MIT-2073-4
(MITNE-61)

FUEL CYCLE ANALYSIS IN A THORIUM FUELED REACTOR USING BIDIRECTIONAL FUEL MOVEMENT

CORRECTION TO REPORT
MIT-2073-1, MITNE-51

by

JAMES D. STEPHEN

DEPARTMENT OF NUCLEAR ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS

JUNE, 1965

WORK PERFORMED UNDER CONTRACT AT(30-1)-2073
WITH THE
NEW YORK OPERATIONS OFFICE
U. S. ATOMIC ENERGY COMMISSION

15

DISTRIBUTION

This report is being distributed under the category "Reactor Technology," TID 4500. Additional copies may be obtained from USAEC Division of Technical Information Extension (DTIE), P. O. Box 62, Oak Ridge, Tennessee 37831.

Previous reports on this project:

NYO-2131	(MITNE-1)
NYO-9715	(MITNE-10)
MIT-2073-1	(MITNE-51)
MIT-2073-2	(MITNE-57)
MIT-2073-3	(MITNE-58)

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warrantee or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to any information pursuant to his employment or contract with the Commission.

MIT-2073-4
(MITNE-61)

FUEL CYCLE ANALYSIS IN A THORIUM FUELED REACTOR USING BIDIRECTIONAL FUEL MOVEMENT

Correction to Report
MIT-2073-1, MITNE-51

by

James D. Stephen

Department of Nuclear Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

June, 1965

Work performed under Contract AT(30-1)-2073
with the
New York Operations Office
U.S. Atomic Energy Commission

TABLE OF CONTENTS

ABSTRACT

This report corrects an error discovered in the code used in the study "Fuel Cycle Analysis in a Thorium Fueled Reactor Using Bidirectional Fuel Movement," MIT-2073-1, MITNE-51. The results of the correction show considerable improvement in the conversion ratio. Although more recent cross-section data make these corrected results somewhat optimistic, the indication is that breeding on the thorium cycle may be possible with the CANDU-type reactor design.

INTRODUCTION

The purpose of this report is to correct a systematic error which was made in all calculations in report MIT-2073-1 of the conversion ratio of a heavy-water moderated reactor of the CANDU type when fueled with a mixture of ThO_2 and its own recycle UO_2. The error consisted in using the thermal flux averaged over the fuel and the slowing down density averaged over the cell to calculate nuclide concentration changes on irradiation, instead of using cell averages for both quantities.

The corrected conversion ratios are substantially higher than those given in MIT-2073-1, and in some cases exceed unity. This indicates that the possibility of being able to breed on the thorium cycle with a reactor of the CANDU type, size and power level is more favorable than would have been judged from the earlier report.

It should be recognized, however, that the results of both the present report and MIT-2073-1 are based on the 1962 cross-section correlation of Westcott[1], which predicts somewhat more favorable (i.e. higher) values of η for U-233 and U-235 than more recent cross-section data. An investigation by M. C. Richardson now in progress at MIT is using a more recent cross-section correlation by the Oak Ridge National Laboratory[2] in a general parametric study of the breeding potential of heavy-water moderated reactors operating on the ThO_2, recycle UO_2 fuel cycle. It is anticipated that the conversion ratios to be found in the forthcoming study will be slightly lower than here presented.

---

[1] Westcott, C.H., Effective Cross Section Values for Well-Moderated Thermal Reactor Spectra, AECL-1101, July 1962.

[2] Personal communication, A.M. Perry, ORNL, August 7, 1964.

The present report summarizes the results of the corrected calculations of conversion ratios, isotopic compositions and flux distributions. Reference should be made to MIT-2073-1 for details of the reactor under examination, the modified two-group reactor physics model assumed and the computer code employed.

SUMMARIZED RESULTS

Table I presents the corrected conversion ratios. Not all cases examined in the previous report have been recalculated, but a sufficient number have been studied to determine the effect of changing radial blanket thickness, fuel volume fraction, maximum linear power, average fuel burnup and fractional reprocessing loss on the conversion ratio.

