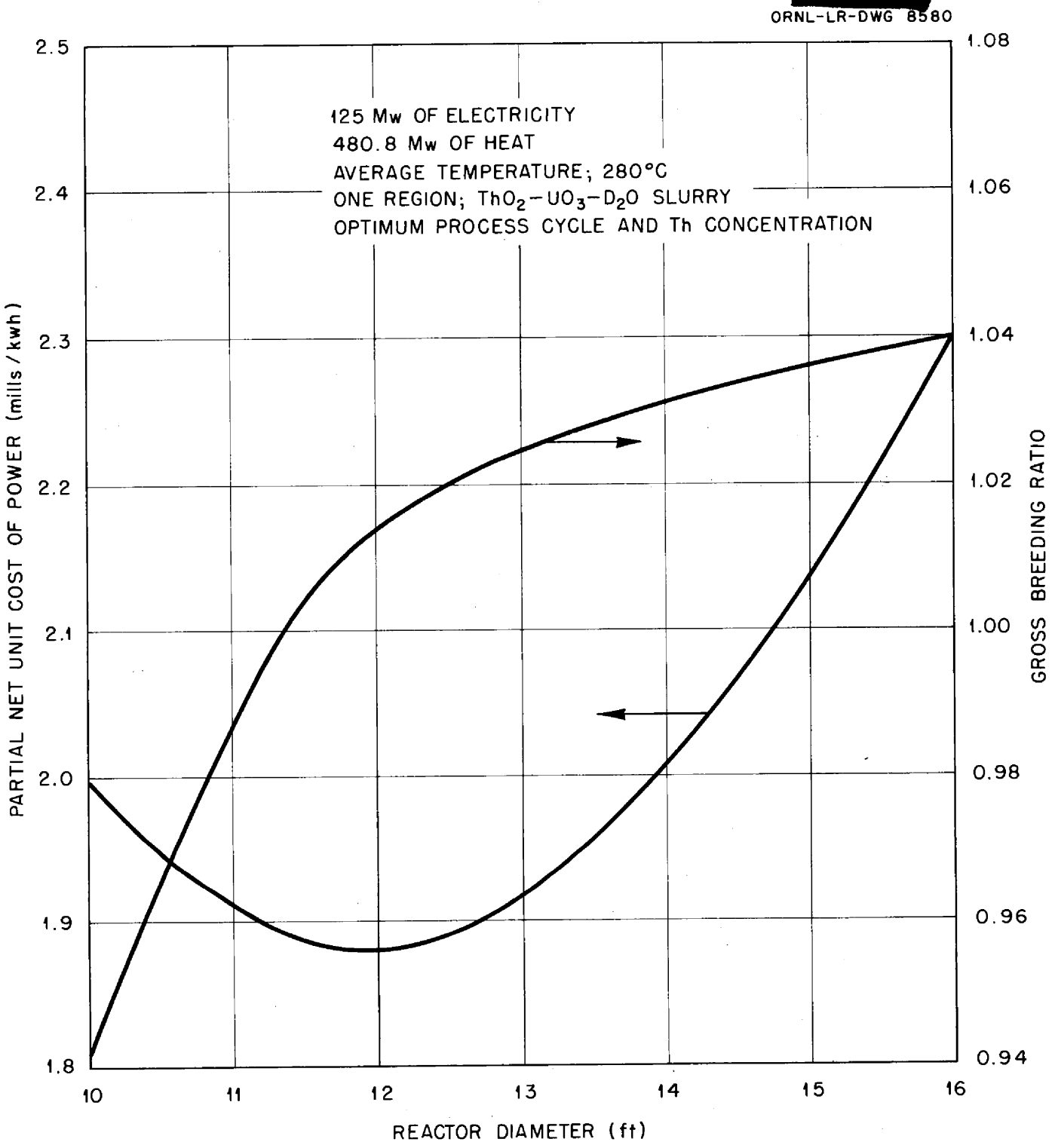

Fig. 16. Effect of Reactor Size on Unit Cost and Breeding Ratio.

