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SOME ECONOMIC AND NUCLEAR CHARACTERISTICS OF CYLINDRICAL THORIUM BREEDER REACTORS

D. C. Hamilton
P. R. Kasten

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REACTOR EXPERIMENTAL ENGINEERING DIVISION

SOME ECONOMIC AND NUCLEAR CHARACTERISTICS OF CYLINDRICAL THORIUM BREEDER REACTORS

by

D. C. Hamilton and P. R. Kasten

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SUMMARY

Nuclear and economic calculations were made for some cylindrical, two-region, thorium breeder reactors to study breeding ratios, core-wall-power density, and fuel costs as a function of reactor size for a given total power. A low power density at the core-tank wall (and low average power density) can be achieved with core tanks of small diameter (core and blanket diameters of 4 to 6 and 10 feet, respectively) for reactor lengths of 20 feet or greater. For a total reactor power of 450 Mw, the core-wall power density would be $\sim$20 kw/liter for a core diameter of four feet (20 - 30 feet long), and $\sim$10 kw/liter for a core diameter of six feet (15 - 20 feet long). The corresponding breeding ratios would be about 1.15 and 1.04, respectively. However, minimum fuel costs were associated with high core-power densities; increasing the reactor length and reducing the power density increased the inventory charge until that charge controlled the fuel cost. If inventory charges were 12%/year and D_2O cost \$40/lb, the economic penalty associated with low wall-power-density would be about 1 mill/kw-hr; if a 4% inventory charge were used and the cost of D_2O were \$28/lb, the economic penalty associated with low wall-power-density would be reduced to about 0.2 mills/kw-hr.

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INTRODUCTION

The technology of aqueous homogeneous reactors has been discussed by Briggs[1] and some economic aspects of spherical, aqueous, homogeneous, thorium breeder reactors have been presented by Claiborne and Tobias.[2] The latter study did not place any restrictions on the power density at the core-tank wall (two-region reactors); it is clear, however, since the average power density is inversely proportional to the reactor volume, that large reactor volumes are associated with low-power density at the core wall. With present metallurgical practice the maximum volume practicably attainable with a spherical pressure vessel for this application is about 25,000 liters, corresponding to a diameter of 12 feet. For the cylindrical geometry there is no such limitation in the volume attainable so it is clear that the cylindrical reactor is more attractive from the standpoint of minimizing the power density at the core-tank wall, but at the expense of larger fuel inventories.

The first objective of the present work was to determine the dimensions for cylindrical two-region, aqueous, homogeneous, thorium breeder reactors which would yield breeding ratios greater than unity and power densities at the core-tank wall compatible with permissible corrosion rates. The second objective was to determine some economic features associated with the above conditions relative to economic results obtained with no restrictions on breeding ratio and power density at the wall.

The calculation methods and the basis for the economic evaluations used by Claiborne and Tobias[2] were used in the present work so that the results of the spherical and cylindrical studies would be comparable.

The calculations were made in two stages: First, a simplified nuclear analysis was made in which the reactor volumes contained only U^{233}, ThO_2, D_2O and poisons; and second, from these results four of the reactors were analysed in a more complete manner.

The three principal parts of this report are the description of the system analysed, the calculation methods, and the results.

NOMENCLATURE

A	neutron absorption rate (neutrons/sec)
B.R.	breeding ratio = $\frac{\text{rate of production of (U-233 + U-235)}}{\text{rate of burn up of (U-233 + U-235)}}$
C	critical concentration (gms 23/kg D_2O); also amortization unit cost (mills/kw-hr)
CP	chemical processing unit cost (mills/kw-hr)
f	poison fraction - ratio of macroscopic poison cross section, also indicates total fission cross section ($\Sigma(f)$)
F	feed unit cost (mills/kw-hr)
g	fraction of Group 3 poisons that can be precipitated(0.75)
H	reactor height (feet)
I	inventory unit cost (mills/kw-hr)
K	power constant = 3.38×10^{16} fissions/Mw sec.
L	neutron leakage (neutron/sec)
	(EL - end leakage)
	(RL - radial leakage)
P	reactor power (Mw)
q	fraction of blanket uranium production that is returned to reactor as feed to the core
R	reactor radius (feet)
T	Thorex chemical processing cycle time (the volumetric rate at which the core and blanket systems are withdrawn for chemical processing are $\frac{V_{cT}}{T_c}$ and $\frac{V_{bT}}{T_b}$, respectively) (T in days)
T^*	hydroclone cycle time (days)
V	volume (liters)
W	blanket uranium concentration (gms 23/kg 02)
y	yield of Group 3 poisons (1.31 atoms/fission)

β	ratio of resonance to thermal absorptions in thorium
σ	miscroscopic cross section (barns)
Σ	macroscopic cross section (cm^{-1})
ϕ	average flux (neutrons/sec cm^2)
λ	decay constant (sec^{-1})

Subscripts

0	fast neutron group
1	slow or thermal neutron group
b	blanket
be	blanket external volume
bT	blanket total volume bT = b + be
c	core
ce	core external volume
cT	core total volume cT = c + ce
r	radiative capture
R	reactor
T	Total

DESCRIPTION OF SYSTEM ANALYSED

Power Station:

For the purposes of the economic studies the reactors analysed were considered to be one of the units in a three-reactor power station having a common fuel processing plant and turbo-generator plant. The thermodynamic characteristics and the unit capital costs taken from Table 12 of ORNL 1642[1] are given in Table I.

TABLE 1

SOME THERMODYNAMIC AND ECONOMIC CHARACTERISTICS OF REACTOR PLANT

Heat output, per reactor, (Mw)	450
Reactor pressure (psia)	2000
Reactor mean temperature (^{o}C)	300
Steam pressure (psia)	560
Steam temperature (^{o}F)	478
Gross plant efficiency, E_G(%)	30.7
Net station efficiency, E_N(%)	27.4
Net station electrical capacity (Mw)	370
Reactor unit cost, C_R ($/ kw of heat)	13.33
Turbogenerator plant unit cost, C_p ($/ kw of gross electrical capacity)	116.00

Fuel Cycle:

The schematic flow sheet for the reactor is shown in Figure 1. Thorium is fed to the blanket system as a ThO_2 - D_2O slurry and part of the uranium produced in the blanket is fed to the core system as a UO_2SO_4 - D_2O solution.

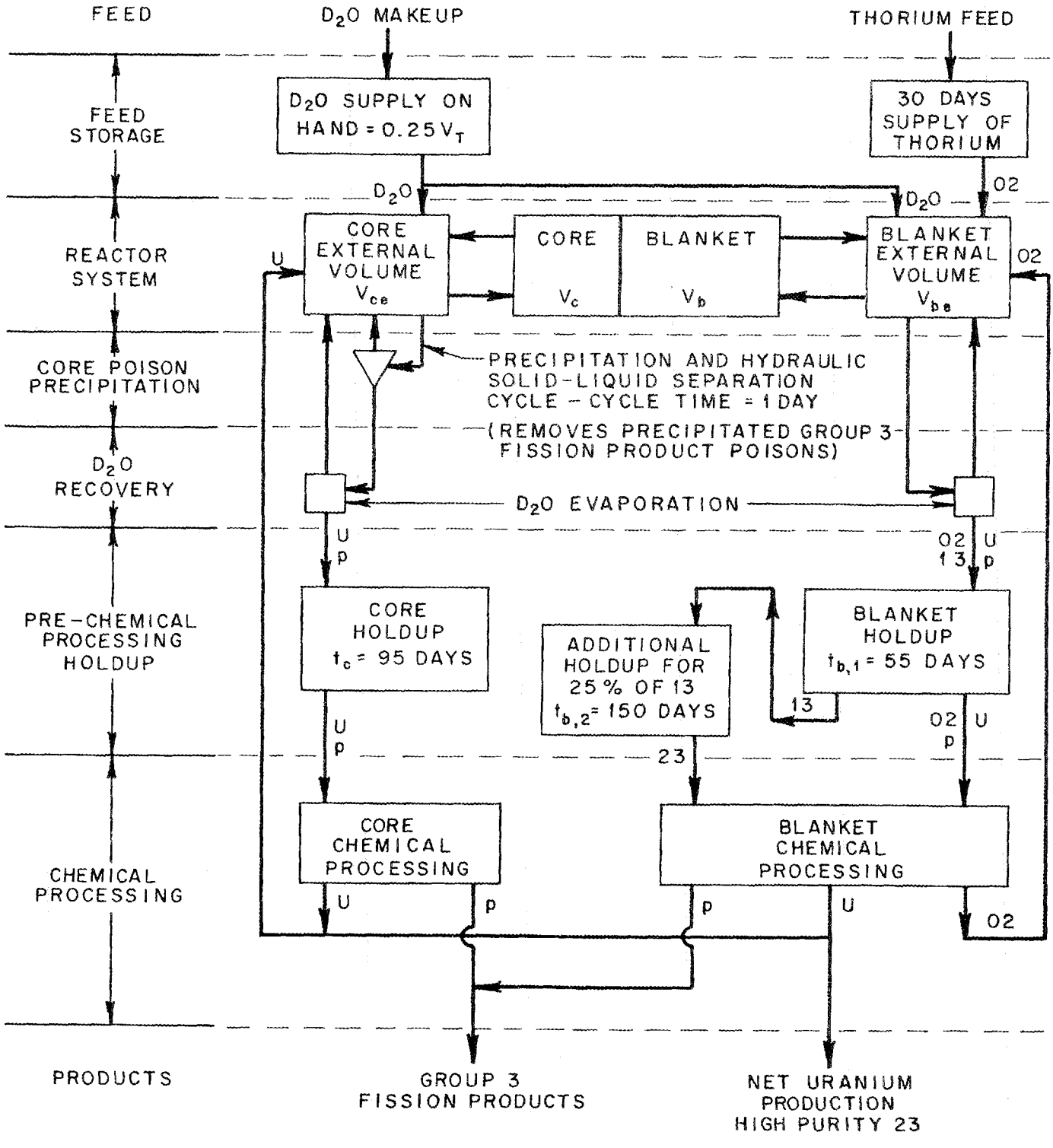

Fig. 1. Schematic Flow Sheet for a Two-Region Homogeneous Thorium Breeder Reactor.

