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PROGRAM

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STATEMENT OF PROBLEM

Perform a nuclear parameter study and an economic evaluation of the reference paste-fueled fast reactor.

ABSTRACT

The reference design is an unmoderated, sodium cooled reactor using a paste fuel of uranium monocarbide in sodium. The core is a cylinder 5 feet in diameter and 5 feet in height. An 18 inch thick breeding blanket surrounds the core, and an 18 inch thick graphite reflector surrounds the blanket. Various changes were made in the reference core to uncover any possible modifications for cost reductions and to evaluate the consequences of certain design modifications which might occur. This table shows all cases studied:

Parameter Varied	Range of Variation
1) fuel volume fraction in the core	0.2 - 0.6
2) fertile material volume fraction in the blanket	0.2 - 0.6
3) blanket thickness	3 in - 24 in
4) fuel material	UC, U metal, UO_2, PuC-UC, Pu-U metal, PuO_2-UO_2,
5) liquid carrier in the paste	Na, Sn, Pb

Results showed that:

1) High fuel volume fractions are desirable. This is based on available cost data.

2) Blanket composition affects only the conversion ratio. The volume fraction of fertile material should be as high as possible.

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DISCLAIMER

3) The 18 inch blanket is near the optimum.

4) The fuels may be ranked in nuclear performance as:

	Uranium Fuels	Plutonium Fuels
I.	Uranium Metal	Plutonium-Uranium Metal
II.	UC	PuC-UC
III.	UO_2	PuO_2 - UO_2

The main reason for this trend is that high uranium density is favorable from a nuclear standpoint. However, physical properties favor UC in the environment of this reactor.

5) Tin and lead may replace sodium as the liquid carrier in the paste with only very slight changes in nuclear performance.

Reference Reactor

The reference reactor in this study has an unmoderated core using uranium monocarbide fuel in the form of a paste. Paste is defined as a thick mixture of fuel particles in a liquid carrier such as sodium. The fast core is surrounded by an unmoderated breeding blanket of natural uranium monocarbide whose form (paste vs. solid rods) is unspecified. The blanket is surrounded by a graphite reflector.

The important characteristics of the reference core are:

Power (MWt)	704
Power (MWe) net	300
Fissile Material	
type	UC
condition	paste(50 v/o UC, 50 v/o Na)
Fertile Material	
type	UC (natural U)
condition	unspecified
Core	
shape	cylinder
height (ft)	5
diameter (ft)	5
volume fractions	
uranium monocarbide	0.20
sodium carrier in the paste	0.20
sodium coolant	0.45
structure (stainless steel)	0.15

Radial Blanket	
thickness (in.)	18
volume fractions	
uranium monocarbide	0.40
sodium	0.49
structural(stainless steel)	0.11
Radial Reflector	
thickness (in.)	18
material	graphite

Modifications in the Reference Core

Various characteristics of the reference design were altered to find what changes might possibly reduce power costs and to evaluate the effect of changes which might be dictated by engineering considerations or materials limitations. These modifications were studied:

1) Vary the UC volume fraction in the core from 0.2 to 0.6.

2) Vary the UC volume fraction in the blanket from 0.2 to 0.6.

3) Vary the blanket thickness from 3 in. to 24 in.

4) Change fuel from UC to uranium metal, UO_2.PuC-UC, plutonium-uranium metal, and PuO_2-UO_2.

5) Change carrier material from sodium to tin and to lead.

Since each change was made independently, no effects due to combinations of changes were determined. Increases in UC volume fractions were accompanied by corresponding decreases in the sodium volume fraction.

Method of Calculation

All calculations were made using the AIM-6 (Ref.(1)) diffusion theory code. An 18-group structure was employed, utilizing the cross-section library furnished with the code except for the case of lead, which was not included in the library. Reported multi-group cross-sections for lead (Ref.(2)) were modified to fit the AIM-6 group structure.

The calculations were all made using a homogeneous model since there is no intracell flux distribution to consider and because the fuel is dispersed enough to make self-shielding in U-238 unimportant.

The search option in the AIM-6 code was used. The amount of fissile material was varied to give a k_{eff} of 1.05. A consequence of using this search is that the final concentrations do not correspond exactly with the assumed volume fractions. Thus it was necessary to make a good initial guess of the U-235 concentration.

For plutonium, an initial composition typical of dirty plutonium from a reactor with 77% Pu 239, 10% Pu 240, and 13% Pu-241 was used. The plutonium was diluted with U-238 in the same chemical form as the plutonium.

The densities used for the materials were:

Material	Density (g/cc)
UC	13.4
U Metal	19.13
UO_2	10.96
PuC	14.0*
Pu Metal	20.0*
PuO_2	11.46
Stainless Steel	7.72
Sodium	.817
Graphite	1.55

No assumptions were made concerning the properties of the materials above and below the core. The axial effects were included in an assumed reflector savings of 15 cm.

Fuel cycle cost estimates were made to determine the most desirable volume fraction. This required that U-235 depletion and Pu buildup be known as a function of volume fraction and burnup. The burnup data was obtained using a simple one-group model. Taking the equations

$$\frac{dN^{25}}{dt} = -N^{25}\sigma_a^{25}\phi$$

$$\frac{dN^{49}}{dt} = N^{28}\phi\sigma_c^{28} - N^{49}\phi\sigma_a^{49} ,$$

---

* Estimated values

one obtains (assuming N^{28} is constant)

$$N^{25} = N_0^{25} e^{-\phi \sigma_a^{25} t}$$

$$N^{49} = \frac{N^{28} \sigma_c^{28} \phi}{\sigma_a^{49} \phi} \left(1 - e^{-\sigma_a^{49} \phi t}\right)$$

Dividing the last equation by N_o^{25}

$$\frac{N^{49}}{N_o^{25}} = \left(\frac{N^{28}}{N_o^{25}}\right)\left(\frac{\sigma_c^{28}}{\sigma_a^{49}}\right)\left(1 - e^{-\sigma_a^{49} \phi t}\right)$$

$$\frac{N^{49}}{N_o^{25}} = \left(\frac{1-E}{E}\right)\left(\frac{\sigma_c^{28}}{\sigma_a^{49}}\right)\left(1 - e^{-\sigma_a^{49} \phi t}\right)$$

where E is initial atomic fraction of U-235 in fuel.

