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SUBJECT: Nuclear Characteristics of Two-Region Slurry Reactors

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ABSTRACT

Nuclear characteristics were computed for over 400 two-region spherical homogeneous reactors having D_2O - ThO_2-$U^{233}O_2$ slurry in both core and blanket. Curves are presented of breeding ratio, core-wall power density, critical concentration, critical ratio, and blanket power as functions of various design parameters. Neutron balances and additional characteristics are given for 10 representative reactors. A simple method for estimating the effects of core and blanket poisons on breeding ratio and critical concentration is described.

INTRODUCTION

In this memorandum the nuclear characteristics of some two-region spherical homogeneous reactors having D_2O- ThO_2-$U^{233}O_2$ slurry in both core and blanket are presented. A two-group, two-region code[1] for the Oracle was used to obtain breeding ratios, critical concentrations, power densities, fluxes, and neutron balances for various reactors. The parameter values considered are given in Table I.

Table I. Parameter Values Employed

Pressure vessel I.D.	10, 12 ft.
Core tank I.D.	6, 7, 8, 9, 10, 11 ft.
Thorium in core	0, 100, 200, 300 gm/liter
Thorium in blanket	0, 500, 1000, 2000 gm/liter
U^{233} in blanket	0, 1, 3, 5 gm/liter
Total reactor power	100 Mw

For all reactors the core tank was of Zircaloy-2 and was 1/2 in. thick. The value of η was taken as 2.25 and $\sigma_f^{23}/\sigma_a^{23}$ as 0.90; the reactor temperature was 280°C. The majority of reactors contained no poisons in either core or blanket, and isotope buildup (including protactinium) was not considered. However, computations for systems containing poisons were used to check an approximate method developed for use in estimating the effects of poisons on breeding ratio and critical concentration.

In the sections which follow, curves of breeding ratio, wall power density, critical concentration, blanket power, and critical ratio are shown as functions of several design variables. Some characteristics of one-region reactors are included for comparison with the two-region system. Two tables give additional results for selected systems, and the appendix contains a table of nuclear properties and other input numbers used in the computations.

RESULTS

Breeding Ratio

The breeding ratio of a reactor is defined as the rate at which fissionable atoms are produced divided by the rate at which they are destroyed (by fission or neutron capture). In the computations employed in this study, the production rate of U^{233} is the sum of the rates of resonance and thermal capture by thorium in both core and blanket. The rate at which fuel is destroyed is the sum of the rates of thermal absorption in U^{233} in core and blanket.

In Figs. 1 - 6, the breeding ratio for two-region reactors is plotted as a function of core diameter and other parameters. Figure 7 shows the breeding ratio of one-region reactors vs. thorium concentration for several pressure vessel sizes. The reactors considered contain no protactinium, other isotopes, or fission products. The effect of poisons on breeding ratio can be estimated using the method described below.

Wall Power Density

The power density (rate of heat generation per unit volume) in the fluid at the surface of the Zircaloy core vessel is plotted in Figs. 8 - 13. For all cases the total reactor power was taken as 100 Mw, and the values of power density are normalized to that figure. Increasing the reactor power would increase the power density in direct proportion.

For fuel concentrations in the blanket higher than in the core, the power density at the outer surface of the core tank is sometimes higher than at the inner surface. In such cases, the greater value was assumed to be significant and was plotted. As a result, some of the curves of wall-power density exhibit a minimum which is associated with the shift of the higher value from the inner to the outer surface.

Critical Concentration

The concentration of U^{233} in the core region required to make the reactor critical is plotted as a function of various parameters in Figs. 14 - 19 for clean two-region systems. In Fig. 20 the critical concentration for comparable one-region reactors is shown. The effect of core poisons on critical concentration can be estimated using the method described below.

Blanket Power

The fraction of total reactor power that is produced in the blanket region, P_B/P_T , is plotted in Figs. 21 - 26.

Critical Ratio

During startup or operation of a slurry reactor, it is conceivable that some event could cause a rapid change in the concentration of slurry in the core with attendant reactivity changes. The uranium in the circulating system will probably be associated with the slurry in such a manner that the ratio of uranium to thorium would remain the same even though the concentration of thoria changed.

In examining reactivity effects resulting from changes in thoria concentration, it is useful to plot the values of the ratio of uranium to thorium required for criticality vs. thorium concentration. This ratio has been plotted in Figs. 27 - 32. If a reactor is critical at some specified thorium concentration, the U^{233} to thorium ratio will be that given by the appropriate curve. Following a sudden change in core slurry concentration, the actual ratio of U^{233} to thorium in the core would be unchanged, but the ratio required for criticality would be that given by the curve at the new thorium concentration. Thus, depending on whether the new critical value were above or below the old, the reactor (for the same temperature) would be either subcritical or supercritical.

At the minimum point of a curve, changes in either direction would, of course, cause the system to become subcritical. Also, in a flat region of the curve, small changes would not appreciably affect the critical ratio.

Additional Nuclear Characteristics

In addition to the other results presented in the figures, Tables I and II give neutron balances and value of power density and flux for a selection of two-region reactors. The power density and flux are normalized to a total reactor power of 100 Mw, and changing the total power would change these values in the same proportion. The absorptions and leakages in the neutron balance are normalized to 100 absorptions in U^{233} (which yield 2.25 fast neutrons each). Table II gives results for five 10-ft reactors and Table III for five 12-ft. vessels.

EFFECTS OF REACTOR POISONS

Consider a single-fuel reactor operating at core power P_C, blanket power P_B, and total power P_T. To estimate the effect on breeding ratio of an increment in the core poison fraction, Δf_{pC}, and an increment of Δf_{pB} in the blanket poison fraction, the following approximate formula is used:

$$\Delta BR = -\Delta f_{pC} \frac{P_C}{P_T} - \Delta f_{pB} \frac{P_B}{P_T}$$

The fuel cross section of a critical reactor which originally has a core poison fraction f_{pC}, and is changed by an amount Δf_{pC}, may be calculated from the data for the original reactor as follows:

$$\Sigma_a^{F'} = \frac{1}{1 - \dfrac{\Delta f_{pC}}{\dfrac{\eta p}{1 + B_{eq}^2 \tau} - (1 + f_{pC})}} \Sigma_a^F$$

By B_{eq}^2 is meant the buckling of a bare reactor with the same material composition as the two-region core. For the cases studied in connection with this report, addition of a 6-inch extrapolation distance to the core radius was found to produce results as accurate as those obtained by individual estimates of B_{eq}^2 because of the high blanket thorium concentration.

Blanket poison changes resulted in negligible critical concentration increments for the highly absorbent blankets treated.

The effect of the presence of protactinium on breeding ratio and critical mass may be treated in a manner similar to that used for poisons, but with due regard for an important difference: each capture of a neutron by Pa results not only in the loss of a neutron but in a potential fuel atom as well. This fact may be correctly taken into account by treating the Pa as a poison but using twice its actual concentration in the computation of breeding ratio changes. For estimating critical mass changes, however, no doubling is required, and the protactinium is treated as if it were another poison.

The derivation of the above equations is discussed in the appendix.

SUMMARY OF RESULTS

1. Effect of Core Thorium

   a. Breeding Gain. -- The breeding gain increased when the thorium concentration was increased in the core; however, it did not change appreciably for thorium concentrations above 200 gm/liter in the core.

   b. Core-Wall Power Density. -- With change in core thorium the wall-power density passed through a minimum for a given system; for 3 gm U^{233}/liter in the blanket the minimum occurred at core thorium concentrations lying between 60 and 100 gm/liter. In most cases, there was little change in wall-power density for core thorium between 100 and 300 gm/liter.

   c. Critical Concentration. -- The critical concentration increased with increasing core thorium concentration.

   d. Blanket Power. -- The fraction of total power generated in the blanket decreased with increase in core thorium concentration.

2. Effect of Blanket Thorium Concentration

   a. Breeding Gain. -- The breeding gain increased with increase in blanket thorium concentration. In most cases there would have been little further increase from raising the concentration above 2000 gm/liter.

   b. Core-Wall Power Density. -- The wall power density decreased as the thorium concentration in the blanket was increased.

   c. Critical Concentration. -- There was little change in critical concentration with change in blanket thorium.

   d. Blanket Power. -- The power in the blanket decreased as blanket thorium was increased. The effect was greatest with small cores and low core thorium concentration.

3. Effect of Core Diameter

   a. Breeding Gain. -- For a given pressure vessel size the breeding gain decreased as the size of the core was increased.

   b. Core-Wall Power Density. -- The wall power density decreased as the size of the core was increased.

   c. Critical Concentration. -- The critical concentration decreased as the core size was increased.

   d. Blanket Power. -- The power in the blanket decreased as the core size was increased. The effect of change in core size was least for the highest blanket thorium concentration.

4. Effect of Blanket Thickness

a. Breeding Gain. -- For constant core size, the breeding gain increased as the blanket thickness was increased. The effect was least for the greatest concentration of thorium in the blanket.

b. Core-Wall Power Density. -- The wall power density was decreased by increase in blanket thickness, but the change was small in the range considered.

c. Critical Concentration. -- There was no appreciable change in critical concentration with change in blanket thickness.

d. Blanket Power. -- The power generated in the blanket increased slightly with increase in blanket thickness. For the more heavily loaded blankets, the change was not appreciable.

5. Effect of Fuel in Blanket

a. Breeding Gain. -- The breeding gain decreased linearly with increase in blanket U^{233} concentration. With 2000 gm Th/liter in the blanket, the change in breeding gain between 0 and 5 gm U^{233}/liter was not significant; but with only 500 gm Th/liter, the change in breeding gain was appreciable.

b. Core-Wall Power Density. -- The wall power density was relatively insensitive to changes in the blanket fuel concentration for thorium concentrations greater than 100 and 500 gm/liter in the core and blanket, respectively. However, at core thorium concentrations less than about 60 gm/liter, the power on the blanket side of the core tank increased rapidly with increase in blanket fuel concentration.

c. Critical Concentration. -- The effect of blanket U^{233} concentration on the critical concentration in the core was insignificant.

d. Blanket Power. -- The power in the blanket increased nearly linearly with increase in blanket U^{233} concentration. The effect was greatest for the lowest blanket thorium concentration.

6. Critical Ratio

Over the range investigated, the ratio of U^{233} to thorium in the core required for criticality passed through a minimum at core-thorium concentrations of less than 200 gm/liter. As the core size was increased, the location of the minimum moved from near 200 gm Th/liter for a 6-ft. I.D. core to below 100 gm Th/liter for a 9-ft. I.D. core. The location of the minimum was not changed appreciably by variation in blanket thickness, blanket thorium concentration, or blanket fuel concentration.

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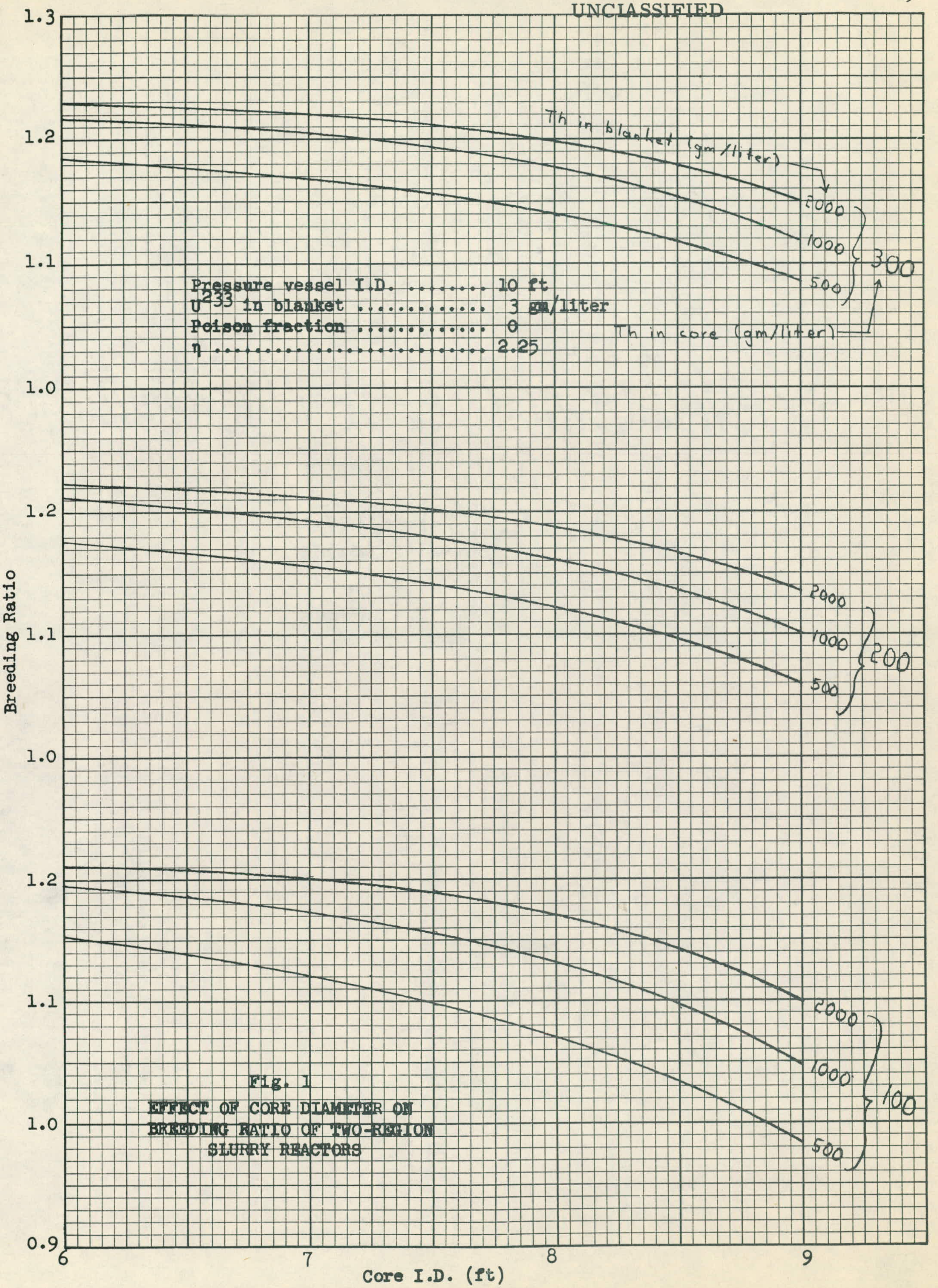

Fig. 1
EFFECT OF CORE DIAMETER ON BREEDING RATIO OF TWO-REGION SLURRY REACTORS

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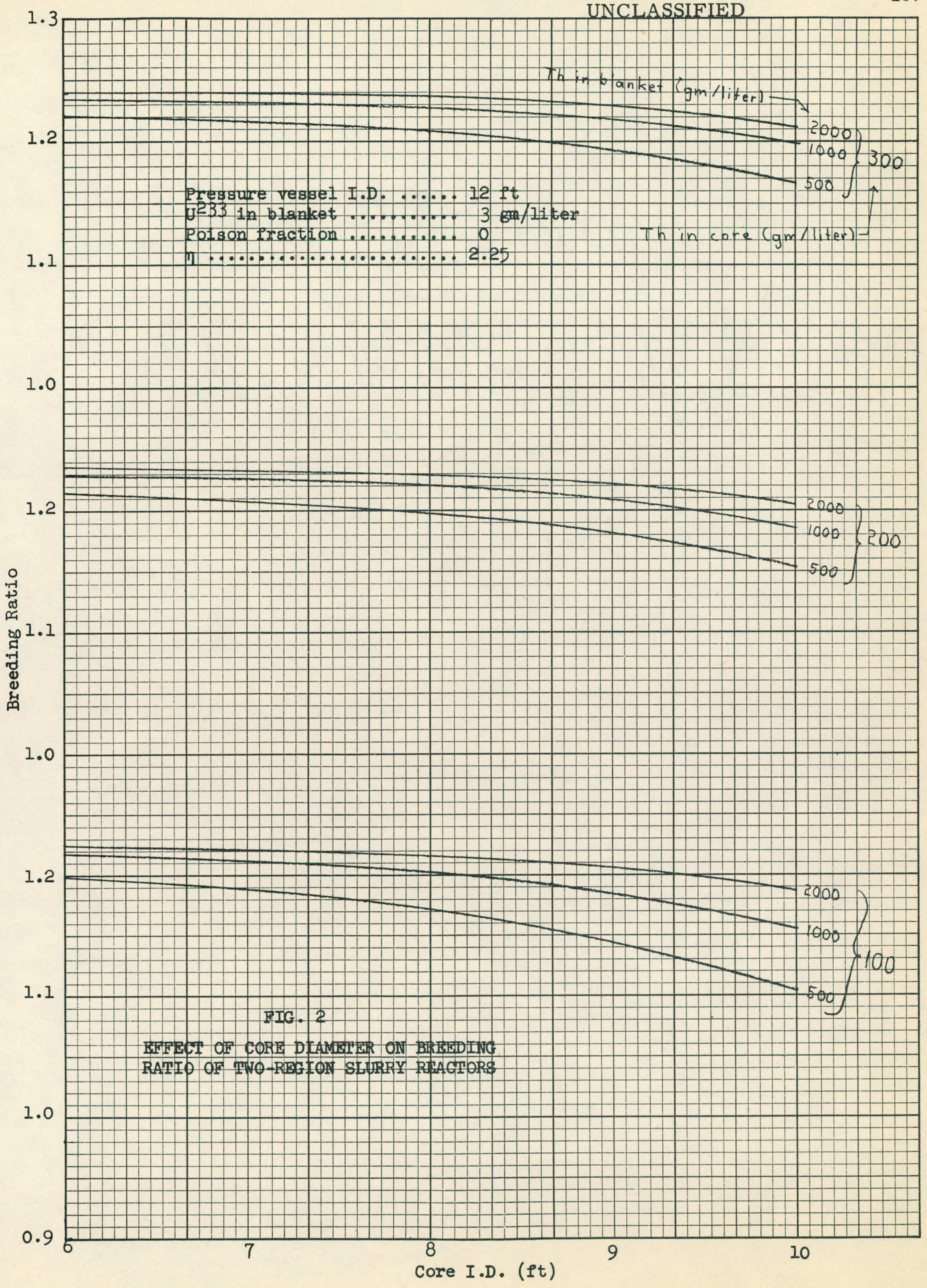