[redacted]

The volume of the core system external to the core proper was calculated on the basis of 50 liters per Mw of core power; the blanket external volume was based on 71.4 liters per Mw of blanket power.

The core fuel material is processed by two stages, in series; the first is a stage employing poison precipitation with subsequent solid-liquid separation (hydroclone cycle) and the second is the Thorex plant. The first stage is capable of removing three-fourths of the Group 3 poisons. (Group 3 poisons are those poison products which transmute by decay or neutron capture to other low cross-section nuclides.) The Thorex plant removes all the poisons but at a much slower rate than the hydroclone cycle. Before the spent fuel is sent to the Thorex plant the D_2O is recovered by evaporation and the material is stored in the core holdup for 95 days. Since the blanket material is a slurry the processing would be done entirely by the Thorex plant. The blanket holdup is 55 days and the remaining protactinium, assumed to be 25 per cent of the original quantity, is held up for an additional 150 days, at which time it is assumed to have decayed entirely to U^{233}. The holdup during chemical processing is considered negligible for inventory purposes. It was assumed that the excess D_2O supply on hand was equal to one-fourth the total reactor volume and that a 30-day supply of thorium was on hand.

Steady-state conditions were assumed throughout the reactor system. Therefore, the blanket chemical processing rate, corresponding to a cycle time, would be the rate of removal which maintained a constant uranium concentration in the blanket. The core chemical processing cycle time was set by the arbitrary choice of the permissible poison level in the core, usually taken as about 6 per cent.

Reactor:

The cylindrical reactor considered consisted of a core of radius, R_1(feet), and height, H (feet), surrounded by a blanket of radius, 5 (feet), and height, H (feet). The ends of the reactor were considered to be bare. The reactor mean temperature and the blanket thorium concentration were taken as 300°C and 1000 grams Th per liter, respectively. The values of the major parameters in the study were as follows:

Core Radius (feet)	- 2 and 3
Height (feet)	- 9, 19, 29, and 39
Blanket Uranium Concentration $\left(\text{gms } U^{233}/\text{kg } Th^{232}\right)$	- 1, 3 and 5

CALCULATION METHODS

The calculations performed may be divided into four parts, the first three of which are interrelated:

(1) calculation of chemical processing cycle time

(2) calculation of uranium isotope concentration

(3) two-group nuclear calculations

(4) unit cost calculations

The nuclear calculations were done on the ORACLE and the other three parts were done by hand calculations. Two types of calculations were made, termed regular and simplified. All of the reactors were first analysed using the simplified calculations and then four reactors of particular interest were chosen and calculated in more detail. The

principal difference in the methods was that in the regular calculations the uranium was considered to be composed of the 233, 234, 235, and 236 isotopes, while in the simplified calculation it was assumed that only the 233 isotope of uranium was present.

Chemical Processing Cycle Times:

The fission product poisons were treated in the same manner as in ORNL 1810 by dividing the poisons into three groups as follows:

Group 1 - noble gases

Group 2 - high cross-section nuclides

Group 3 - low cross-section nuclides which transmute by decay or neutron capture to other low cross-section nuclides.

Only Group 3 poisons are affected by the chemical processing rates required for homogeneous reactors. The poison fractions for Group 1 and Group 2 are about 0.005 and 0.008, respectively (if gases are removed from reactor). The yield, y, of Group 3 poisons is 1.31 atoms per fission.

For the core solution the Group 3 poisons are removed by two methods, in series: first the poison precipitation with subsequent liquid-solid separation (hydroclone cycle), and second, Thorex. The precipitation step is capable of removing only part (0.75) of the Group 3 poisons, which are designated as subgroup 3A. Some of the subgroup 3A poisons, designated as sub-subgroup 03A, are not removed by the hydroclone. The equilibrium equations for the core poisons are thus (neglecting poison burnup):

$$\sigma(3)\ g\ y\ V_c\ \phi_c = \frac{\left(f_c(3A) - f_c\ (03A)\right)\ V_{cT}}{T_c^*} + \frac{f_c(03A)\ V_{cT}}{T_c} \qquad (1)$$

$$\sigma(3)\ (1 - g)\ y\ V_c\ \phi_c = \frac{\left[f_c(3) - f_c(3A)\right]}{T_c}\ V_{cT} \tag{2}$$

T_c is obtained from the above equations as:

$$T_c = C_1\ T_c^*\left[N - 1 + \sqrt{(N - 1)^2 + C_2\ N}\right] \tag{3}$$

where $C_1 = \dfrac{g}{2\ (1 - g)} = 1.5$

$$C_2 = \frac{4(1 - g)\ \ f_c(03A)}{g\left[f_c(p) - f(1) - f(2) - f_c(03A)\right]} = \frac{0.04}{3\left[f_c(p) - 0.023\right]}$$

and $$N = \frac{V_{cT}\ \left[f(p) - f(1) - f(2) - f(03A)\right]}{y\ g\ \sigma(3)\ V_c\ \phi_c\ T_c^*} = \frac{V_{cT}\ \left[f(p) - 0.023\right]}{y\ g\ \sigma(3)\ V_c\ \phi_c\ T_c^*}$$

The recommended value for $f_c(03A)$ was 0.01. In ORNL 1810 it was determined that, for the range, $0.04 < f_c(p) < 0.10$, the unit cost was virtually unaffected by $f_c(p)$, with the optimum at about 0.06. That value was used in the present study. A hydroclone cycle time, T_c^*, of one day was used throughout this study.

Since the blanket material is a slurry the hydroclone cycle cannot be used and the equilibrium equation for the poison involves only the Thorex cycle time, T_b. T_b is evaluated from the equation (neglecting poison burnup).

$$y\ \sigma(3)\ V_b\ \phi_b = \frac{f_b(3)\ V_bT}{T_b} \tag{4}$$

and so $$T_b = \frac{\left[f_b(p) - 0.013\right]\ V_{bT}}{y\sigma(3)\ V_b\ \phi_b} \tag{5}$$

[redacted]

Isotope Equations:

The core was assumed to contain the uranium isotopes 233, 234, 235, and 236; the blanket contained the same uranium isotopes and, in addition, contained Pa-233 and Th-232. The concentrations of Th^{233} and Pa^{234} were considered negligible due to their short half lives. At equilibrium conditions the isotope balance equations for the blanket are (neglecting chemical processing losses):

$$(1 + \beta)\ \Sigma_b(02) = \left[1 + Q_b\ (1 + \lambda(13)\ T_b)\right]\ \Sigma_b(13) \tag{6}$$

where $$Q_b = \frac{V_{bT}}{V_b\ \phi_b\ \sigma(13)\ T_b} \tag{7}$$

$$\lambda\ (13)\ T_b\ Q_b\ \Sigma_b(13) = \left[1 + \frac{\sigma(13)}{\sigma(23)}\ Q_b\right]\ \Sigma_b(23) \tag{8}$$

$$\Sigma_b(13) + \frac{\sigma_r(23)}{\sigma(23)}\ \Sigma_b(23) = \left[1 + \frac{\sigma(13)}{\sigma(24)}\ Q_b\right]\ \Sigma_b(24) \tag{9}$$

$$\Sigma_b(24) = \left[1 + \frac{\sigma(13)}{\sigma(25)}\ Q_b\right]\ \Sigma_b(25) \tag{10}$$

$$\frac{\sigma_r(25)}{\sigma(25)}\ \Sigma_b(25) = \left[1 + \frac{\sigma(13)}{\sigma(26)}\ Q_b\right]\ \Sigma_b(26) \tag{11}$$

$$V_b\ \phi_b = \frac{K\ P_b}{\Sigma_b(f)} \tag{12}$$

To aid in writing the equations for the core, let

$$Q_c = \frac{q\ V_{bT}}{V_c\ \phi_c\ \sigma(13)\ T_b} \tag{13}$$

where q is the fraction of uranium from the blanket Thorex plant returned to the reactor as feed for the core.

[redacted]

Again neglecting chemical processing losses and assuming that the breeding ratio ≥ 1, the corresponding equations for the core are given below:

$$\Sigma_c(23) = \left[\frac{\sigma(13)}{\sigma(23)} \Sigma_b(23) + \Sigma_b(13)\right] Q_c \tag{14}$$

$$\Sigma_c(24) = \frac{\sigma_r(23)}{\sigma(23)} \Sigma_c(23) + \frac{\sigma(13)}{\sigma(24)} Q_c \Sigma_b(24) \tag{15}$$

$$\Sigma_c(25) = \Sigma_c(24) + \frac{\sigma(13)}{\sigma(25)} Q_c \Sigma_b(25) \tag{16}$$

$$\Sigma_c(26) = \frac{\sigma_r(25)}{\sigma(25)} \Sigma_c(25) + \frac{\sigma(13)}{\sigma(26)} Q_c \Sigma_b(26) \tag{17}$$

Nuclear Calculations:

The critical concentration and neutron balance were obtained using a two-group code[3] which employed a "thin shell" approximation to account for the neutron absorption in the zirconium core tank. The nuclear properties used are given in Appendix I. The code used does not contain provisions for an extrapolation distance. (This was provided for by adding one foot to the diameter and height dimensions used in the code.) The result of this deficiency in the code was to cause the neutron leakages, core and blanket volumes, and total neutron production and absorptions to be too large. However, the influence on the calculated leakage was minor; the correct volumes were easily computed; and the error in the productions and absorptions was estimated to be no more than 3% (obtained by integration of flux distribution data that were available from a comparable spherical reactor). The omission of the reflector, or blanket from the ends of the reactor caused the leakages and breeding ratio to be conservative.