The value of $\frac{\sigma_c^{28}}{\sigma_a^{49}}$ was obtained from earlier fast reactor work.(Ref.(3)) The terms

$$\sum_{\text{group } 1}^{18} \left(\int \phi \, dA\right) \sigma$$

were obtained for σ_c^{28}, σ_a^{25}, σ_a^{49}, and σ_f^{25}. The values were:

Cross Section	$\sum_{\text{group } 1}^{18} \left(\int \phi \, dA\right) \sigma$
σ_c^{28}	29.00
σ_a^{25}	284.3
σ_a^{49}	280.7
σ_f^{25}	227.1

Thus the N^{49} equation becomes

$$\frac{N^{49}}{N_0^{25}} = \left(\frac{1-E}{E}\right)\left(\frac{29}{280.7}\right)\left(1-e^{-\sigma_a^{49}\phi t}\right)$$

$$= \left(\frac{1-E}{E}\right)(0.103)\left(1-e^{-\sigma_a^{49}\phi t}\right)$$

To find the coefficients of the exponents, the relation,

$$\sigma_f^{25}\phi = \frac{P}{(8.3\times10^{19}g^{25})}$$

was used with the result that $\phi\sigma_f^{25} = 4.437 \times 10^{-4}$ days^{-1}. This was normalized using the values of $\sum_{\text{group}}\left(\int\phi\, dA\right)\sigma$ to give the coefficients. The results were:

$$\phi\sigma_a^{25} = 4.437 \times 10^{-4} \times \frac{284.3}{227.1} = 5.554 \times 10^{-4}$$

$$\phi\sigma_a^{49} = 4.437 \times 10^{-4} \times \frac{280.7}{227.1} = 5.485 \times 10^{-4}$$

The isotope equations with the appropriate constants are:

$$\frac{N^{25}}{N_0^{25}} = e^{-5.554\times10^{-4}t}$$

$$\frac{N^{49}}{N_0^{25}} = (0.103)\left(\frac{1-E}{E}\right)\left(1-e^{-5.485t}\right)$$

The depletion costs for U-235 were taken as the differences between the value of the fuel at its initial enrichment and the value of the fuel at the end of its stay in the reactor. The worth of the U-235 was based on the AEC press release dated November 18, 1956. The worth of the plutonium (based on a value of $12/g) was subtracted from the U-235 depletion charge to give the net burnup charge.

The inventory charge was based on a lease charge of 4% of the value of the fuel per year. In addition, 15% of the fuel in the core was assumed to be available in spares. A four month cooling time was included in the use charge.

Results

The effects of changing the volume fraction of UC in the core on enrichment, fuel mass, and initial conversion ratio are shown in Figures 1 and 2. Since the decrease in enrichment and increase in conversion ratio is accompanied by an increase in fuel mass, the economic advantages of any volume fraction are not obvious from the fabrication and recovery charges, burnup charges, and inventory charges. Because of the lack of prior experience with paste fuels, no good estimate of fuel fabrication and recovery costs is possible. However, the costs should decrease with higher volume fractions and the corresponding lower enrichments. Thus, if the sum of the burnup and the inventory charges decreases with volume fraction, then the total fuel cycle cost decreases with volume fraction.

The variation of the concentration of U-235 and plutonium with fuel exposure is shown in Figure 3. These results were used to obtain the burnup charges.

The calculated variation of burnup costs, inventory costs, and the sum of these costs as a function of volume fraction appears in Figures 4, 5, and 6 for three different fuel exposures. These curves show that higher volume fractions cause fuel cycle costs to decrease.

Blanket composition was found to have no effect on the fast core enrichment for the range of volume fractions studied; but the effect on the initial conversion ratio is shown in Figure 7. Part of the change is due to leakage and non-U-238 captures, but spectral effects were also encountered as are seen in the variation of the reactor median fission energy in Figure 8. The variation of the conversion ratio with blanket compositions indicates that the highest possible volume fraction is desirable. However, the volume fraction of 0.4 used in the reference core is probably near the upper limit allowed by space considerations for coolant and structure.

The effects of blanket thickness were similar to the effects of blanket composition. The effect on fast core enrichment was again negligible, and the effect on conversion ratio is shown in Figure 9. The changes are again due to leakage, non-U-238 captures, and spectral changes. The effect of thickness on the reactor median fission energy is shown in Figure 10. Figure 9 shows that the conversion ratio seems to be approaching an upper limit. This limit is the value which would be obtained with an infinite blanket. The 18 inch blanket used in the reference core is a good choice since the effect is very close to the effect of an infinite blanket.

The effect of using uranium fuels other than UC is shown below:

Fuel	Core Enrichment a/o U-235	Initial Conversion Ratio ($k_{eff} = 1.05$)	Median Fission Energy (kev)
UC	21.2	.838	132
U Metal	16.7	.946	214
UO_2	23.6	.779	102

Thus it was found that uranium metal, with its high density and lack of moderating elements found in compounds, has distinct nuclear advantages. Because of the high burnup and the high temperatures required in the system, UC should remain the choice for the reference fuel. However, if any unique features are devised which will permit the system to tolerate the properties of the metal, then changes in the reference fuel should be considered. The use of UO_2 impairs the nuclear performance of the reactor. However, the change is slight; and UO_2, with its proven physical properties, provides a suitable alternate fuel if UC should for any reason prove unsatisfactory. The effects of using plutonium fuels is similar to the effects observed with uranium fuel. The results are:

Fuel	Pu atom ratio* N^{49}/N^{28}	$\frac{\text{U-238 captures*}}{\text{Pu-239 absorptions}}$	Median Fission energy (kev)
PuC-UC	.178	1.269	233
Pu-U Metal	.115	1.589	307
PuO_2-UO_2	.223	1.121	192

*These ratios were taken as indicative of the same effects described by enrichment and conversion ratio in U-235-U-238 systems. This was done to avoid the necessity of introducing Pu-240 and Pu-241 into the definitions of enrichment and conversion ratio.

The effects of tin and lead as carriers for the paste were very small. Tin was used to replace sodium in the reference case, but a fuel volume fraction of 0.3 in the fast core was inadvertently used in the case of lead. However, since the effect is so small, the case was not rerun. The results are shown below:

Carrier in the Paste	Fuel Volume Fraction in the Fast Core	Enrichment (a/o U-235)	Initial Conversion Ratio
Na	0.20	21.2	.838
Sn	0.20	20.3	.839
Na	0.30	16.1	.940
Pb	0.30	15.6	.940

Conclusions and Recommendations

The conclusions which may be drawn from this work are:

1) High fuel volume fractions are desirable.

2) Blanket volume fractions should be as high as possible.

3) The blanket thickness of 18 inches is adequate.

4) The fuels may be ranked in nuclear performance as:

	Uranium Fuels	Plutonium Fuels
I.	Uranium Metal	Plutonium-Uranium Metal
II.	UC	PuC - UC
III.	UO_2	PuO_2 - UO_2

5) Tin and lead may be used in place of sodium bond if desired for other, non-nuclear, reasons.

Addition physics studies which will further aid in choosing the optimum core are:

1) Examine unreflected systems.

2) Determine the physical requirements of the reactor structural materials. If stainless steel is unsatisfactory, determine the nuclear effects of alternate materials.

3) Examine the burnup characteristics of the reference core.