FIG. 2

EFFECT OF CORE DIAMETER ON BREEDING RATIO OF TWO-REGION SLURRY REACTORS

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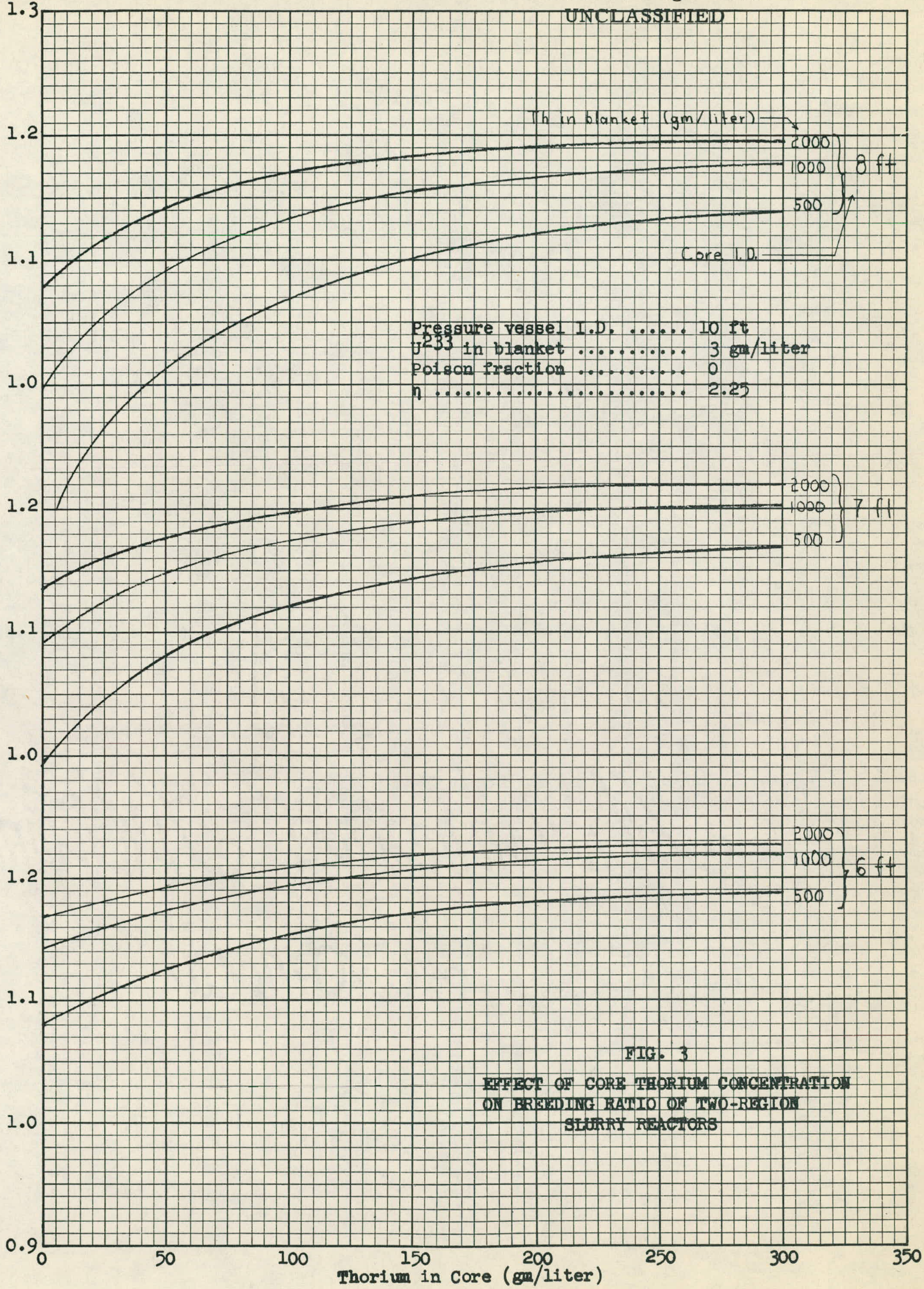