These variables were changed one at a time from the "standard reactor" in which these five variables had the following values:

Blanket radius	255.00 cm
Fuel volume fraction	0.0567
Avg. fuel burnup	10,000 MWD/T
Max. linear power	8.712 Kw/cm
Recycle losses	2.0%

These values correspond to the CANDU design, except for the blanket radius and recycle loss (CANDU has no blanket and does not recycle the spent fuel).

The following reactor characteristics were held constant throughout the study:

Core radius	225.61 cm
Reflector outside radius	299.70 cm
Core height	500.40 cm
Blanket discharge flux time	0.1 n/Kb
Square lattice pitch	
Infinite spent fuel cooling time	
Constant fuel velocity in core	

The core radius, reflector outside radius, and core height are CANDU reference design values.

Two conversion ratios were evaluated:

CR the conversion ratio in the reactor, with all discharged Pa233 decayed to U233, before allowance for recycle losses

and

CR_L the conversion ratio in the entire system, with allowance for recycle losses.

Table I. Corrected Conversion Ratios in Thorium-Fueled CANDU Reactor

* = Value in CANDU design

** = Standard case

Blanket Thickness (cm)	Fuel Volume Fraction	Max. Linear Power (kw/cm)	Burnup (MWD/T)	Recycle Loss (%)	Conversion Ratio Reactor CR	Conversion Ratio System CR_L
0.0*	0.0567*	8.712*	10,000	2.0*	0.9663	0.9397
29.39**	0.0567	8.712	10,000	2.0	1.0203	0.9905
29.39	0.0167	8.712	10,000	2.0	0.9064	0.8803
29.39	0.0267	8.712	10,000	2.0	0.9837	0.9565
29.39	0.0367	8.712	10,000	2.0	1.0108	0.9828
29.39**	0.0567	8.712	10,000	2.0	1.0203	0.9905
29.39	0.0567	8.712	6,000	2.0	1.0294	0.9813
29.39	0.0567	8.712	8,000	2.0	1.0247	0.9881
29.39**	0.0567	8.712	10,000	2.0	1.0203	0.9905
29.39	0.0567	8.712	12,000	2.0	1.0163	0.9912
29.39	0.0567	4.712	10,000	2.0	1.0501	1.0207
29.39	0.0567	6.712	10,000	2.0	1.0357	1.0060
29.39**	0.0567	8.712	10,000	2.0	1.0203	0.9905
29.39	0.0567	8.712	10,000	1.5	1.0218	0.9992
29.39**	0.0567	8.712	10,000	2.0	1.0203	0.9905

DETAILED RESULTS

The effect of the five variables on the two conversion ratios and the fuel feed atom ratios is shown in figures 1-5.