References

1. H. P. Flatt and D. C. Baller, "Notes on the AIM-6 Diffusion Theory Code", January 15, 1960.
2. W. B. Henderson, "Cross Sections for Reactor Analysis", XDC-57-7-83 (Classified), May 31, 1957.
3. K. W. Foster, "A Comparison of Typical Fuel Cycle Costs for Thermal and Non-Thermal Sodium-Cooled Reactors", NAA-SR-5190.

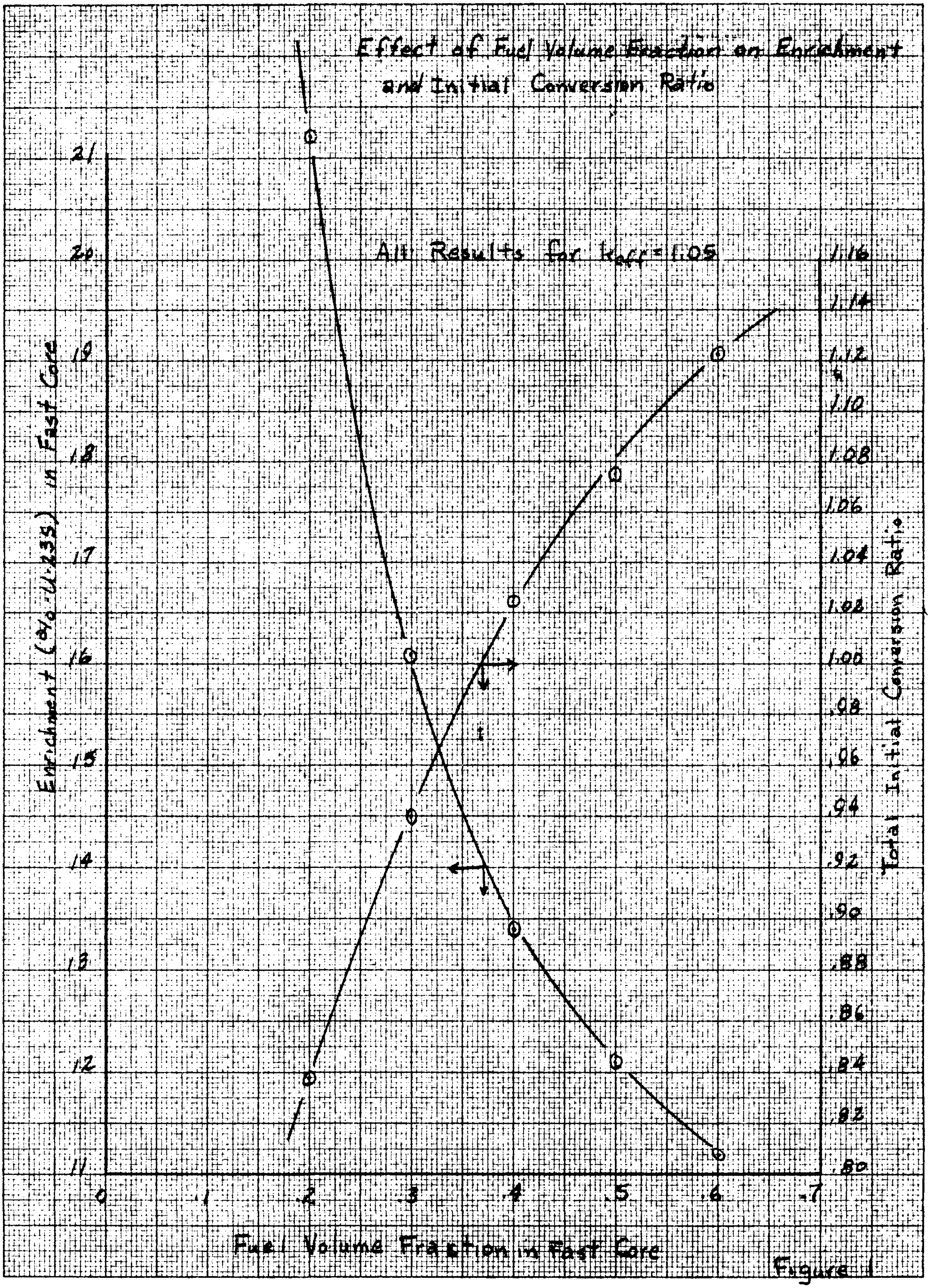

Effect of Fuel Volume Fraction on Enrichment and Initial Conversion Ratio
All Results for k_{eff} = 1.05
Enrichment (a/o U-235) in Fast Core
21
20
19
18
17
16
15
14
13
12
11
Total Initial Conversion Ratio
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
.98
.96
.94
.92
.90
.88
.86
.84
.82
.80
0
.1
.2
.3
.4
.5
.6
.7
Fuel Volume Fraction in Fast Core