Unit Cost Estimation:

The total unit cost of electricity may be divided into two parts, the total fixed charges and the total variable fuel costs. The total fixed charges were assumed to be about 5.4 mills/kw-hr for all reactors considered in the present study. (The total power and operating temperature are the major variables which influence total fixed charge and in this study power and temperature were considered constant.) However, fuel costs were sensitive to the parameters varied in this report.

Fixed Charges -

The fixed charges consist of amortization charges on reactor and turbogenerator plant, the operation and maintenance charges, and the fixed charges on the chemical processing plant. The amortization charges, $\mathcal{F}$, may be computed from Equation (18) using the data from Table I. The values used for plant factor, e, and annual amortization rate, $\mathcal{R}$, were 0.8 and 0.15, respectively. The remaining symbols in Equation (18) are defined in Table I.

$$\mathcal{F} = \mathcal{R} \left[\frac{C_R + E_G C_p}{8760 \; e \; E_N} \right] \qquad (18)$$

The annual operation and maintenance charge was taken as 3% of the total reactor and turbogenerator plant investment. Chemical processing fixed charges, per reactor, were taken as $70 per day for the poison precipitation and hydraulic separation plant and $1830 per day for the Thorex plant.

On the above bases, the total fixed charges given in Table 2 were obtained.

TABLE 2

TOTAL FIXED CHARGES

Reactor and Power Station Amortization Charges	3.82 mills/kw-hr
Operation and Maintenance	0.77
Chemical Processing Plant Fixed Charges	0.80
Total Fixed Charges	5.39

Cost Factors and Variable Fuel Costs -

The variable fuel costs are composed of critical materials inventory charges, variable chemical processing charges and feed costs. The net feed costs may be negative since the value of the net uranium produced may be greater than the gross feed costs.

An annual inventory charge of 12% was assessed against all U-233, U-235, Th-232, D_2O (and Pa-233 when outside the reactor). Fissionable materials were valued at 20 dollars per gram. Thorium and D_2O were valued at 5 and 40 dollars per pound, respectively. The holdup times before chemical processing are shown in Figure 1 and are given in Table 3.

TABLE 3

HOLDUP TIMES OF REACTOR MATERIALS
BEFORE CHEMICAL PROCESSING

Material	Holdup Time
Core material	95 days
Blanket Material	
Th + U + 75% of Pa	55 days
25% of Pa	205 days

It was assumed that a 30-day supply of Thorium feed was on hand. An amount of D_2O equal to 25% of the total reactor system volume was also assumed to be in storage.

The variable chemical processing costs were assumed to be 0.3 and 50 cents per gram for Thorium and fissionable isotopes (23, 25, and 13), respectively. These are the same costs used in ORNL-1810. More recent information bases the cost on total uranium processed, rather than on fissionable isotopes processed. The older method was used here since it was desired to use the cost factor of ORNL-1810 as much as possible so that the results for the two geometries (spherical and cylindrical) would be comparable; also, the variable chemical processing costs were relatively minor costs in the present study. Other cost factors included uranium losses, which were considered to be 0.1% of the amount processed. A charge of 35 cents per liter was made for D_2O recovery. All the reactors analysed were breeders, so the net feed costs were usually negative. The annual D_2O makeup was considered to be 5% of the reactor volume.

RESULTS AND DISCUSSION

The characteristics of the reactors studied are given in Tables 4 and 5. The identification numbers of the reactor gives the important parameters; e. g., reactor 3-30-1 has a core radius of 3 feet, an overall height (including 6-inch extrapolation distance at each end) of 30 feet and a U-233 concentration in the blanket of 1 gram 233/kilogram of Thorium. The reactors listed in Table 4 have an S following the identification number. This means that a simplified nuclear and economic analysis was made in contrast to the more complete analysis used in the reactors of Table 5. In the simplified nuclear calculations the core region was considered to contain only D_2O, $U^{233}O_2SO_4$ and 6% poisons, and the blanket region only D_2O, ThO_2 and $U^{233}O_2$. The Th^{233} formed was assumed to decay instantly to U^{233}. In the complete nuclear analysis (see Table 5 for results) the U^{233}, U^{234}, U^{235}, and U^{236} isotopes of uranium were considered as well as the formation of Pa^{233}. From these latter calculations, it was found that the inventory charge due to the holdup required for Pa^{233} decay, was between 0.2 and 1.6 as great as the U^{233} holdup inventory charge if there were no Pa^{233} present. Since this term did not control the fuel cost, an average value of 0.4 was used. Thus, the blanket U^{233} holdup inventory charge for the "simplified reactors" was multiplied by 1.4 to account for the influence of Pa^{233} upon holdup time.

The calculated results are given in Tables 4 and 5. These consist of nuclear results based on 2-group, 2-region critical calculations, and economic results based on the assumed cost factors given previously. The results in Table 5 are based on nuclear calculations which considered the

important isotope equations, and are more accurate than those given in Table 4. However, the more exact calculations indicate that the economic results given in Table 4 are adequate, and that the breeding ratios given there were too large by approximately 0.03.

The results are also presented in Figures 2 - 7. Fig. 2 gives the variation of the maximum power density at the core tank wall (core side) as a function of reactor length, core radius, and blanket fuel concentration. The results indicate that the maximum wall-power-density can be appreciably decreased by increasing the reactor length from 10 to 20 feet but that this effect becomes smaller for lengths greater than 20 feet. A more effective way to decrease wall-power-density would be to increase the core radius from 2 feet to 3 feet.

Together with a low wall-power-density, another desirable reactor feature would be a high breeding ratio. The effect of reactor length, core diameter, and blanket composition upon breeding ratio is indicated in Fig. 3; as shown, the breeding ratio increased with increasing reactor length and increasing blanket fuel concentration, but decreased with increasing core radius. Thus, it does not appear possible to optimize wall-power-density and breeding ratio independently.

A third feature was the fuel cost associated with a particular reactor. Fig. 4 gives the unit fuel cost as a function of reactor length, core diameter, and blanket fuel concentration. The fuel cost consisted of the inventory charge, fuel processing cost, and net feed cost; as shown in Fig. 4, the inventory charge becomes dominant as the reactor length and/or the blanket fuel concentration is increased. The importance of the inventory charge is also indicated in Fig. 5, where the total variable fuel cost is given in terms of reactor parameters.

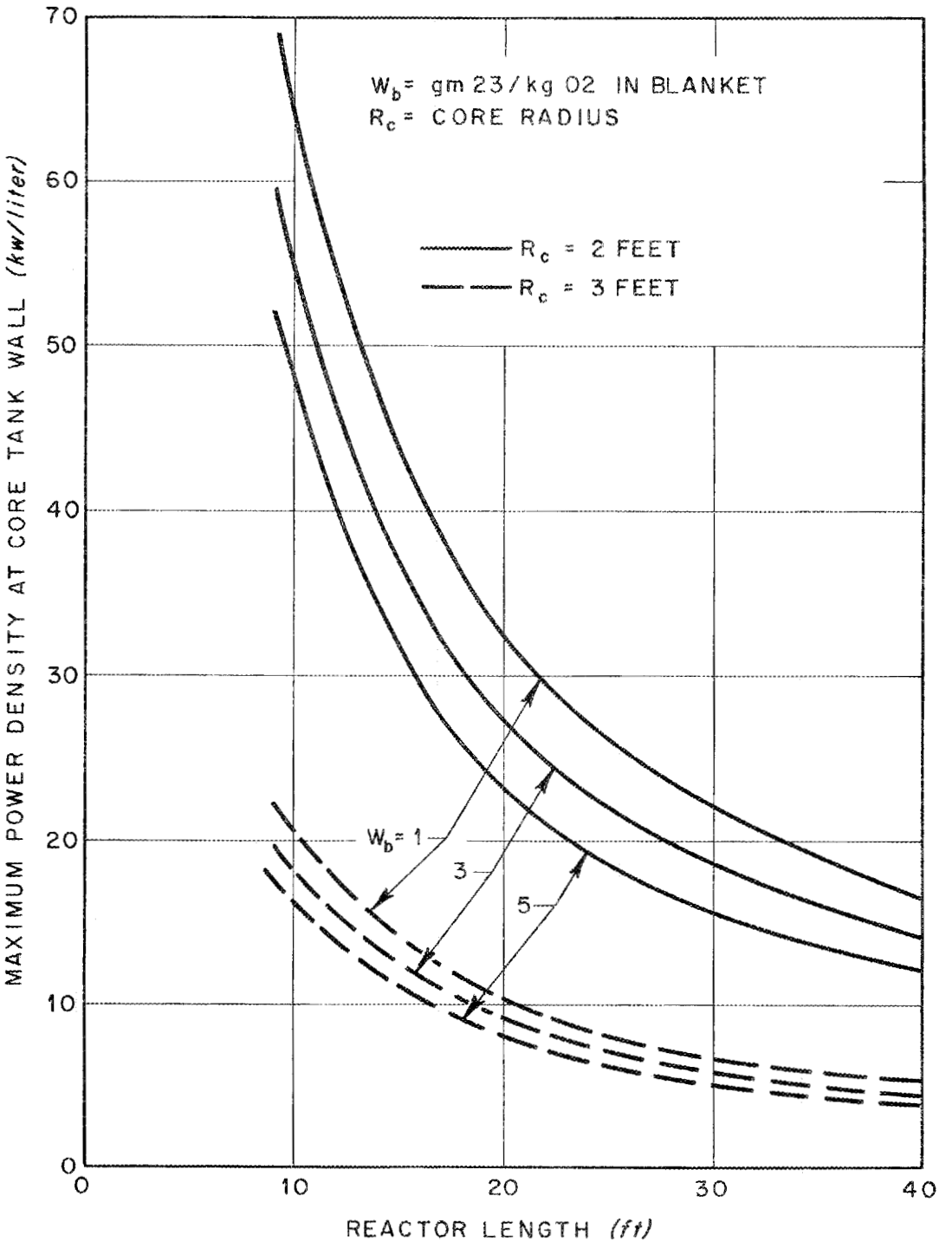

Fig. 2. Maximum Power Density at Core Tank Wall (Core Side) for Simplified Cylindrical Reactors.