NOMENCLATURE

a	Core radius, cm
B_R	Breeding gain, atoms of fissionable material produced per atom of fuel burned
B^2	Reactor buckling, cm^{-2}
B(G)	Net grams of fissionable material produced per day
C	Turbogenerator plant investment, $/kw
C_T	Total power cost, mills/kwh
C_x	Credit for excess fissionable material produced, mills/kwh
D_1	D_2 diffusion constant, cm^{-1}, for fast and slow groups, respectively
E_G	Gross efficiency of power plant
E_N	Net efficiency of power plant
f	Poison fraction
F	Net feed to reactor, atoms/sec
G(U)	Core uranium concentration grams of uranium per kg of heavy water
g	Fraction of group-3 poisons that can be precipitated
J	External power density, kw/liter
K	Power constant, 3.38×10^{16} fissions/Mw sec
N	Concentration, atoms/cm^3
p	Resonance escape probability
P	Reactor power, Mw
q	Fraction of material processed and returned to reactor
R	Inside Radius of pressure vessel, cm
t	Thickness of core vessel, cm $t = 1.39\ R \times 10^{-2}$
T	Chemical process cycle time, sec
V	Reactor or system volume, cm^3
y	Yield of group-3 fission products, 1.31 atoms/fission

β Ratio of resonance to thermal absorption

σ Microscopic cross section, cm^2

Σ Macroscopic cross section, cm^{-1}

ϕ Average neutron flux of system, neutrons/cm^2-sec

λ Decay constant, sec^{-1}

τ Fermi age, cm^2

Subscripts:

a Total capture

B Blanket

c Core

f Fission capture

r Radiative capture

T Total system

1 Hydraulic separator processing

2 Thorex processing

3 Group-3 poisons

Parenthetical Symbols (used to identify N, λ, σ, and Σ):

A Group-3 poison subgroup A

B Group-3 poison subgroup B

0 Precipitated poisons not removed in hydraulic separators

3 Group-3 poisons

23 U-233

24 U-234

25 U-235

26 U-236

13 Pa-233

02 Th-232

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APPENDIX I

Constants Used in the Nuclear Calculations

1. Thermal Microscopic Cross Sections at 280°C, barns. (Corrected for a Maxwell Boltzmann Distribution)

Substance	Absorption Cross Section, σ_a	Radiative Capture Cross Section, σ_r	Fission Cross Section, σ_f
Th-232	4.52	--	--
Pa-233	96.8	--	--
U-233	380.7	34.3	346.4
U-234	57.4	--	--
U-235	414.0	65.1	348.9
U-236	5.81	--	--
D_2O	1.76×10^{-3}	--	--
S	0.316	--	--
Group 3 poisons	13.1	--	--

2. Macroscopic Absorption Cross Section of Zircalloy at 280°C = 5.897×10^{-3} cm^{-1}.

3. Diffusion Constants, Ages, and Resonance Escape Probabilities at 280°C for Various Thoria-Heavy Water Slurries.

Concentration of Slurry, g Th/l	Fast Diffusion Constant, D_{1B}, cm	Slow Diffusion Constant, D_{2B}, cm	Fermi Age τ_B, cm^2	Resonance Escape Probability, p_B
500	1.73	1.19	214	0.728
750	1.53	1.18	212	0.638
1000	1.49	1.17	212	0.560
1500	1.47	1.17	207	0.435

4. Diffusion Constants, Ages, and Resonance Escape Probabilities at Various Temperatures for a Thoria-Heavy Water Slurry containing 1000 g Th/l.

Temp. °C	Fast Diffusion Constant, D_{1B}, cm	Slow Diffusion Constant, D_{2B}, cm	Fermi Age τ_B, cm^2	Resonance Escape Probability
200	1.34	0.998	168	0.590
250	1.42	1.09	190	0.575
280	1.49	1.17	212	0.560
300	1.56	1.24	234	0.547
320	1.62	1.34	260	0.530

5. Diffusion Constants and Ages for Uranyl Sulfate-Heavy Water Solutions at Various Temperatures. Resonance Escape Probability Taken as Unity for all Cases.

Temp. °C	Fast Diffusion Constant, D_{1C}, cm	Slow Diffusion Constant, D_{2C}, cm	Fermi Age τ, cm^2
200	1.46	1.05	167
250	1.57	1.14	193
280	1.67	1.23	218
300	1.76	1.30	244
320	1.87	1.40	276

6. Density of Heavy Water, Zircalloy and Thoria at Various Temperature, g/cm^2.

Temp. °C	Thoria	Zircalloy	Heavy Water, 99.84% D_2O at 2000 psi
200	9.69	6.55	0.9594
250	(all temperatures)	(all temperatures)	0.8935
280			0.8395
300			0.7959
320			0.7480