Figure 1

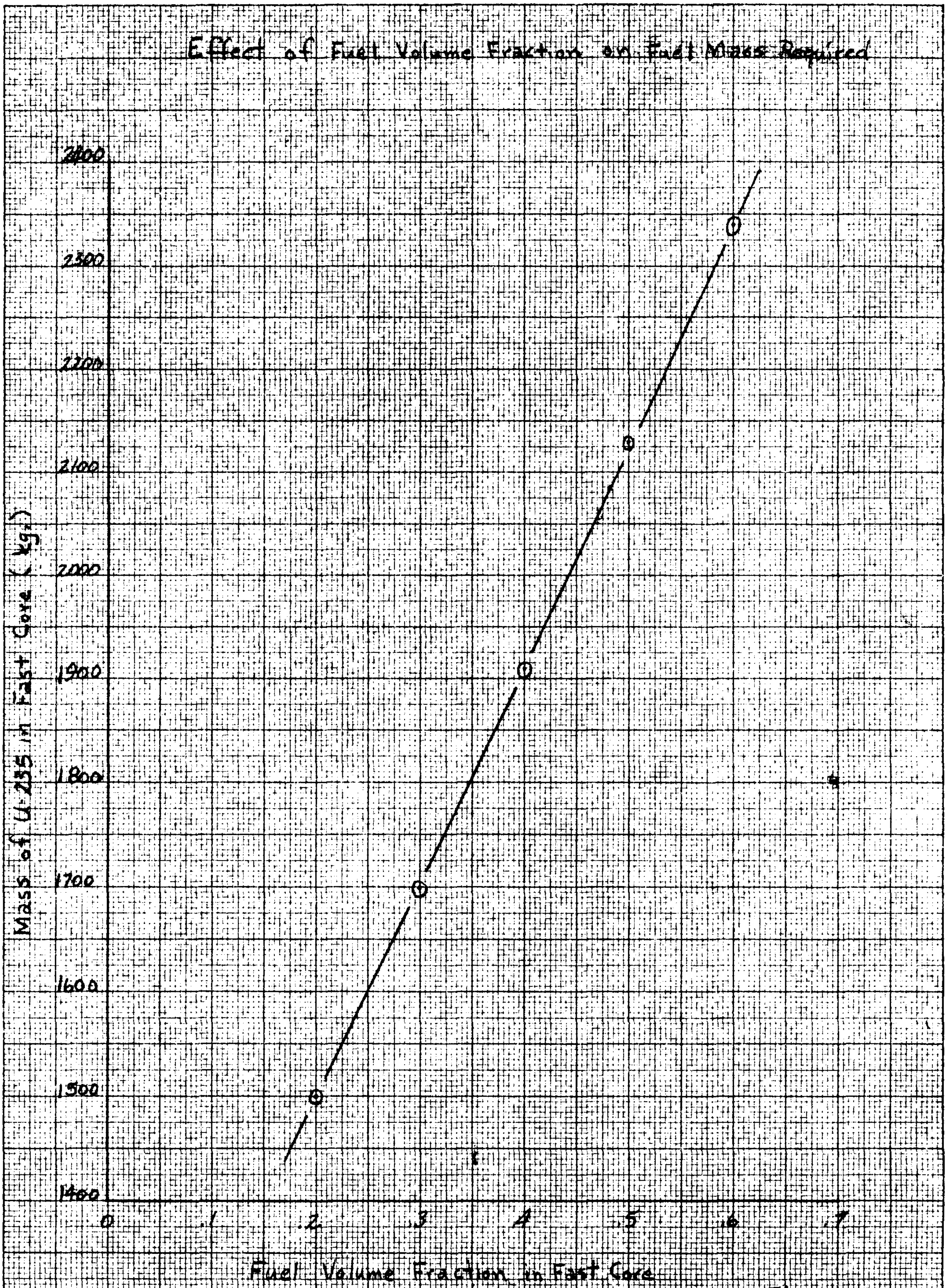

Effect of Fuel Volume Fraction on Fuel Mass Required
Mass of U-235 in Fast Core (kg.)
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