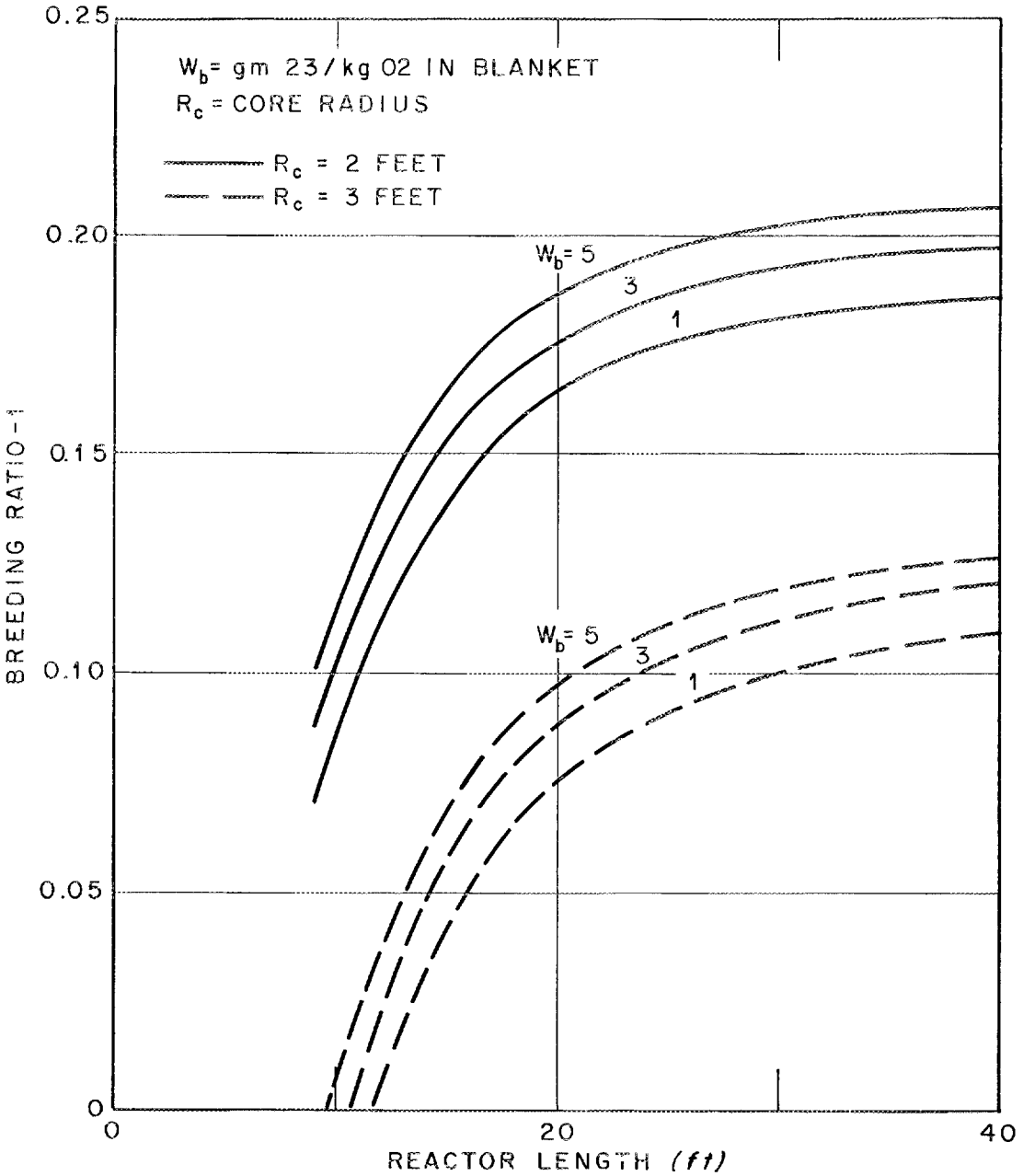

Fig. 3. Gross Breeding Ratio of Simplified Cylindrical Reactors.

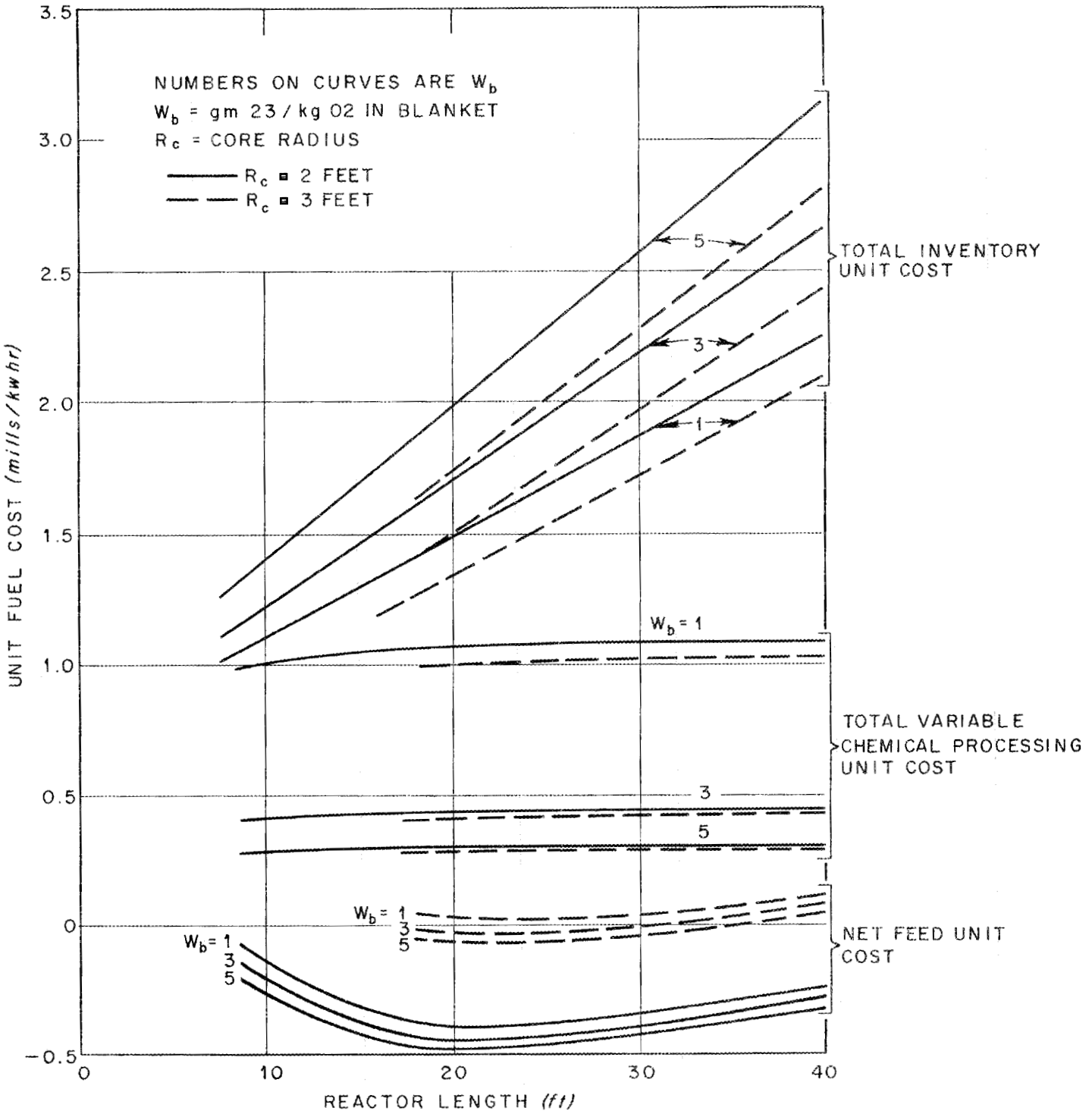

Fig. 4. Comparison of Inventory, Processing and Feed Unit Costs for Simplified Cylindrical Reactors.