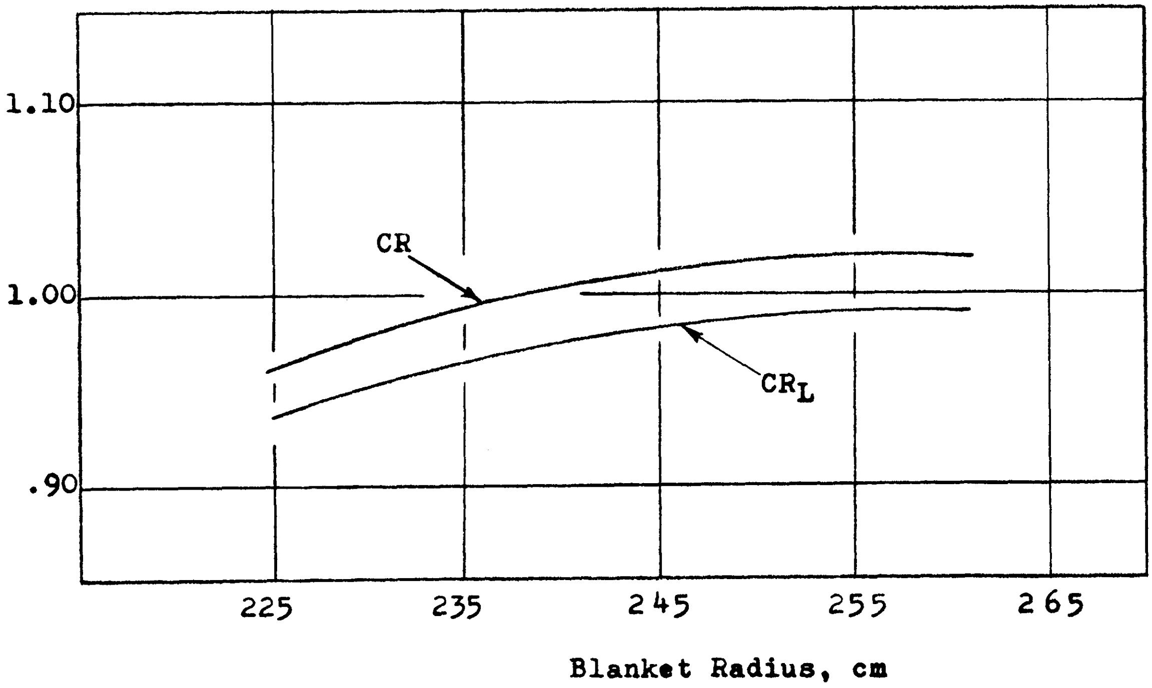
Figures 6 and 7 give the radial and axial thermal flux distributions in the standard reactor. For comparison, figure 8 is the radial flux distribution in the standard reactor without a blanket (the CANDU design).

Figure 9 shows two flux spectra in the same reactor, one at the center of the core and the other in the blanket. The two spectra are almost identical. The effective thermal cross-sections are therefore essentially independent of position.

In figure 10, the flux spectra of two reactors having different fuel volume fractions are compared. It is clear that the reactor with the higher fuel volume fraction (VFL) has the harder spectrum.

The nuclide concentrations in the central fuel channel and a blanket channel as a function of axial distance from the midplane of the reactor are given in figures 11 and 12. The movement through the channel is from left to right (arrow). The curves are for the standard reactor.

Figure 13 shows the maximum concentration of Pa233 relative to the concentration of U233 in the reactor as a function of the maximum thermal flux in the reactor. The point at $\phi_{max} = 1.405 \times 10^{14}$ n/cm^2-sec corresponds to the peak of the Pa233 curve of figure 11. Since the U233 concentration varies only slightly with the flux level, figure 13 shows the essentially proportional relationship between the Pa233 concentration and the thermal flux level.