0
.1
.2
.3
.4
.5
.6
.7
Fuel Volume Fraction in Fast Core

Figure 2

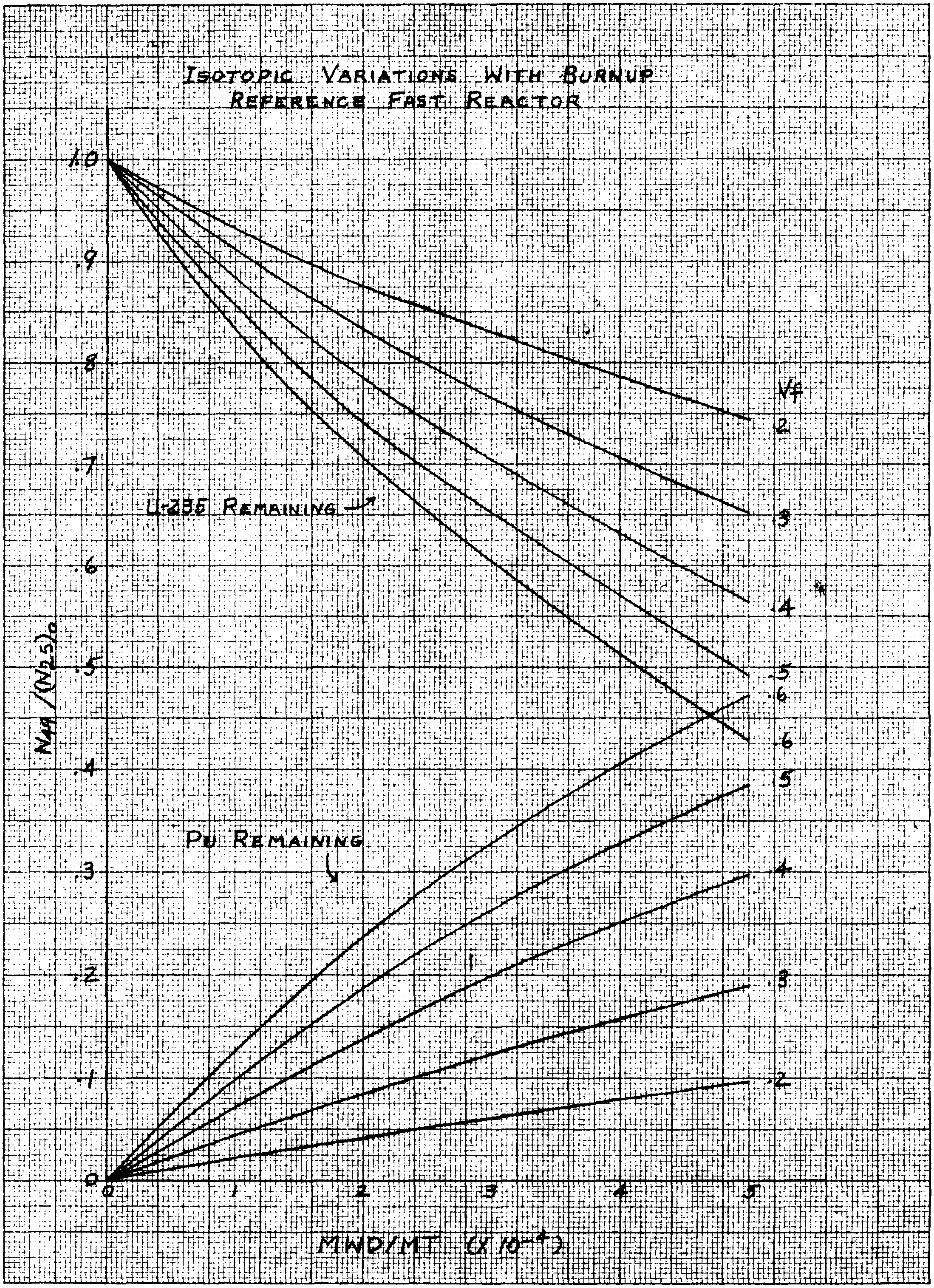
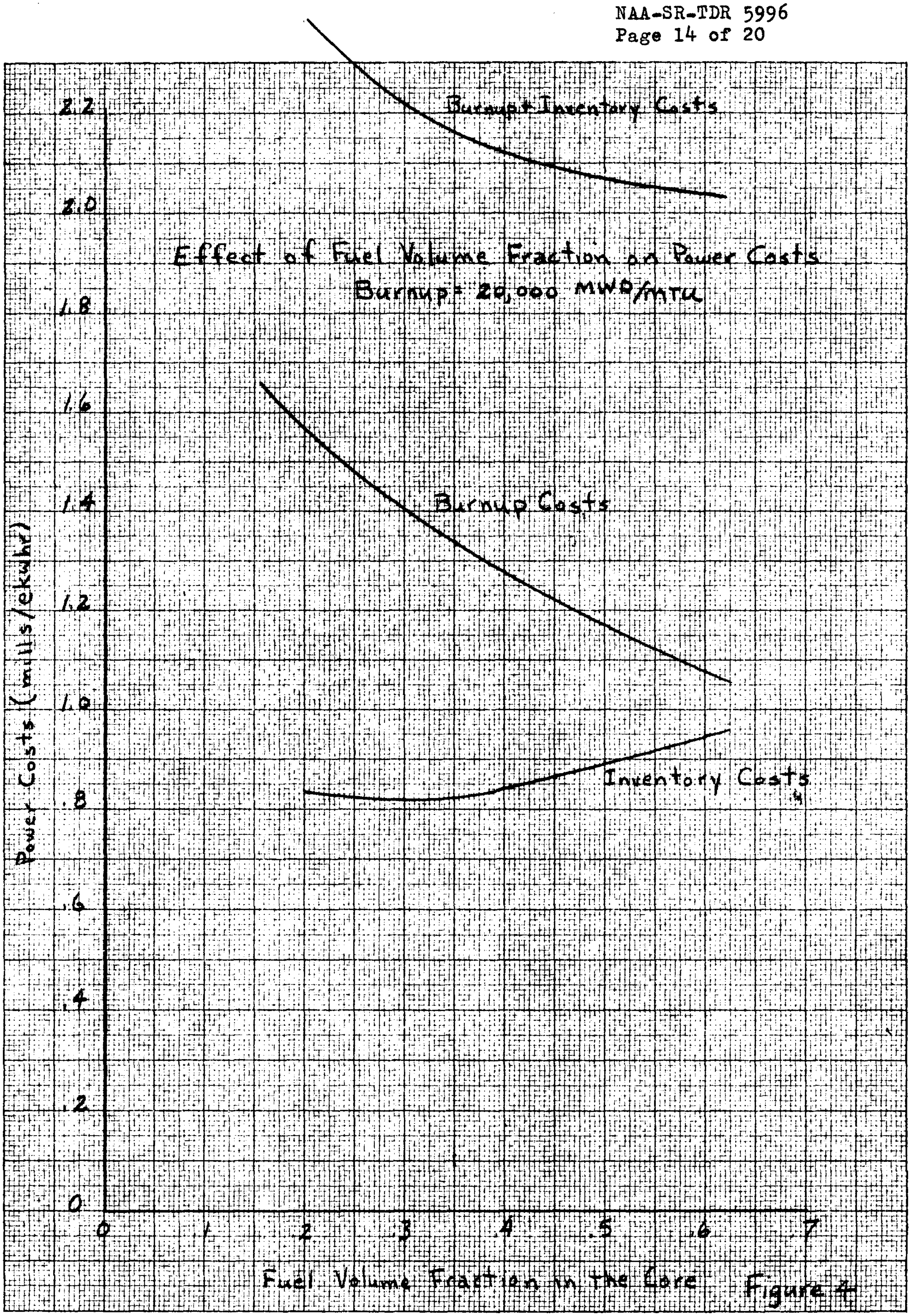