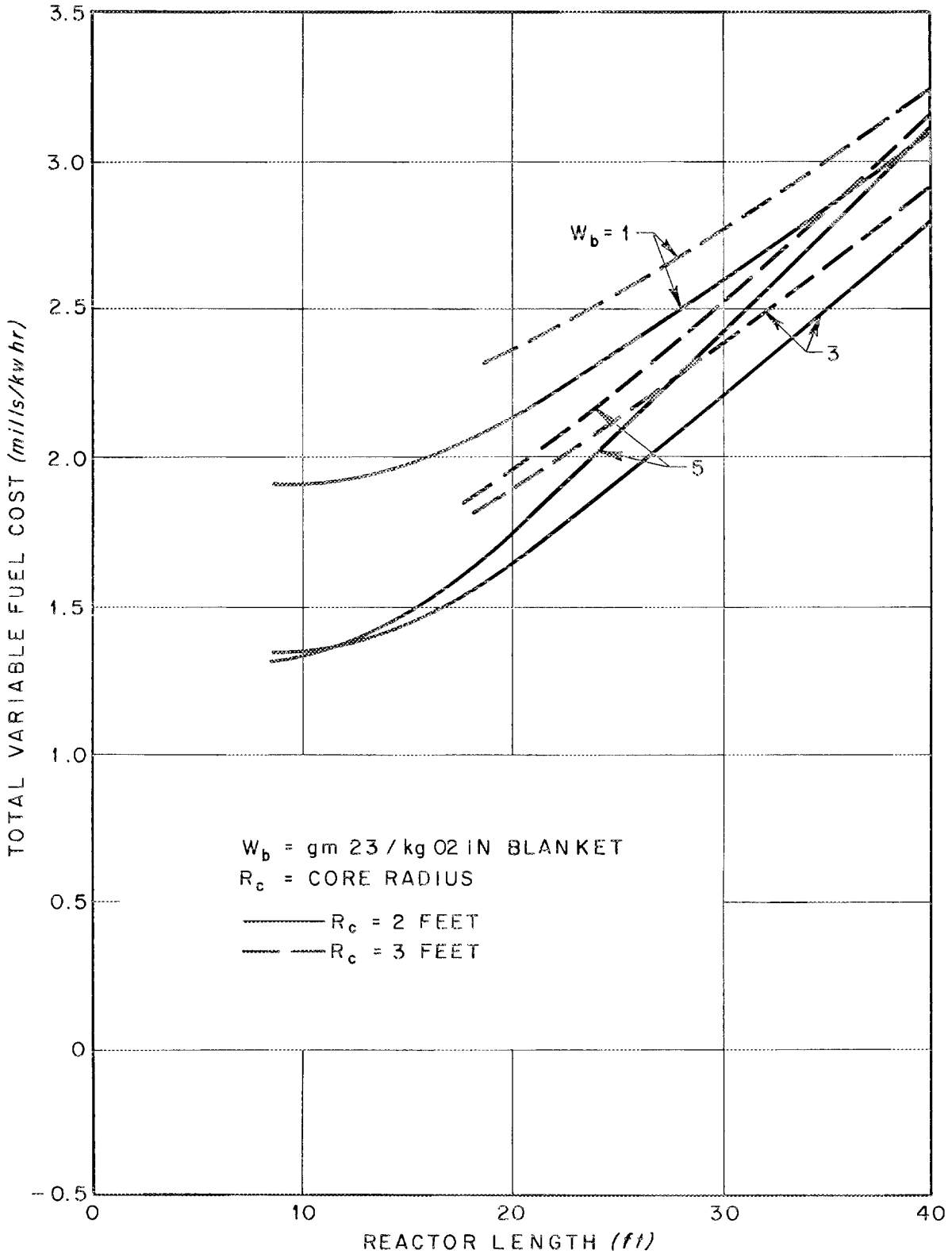

Fig. 5. Total Variable Fuel Cost for Simplified Cylindrical Reactors.

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TABLE 4A

NUCLEAR CHARACTERISTICS OF
SIMPLIFIED CYLINDRICAL REACTORS

Reactor No.	2-10-1S	2-10-3S	2-10-5S	2-20-1S	2-20-3S
R_c (feet)	2	2	2	2	2
H (feet)	9	9	9	19	19
W_b(gms 23/kg 02)	1	3	5	1	3
B.R.	1.07238	1.08814	1.10095	1.16185	1.17433
C_c (gms 23/kg D_2O)	2.66068	2.51846	2.37807	2.39711	2.25612
f_c (p)	.061643	.061681	.061717	.061780	.061820
β (02)	.270805	.39073	.512363	.258602	.380209
P_b/P_T	.071114	.197811	.30674	.077794	.215107
V_c (liters)	3,200	3,200	3,200	6,760	6,760
V_{cT} (liters)	24,100	21,250	18,800	27,510	24,420
V_b (liters)	16,810	16,810	16,810	35,490	35,490
V_{bT} (liters)	19,100	23,170	26,670	37,990	42,410
Neutron Balance					
Leakages*					
$E\ L_{0,c}$	.209378	.219334	.230214	.0524821	.0552462
$E\ L_{1,c}$	.28848	.305828	.324898	.0787626	.0839626
$E\ L_{0,b}$	.0577061	.0897029	.127031	.0149355	.023859
$E\ L_{1,b}$	.0444193	.0478558	.0516827	.0120391	.013081
$R\ L_{0,b}$	.0097742	.0256112	.0501421	.0107023	.0288689
$R\ L_{1,b}$	.0036317	.0068185	.0107675	.0039842	.0076871
Absorptions					
$A_{1,b}$	4.22429	5.2562	6.438	4.57969	5.74695
$A_{0,b}$	1.05156	1.63463	2.31487	1.08866	1.73911
A (shell)	.18583	.197085	.209498	.202297	.21591
$A_{1,c}$	4.60056	4.62157	4.64163	4.53645	4.55759
Productions					
Core	9.91647	9.95087	9.98207	9.75698	9.78939
Blanket	.75919	2.45378	4.41666	.823063	2.68287
Total	10.67566	12.40465	14.39873	10.580043	12.47226
Ave. core power density (kw/l.)	130.54	112.74	97.43	61.38	52.24
Max. core tank power density	69	89.4	138	33.8	48.4
Max. core tank power density (core side)	69	59.5	52	33.8	28.8
Ave. core thermal flux $x10^{-15}$	2.3698	2.1622	1.9789	1.2368	1.1184

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TABLE 4A (Cont'd)

NUCLEAR CHARACTERISTICS OF
SIMPLIFIED CYLINDRICAL REACTORS

Reactor	2-20-5S	3-20-1S	3-20-3S	3-20-5S	2-30-1S
R_c (feet)	2	3	3	3	2
H (feet)	19	19	19	19	29
W_b (gms 23/kg 02)	5	1	3	5	1
B.R.	1.18393	1.07103	1.08418	1.09365	1.17969
C_c (gms 23/kg D_2O)	2.11647	1.02238	0.978246	0.932842	2.3497
f_c (p)	.061856	.062432	.062448	.062463	.061806
β (02)	.503657	.164871	.284643	.405158	.25636
P_b/P_T	.33177	.077484	.213368	.327954	.07913
V_c (liters)	6,760	15,210	15,210	15,210	10,320
V_{cT} (liters)	21,800	35,970	32,910	30,330	31,040
V_b (liters)	35,490	27,040	27,040	27,040	54,180
V_{bT} (liters)	46,160	29,530	33,900	37,580	56,720
Neutron Balance					
Leakages*					
$E\ L_{0,c}$	.0583121	.108076	.114963	.12271	.0233376
$E\ L_{1,c}$	.0897661	.344362	.364717	.387713	.0355983
$E\ L_{0,b}$	.0344555	.0176795	.0332964	.0518609	.0066828
$E\ L_{1,b}$	.0142605	.022353	.0243841	.0266826	.005434
$R\ L_{0,b}$	.0576304	.0743313	.192746	.356324	.0108881
$R\ L_{1,b}$	.0123757	.0327656	.0541141	.0782364	.0040548
Absorptions					
$A_{1,b}$	7.10559	8.50309	10.7128	13.2951	4.65098
$A_{0,b}$	2.5115	1.28868	2.42701	3.78019	1.09602
A (shell)	.231156	.630424	.678701	.733525	.205601
$A_{1,c}$	4.57781	8.70079	8.83626	8.9791	4.5247
Productions					
Core	9.81821	18.1943	18.4378	18.6906	9.72746
Blanket	4.87465	1.52817	5.00111	9.12089	.835875
Total	14.69286	19.72247	23.43891	27.81149	10.563335
Ave. core power density (kw/l.)	44.48	27.29	23.27	19.88	40.16
Max.core tank power density	74.5	13.2	35.9	54.5	22.5
Max. core tank power density (core side)	24.5	10.7	9.28	8.06	22.5
Ave. core thermal flux $x10^{-15}$	1.015	1.2892	1.149	1.0296	0.8254

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TABLE 4A (Cont'd)

NUCLEAR CHARACTERISTICS OF
SIMPLIFIED CYLINDRICAL REACTORS

Reactor No.	2-30-3S	3-30-1S	3-30-3S	3-30-5S	2-40-1S
R_c (feet)	2	3	3	3	2
H (feet)	29	29	29	29	39
W_b (gms 23/kg 02)	3	1	3	5	1
B.R.	1.19139	1.09879	1.10997	1.11765	1.18604
C_c (gms 23/kg D_2O)	2.20929	0.990814	0.946727	0.901332	2.33373
f_c (p)	.061844	.0624533	.062469	.062484	.061814
β (02)	.378285	.162608	.28272	.403584	.255575
P_b/P_T	.218536	.079647	.21877	.335526	.079606
V_c (liters)	10,320	23,220	23,220	23,220	13,880
V_{cT} (liters)	27,900	43,930	40,800	38,170	34,590
V_b (liters)	54,180	41,280	41,280	41,280	72,860
V_{bT} (liters)	61,200	43,840	48,310	52,060	75,420
Neutron Balance					
Leakages*					
$E\ L_{0,c}$	.0245911	.0480685	.0512187	.0547764	.0131299
$E\ L_{1,c}$	.0379912	.157397	.166948	.177779	.0201428
$E\ L_{0,b}$	.0107327	.007958	.0151254	.0236828	.003768
$E\ L_{1,b}$	.0059142	.0102017	.0111522	.0122323	.0030733
$R\ L_{0,b}$	.0295353	.0759416	.198527	.368677	.0109542
$R\ L_{1,b}$	.0078648	.0335651	.0557586	.0809551	.00408
Absorptions					
$A_{1,b}$	5.84625	8.73166	11.024	13.7138	4.67637
$A_{0,b}$	1.76021	1.30516	2.48064	3.88409	1.09863
A (shell)	.219716	.647866	.698706	.756668	.206779
$A_{1,c}$	4.54588	8.68494	8.82217	8.96718	4.5206
Productions					
Core	9.75947	18.1334	18.3778	18.6318	9.71712
Blanket	2.72923	1.56925	5.1464	9.40811	.840439
Total	12.4887	19.70265	23.5242	28.03991	10.557559
Ave. core power density (kw/l.)	34.08	17.84	15.14	12.88	29.85
Max. core tank power density	32.6	9.06	24.5	37.1	16.8
Max. core tank power density (core side)	19	7.1	6.1	5.3	16.8
Ave. core thermal flux $x10^{-15}$	0.7451	0.86958	0.77247	0.69011	0.61772