FIG. 3
EFFECT OF CORE THORIUM CONCENTRATION ON BREEDING RATIO OF TWO-REGION SLURRY REACTORS

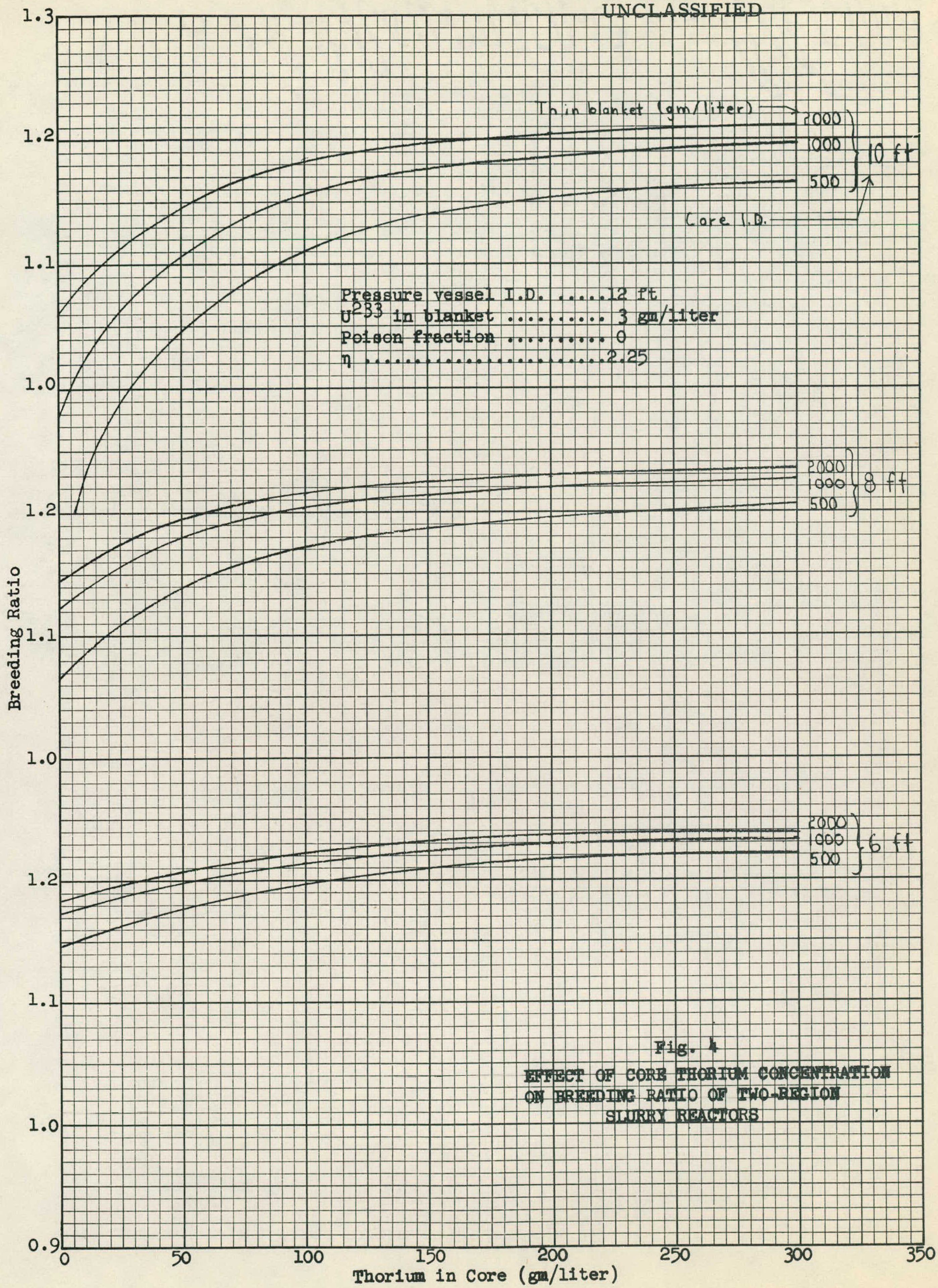

Fig. 4

EFFECT OF CORE THORIUM CONCENTRATION ON BREEDING RATIO OF TWO-REGION SLURRY REACTORS

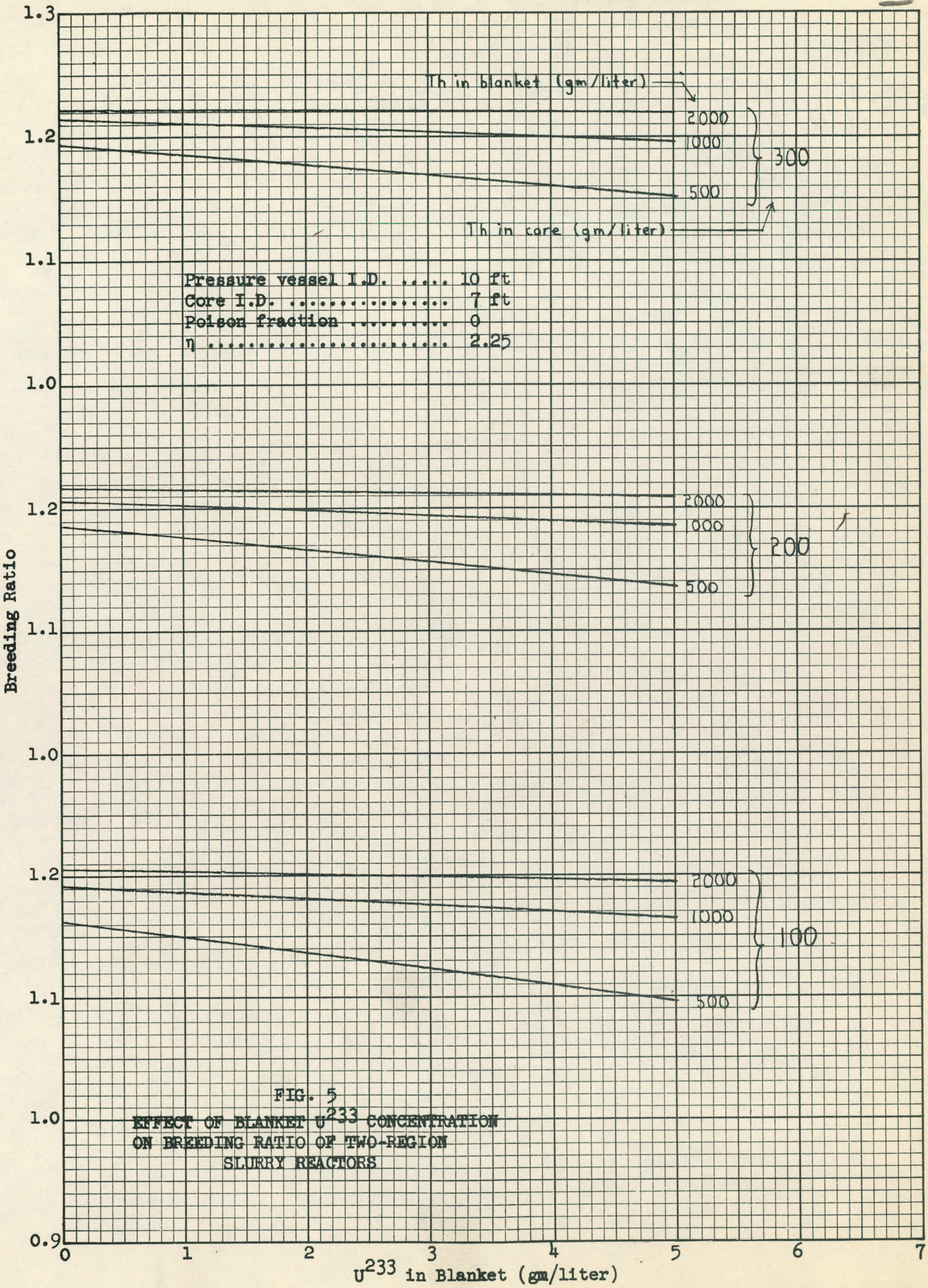

FIG. 5
EFFECT OF BLANKET U^{233} CONCENTRATION ON BREEDING RATIO OF TWO-REGION SLURRY REACTORS

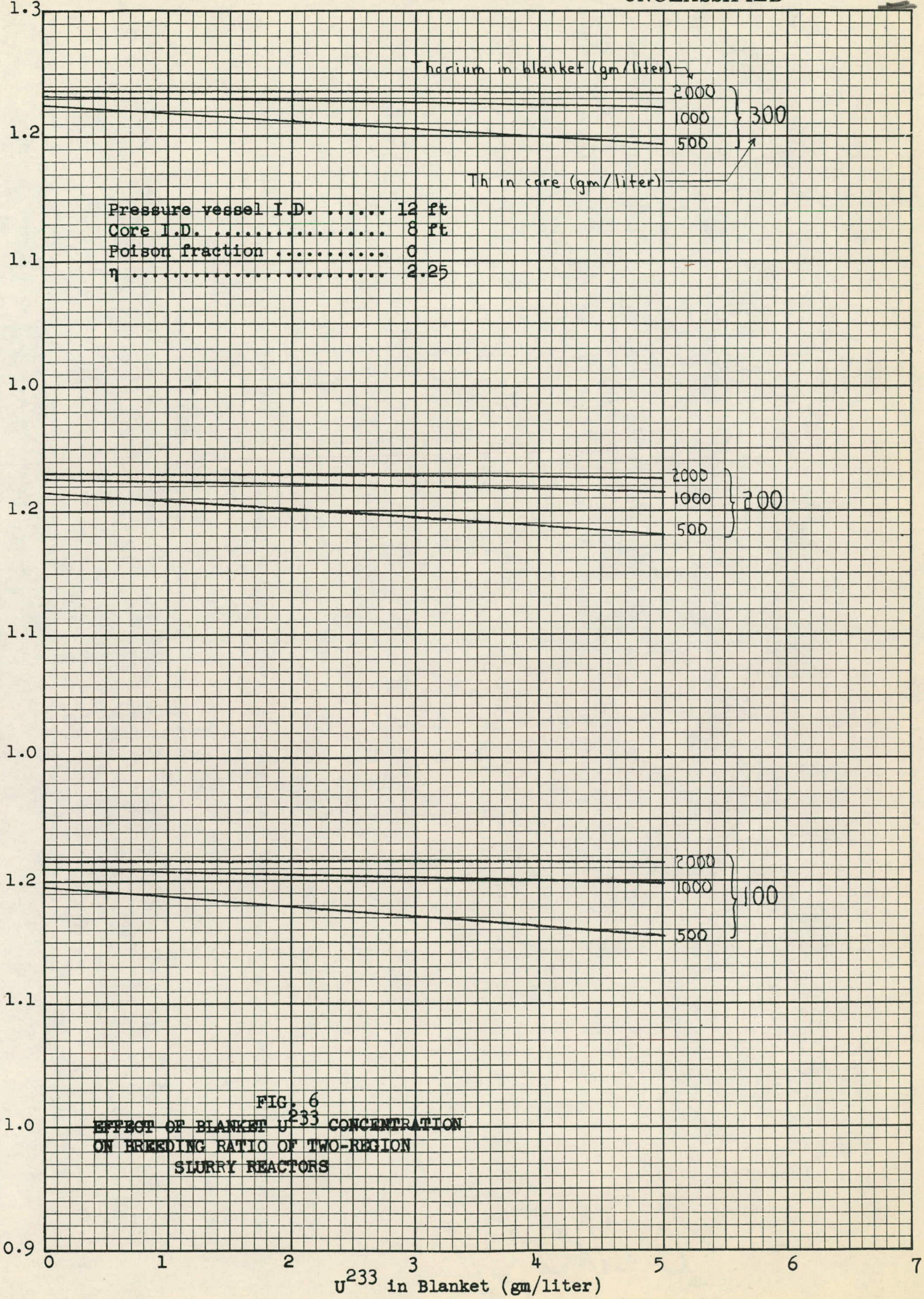

FIG. 6
EFFECT OF BLANKET U^{233} CONCENTRATION
ON BREEDING RATIO OF TWO-REGION
SLURRY REACTORS

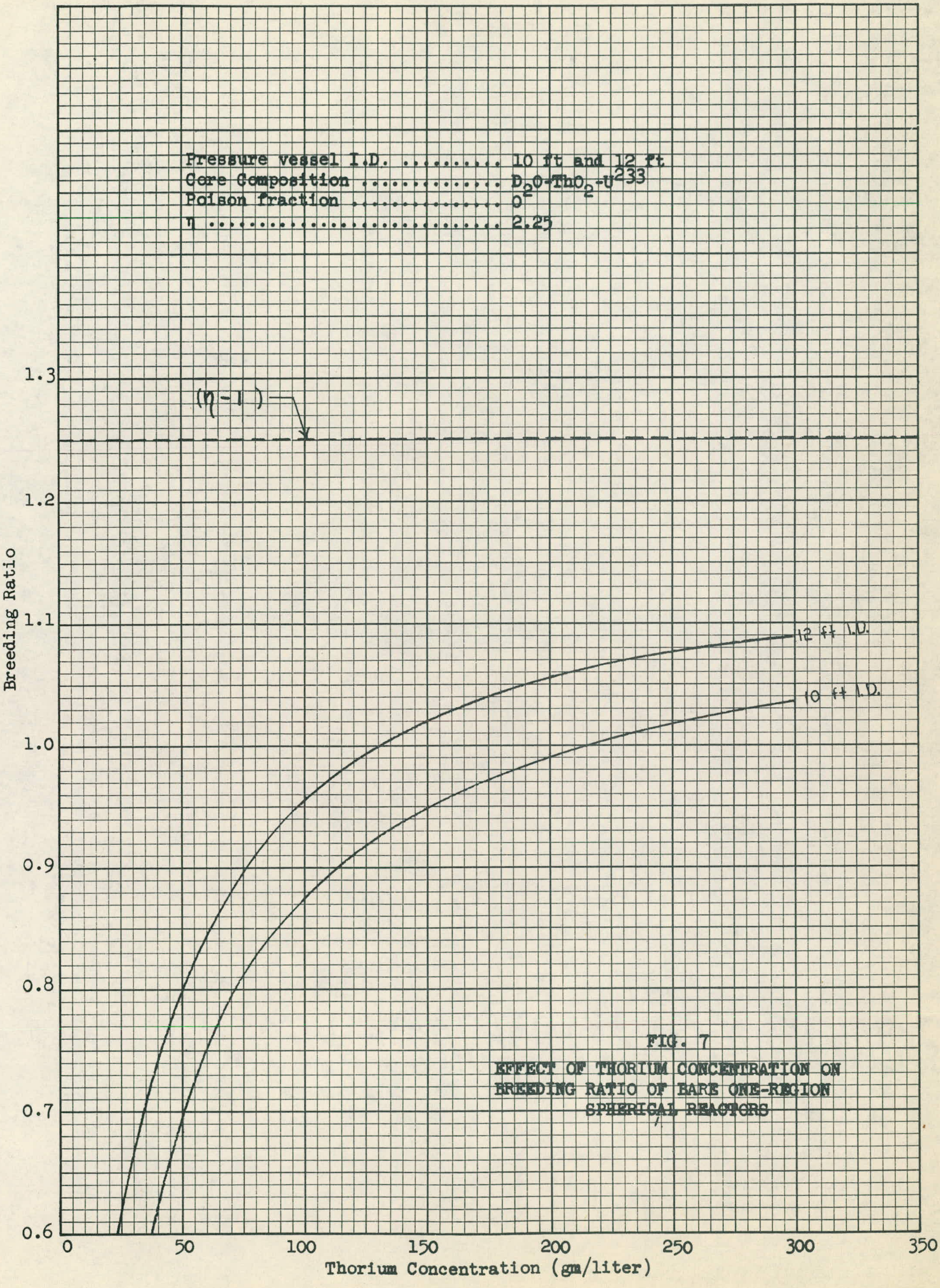

FIG. 7
EFFECT OF THORIUM CONCENTRATION ON BREEDING RATIO OF BARE ONE-REGION SPHERICAL REACTORS

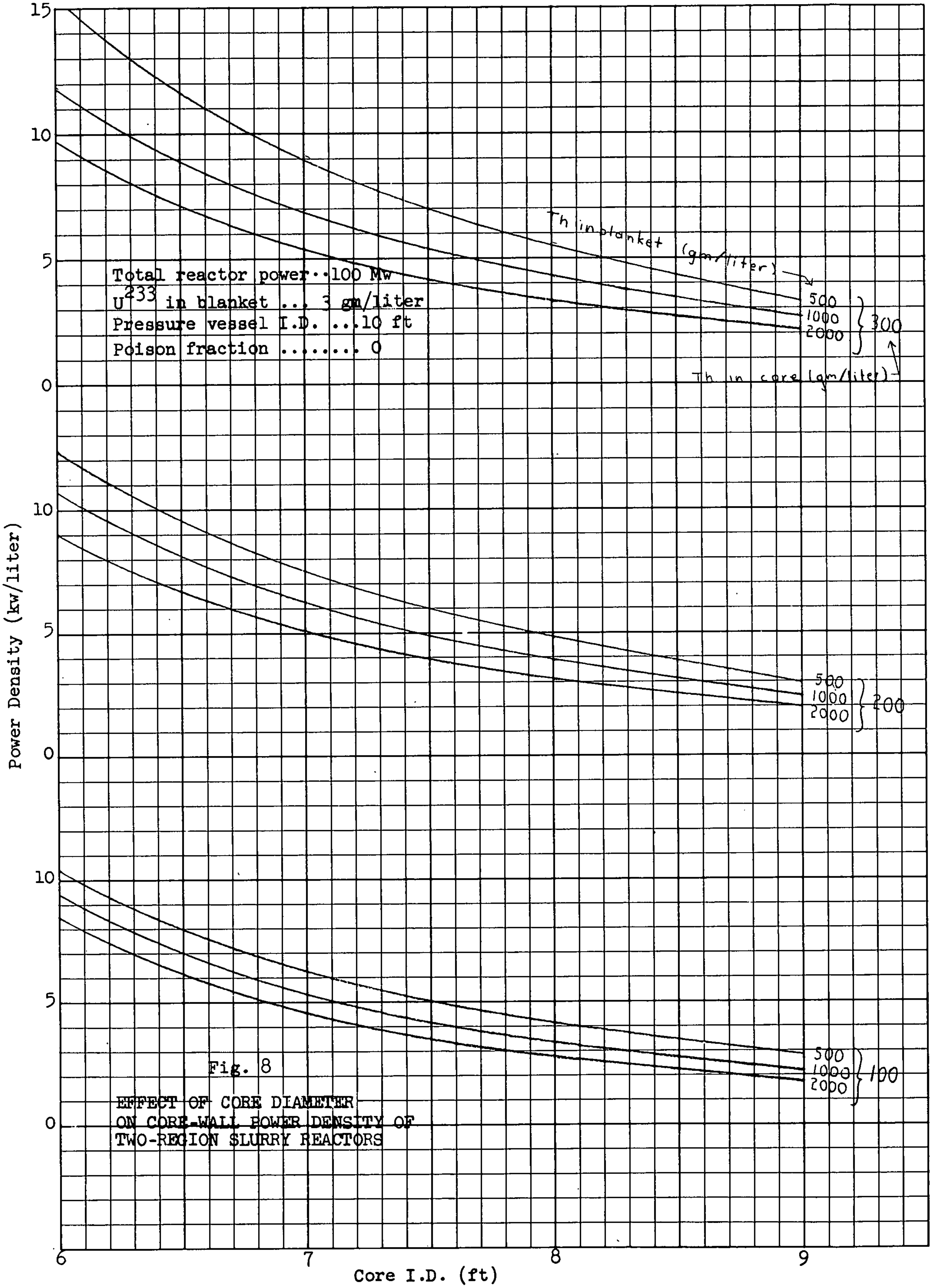

Fig. 8

EFFECT OF CORE DIAMETER ON CORE-WALL POWER DENSITY OF TWO-REGION SLURRY REACTORS

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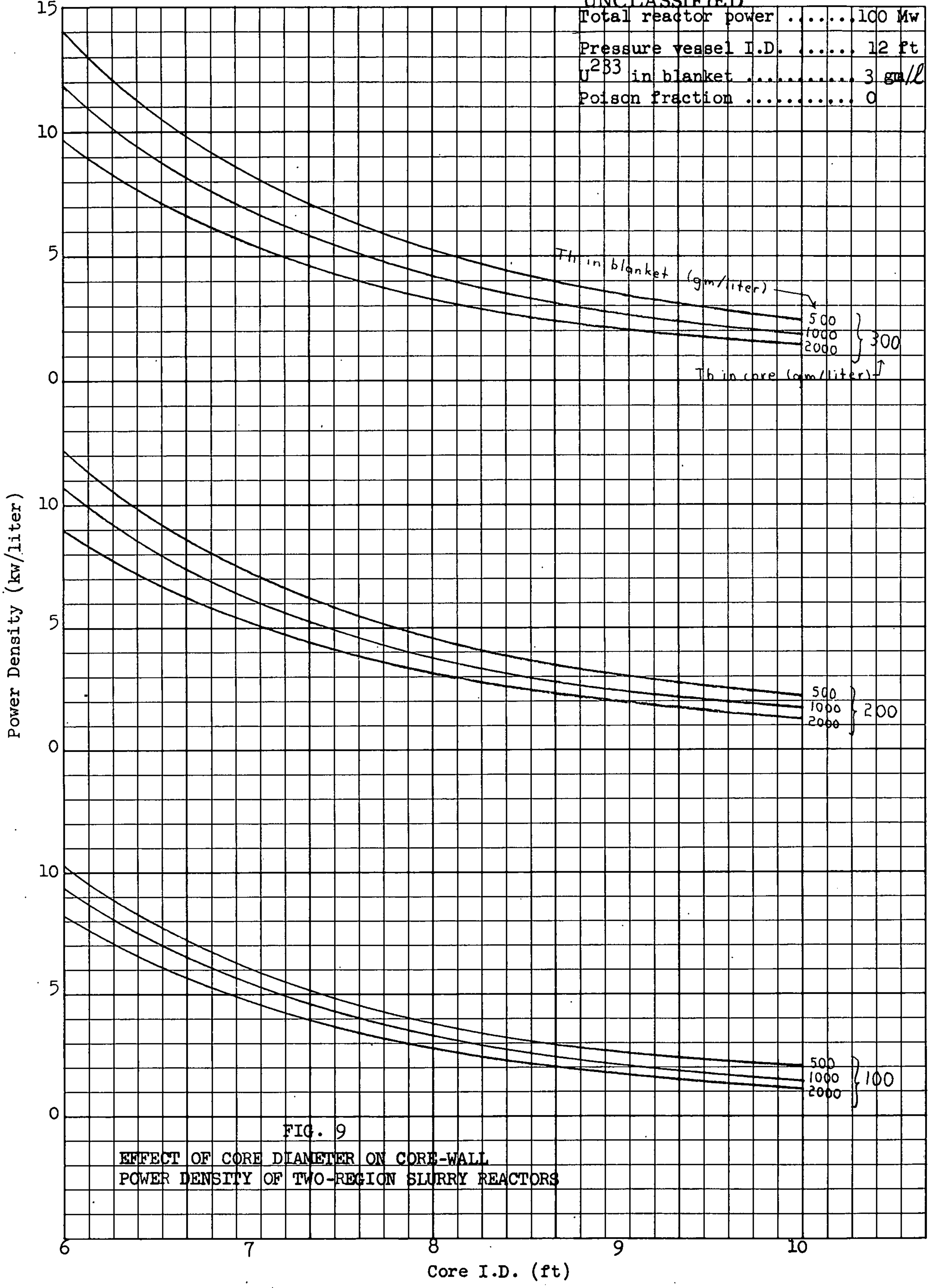