ISOTOPIC VARIATIONS WITH BURNUP
REFERENCE FAST REACTOR
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
$N_{49}/(N_{25})_0$
Vf
.2
.3
.4
.5
.6
.6
.5
.4
.3
.2
U-235 REMAINING
Pu REMAINING
0
1
2
3
4
5
MWD/MT (X 10^-4)

Figure 3



Effect of Fuel Volume Fraction on Power Costs
Burnup = 20,000 MWD/MTU

Figure 4

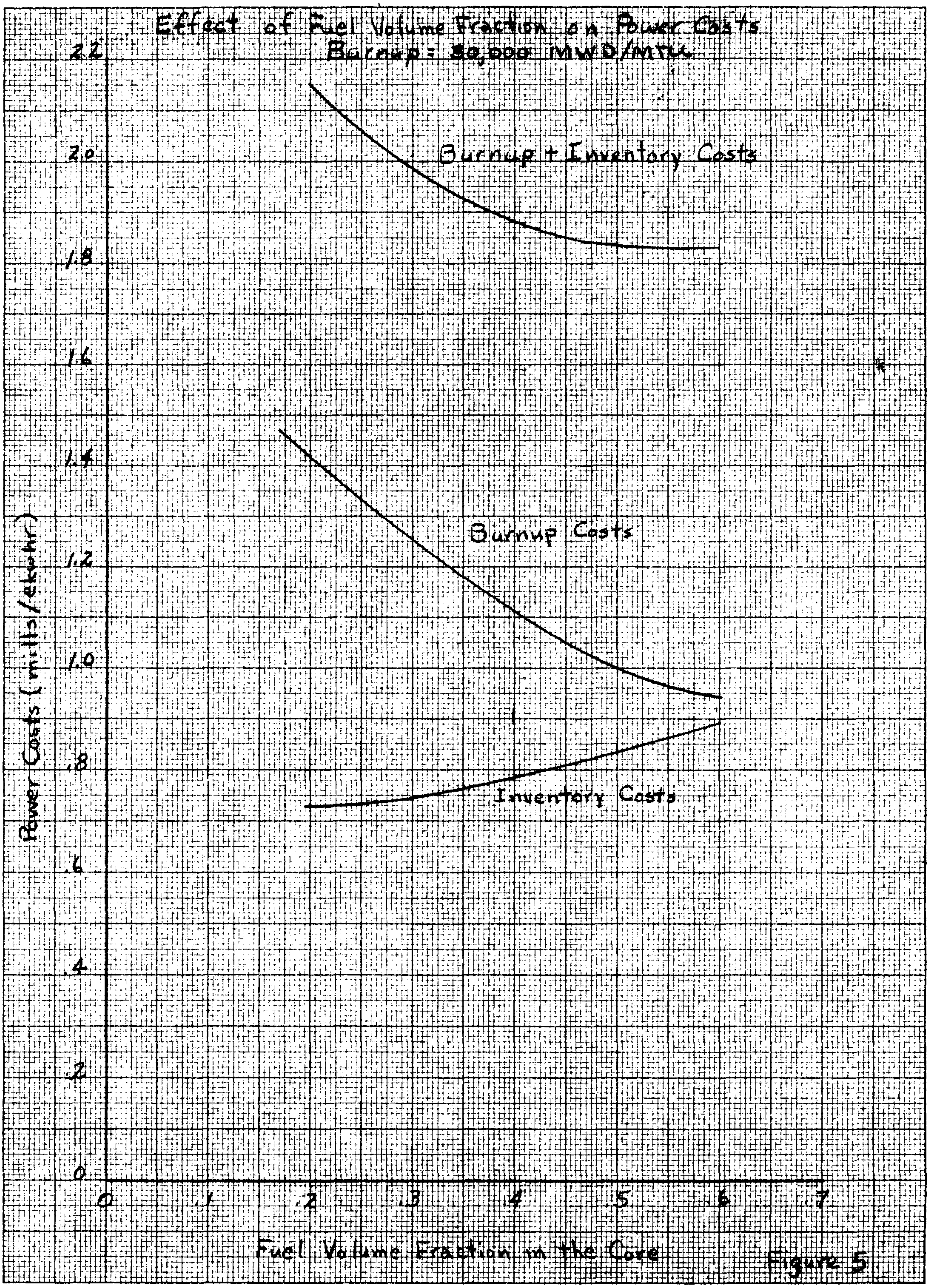
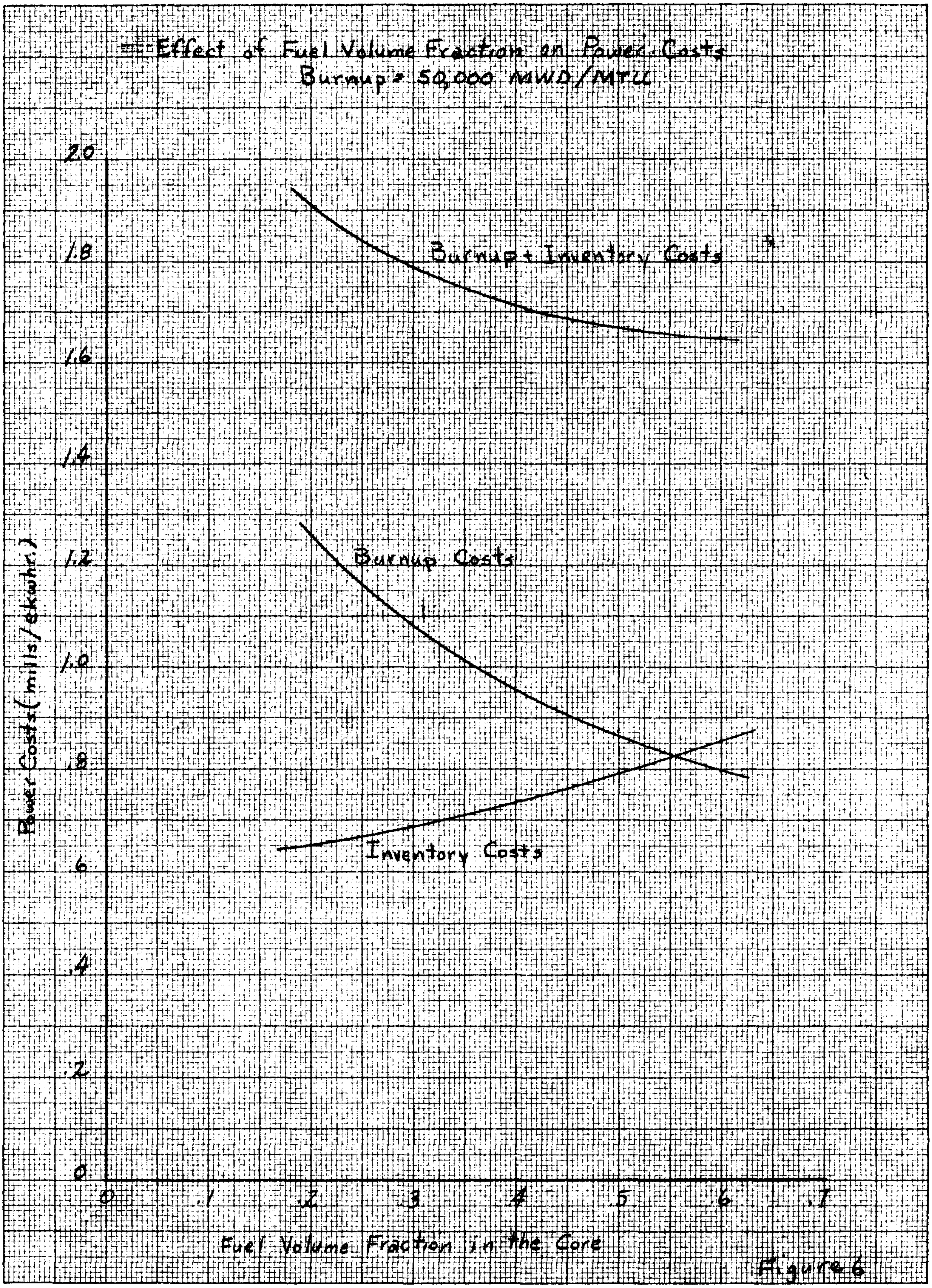

Effect of Fuel Volume Fraction on Power Costs
Burnup = 30,000 MWD/MTU
Burnup + Inventory Costs
Burnup Costs
Inventory Costs
Power Costs (mills/ekwhr)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
.1
.2
.3
.4
.5
.6
.7
Fuel Volume Fraction in the Core