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TABLE 4A (Cont'd)

NUCLEAR CHARACTERISTICS OF
SIMPLIFIED CYLINDRICAL REACTORS

Reactor No.	2-40-3S	2-40-5S	3-40-1S	3-40-3S	3-40-5S
R_c (feet)	2	2	3	3	3
H (feet)	39	39	39	39	39
W_b (gms 23/kg 02)	3	5	1	3	5
B.R.	1.19745	1.20602	1.10881	1.11924	1.12624
C_c (gms 23/kg D_2O)	2.19303	2.05355	0.979853	0.935784	0.890391
f_c (p)	.061853	.061891	.062461	.062476	.062491
β (02)	.377617	.501539	.161816	.282048	.403036
P_b/P_T	.219754	.338437	.080428	.220713	.338239
V_c (liters)	13,880	13,880	31,240	31,240	31,240
V_{cT} (liters)	31,430	28,760	51,930	48,780	46,130
V_b (liters)	72,860	72,860	55,510	55,510	55,510
V_{bT} (liters)	79,920	83,730	58,100	62,600	66,380
Neutron Balance					
Leakages*					
$E\ L_{0,c}$	.01384	.0146308	.0270455	.0288358	.0308604
$E\ L_{1,c}$	.0215054	.0230324	.0894214	.0948978	.101117
$E\ L_{0,b}$	.0060629	.0088012	.0044967	.0085747	.0134511
$E\ L_{1,b}$	.0033469	.003658	.0057928	.0063373	.006957
$R\ L_{0,b}$	.0297737	.059742	.0765225	.200624	.373172
$R\ L_{1,b}$	.0079283	.0128292	.0338539	.0563551	.0819443
Absorptions					
$A_{1,b}$	5.88168	7.29079	8.81436	11.1369	13.866
$A_{0,b}$	1.76775	2.56612	1.3111	2.50009	3.92187
A (shell)	.221074	.237152	.654178	.70596	.765081
$A_{1,c}$	4.54179	4.56207	8.67953	8.8174	8.9632
Productions					
Core	9.74899	9.77713	18.1121	18.3568	18.6112
Blanket	2.74577	5.0017	1.58412	5.19909	9.51253
Total	12.49476	14.77883	19.69622	23.55589	28.12373
Ave. core power density (kw/l.)	25.3	21.45	13.24	11.22	9.53
Max. core tank power density	24.6	37.2	6.8	18.5	28
Max. core tank power density (core side)	14.3	12.1	5.3	4.6	4
Ave. core thermal flux $x10^{-15}$	0.55727	0.50459	0.65285	0.57933	0.51702

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TABLE 4B

ECONOMIC CHARACTERISTICS OF
SIMPLIFIED CYLINDRICAL REACTORS

Reactor No.	2-10-1S	2-10-3S	2-10-5S	2-20-1S	2-20-3S
T_c	335.9	324.5	313.6	348.0	341.6
T_b	34.06	139.3	299.6	62.58	236.7
C_c	2.6607	2.5185	2.3781	2.3971	2.2561
B.R.	1.07238	1.08814	1.10095	1.16185	1.17433
I_c (D_2O)	0.32472	0.28632	0.25331	0.37067	0.32904
I_c (23)	0.18178	0.15290	0.12874	0.18552	0.15562
I_b (D_2O)	0.25735	0.31219	0.35935	0.51188	0.57143
I_b (02,23,13)	0.25116	0.35077	0.51529	0.34649	0.55006
I_T (D_2O)	0.58207	0.59851	0.61266	0.88255	0.90047
I_T	1.0150	1.1022	1.2567	1.4146	1.6062
CP_c (D_2O)	0.01061	0.00968	0.00886	0.01169	0.01057
CP_c (23)	0.03338	0.02883	0.02493	0.03312	0.02820
CP_b (D_2O)	0.08293	0.02460	0.01317	0.08979	0.02650
CP_b(02,23,13)	0.86093	0.34288	0.23049	0.93207	0.36940
CP_c	0.04398	0.03852	0.03379	0.04481	0.03877
CP_b	0.94386	0.36748	0.24366	1.0219	0.39590
CP_T	0.98784	0.40600	0.27745	1.0667	0.43467
F(D_2O)	0.24253	0.24938	0.25528	0.36773	0.37520
F (02)	0.00279	0.00283	0.00287	0.00302	0.00306
23 Credit	0.34185	0.41628	0.47679	0.76442	0.82336
Feed Total	-0.09653	-0.16407	-0.21864	-0.39366	-0.44510
Total Variable Fuel Cost	1.9063	1.3441	1.3155	2.0876	1.5958
Net Unit Cost	7.2967	6.7345	6.7059	7.4780	6.9862

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TABLE 4B (Cont'd)

ECONOMIC CHARACTERISTICS OF

SIMPLIFIED CYLINDRICAL REACTORS

Reactor No.	2-20-5S	3-20-1S	3-20-3S	3-20-5S	2-30-1S
T_c	335.9	192.8	197.9	203.7	385.9
T_b	482.9	53.07	208.4	437.5	92.03
C_c	2.1165	1.0224	0.97825	0.93284	2.3497
B.R.	1.18393	1.07103	1.08418	1.09365	1.17969
I_c (D_2O)	0.29373	0.485	0.44343	0.40867	0.41823
I_c (23)	0.13080	0.1214	0.10530	0.091691	0.20087
I_b (D_2O)	0.62196	0.39789	0.45677	0.50635	0.76424
I_b (02,23,13)	0.82345	0.29480	0.45395	0.67982	0.42998
I_T (D_2O)	0.91569	0.88300	0.90020	0.91502	1.1825
I_T	1.8699	1.2992	1.4594	1.6865	1.8134
CP_c(D_2O)	0.00959	0.02759	0.02459	0.02202	0.01189
CP_c(23)	0.02401	0.03336	0.02844	0.02429	0.03304
CP_b(D_2O)	0.01414	0.08230	0.02406	0.01270	0.09116
CP_b(02,23,13)	0.24745	0.85436	0.33540	0.22238	0.94631
CP_c	0.03361	0.06095	0.05303	0.04631	0.04494
CP_b	0.26159	0.93666	0.35946	0.23508	1.0375
CP_T	0.29520	0.99761	0.41249	0.28139	1.0824
F(D_2O)	0.38154	0.36792	0.37508	0.38126	0.49271
F(02)	0.00308	0.00279	0.00282	0.00285	0.00307
23 Credit	0.86870	0.33550	0.39758	0.44231	0.84868
Feed Total	-0.48408	0.03521	-0.02425	-0.05820	-0.35290
Total Variable Fuel Cost	1.6810	2.3320	1.8477	1.9097	2.5429
Net Unit Cost	7.0714	7.7224	7.2381	7.3001	7.9333

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TABLE 4B (Cont'd)

ECONOMIC CHARACTERISTICS OF
SIMPLIFIED CYLINDRICAL REACTORS

Reactor No.	2-30-3S	3-30-1S	3-30-3S	3-30-5S	2-40-1S
T_c	384.2	229.2	239.7	251.2	427.6
T_b	336.8	76.81	290.2	593.3	121.7
C_c	2.2093	0.99081	0.94673	0.90133	2.3337
B.R.	1.19139	1.09879	1.10997	1.11765	1.18604
$I_c(D_2O)$	0.37592	0.59191	0.54974	0.51430	0.46606
I_c (23)	0.16991	0.13607	0.11919	0.10479	0.21804
I_b (D_2O)	0.82461	0.59070	0.65093	0.70146	1.0161
I_b (02,23,13)	0.73722	0.36076	0.59885	0.90527	0.51152
I_T (D_2O)	1.2005	1.1826	1.2007	1.2158	1.4822
I_T	2.1076	1.6795	1.9187	2.2259	2.2117
$CP_c(D_2O)$	0.01074	0.02834	0.02517	0.02247	0.01196
CP_c (23)	0.02805	0.03321	0.02817	0.02395	0.03308
$CP_b(D_2O)$	0.02688	0.08441	0.02462	0.01298	0.09165
CP_b(02,23,13)	0.37468	0.87630	0.34323	0.22716	0.95143
CP_c	0.03878	0.06155	0.05334	0.04642	0.04504
CP_b	0.40156	0.96071	0.36785	0.24014	1.0431
CP_T	0.44034	1.0223	0.42119	0.28656	1.0881
$F(D_2O)$	0.50021	0.49275	0.50029	0.50658	0.61758
F(02)	0.00310	0.00286	0.00289	0.00291	0.00309
23 Credit	0.90393	0.46658	0.51939	0.55566	0.87867
Feed Total	-0.40062	0.02903	-0.01621	-0.04617	-0.25800
Total Variable Fuel Cost	2.1473	2.7308	2.3237	2.4663	3.0418
Net Unit Cost	7.5377	8.1212	7.7141	7.8567	8.4322

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TABLE 4B (Cont'd)