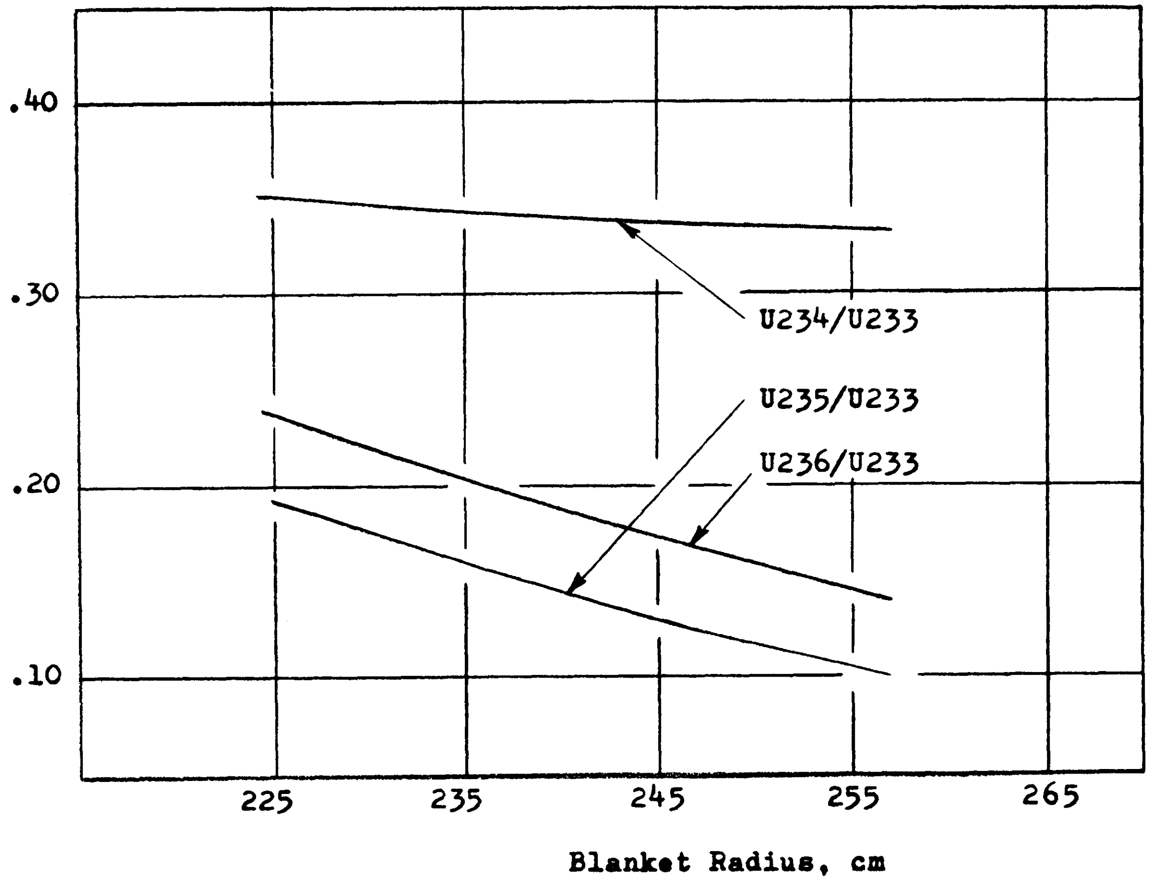
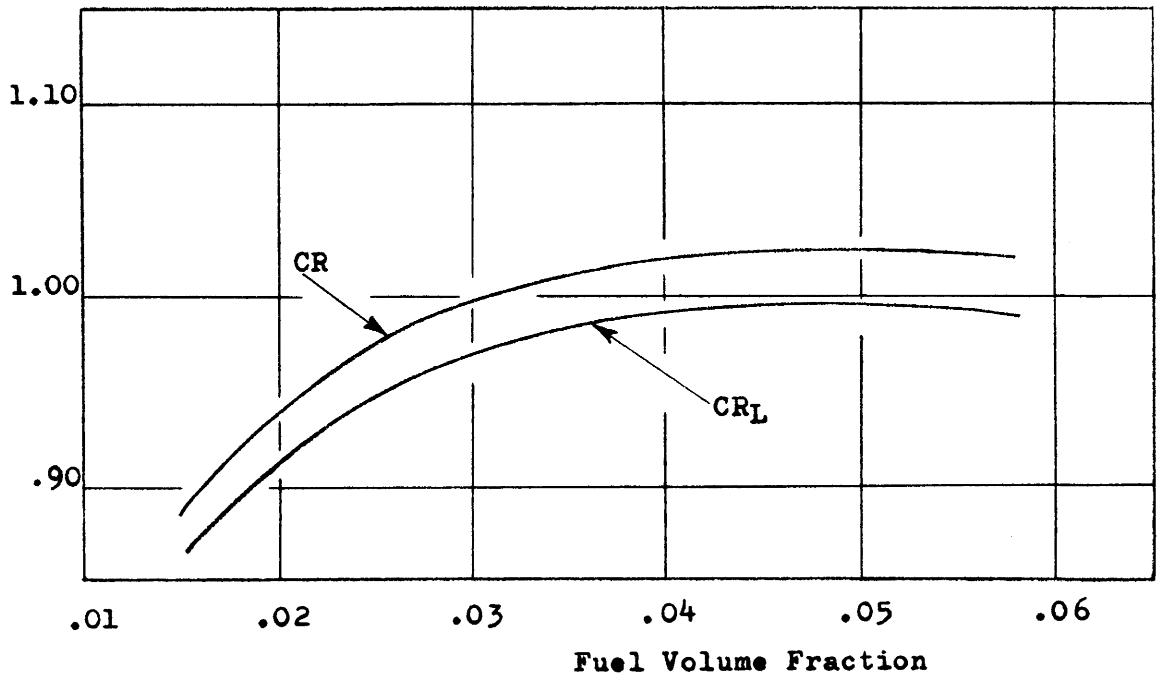