Figure 5



Effect of Fuel Volume Fraction on Power Costs
Burnup = 50,000 MWD/MTU

Figure 6

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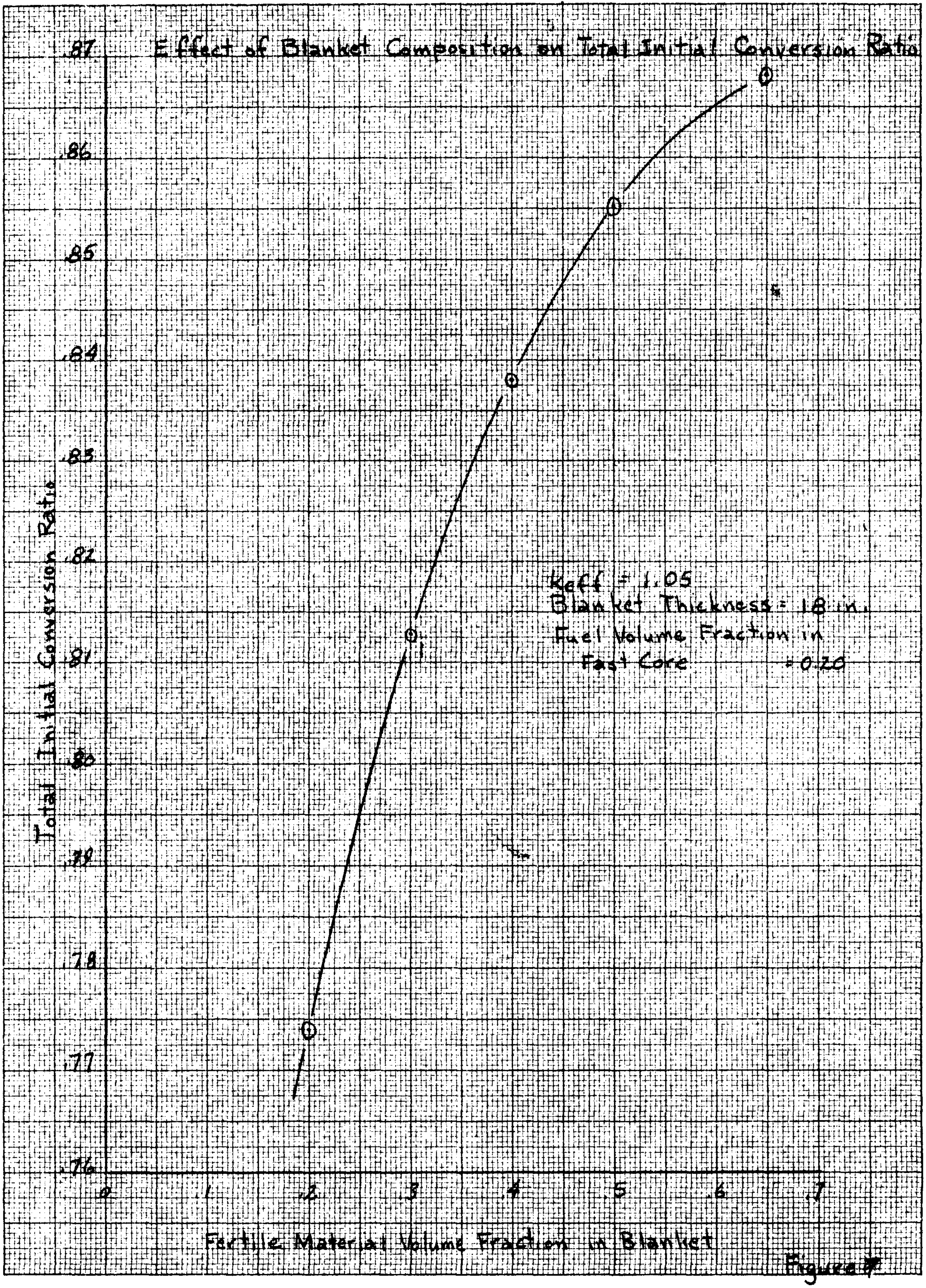
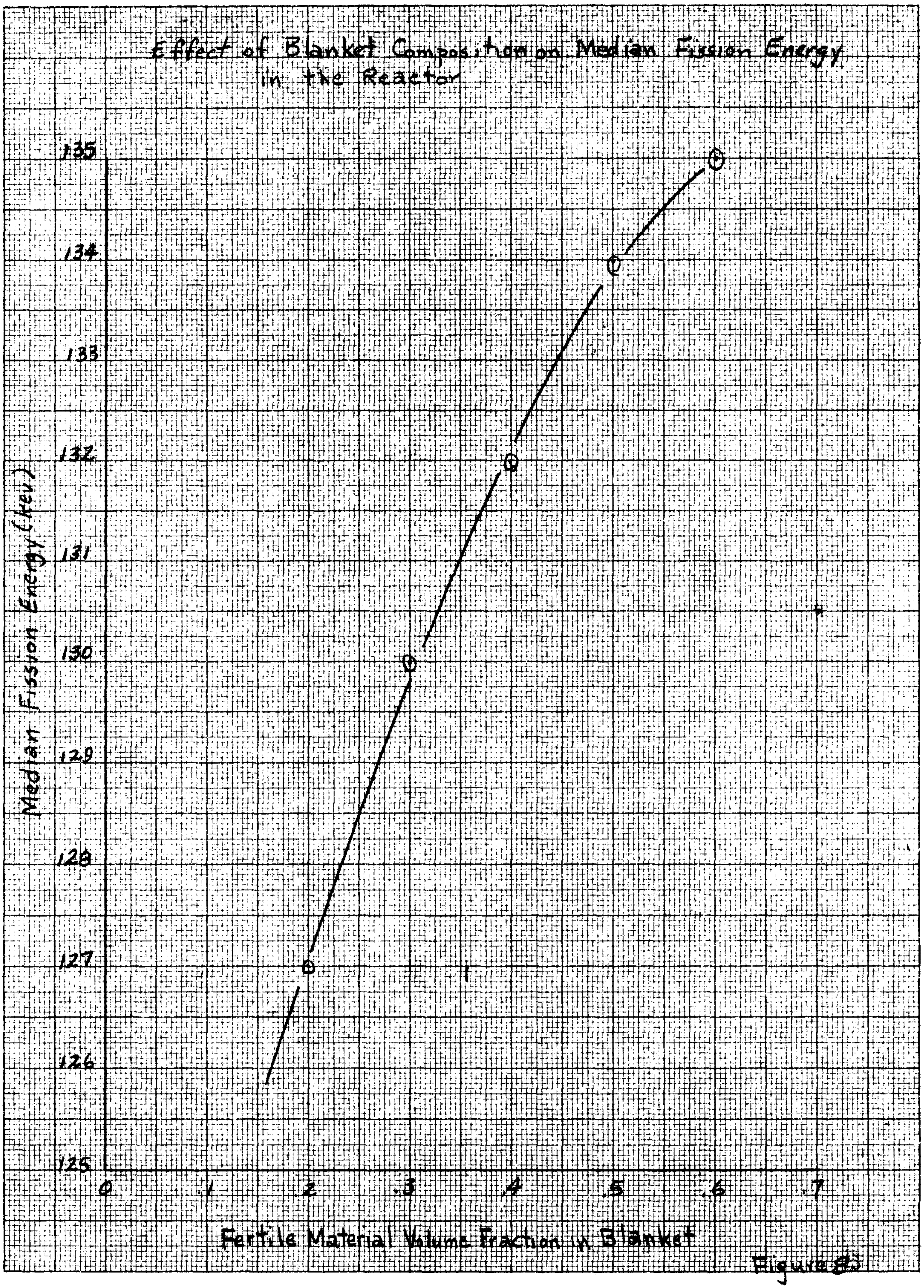

Effect of Blanket Composition on Total Initial Conversion Ratio
Total Initial Conversion Ratio
.87
.86
.85
.84
.83
.82
.81
.80
.79
.78
.77
.76
0
.1
.2
.3
.4
.5
.6
.7
Fertile Material Volume Fraction in Blanket
Keff = 1.05
Blanket Thickness = 18 in.
Fuel Volume Fraction in
Fast Core = 0.20
Figure #