FIG. 9

EFFECT OF CORE DIAMETER ON CORE-WALL POWER DENSITY OF TWO-REGION SLURRY REACTORS

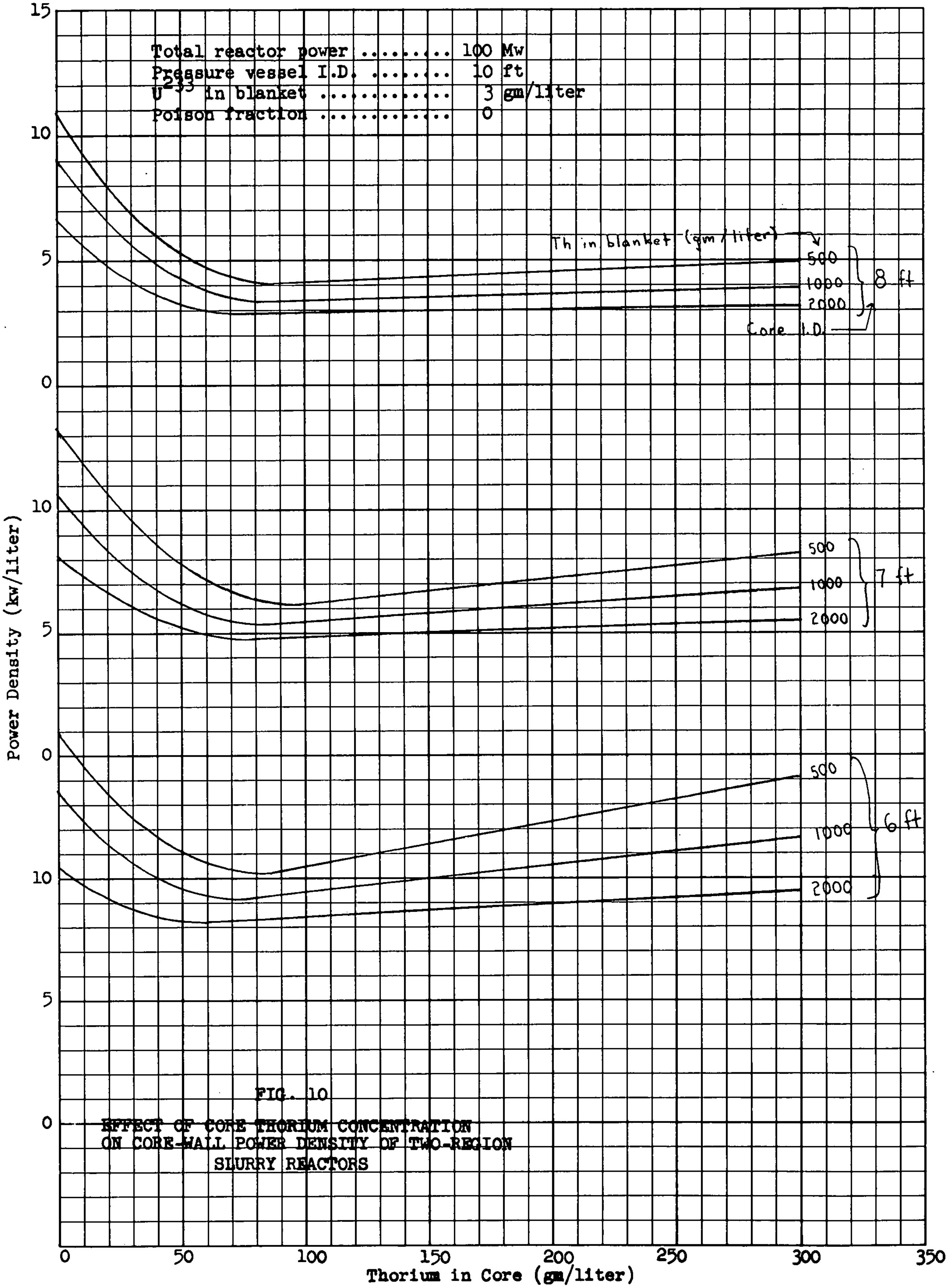

FIG. 10

EFFECT OF CORE THORIUM CONCENTRATION ON CORE-WALL POWER DENSITY OF TWO-REGION SLURRY REACTORS

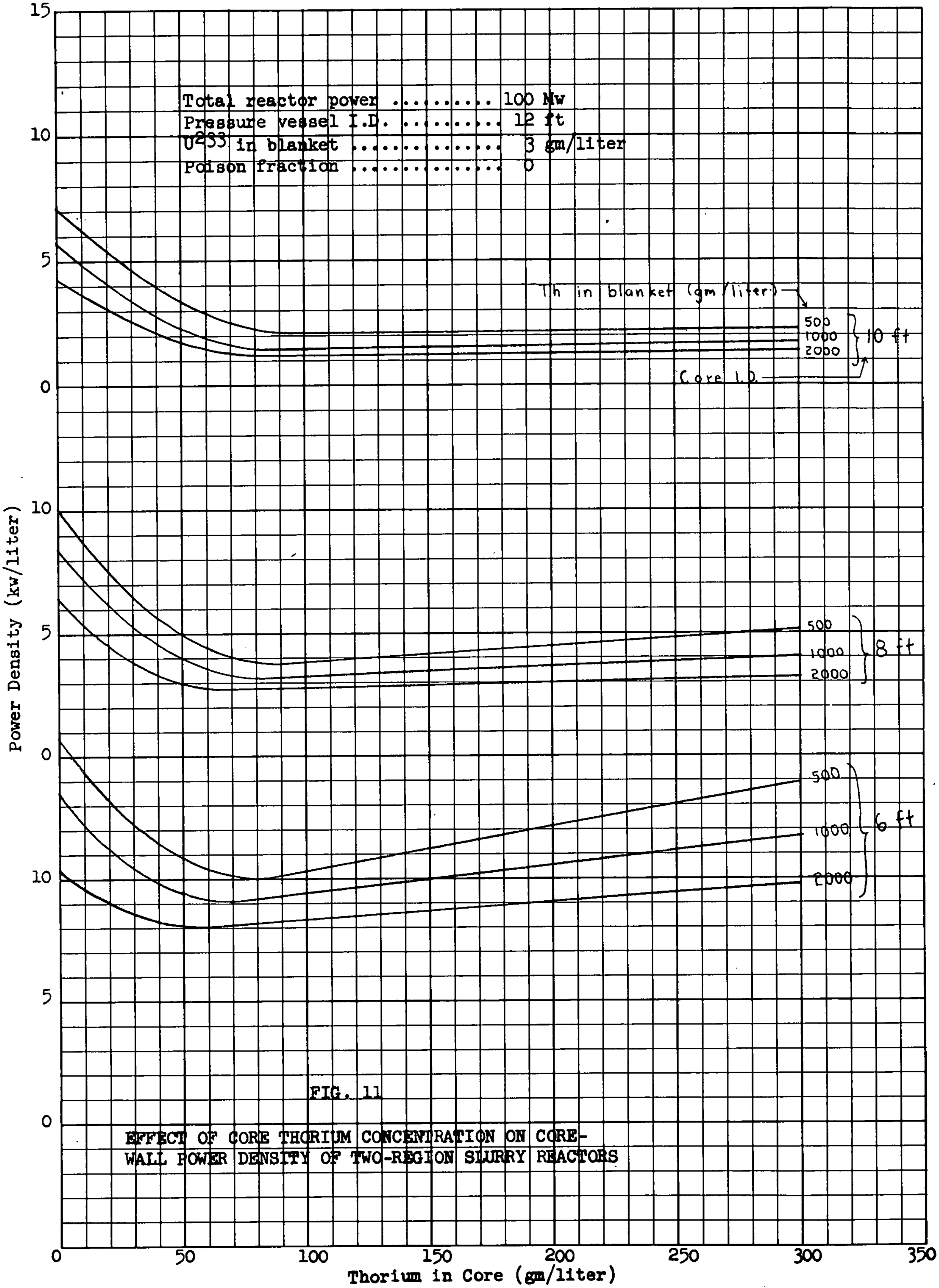

FIG. 11

EFFECT OF CORE THORIUM CONCENTRATION ON CORE-WALL POWER DENSITY OF TWO-REGION SLURRY REACTORS

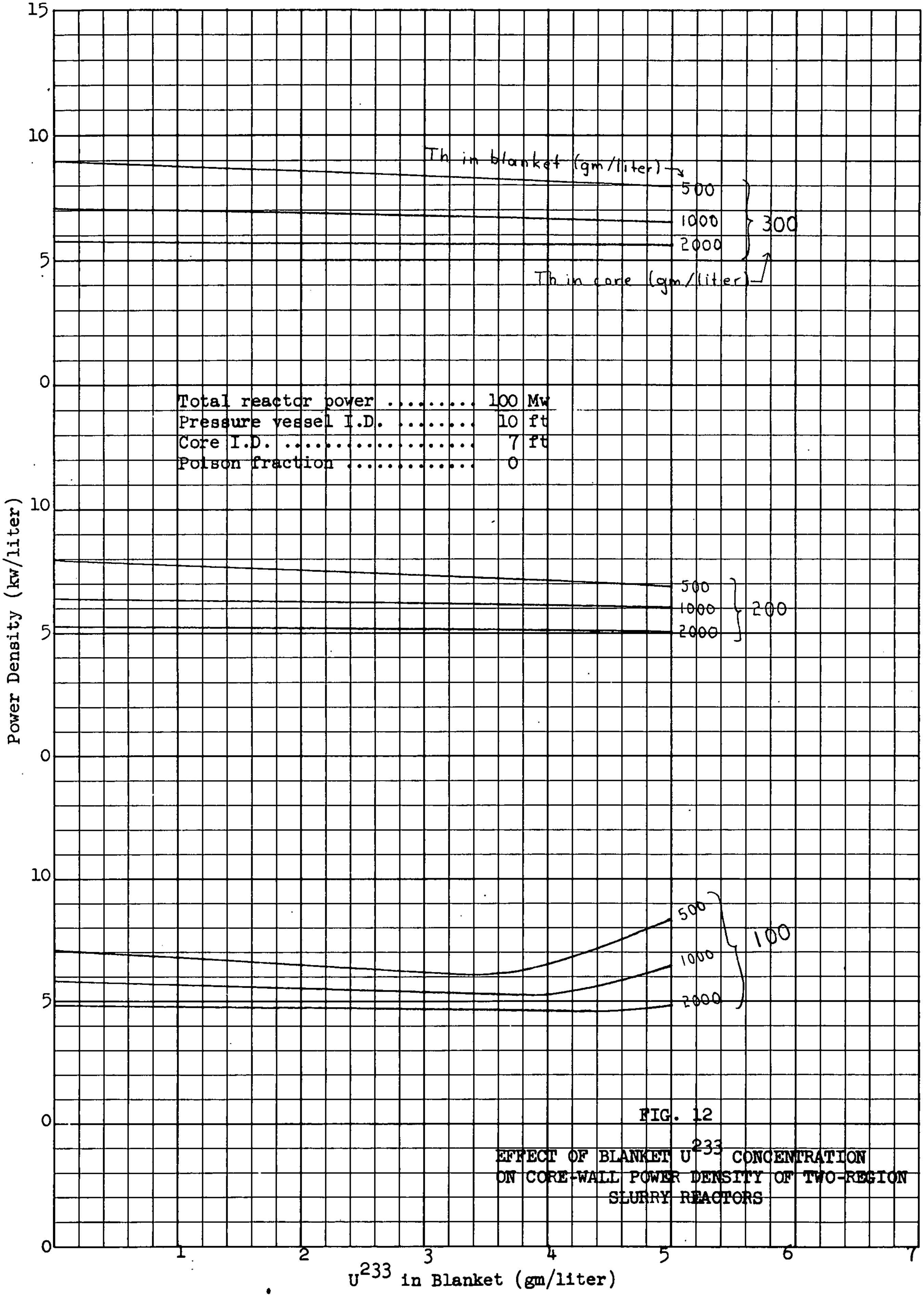

FIG. 12

EFFECT OF BLANKET U^{233} CONCENTRATION ON CORE-WALL POWER DENSITY OF TWO-REGION SLURRY REACTORS

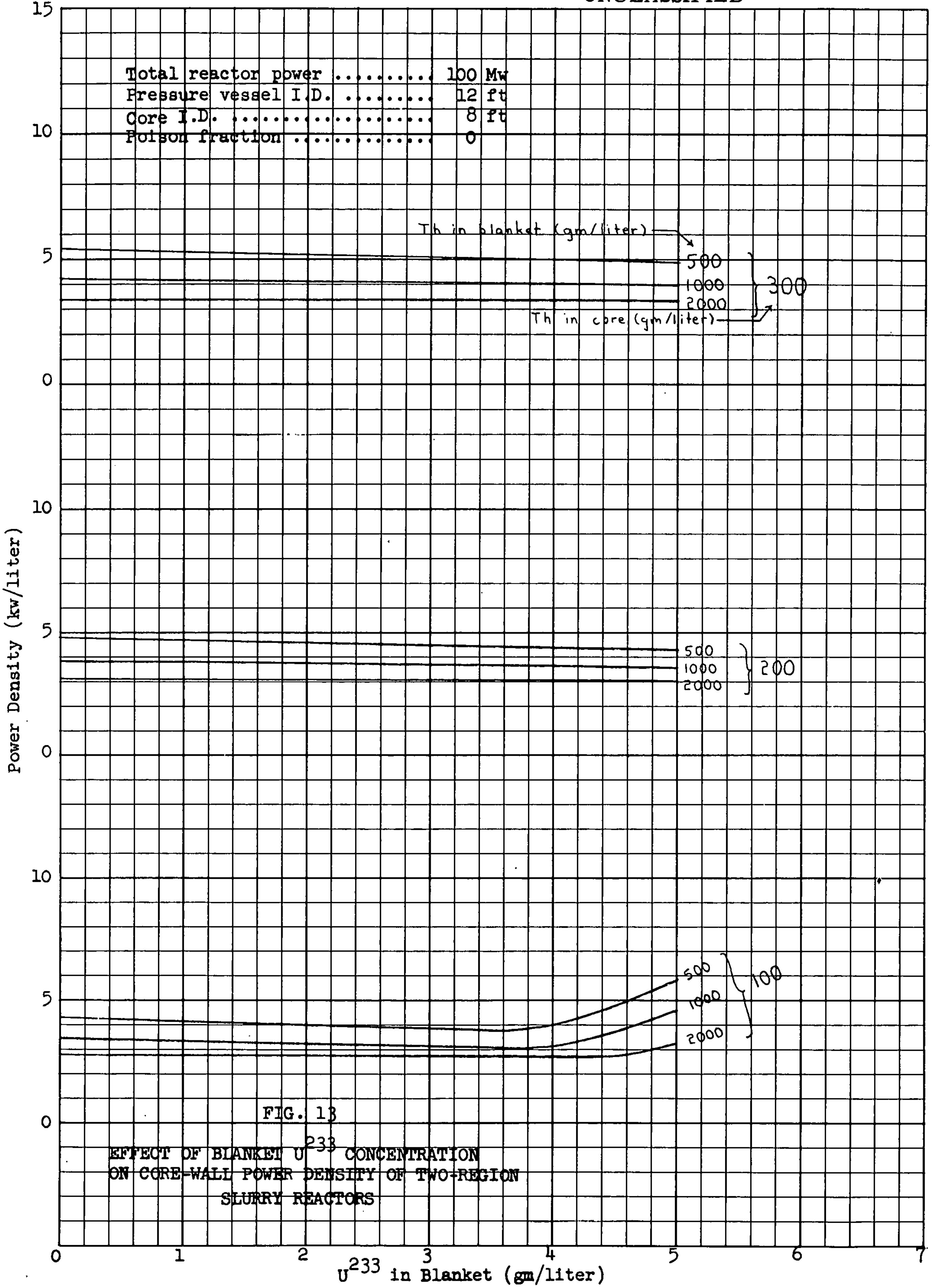

FIG. 13

EFFECT OF BLANKET U^{233} CONCENTRATION ON CORE-WALL POWER DENSITY OF TWO-REGION SLURRY REACTORS

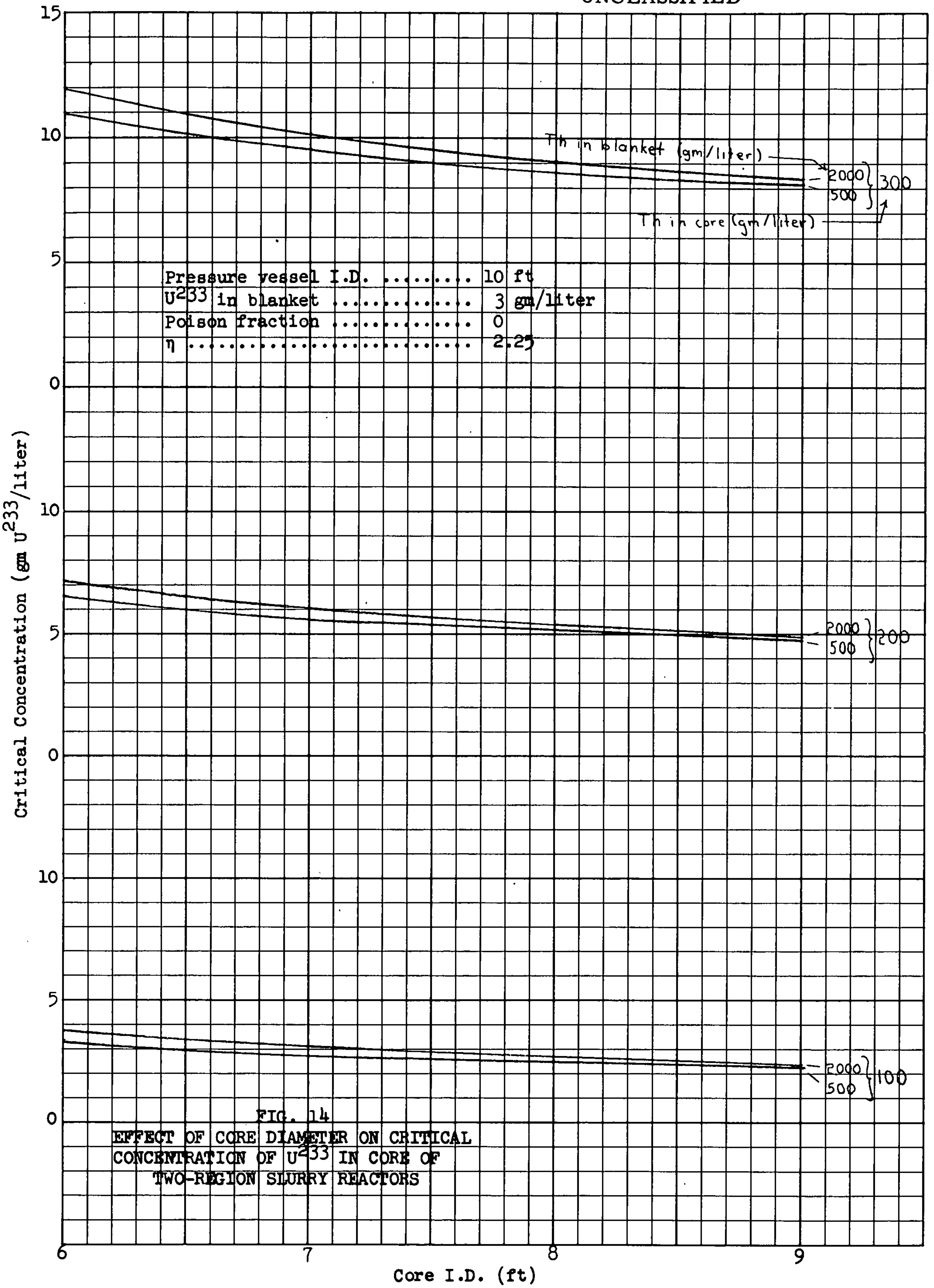

FIG. 14
EFFECT OF CORE DIAMETER ON CRITICAL CONCENTRATION OF U^{233} IN CORE OF TWO-REGION SLURRY REACTORS

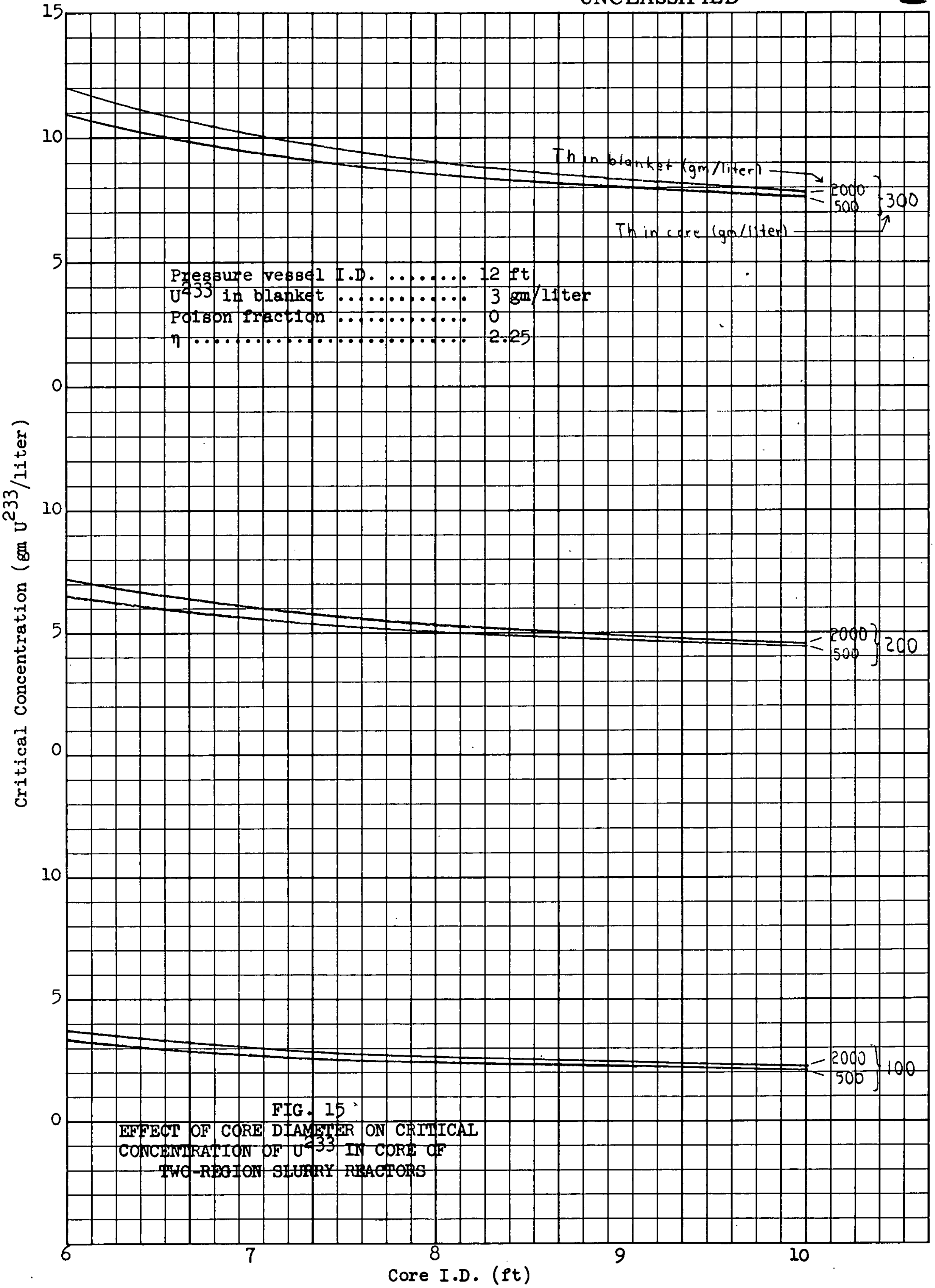

FIG. 15
EFFECT OF CORE DIAMETER ON CRITICAL CONCENTRATION OF U^{233} IN CORE OF TWO-REGION SLURRY REACTORS

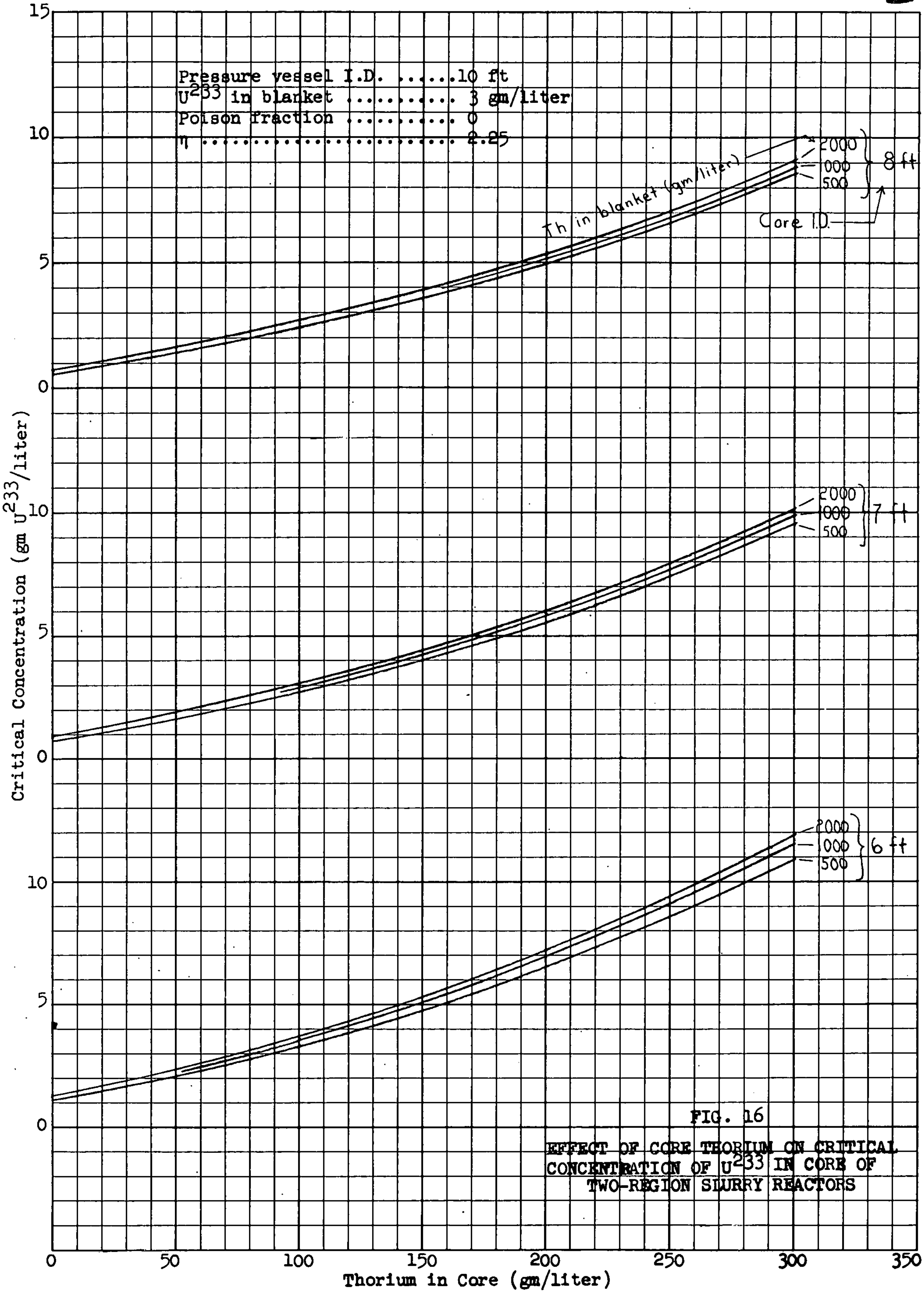

FIG. 16

EFFECT OF CORE THORIUM ON CRITICAL CONCENTRATION OF U^{233} IN CORE OF TWO-REGION SLURRY REACTORS

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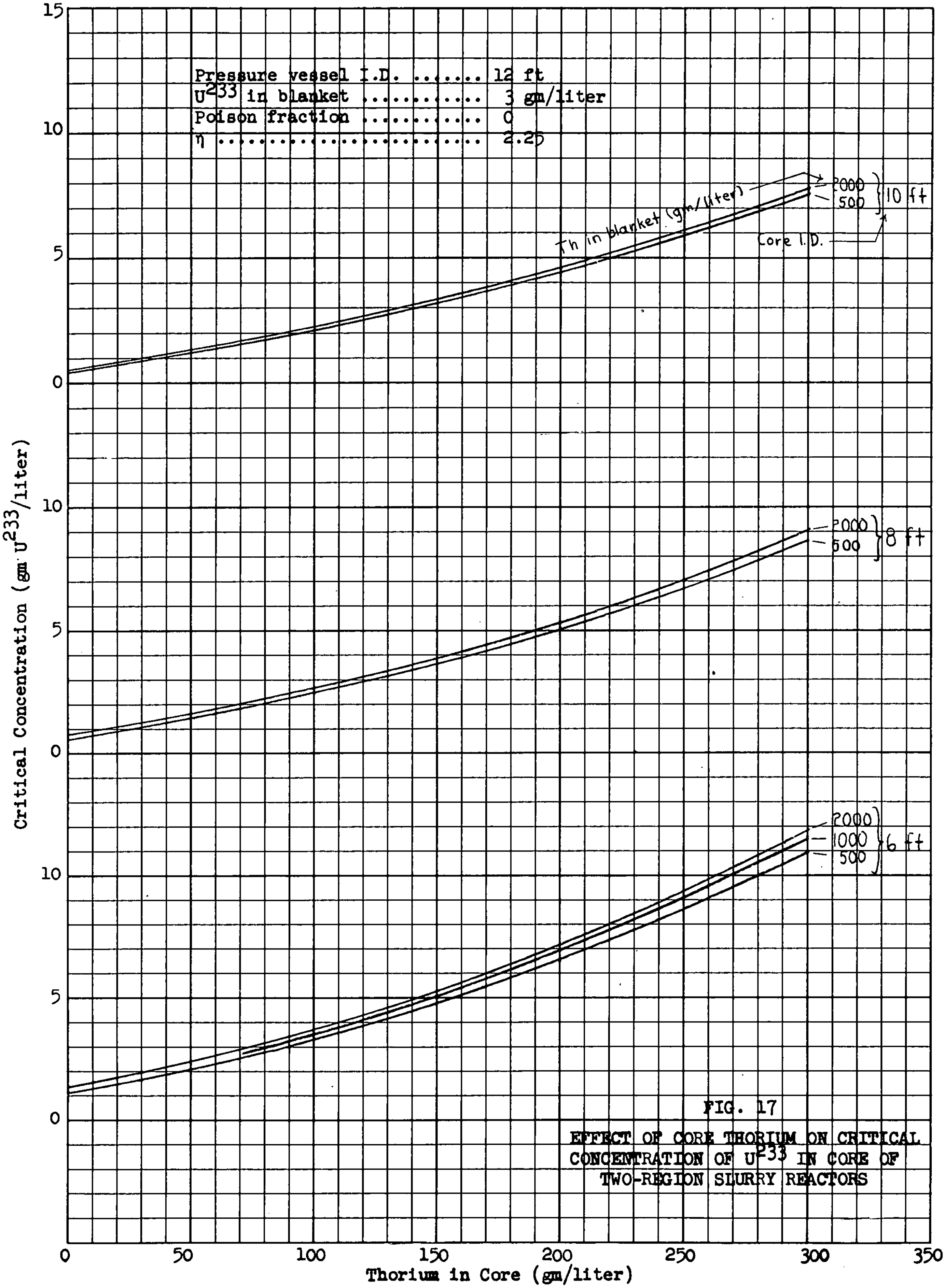