FIG. 1 CONVERSION RATIO AND ATOM RATIOS AS A FUNCTION OF BLANKET RADIUS



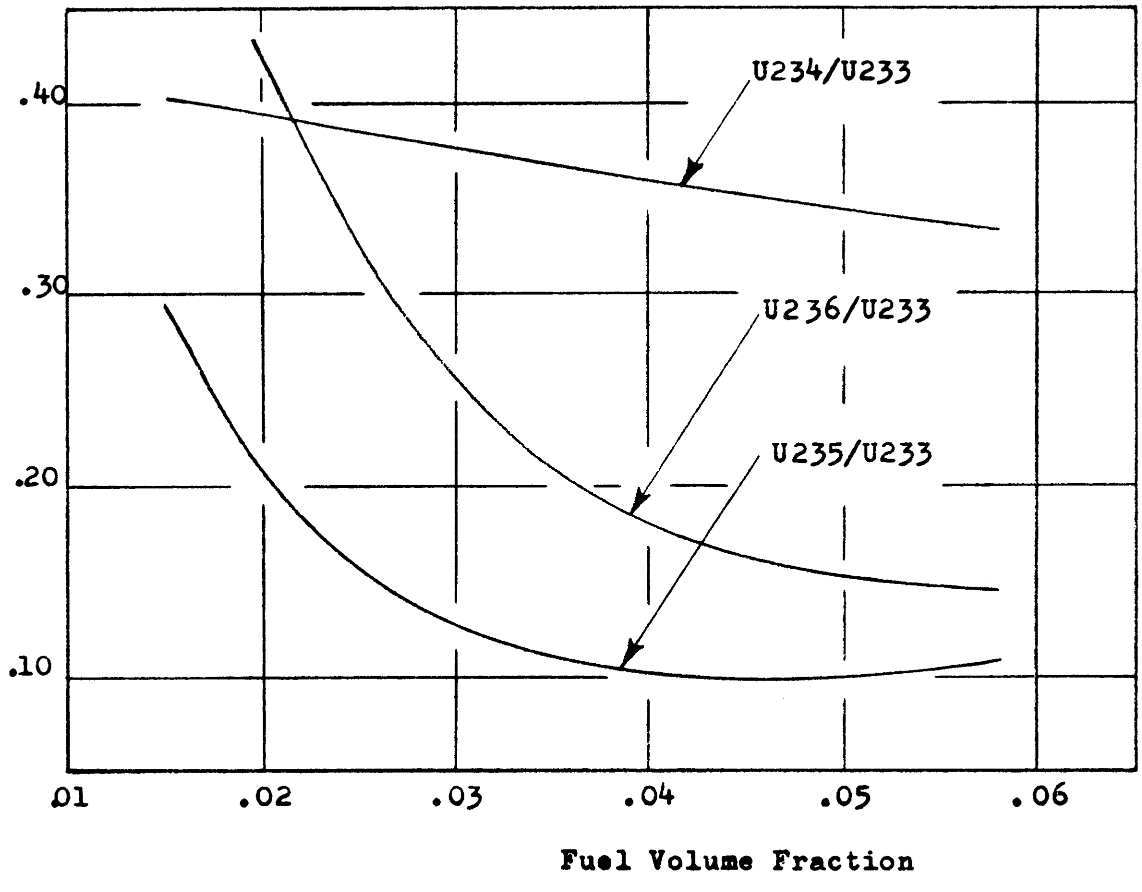


FIG. 2 CONVERSION RATIO AND ATOM RATIOS