Effect of Blanket Composition on Median Fission Energy in the Reactor

Figure #3

Effect of Blanket Thickness on Total Initial Conversion Ratio

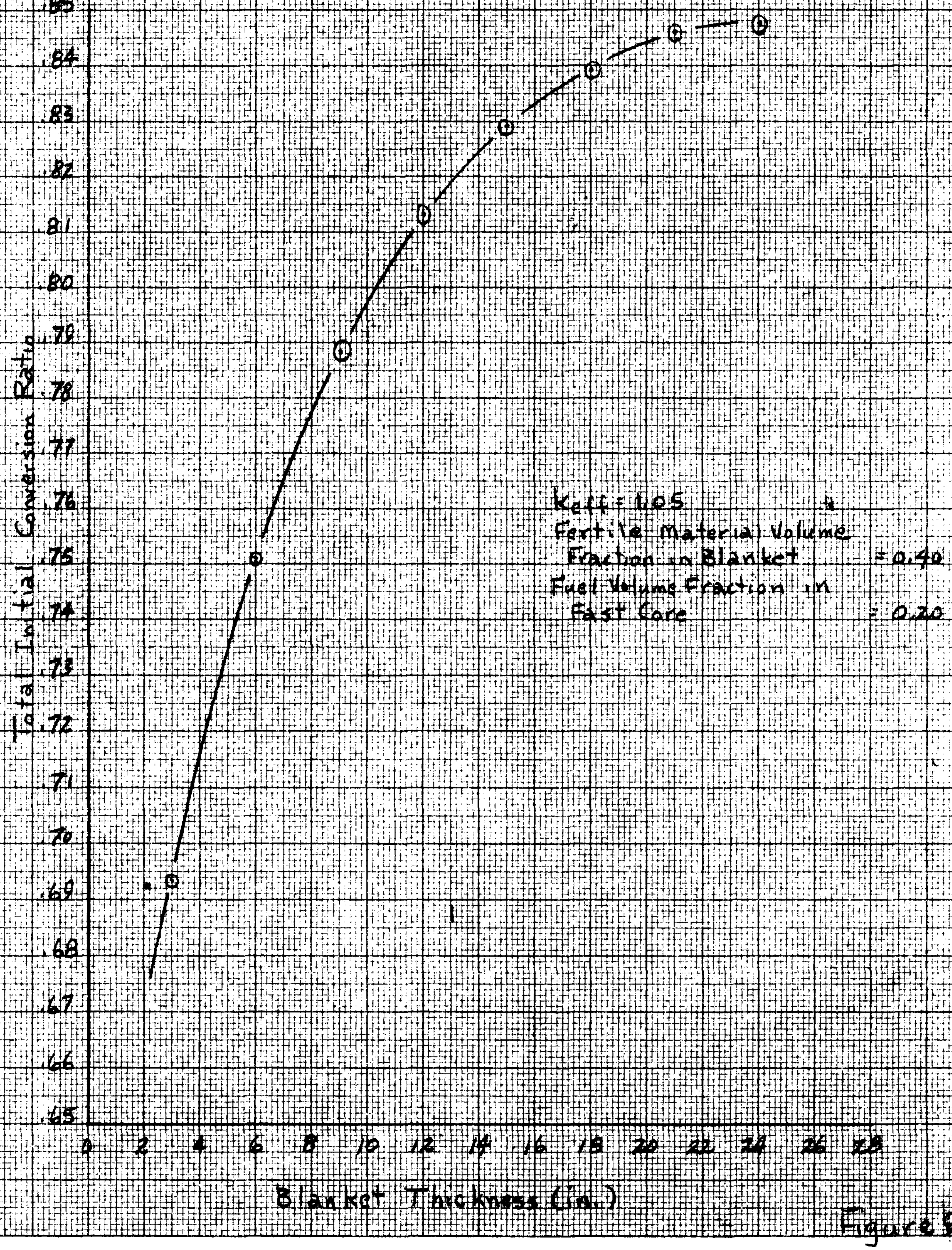


Figure 9

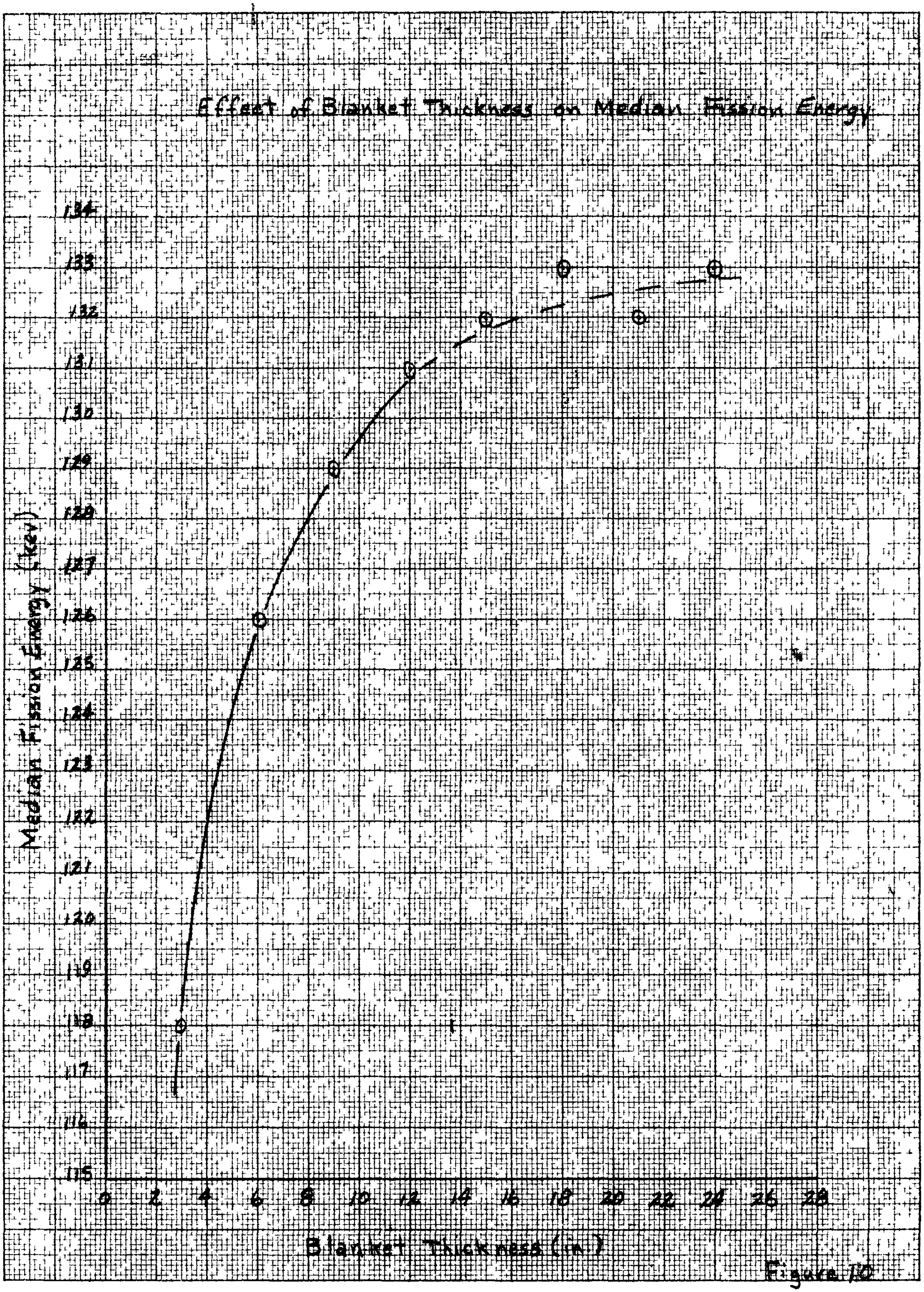

Effect of Blanket Thickness on Median Fission Energy
Median Fission Energy (kev)
134
133
132
131
130
129
128
127
126
125
124
123
122
121
120
119
118
117
116
115
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Blanket Thickness (in.)

Figure 10