FIG. 17

EFFECT OF CORE THORIUM ON CRITICAL CONCENTRATION OF U^{233} IN CORE OF TWO-REGION SLURRY REACTORS

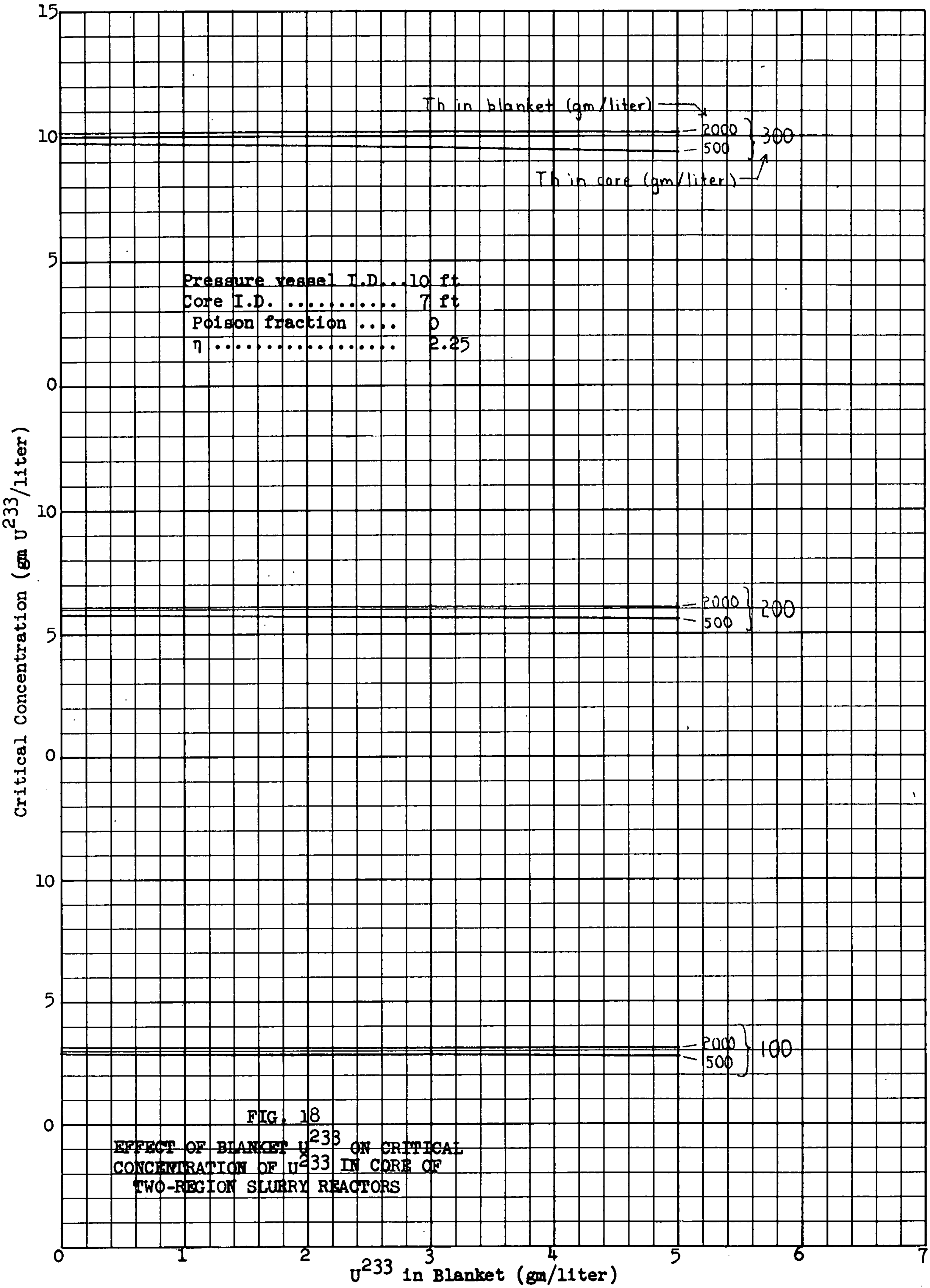

FIG. 18
EFFECT OF BLANKET U^{233} ON CRITICAL CONCENTRATION OF U^{233} IN CORE OF TWO-REGION SLURRY REACTORS

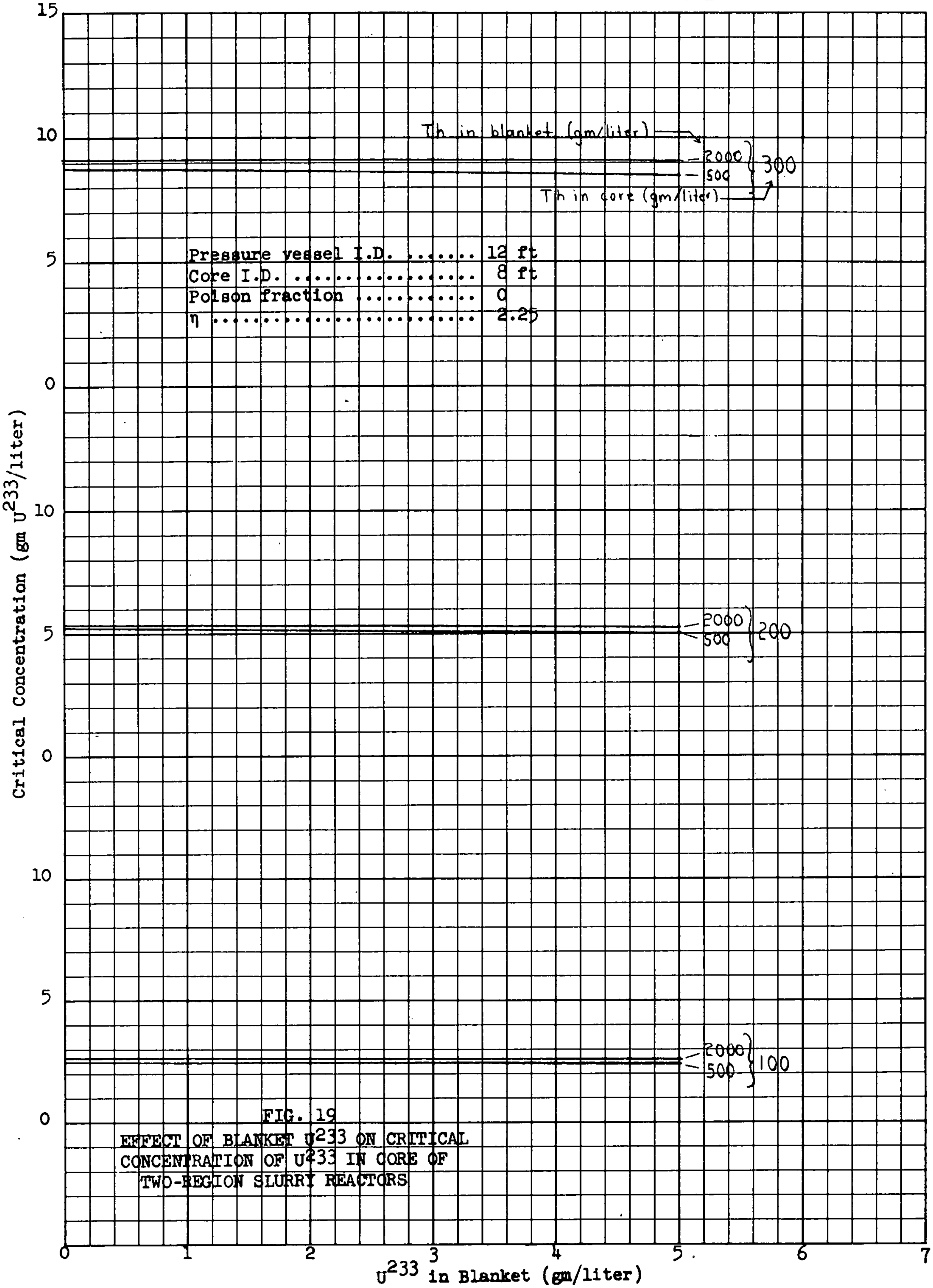

FIG. 19
EFFECT OF BLANKET U^{233} ON CRITICAL CONCENTRATION OF U^{233} IN CORE OF TWO-REGION SLURRY REACTORS

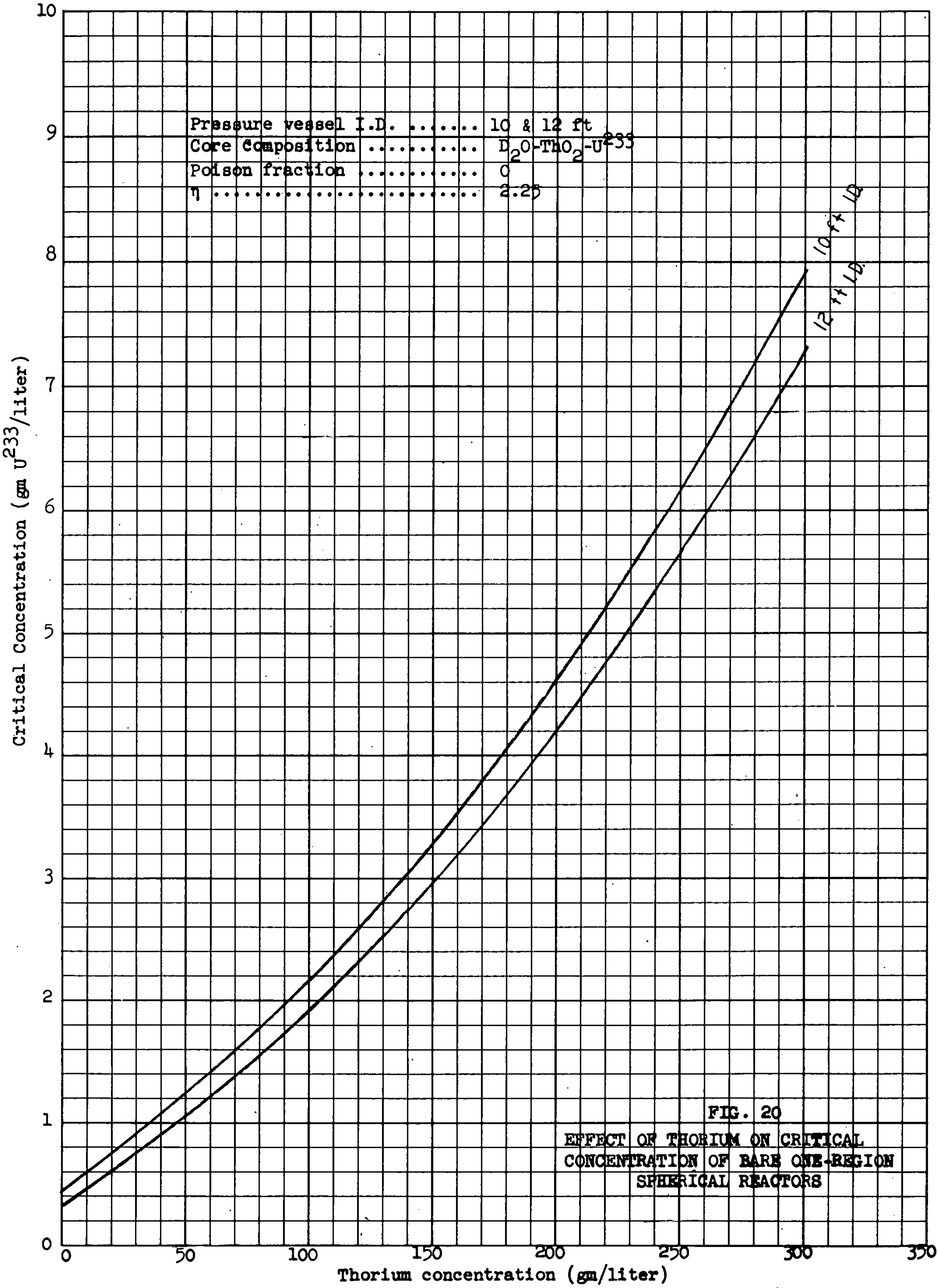

FIG. 20
EFFECT OF THORIUM ON CRITICAL CONCENTRATION OF BARE ONE-REGION SPHERICAL REACTORS

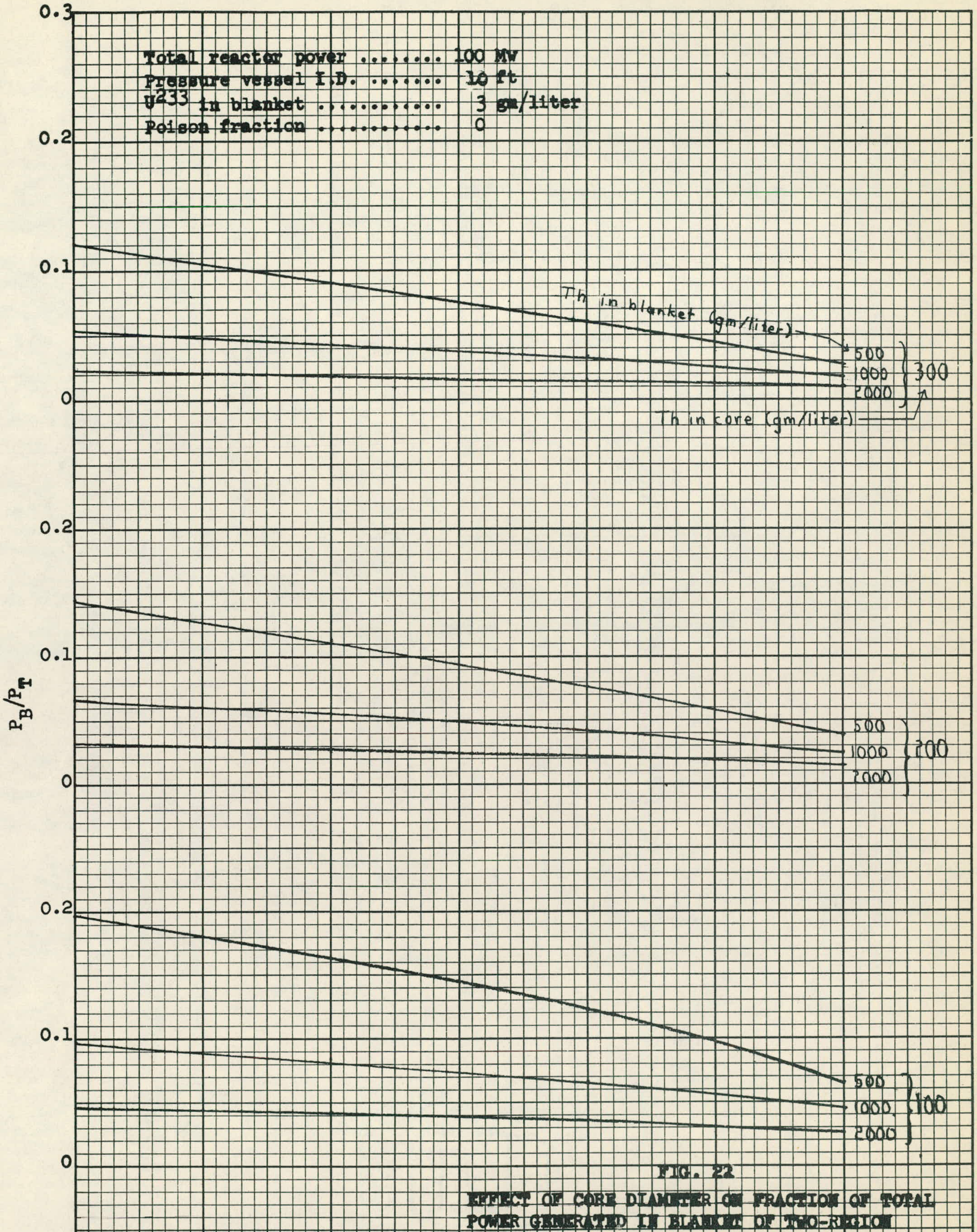

FIG. 22
EFFECT OF CORE DIAMETER ON FRACTION OF TOTAL POWER GENERATED IN BLANKET OF TWO-REGION SLURRY REACTORS

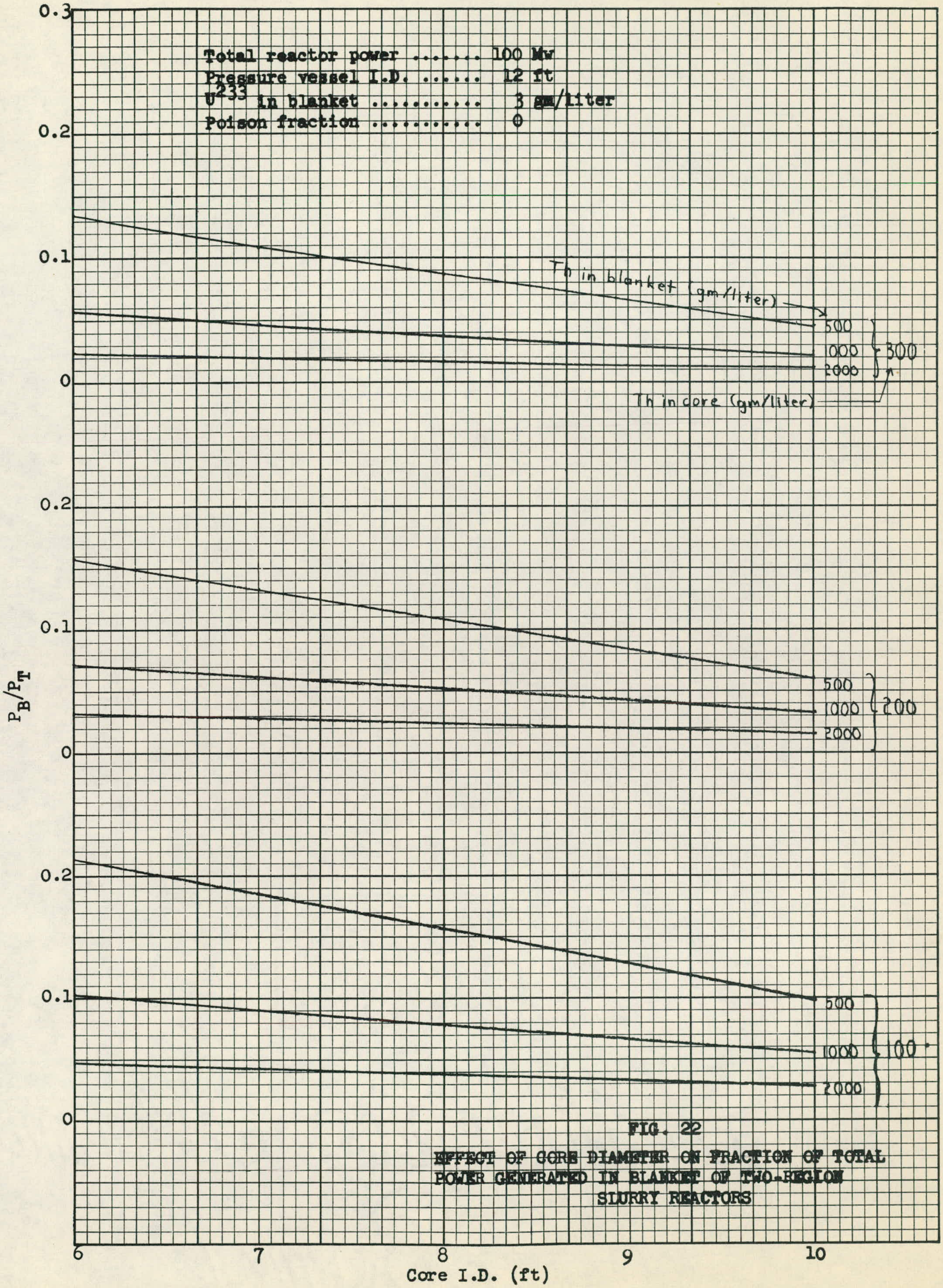

FIG. 22