ECONOMIC CHARACTERISTICS OF

SIMPLIFIED CYLINDRICAL REACTORS

Reactor No.	2-40-3S	2-40-5S	3-40-1S	3-40-3S	3-40-5S
T_c	430.7	435.2	268.6	284.6	301.7
T_b	437.6	860.5	100.9	373.0	751.0
T_c	2.1930	2.0536	0.9798	0.9358	0.8904
B.R.	1.19745	1.20602	1.10881	1.11924	1.12624
$I_c(D_2O)$	0.42349	0.38751	0.69970	0.65726	0.62156
$I_c(23)$	0.18593	0.15902	0.15222	0.13456	0.11936
$I_b(D_2O)$	1.0768	1.1282	0.78284	0.84347	0.89440
I_b (02,23,13)	0.92260	1.4048	0.42376	0.74087	1.1268
I_T (D_2O)	1.5003	1.5157	1.4825	1.5007	1.5160
I_T	2.6088	3.0795	2.0585	2.3762	2.7622
$CP_c(D_2O)$	0.01079	0.00977	0.02858	0.02535	0.02261
$CP_c(23)$	0.02798	0.02372	0.03312	0.02805	0.02380
$CP_b(D_2O)$	0.02701	0.01439	0.08518	0.02482	0.01307
$CP_b(02,23,13)$	0.37653	0.25191	0.88425	0.34606	0.22886
CP_c	0.03877	0.03349	0.06170	0.05340	0.04641
CP_b	0.40354	0.2663	0.96943	0.37088	0.24193
CP_T	0.44231	0.29979	1.0311	0.42428	0.28834
$F(D_2O)$	0.62512	0.63154	0.61771	0.62529	0.63167
F(02)	0.00312	0.00314	0.00289	0.00291	0.00293
23 Credit	0.93256	0.97303	0.51391	0.56317	0.59623
Feed Total	-0.30432	-0.33835	0.10669	0.06503	0.03837
Total Variable Fuel Cost	2.7468	3.0409	3.1963	2.8655	3.0889
Net Unit Cost	8.1372	8.4313	8.5867	8.2559	8.4793

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TABLE 5A

NUCLEAR CHARACTERISTICS OF
FOUR CYLINDRICAL REACTOR SYSTEMS

Reactor No.	3-20-1	2-30-1	3-30-1	3-30-3
R_c (feet)	3	2	3	3
H (feet)	19	29	29	29
W_b (gms 23/kg 02)	1	1	1	3
C_c (gms 23/kg D_2O)	1.053309	2.440245	1.010958	0.969324
$f_b(p)$	0.0518	0.044	0.047	0.105
$f_c(p)$	0.0641	0.05	0.0574	0.0551
P_b/P_T	0.06945	0.07175	0.0639	0.1957
B. R.	1.0431	1.1545	1.0784	1.0747
β (02) (resonance to thermal absorptions)	0.177818	0.27794	0.173677	0.296608
$V_c \phi_c / V_b \phi_b$	14.643	6.1533	14.661	14.487
V_c (liters)	15,210	10,320	23,218	23,218
V_{cT} (liters)	36.150	31,220	44,290	41,320
V_b (liters)	27,040	54,180	41,280	41,280
V_{bT} (liters)	29,280	56,480	43,330	47,570
Core 23 absorptions (gms 23/day)	473.282	473.952	478.092	414.907
Absorptions and Leakages Normalized to Core 23 absorptions				
A_b (23)	.081812	.084037	.085136	.269578
A_b (D_2O)	.003490	.003585	.003632	.003833
A_b (02) (fast plus thermal)	1.143431	1.274369	1.185701	1.382564
A_b(13)	.010431	.007034	.007611	.009548
A_b (24)	.000307	.000204	.000231	.001356

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TABLE 5A (Cont'd)

NUCLEAR CHARACTERISTICS OF

FOUR CYLINDRICAL REACTOR SYSTEMS

Reactor No.	3-20-1	2-30-1	3-30-1	3-30-3
A_b(25)	.000034	.000019	.000023	.000314
A_b (26)	1×10^{-8}	$.42 \times 10^{-8}$	$.56 \times 10^{-8}$	20.7×10^{-8}
A_b (p)	.00385	.00338	.003627	.025793
A_c (23)	1.000000	1.000000	1.000000	1.000000
A_c (24)	.10669	.10219	.10186	.11938
A_c (25)	.10695	.10234	.10202	.12032
A_c (26)	.0168	.01608	.01603	.0189
A_c (p)	.0641	.0498	.0572	.05435
A_c (D_2O)	.051106	.02206	.053247	.055534
A_c (O_2SO_4)	.002414	.002346	.002342	.002608
A_s (core tank)	.078186	.047374	.081404	.085688
Fast Leakage				
End *	.017434	.007724	.007767	.009028
Radial	.009734	.002701	.010010	.024536
Thermal Leakage				
End *	.045397	.009409	.021020	.021939
Radial	.004142	.000988	.004296	.066589
Average Core Flux	1.15×10^{15}	7.32×10^{14}	7.92×10^{14}	7.17×10^{14}
Max. Power Density at Core Tank Wall (kw/liter)	10.8	24.6	7.2	6.62

*See top of page 34 for comment

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TABLE 5B

ECONOMIC CHARACTERISTICS OF
FOUR CYLINDRICAL REACTOR SYSTEMS

Reactor	3-20-1	2-30-1	3-30-1	3-30-3
Core Thorex cycle time (days)	229.6	302.3	223.7	215
Blanket Thorex cycle time (days)	88.1	132.6	126.2	362.5
q - fraction of U production returned to reactor as feed	0.966	0.8757	0.923	0.9078
Total fissile inventory (23, 25, 13) (kg)	110	180.2	129	220.7
Total Thorium Inventory (kg)	47,500	80,000	62,200	54,800
ECONOMICS (mills/kwhr)				
Inventory Charge				
Core D_2O	.4870	.4208	.5965	.5565
Core 23, 25	.1308	.2423	.1544	.1420
Blanket D_2O	.3943	.7610	.5835	.6410
Blanket 23, 25, 13	.1749	.2580	.2039	.4710
Blanket 02	.0728	.1560	.0952	.0839
Total	1.2598	1.8381	1.6335	1.8944
Chemical Processing Costs				
Core D_2O	.0233	.01527	.02927	.02842
Core 23, 25	.0319	.04828	.03833	.0362
Blanket D_2O	.04915	.063	.05075	.0195
Blanket 02	.4226	.5420	.4367	.1669
Blanket 23, 25, 13	.1096	.1247	.1020	.0987
Total	.6366	.7932	.6570	.3497
Feed Costs				
D_2O makeup	.3670	.4928	.4920	.4990
02 feed	.0025	.0028	.0026	.0027
23, 25 credit	.2048	.7350	.3762	.3643
Total	.1647	-.2394	.1184	.1374
Total Variable Fuel Costs	2.0610	2.3920	2.4090	2.3815
Total Fixed Costs	5.3904	5.3904	5.3904	5.3904
Net Unit Cost	7.4514	7.7824	7.7994	7.7719

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End leakages were calculated by assuming that the ends of the reactor were bare. In practice, however, the blanket region would also cover most of the end areas of the core region. The end leakages as given in Tables 4 and 5 would therefore be high, and correcting this would tend to increase the breeding ratios.

The results given in Figs. 2 and 5 are combined in Fig. 6, and indicate the economic penalty associated with maintaining a low wall-power-density. The breeding ratio associated with different values of the reactor parameters is given in Fig. 7, where the specific values obtained are indicated. As shown, the breeding ratio was practically independent of the blanket fuel concentration.

In the calculations, an effective extrapolation distance which was independent of region was used for the reactor ends. If a blanket were considered at the ends of the core region, the breeding ratio would increase, particularly for those reactors of relatively short length. Under these conditions the breeding-ratio curves in Fig. 7 would tend to become more horizontal and could possibly change to a positive slope as the power density increased (smaller reactor length). However, this effect would be relatively unimportant insofar as the fuel costs given here are concerned.

The results indicate that minimum fuel costs are associated with high core-wall-power densities, and that highest breeding ratios are obtained with small core radii, thick blankets, and long reactors. Thus, the reactors with the lowest fuel costs do not have the lowest core-wall power densities or the highest breeding ratios. If corrosion difficulties do not permit high power densities at the core wall, some compromise would