EFFECT OF CORE DIAMETER ON FRACTION OF TOTAL POWER GENERATED IN BLANKET OF TWO-REGION SLURRY REACTORS

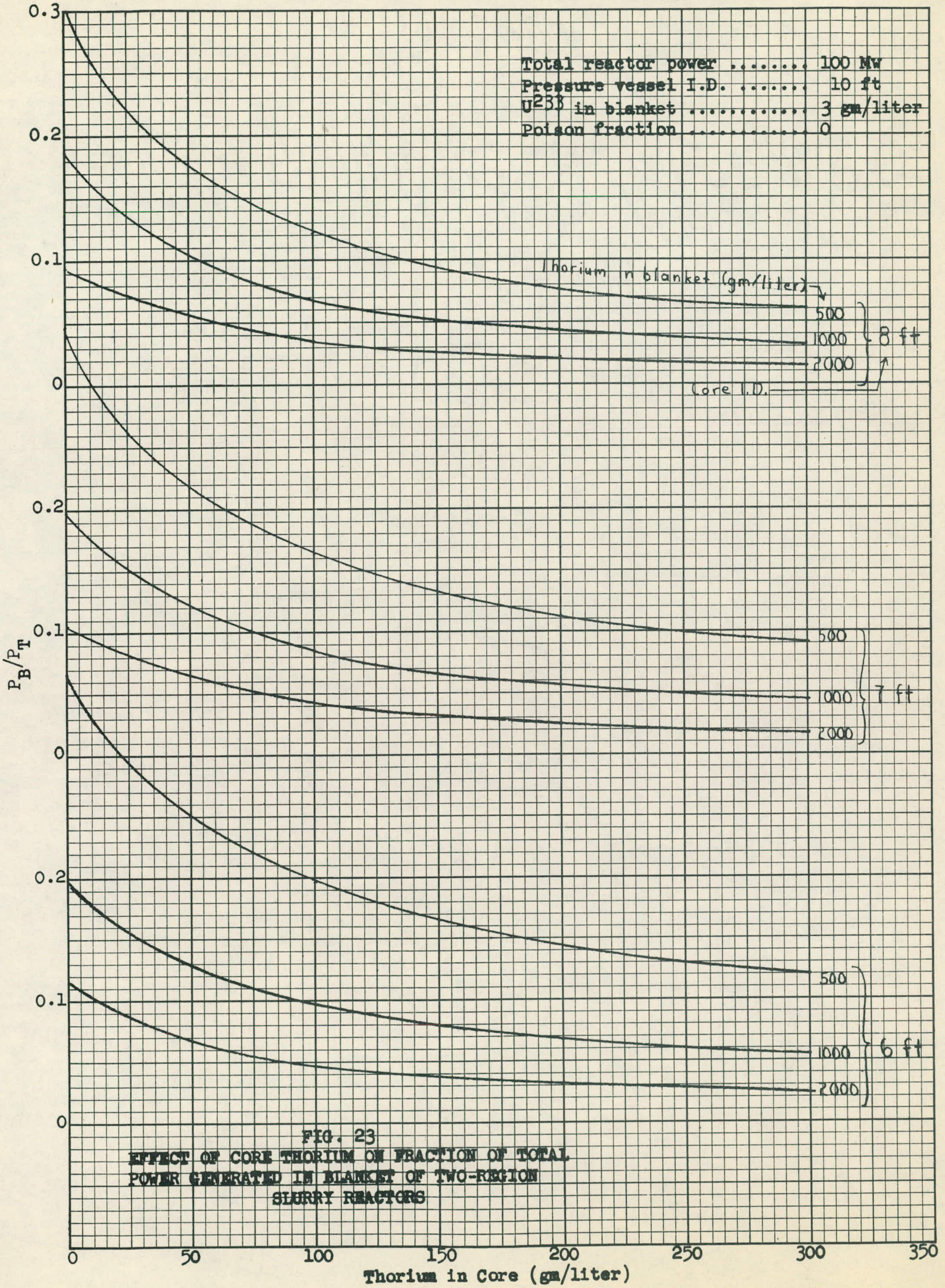

FIG. 23
EFFECT OF CORE THORIUM ON FRACTION OF TOTAL POWER GENERATED IN BLANKET OF TWO-REGION SLURRY REACTORS

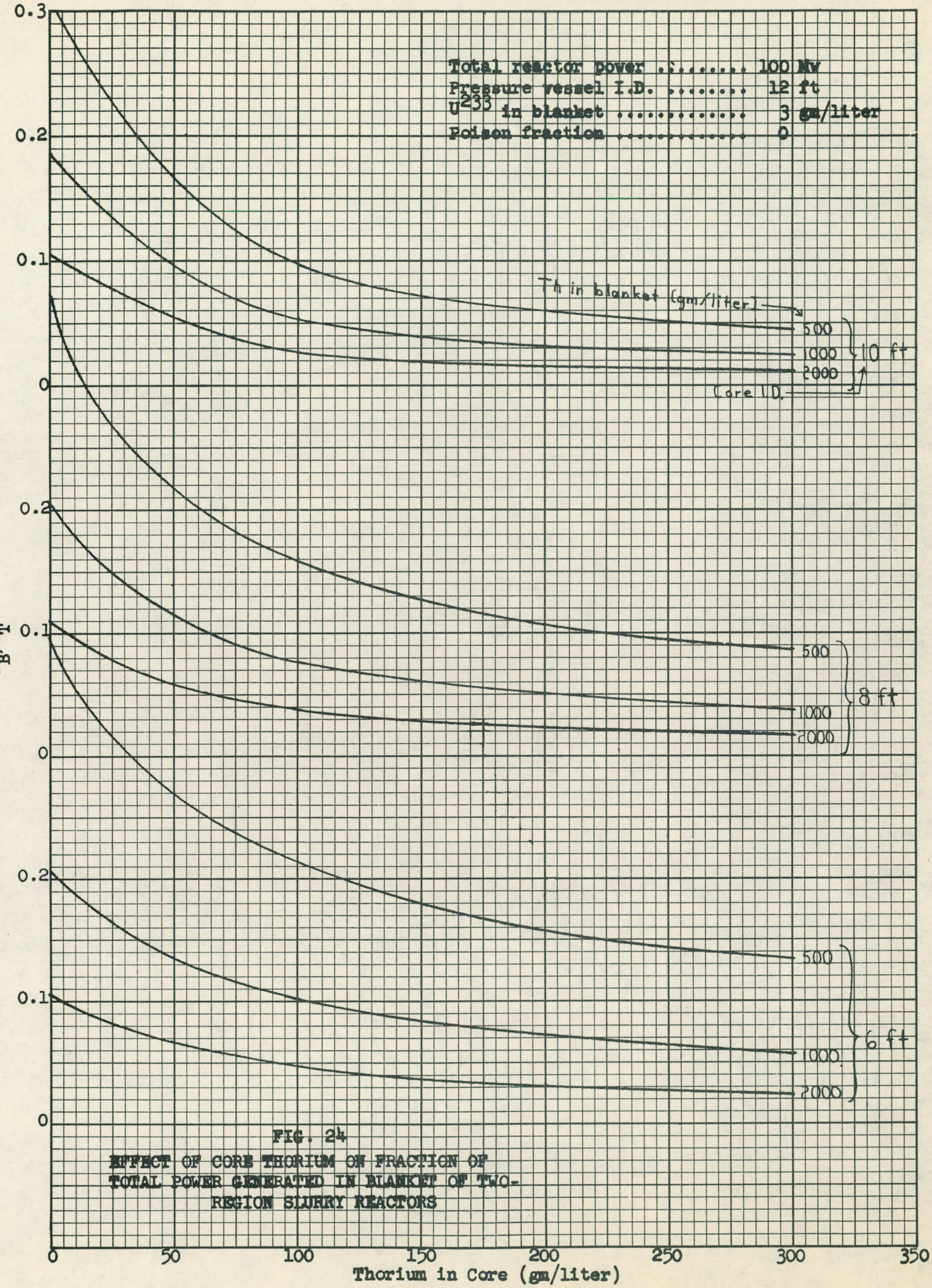

FIG. 24
EFFECT OF CORE THORIUM ON FRACTION OF TOTAL POWER GENERATED IN BLANKET OF TWO-REGION SLURRY REACTORS

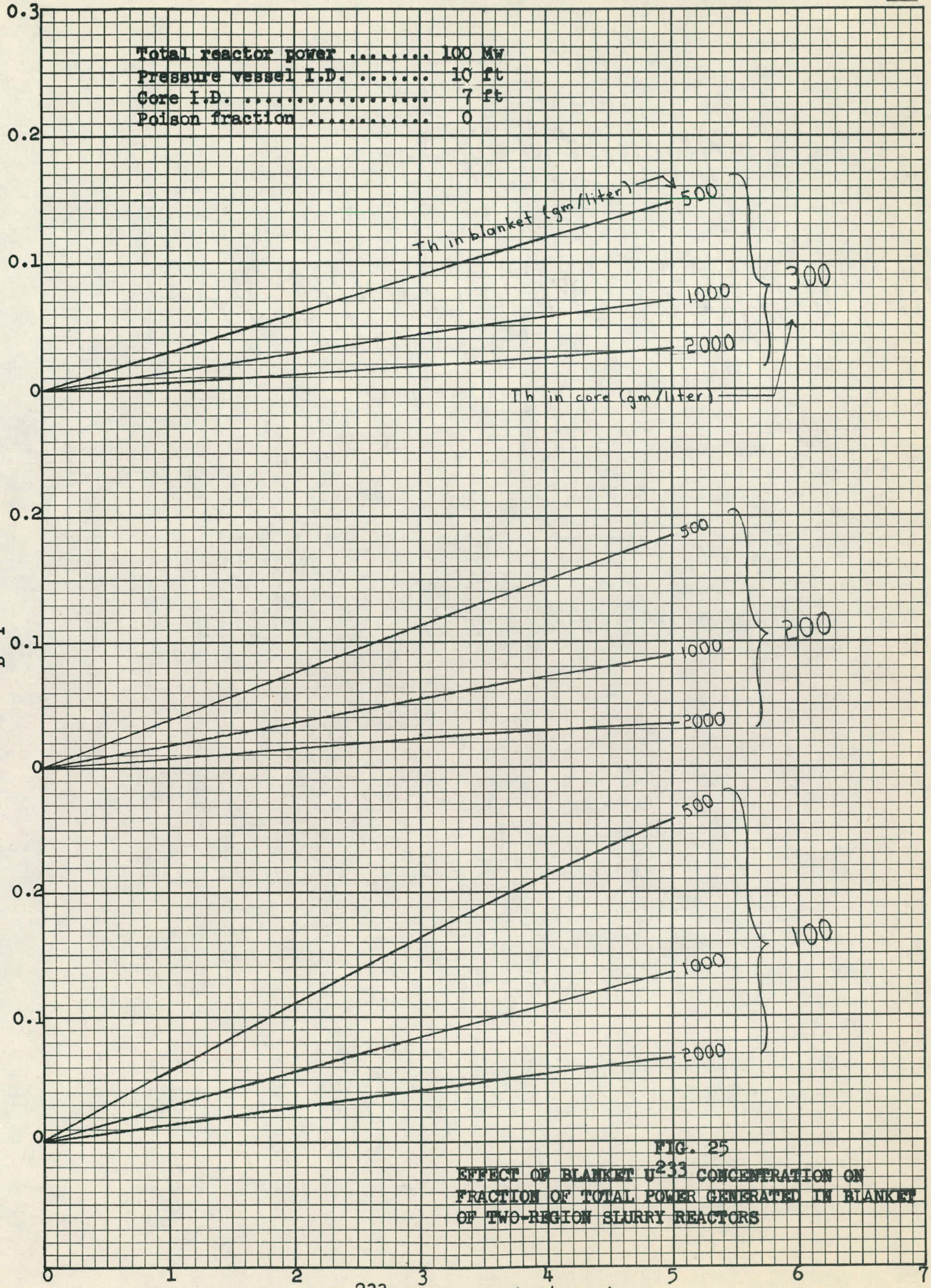

FIG. 25
EFFECT OF BLANKET U^{233} CONCENTRATION ON FRACTION OF TOTAL POWER GENERATED IN BLANKET OF TWO-REGION SLURRY REACTORS

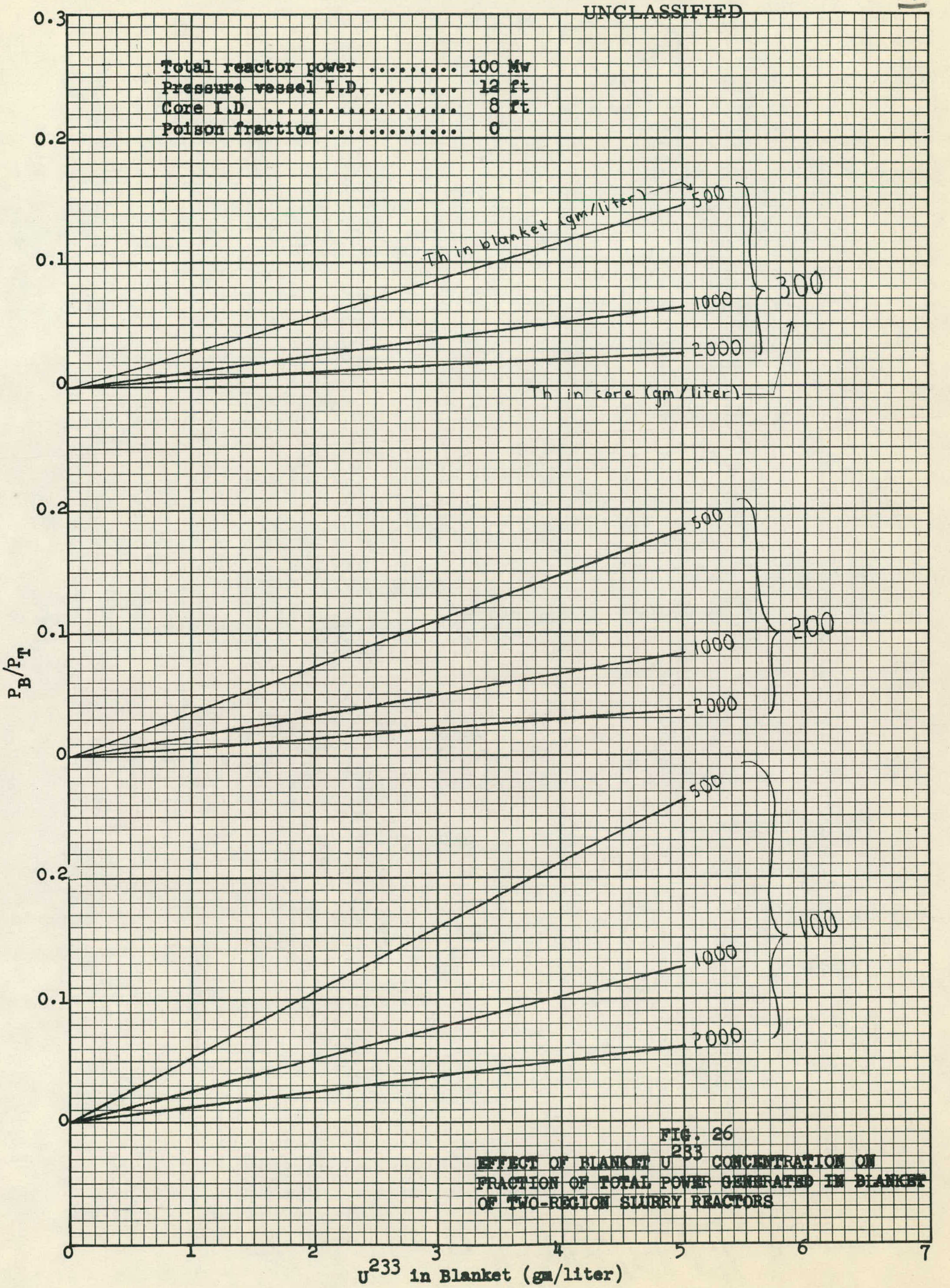

FIG. 26
EFFECT OF BLANKET U^{233} CONCENTRATION ON FRACTION OF TOTAL POWER GENERATED IN BLANKET OF TWO-REGION SLURRY REACTORS