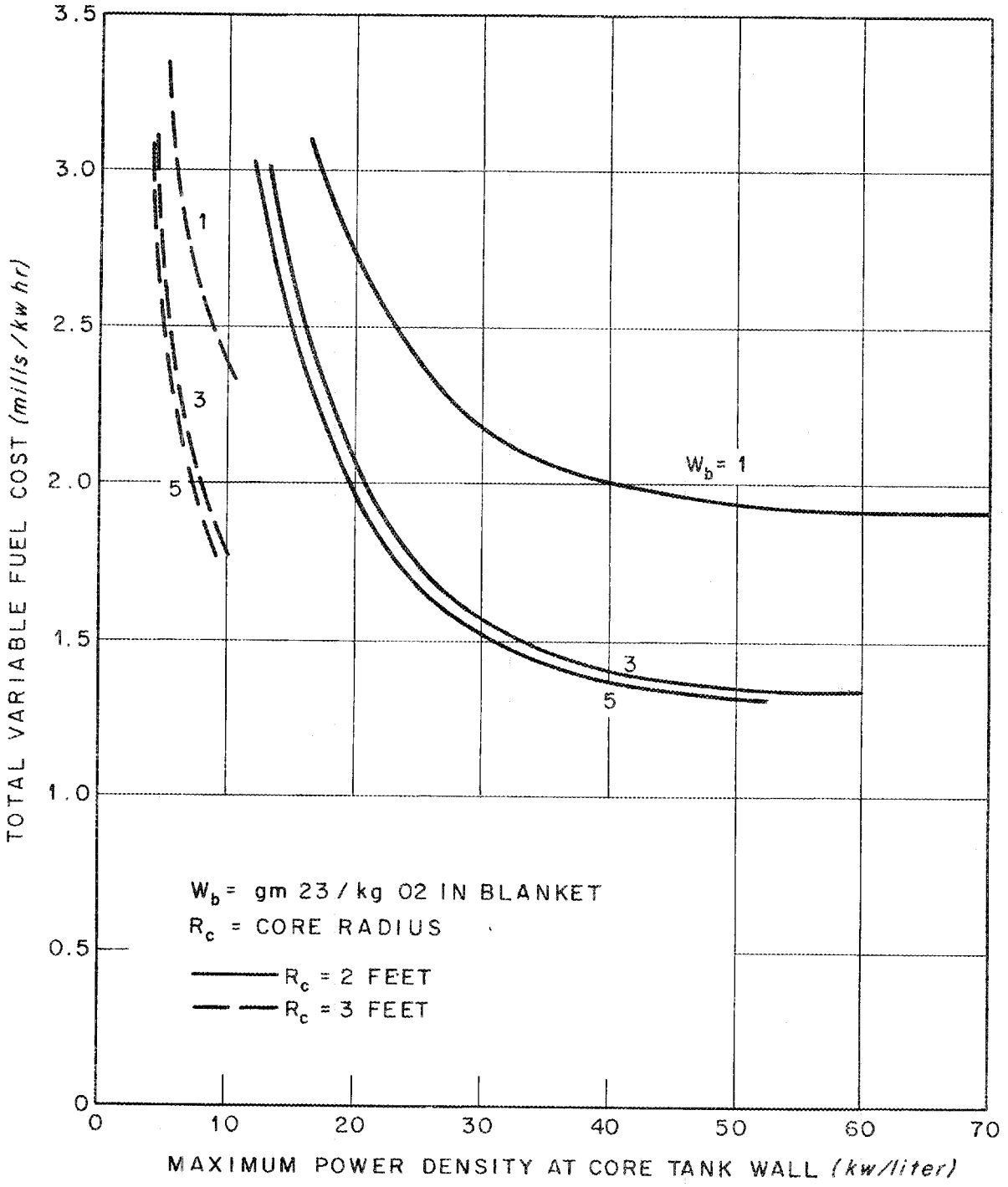

Fig. 6. Effect of Power Density on Total Variable Fuel Costs for Simplified Cylindrical Reactors.

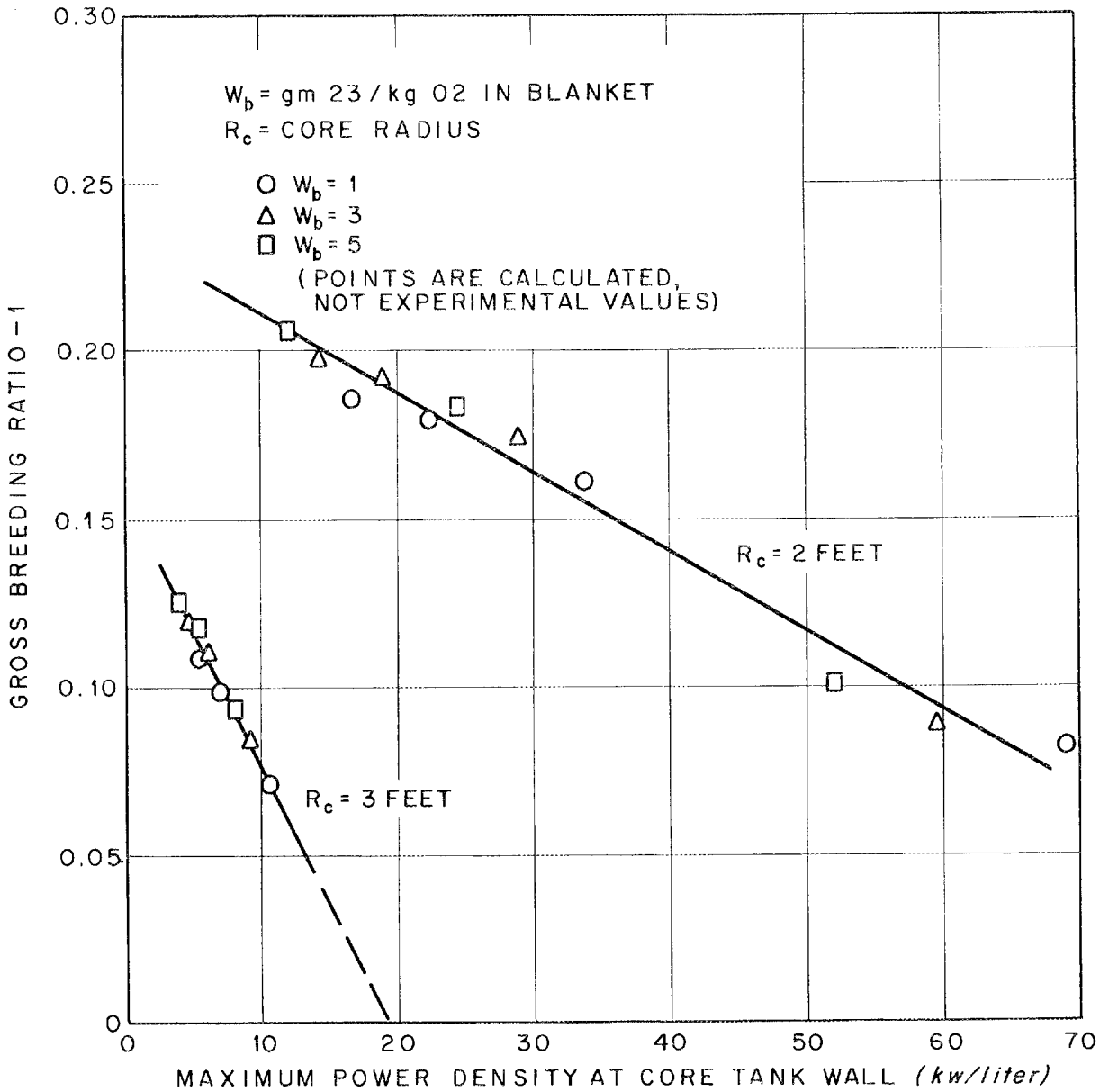

Fig. 7. Effect of Power Density on Breeding Ratio for Simplified Cylindrical Reactors.

be required. Increasing the reactor length decreased the wall-power-density, but increased the inventory charge until that charge controlled the fuel cost; the associated increase in breeding ratio was slight.

The minimum variable fuel cost given in Fig. 5 appears to be about 1.3 mills/kw-hr with a blanket fuel concentration between 3 and 5 gm U^{233}/kg Th. This value can be compared with a variable fuel cost of about 1.0 mills/kw-hr for an optimum, comparable spherical two-region reactor.[2] Thus, a change from spherical to cylindrical geometry would increase the fuel cost by $\sim$ 0.3 mills/kw-hr if there were no restrictions on power density at the core wall, based on the cost factors used here. This increase would be due almost entirely to the higher inventory charges associated with the cylindrical reactor. If 4% inventory charges were used and the D_2O cost were \$28/lb, the 0.3 mills/kw-hr difference would be reduced to less than 0.1 mill/kw-hr. If the core wall-power-density were limited to 20 kw/liter, the fuel costs would be greater than the above values for both spherical and cylindrical reactors. If no limit were placed on reactor size, a spherical reactor would probably result in lower fuel costs than if cylindrical geometry were considered; however, the difference in fuel costs associated with the two geometries would decrease as the permissible wall-power-density were decreased. Cylindrical geometry does, however, permit low wall-power-densities in combination with relatively small reactor diameters.

The results given in Figs. 4, 5 and 6 indicate that limitations on core-wall-power density may result in fuel costs 1-2 mills/kw-hr higher than fuel costs for reactors in which no power-density limitation exists.

This higher value was due primarily to the inventory charges, which were assumed to be 12% of the inventory value per year. If the inventory charge were 4% rather than 12%, less economic penalty would be associated with low wall-power-density; i.e., the fuel cost curve would be flatter (and lower) than shown in Figs. 4, 5, and 7. Specifically, if the core-wall-power-density were limited to 15 kw-liter, R_1 = 2 ft, W = 5 gm U^{233}/kg Th, and a 12% inventory charge were used, the variable fuel costs would be about 1 mill/kw-hr higher than the economic minimum if there were no power density limitation; if a 4% inventory charge were used, the economic penalty imposed by the power density limitation would be about 0.33 mills/kw-hr. Also, since D_2O inventory charges were a substantial fraction (> 50%) of the total inventory charge, use of \$28/lb for D_2O rather than the \$40/lb used would result in fuel costs which were not as dependent upon inventory charges (in the above case, the 0.33 mill/kw-hr penalty due to the power density limitation would be lowered to about 0.2 mills/kw-hr).

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3. Hullings, M. K., and C. W. Nestor, Jr., ORACLE Code for Evaluating Two-Group, Two-Region Cylindrical Reactors, CF-56-5-18, May 3, 1956.

APPENDIX

NUCLEAR PROPERTIES USED IN CALCULATIONS

Nuclear Properties of Basic Materials at 300°C

Material	Microscopic Cross Section (barns)
Th-232	4.438
Pa-233	95.1
U-233	374
U-234	56.4
U-235	406
U-236	5.71
O_2SO_4	0.3106
D_2O	0.001731
Group 3 Poison	12.9
	Microscopic Fission Cross Section (barns)
U-233	340.3
U-235	342.2
	Macroscopic Cross Section (cm^{-1})
Zirconium	0.005793
	η(neutrons per capture)
U-233	2.32
U-235	2.09
	λ (13), Decay Constant (day^{-1})
Pa-233	0.0252956

INPUT DATA COMMON TO ALL CALCULATIONS

	Core	Blanket
Fermi Age (cm^2)	244	234
Resonance escape probability	1	0.547
Diffusion coefficient, fast group (cm)	1.76	1.56
Diffusion coefficient, slow group (cm)	1.30	1.24