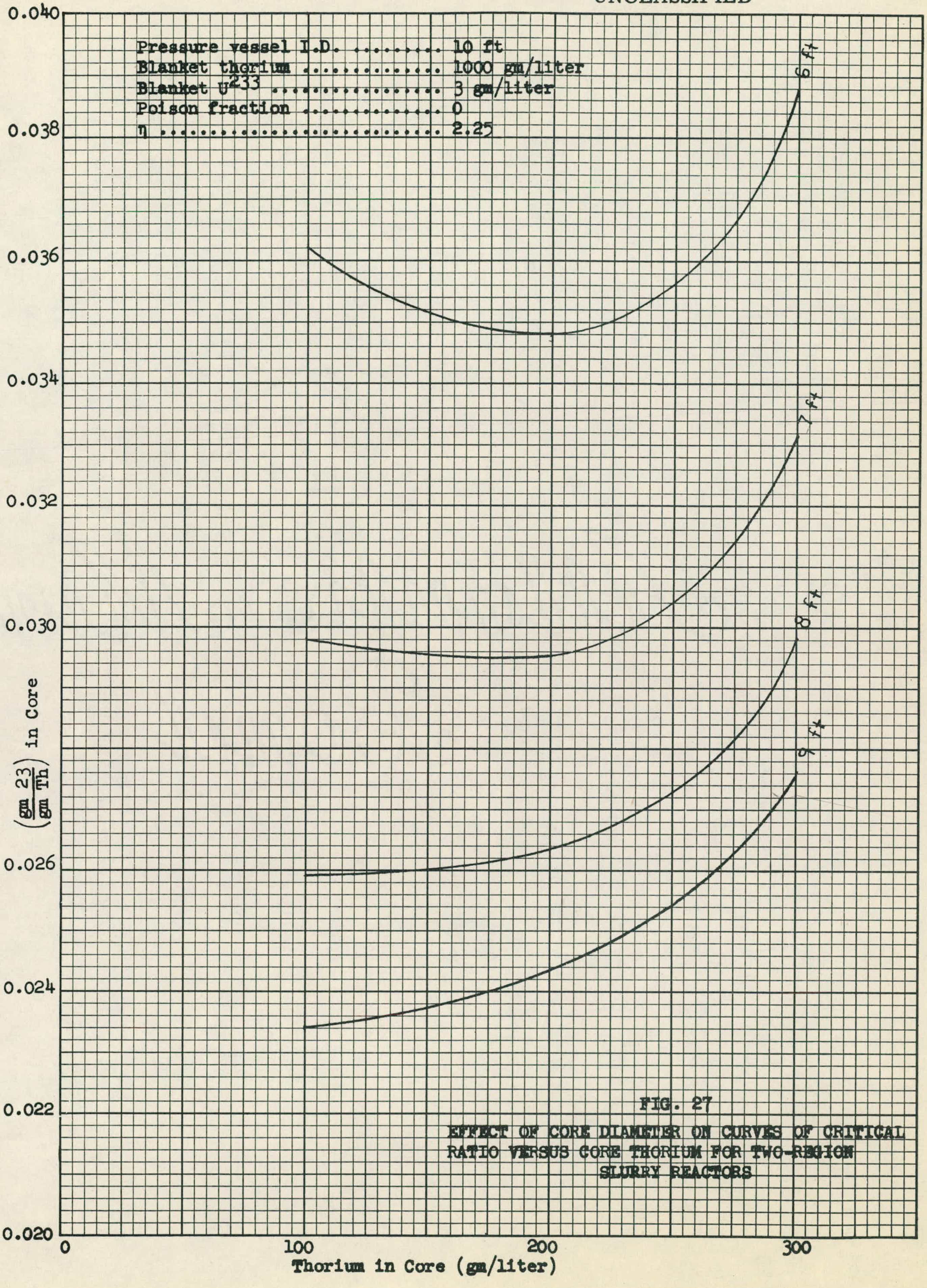

FIG. 27

EFFECT OF CORE DIAMETER ON CURVES OF CRITICAL RATIO VERSUS CORE THORIUM FOR TWO-REGION SLURRY REACTORS

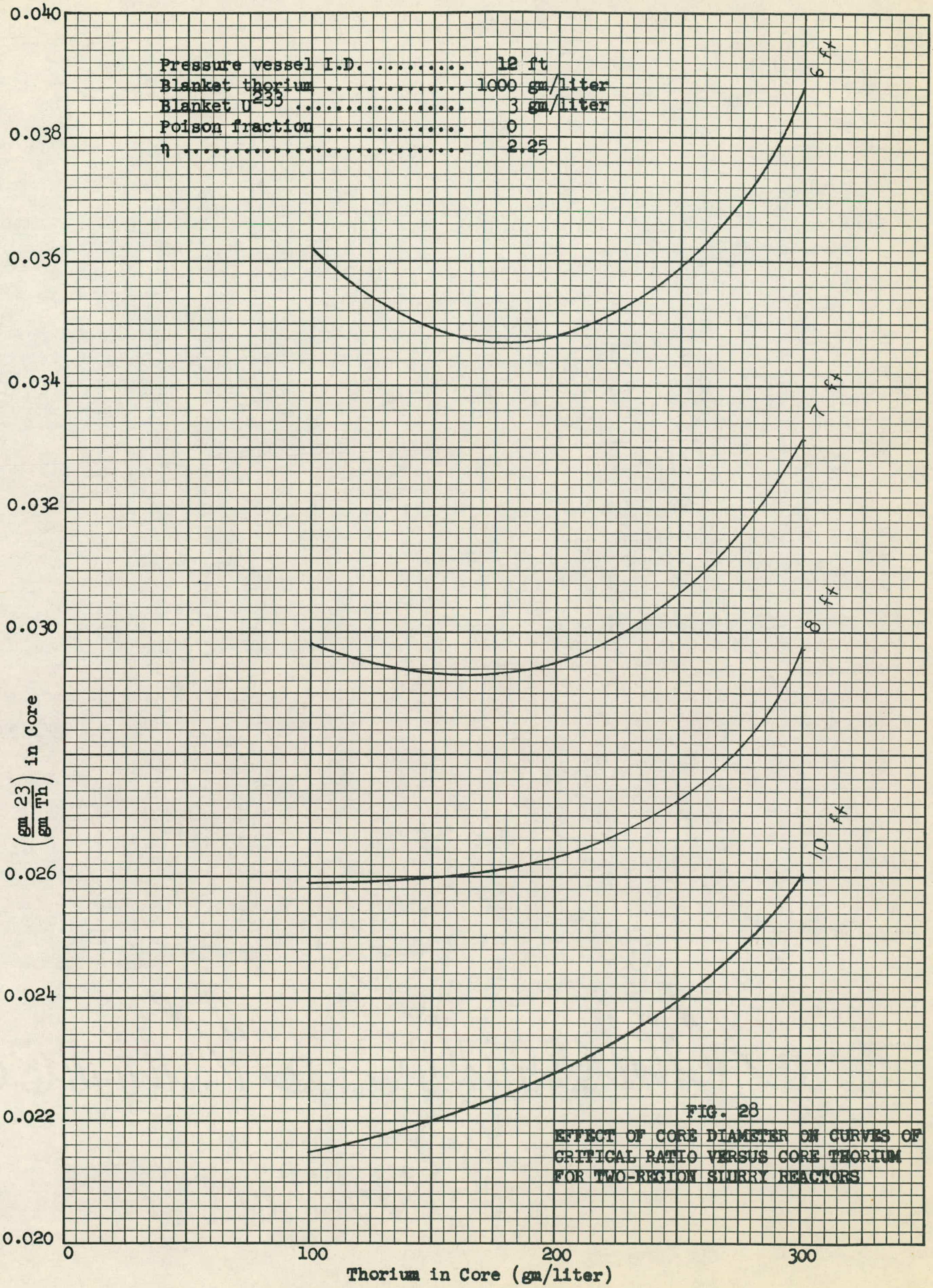

FIG. 28
EFFECT OF CORE DIAMETER ON CURVES OF CRITICAL RATIO VERSUS CORE THORIUM FOR TWO-REGION SLURRY REACTORS

ORNL-LR-Dwg.-17891
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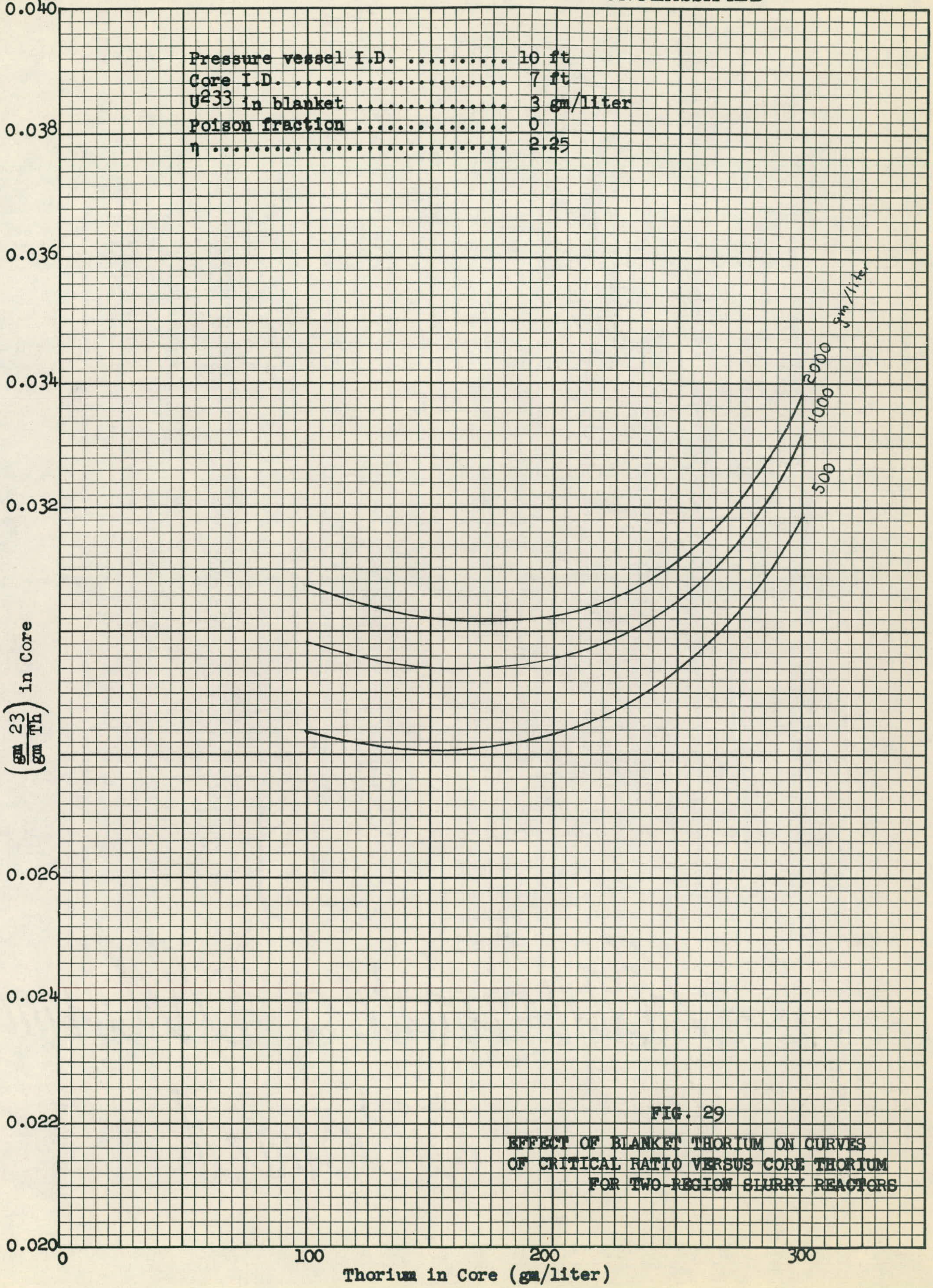

FIG. 29

EFFECT OF BLANKET THORIUM ON CURVES OF CRITICAL RATIO VERSUS CORE THORIUM FOR TWO-REGION SLURRY REACTORS

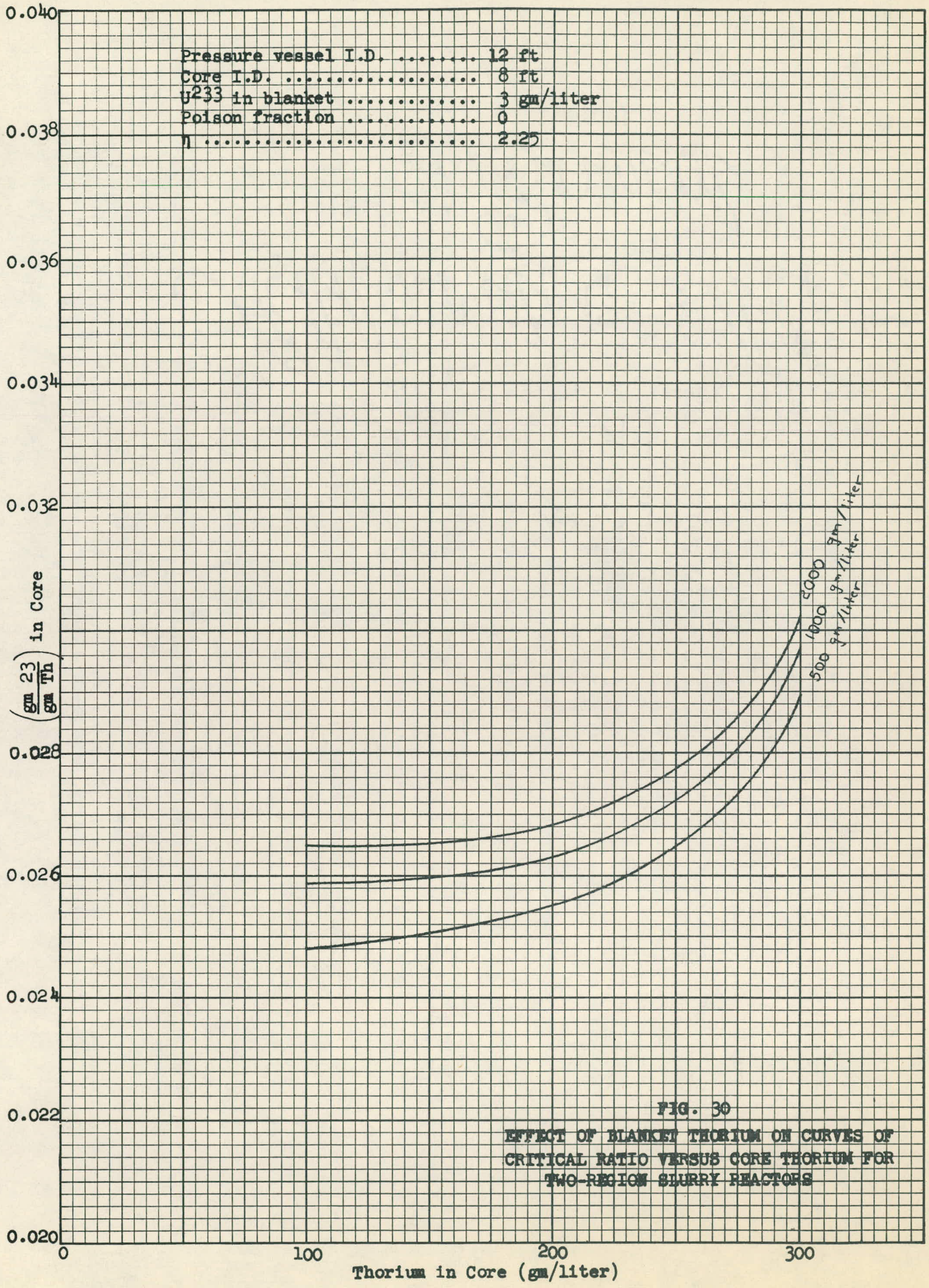

FIG. 30

EFFECT OF BLANKET THORIUM ON CURVES OF CRITICAL RATIO VERSUS CORE THORIUM FOR TWO-REGION SLURRY REACTORS

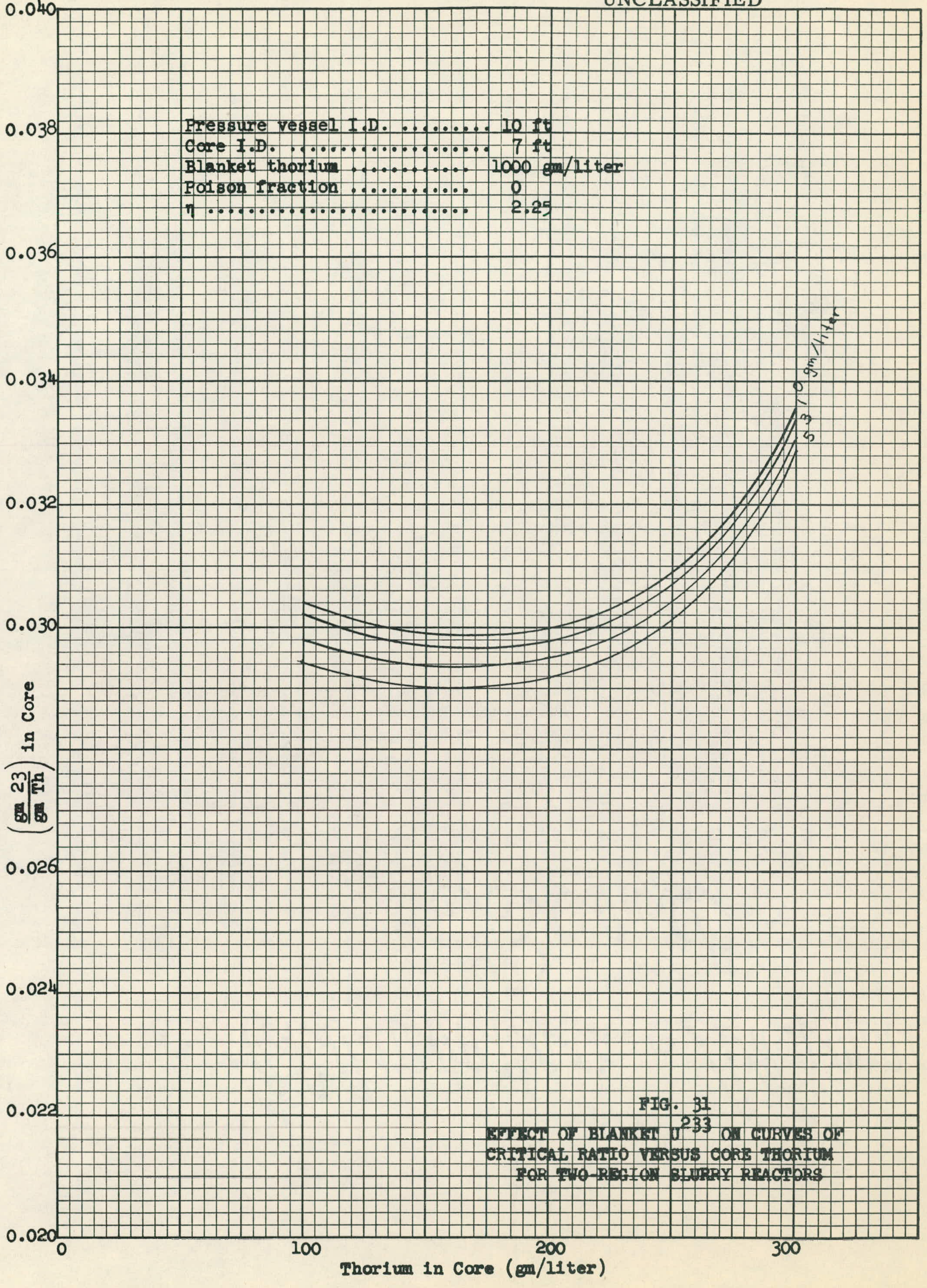

FIG. 31
EFFECT OF BLANKET U^{233} ON CURVES OF CRITICAL RATIO VERSUS CORE THORIUM FOR TWO-REGION SLURRY REACTORS

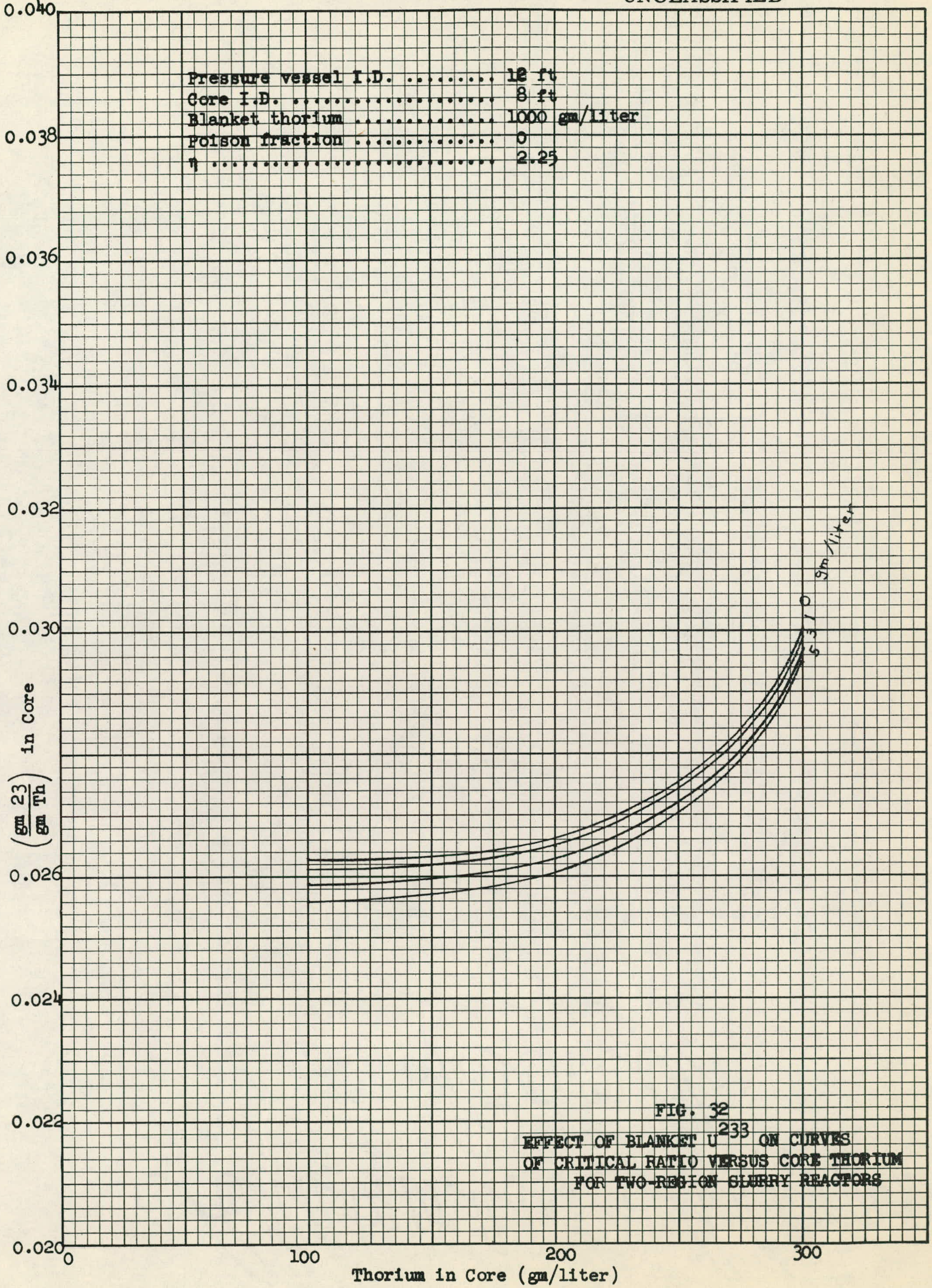

FIG. 32
EFFECT OF BLANKET U^{233} ON CURVES OF CRITICAL RATIO VERSUS CORE THORIUM FOR TWO-REGION SLURRY REACTORS

Table II

Nuclear Characteristics of Some 10-ft Reactors*

Feature	Values				
Pressure vessel I.D., ft	10	10	10	10	10
Core I.D., ft	7	7	7	7	9
Core Th, gm/liter	100	200	0	300	100
Blanket Th, gm/liter	1000	2000	2000	0	1000
Blanket U^{233}, gm/liter	3.0	3.0	3.0	0	3.0
Core critical conc., gm U^{233}/liter	3.0	6.0	0.96	8.0	2.3
Total power, Mw	100	100	100	100	100
Blanket power, Mw	8.5	2.6	10.6	0	4.4
Breeding ratio	1.18	1.21	1.14	0.97	1.05
PD (core avg), kw/liter	18.0	18.5	17.6	19.7	8.6
PD (blanket avg), kw/liter	0.89	0.27	1.1	0	1.2
PD (0), kw/liter	43	46	45	29	22
PD (a), kw/liter	5.4	5.0	4.0	19	2.1
PD (b) kw/liter	4.1	1.7	8.1	0	2.0
ϕ_{2C}(avg) x 10^{-14}	2.3	1.2	7.0	0.96	1.4
ϕ_{2B}(avg) x 10^{-13}	1.1	0.34	1.4	7.6	1.5
ϕ (0) x 10^{-14}	5.5	2.9	17.9	1.4	3.6
Absorptions ** in core by:					
U^{233}	91.5	97.4	89.4	100.0	95.6
Th^{232} (resonance)	24.6	40.5	-	48.3	26.6
Th^{232} (slow)	39.7	41.6	-	48.4	52.8
D_2O	1.4	0.7	4.2	0.6	1.8
Absorptions in core tank	1.5	0.7	3.3	2.4	1.2
Absorptions in blanket by:					
U^{233}	8.5	2.6	10.6	-	4.4
Th^{232} (resonance)	16.6	16.6	22.3	-	6.0
Th^{232} (slow)	36.6	22.5	91.6	-	19.3
D_2O	0.1	0.0	0.1	0.8	0.1
Fast leakage	3.5	2.2	3.2	2.7	10.5
Slow leakage	1.0	0.2	0.3	21.8	6.7

* Reactors have no isotope buildup or poisons in core or blanket

** Absorptions and leakages normalized to 100 absorption in U^{233}

Table III

Nuclear Characteristics of Some 12-ft Reactors*

Feature	Values				
Pressure vessel I.D., ft	12	12	12	12	12
Core I.D., ft	8	8	8	8	10
Core Th, gm/liter	100	200	0	300	100
Blanket Th, gm/liter	1000	2000	2000	0	1000
Blanket U^{233}, gm/liter	3.0	3.0	3.0	0	3.0
Core critical conc., gm U^{233}/liter	2.6	5.4	0.72	7.4	2.2
Total power, Mw	100	100	100	100	100
Blanket power, Mw	7.8	2.3	10.8	0	5.4
Breeding ratio	1.20	1.23	1.15	1.02	1.16
PD (core avg), kw/liter	12.1	12.9	11.8	13.2	6.4
PD (blanket avg), kw/liter	0.44	0.13	0.61	0	0.50
PD (0), kw/liter	30	32	31	19	16
PD (a), kw/liter	3.3	3.0	2.4	13.3	1.4
PD (b), kw/liter	2.8	1.1	6.4	0	1.5
ϕ_{2C}(avg) x 10^{-14}	1.8	0.93	6.2	0.68	1.2
ϕ_{2B}(avg) x 10^{-13}	0.56	0.17	0.76	2.1	0.66
ϕ_{2C}(0) x 10^{-14}	4.4	2.3	16.3	0.98	2.9
Absorptions ** in core by:					
U^{233}	92.2	97.7	89.2	100.0	94.6
Th (resonance)	25.4	41.5	-	49.5	26.7
Th (slow)	46.0	47.1	-	52.6	56.8
D_2O	1.6	0.8	5.6	0.6	2.0
Absorptions in core tank	1.4	0.6	3.4	2.4	1.1
Absorptions in blanket by:					
U^{233}	7.8	2.3	10.8	-	5.4
Th (resonance)	15.0	14.3	21.0	-	8.6
Th (slow)	33.9	19.9	93.6	-	23.5
D_2O	0.1	0.0	0.1	1.1	0.1
Fast leakage	1.3	0.7	1.2	0.9	4.5
Slow leakage	0.3	0.1	0.1	17.9	1.7

* Reactors have no isotope buildup or poisons in core or blanket

** Absorptions and leakages normalized to 100 absorption in U^{233}

APPENDIX

Table IV

Nuclear Properties and Input Numbers

gm Th / liter	$\sum_a^{Th}$ cm^{-1}	$\sum_a^{D_2O}$ cm^{-1}	p	τ cm^2	D_1 cm	D_2 cm
0	0	4.445×10^{-5}	1.000 (2)	206.6 (3)	1.621 (3)	1.226 (3)
100	1.27×10^{-3}	4.393×10^{-5}	0.868	206.7	1.605	1.218
200	2.54×10^{-3}	4.342×10^{-5}	0.795	206.9	1.590	1.209
300	3.81×10^{-3}	4.290×10^{-5}	0.740	207.2	1.576	1.201
500	6.35×10^{-3}	4.189×10^{-5}	0.660	207.6	1.548	1.184
1000	1.27×10^{-2}	3.924×10^{-5}	0.524	209.7	1.483	1.142
2000	2.54×10^{-2}	3.402×10^{-5}	0.346	217.0	1.367	1.070

Temperature = 280°C

Wt % D_2O in moderator = 99.75

Extrapolation distance = 15 cm

$\overline{\sigma_a}(23)$ = 380.7 bn

$\overline{\sigma_a}(Th)$ = 4.89 bn

$\overline{\sigma_a}(D_2O)$ = 1.758 mb

$\sigma_f(23)/\sigma_a(23)$ = 0.90

η = 2.25

$\rho(ThO_2)$ = 9.69 gm/ml

$\rho(D_2O)$ = 0.8395 gm/ml

D_S = 0.980 cm

$\sum_a^S$ = 5.059×10^{-3} cm^{-1}

$\sum_a^{23}$ = 9.842×10^{-4} x gm 23/liter, cm^{-1}

Estimation of the Effect of Core and Blanket Poisons Upon Breeding Ratio and Critical Mass

It is desirable to have a simple method of estimating the effect of changing core and blanket poisons upon breeding ratio and critical mass in thermal reactors without the need of making complete additional two-group calculations. Satisfactory approximations may indeed be made for poison-fraction increments of less than 15% of the fuel absorption cross section and for reactors that are large compared with a neutron mean-free-path.

Consider the case where only one fuel is used in both core and blanket. The breeding ratio may be written as

$$B.R. = \eta - 1 - \frac{A_C^M + A_B^M + A_S + A_C^p + A_B^p + L_1 + L_2}{A_C^F + A_B^F}$$

where A_C^M, A_B^M = absorptions in core and blanket, respectively, in any homogeneously distributed material which is not fuel, poison or fertile material

A_S = absorptions in the core tank

A_C^p, A_B^p = absorptions in the core and blanket, respectively, in poisons

L_1, L_2 = fast and slow leakage from the reactor

A_C^F, A_B^F = absorptions in fuel in core and blanket, respectively

Assume now that a small change in the core and blanket poison levels produces a change in the rate of neturon absorption by poisons only, and that the other rates of neutron absorption and leakage are unaffected. Then

$$\Delta B.R. = - \frac{\Delta A_C^p + \Delta A_B^p}{A_C^F + A_B^F} = - \frac{\Delta f_{pC} A_C^F}{A_C^F + A_B^F} - \frac{\Delta f_{pB} A_C^F}{A_C^F + A_B^F}$$

where Δf_{pC}, Δf_{pB} = the incremental change in the poison fraction in the core and blanket, respectively, where the poison fraction is defined as the ratio of neutron absorptions in poison to neutron absorptions in fuel in a given region.

For one fuel we may write

$$\frac{A_C^F}{A_C^F + A_B^F} = \frac{P_C}{P_T} ; \quad \frac{A_B^F}{A_C^F + A_B^F} = \frac{P_B}{P_T}$$

where P_C, P_B, and P_T are the core, blanket, and total reactor powers, respectively. Therefore

$$\Delta \text{ B.R.} = - \Delta f_{pC} \frac{P_C}{P_T} - \Delta f_{pB} \frac{P_B}{P_T}$$

This approximation is in very good agreement with breeding increments obtained by comparison of complete two-group two-region calculations, as will be shown later.

Estimates of the change in critical mass are somewhat more difficult to make. Generally, for blankets which are fairly "black" to neutrons or for a large core, increments of a few percent in the blanket poison will produce negligible changes in the core fuel concentration. In the case of a "black" blanket, the core behaves almost like a bare reactor; in the case of a large core, the blanket is a region of low importance. Changes in core poisons produce much more significant effects upon the critical concentration. In the case of a bare reactor, the two-group model gives the critical fuel macroscopic absorption cross section as:

$$\Sigma_a^F = \frac{(1 + \tau B^2)(\Sigma_a^E + D_2 B^2)}{\eta p - (1 + \tau B^2)(1 + f_{pC})}$$

Where Σ_a refers to the absorption cross section of F(fuel), and E (all other materials except poison but including fertile), D_2 is the thermal diffusion constant, p is the resonance escape probability, f_{pC} is the poison fraction, and η, τ, and B^2 have their customary meanings. If an increment Δf_{pC} is made in the poison fraction, (i.e., Δf_{pC} = final poison fraction - initial poison fraction) the new fuel cross section is

$$\Sigma_a^{F'} = \frac{(1 + \tau B^2)\left[\Sigma_a^E + D_2 B^2\right]}{\eta p - (1 + \tau B^2)(1 + f_{pC} + \Delta f_{pC})}$$

$$\frac{\Sigma_a^{F'}}{\Sigma_a^F} = \frac{\eta_p - (1 + \tau B^2)(1 + f_{pC})}{\eta p - (1 + \tau B^2)(1 + f_{pC}) - \Delta f_{pC}(1 + \tau B^2)}$$

$$= \frac{1}{1 - \dfrac{\Delta f_{pC}}{\dfrac{\eta p}{1 + \tau B^2} - (1 + f_{pC})}}$$

This result is correct for a one-region reactor. For a reflected reactor an equivalent B^2 would be found by solving the one-region critical equation as a quadratic in B^2 using the known core cross sections for the two-region reactor. The result of this procedure will not be exact, but for the cases examined here the results were quite accurate.

Illustration A. -- Calculation of change in breeding ratio due to adding poison to core, blanket, or both.

Consider a 7-ft. I.D. core in a 10-ft. I.D. pressure vessel. The core contains 100 gm Th/liter in the core and the blanket contains 1000 gm Th/liter and 3 gm U-233/liter. The breeding ratio with no poisons in the core is 1.175; P_C = 91.5 Mw, P_B = 8.5 Mw. What is the estimated breeding ratio change if: (a) the blanket poison fraction is 0.04; (b) the core poison fraction is 0.036; (c) the core poison fraction is 0.036 and the blanket poison fraction is 0.04?

Solution to (a): $\Delta B.R. = -\frac{(0.04)\ (8.5)}{100} = -0.003$

Solution to (b): $\Delta B.R. = -\frac{(0.036)\ (91.5)}{100} = -0.033$

Solution to (c): $\Delta B.R. = -0.003 - 0.033 = -0.036$

The changes in breeding ratio calculated using the two-group two-region Oracle code were - 0.003, - 0.0031, and - 0.034 for conditions (a), (b), and (c), respectively. A total of 23 cases were compared, all 10-ft. pressure vessels with cores from 6 to 9 ft. I.D., core Th concentrations of 100 and 300 gm/liter, and blanket Th concentrations of 500 and 1000 gm Th/liter. Core poison fractions were 0, 0.036, and 0.072 of the fuel absorption cross-section, and blanket poison fractions were 0, 0.013, 0.024, 0.04, and 0.08 of the fuel absorption cross section in the blanket. Blanket U-233 concentrations employed were 1, 3, and 5 gm/liter. The estimated change in breeding ratio was high in all cases, and for most was in agreement with the Oracle value by 10% or better. In four cases errors of 15 to 38% were noted. Two of the cases were for 9-ft. cores and the other two were for 500 gm Th/liter blankets. In all these cases the error was connected principally with core poison increments. It would appear that these larger errors are due to increased leakage from the reactor. In the 9-ft. cases increased leakage is due to the smaller blanket thickness, and in the 500 gm Th per liter cases, the higher power density and lower Th concentration would increase leakage. (It must also be noted that none of the four cases are of great practical interest, nor are the estimated breeding gains in serious error.)

Illustration B. -- Calculation of change in critical concentration due to adding poison to core.

Consider the same reactor as described in the previous section, example (b). The buckling of the unpoisoned bare reactor which contains the same amount of fuel and thorium as the reflected reactor is:

$$B_{eq}^2 = -\frac{1}{2}\left[\frac{\Sigma_a^E + \Sigma_a^F}{D_2} + \frac{1}{\tau}\right]\sqrt{\left(\frac{1}{2}\left(\frac{\Sigma_a^E + \Sigma_a^F}{D_2} + \frac{1}{\tau}\right)\right)^2 + \frac{(\eta p-1)\,\Sigma_a^F - \Sigma_a^E}{D_2\tau}}$$

where $\Sigma_a^E = 1.314 \times 10^{-3}\ \text{cm}^{-1}$

$\Sigma_a^F = 2.93273 \times 10^{-3}\ \text{cm}^{-1}$

$D_2 = 1.218\ \text{cm}$

$\tau = 206.7\ \text{cm}^2$

$\eta = 2.25$

$p = 0.868$

$B_{eq}^2 = 6.5505 \times 10^{-4}\ \text{cm}^{-2}$

This corresponds to an extrapolated radius of 122.75 cm or adding an extrapolation distance of 6.33 in. to the core radius. The correction to the critical concentration was obtained from the formula:

$$\frac{\Sigma_a^{F'}}{\Sigma_a^F} = \frac{1}{1 - \dfrac{\Delta f_{pC}}{\dfrac{\eta p}{1 + \tau B^2} - (1 + f_{pC})}}$$

For this case, $f_{pC} = 0$, $\Delta f_{pC} = 0.036$. The new critical concentration estimated from this formula is 3.14 gm 23/ℓ as compared with the two-group Oracle calculation result of 3.13.

Similar excellent agreement was obtained in all other cases where comparison was possible. (An extrapolation distance of six inches was shown to be adequate for all of these cases.) Although further tests will be necessary to discover the limitations of this method of estimation, it is likely to prove successful in the majority of cases of interest.

References

1. T. B. Fowler, "Oracle Code for a General Two-Region, Two-Group Spherical Homogeneous Reactor Calculation," ORNL CF-55-9-133, (Sept. 22, 1955).

2. C. W. Nestor, personal communication.

3. Computed using the code given in: Melvin Tobias, "An Oracle Code for Calculation of Fermi Ages by Numerical Integration," ORNL CF-56-4-53 (April 10, 1956).

Notation

A_{2C}, A_{2B}	Thermal absorption rates in core and blanket, respectively. (A superscript indicates the material.)
A_C^M, A_B^M	Absorption rates in core and blanket, respectively, in material which is not fuel, poison, or fertile material.
ΔA_C^p , ΔA_B^p	An increment in A_C^p or A_B^p
A_C^p , A_B^p	Absorption rates in core and blanket poisons, respectively.
A_C^F , A_B^F	Absorption rates in core and blanket fuels, respectively.
A_S	Absorption rate in core wall.
A_{1C}^{Th} , A_{1B}^{Th}	Fast absorption rates in thorium in core and blanket, respectively.
B_{eq}^2	$(\pi/\tilde{R})^2$ for a bare reactor which is critical with the same material composition as the core of a two-region reactor (i.e., same fuel, moderator, poison, fertile material concentrations), cm.$^{-2}$
BR	Breeding ratio (absorption rate in fertile material in core and blanket divided by absorption rate in fuel in core and blanket).
ΔBR	An increment in BR.
D_1	Fast diffusion coefficient, cm.
D_2	Thermal diffusion coefficient, cm.
D_S	Core tank diffusion coefficient, cm. (Taken as the same for both fast and slow groups.)
f_{pB}	Poison fraction in blanket (ratio of poison absorption cross section in blanket to fuel absorption cross section in blanket).

Δf_{pB}	An increment in f_{pB}
f_{pC}	Poison fraction in core (ratio of poison absorption cross section in core to fuel absorption cross section in core).
Δf_{pC}	An increment in f_{pC}
L_1	Rate of fast leakage
L_2	Rate of slow leakage
p	Resonance escape probability
P_B	Blanket power, megawatts
P_C	Core power, megawatts
P_T	Total reactor power, megawatts
PD	Power density, kw/liter. PD(0) is the power density in the center of the core; PD(a) is the power density at the inner surface of the core wall; PD(b) is the power density at the outer surface of the core wall.
$\tilde{R}$	The extrapolated radius of a reactor, cm.
η	Number of fission neutrons produced per absorption of a neutron in a fuel atom.
ϕ_{2C}(avg.), ϕ_{2B}(avg.)	Average thermal fluxes in core and blanket regions, respectively, neut/cm^2 - sec.
$\phi_{2C}(0)$	Thermal flux at center of reactor core, neut/cm^2-sec.
ρ	Density, gm/ml.
$\bar{\sigma}_a$,	Miscroscopic absorption cross section in barns averaged over Maxwell-Boltzmann distribution. (A superscript is used to indicate the material.)
$\sigma_f^{23}/\sigma_a^{23}$	Ratio of fission to absorption microscopic cross sections in U^{233}.

Σ_a	Macroscopic absorption cross section averaged over a Maxwell-Boltzmann distribution, cm^{-1}, (A superscript is used to indicate the material.)
Σ_a^F	Fuel absorption cross section in reactor core, cm^{-1}.
Σ_a^E	Absorption cross section in core of all material which is not fuel or poison, cm^{-1}
τ	Fermi age