AS A FUNCTION OF FUEL VOLUME RATIO

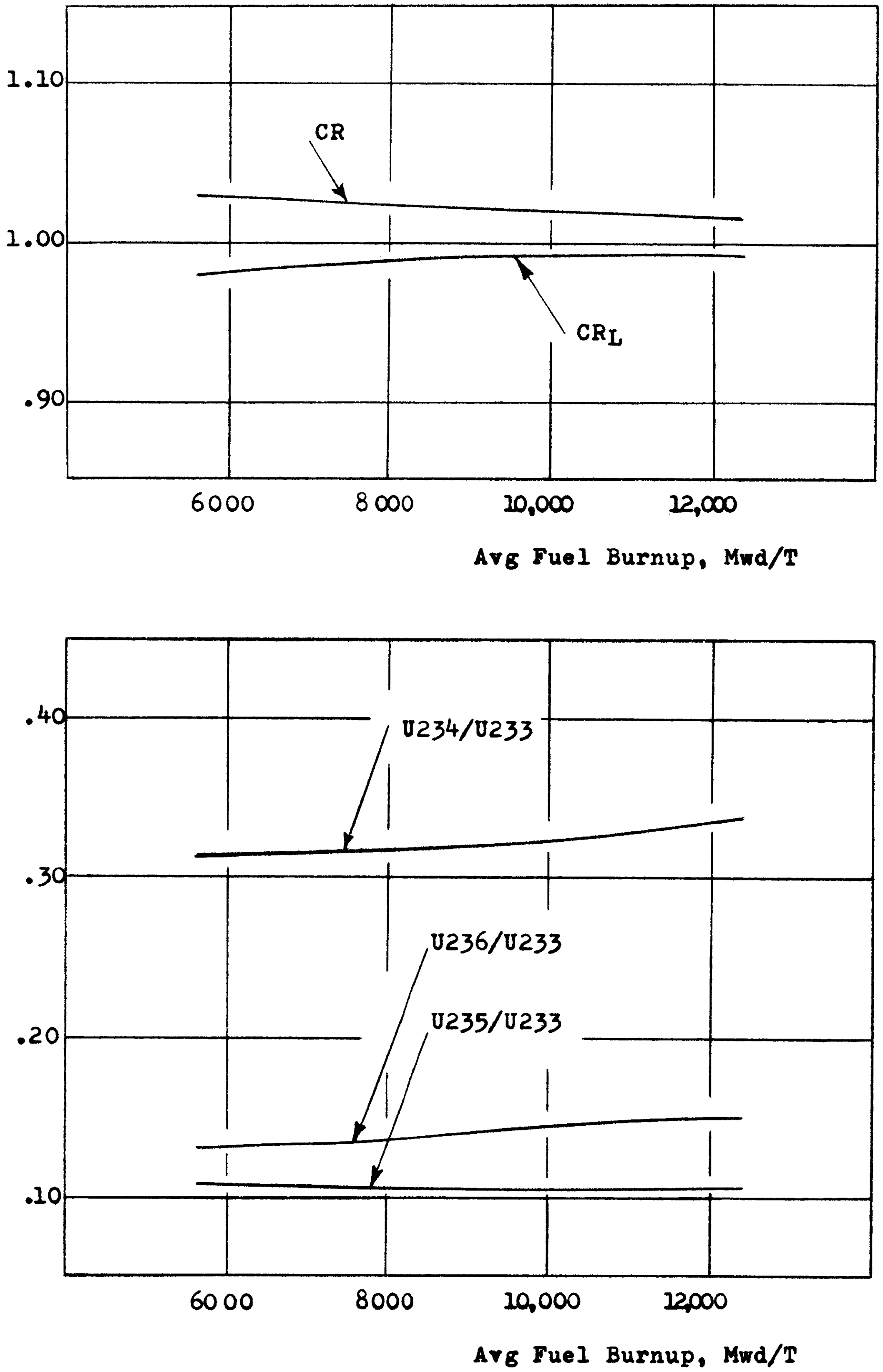


FIG. 3 CONVERSION RATIO AND ATOM RATIOS AS A FUNCTION OF AVERAGE FUEL BURNUP

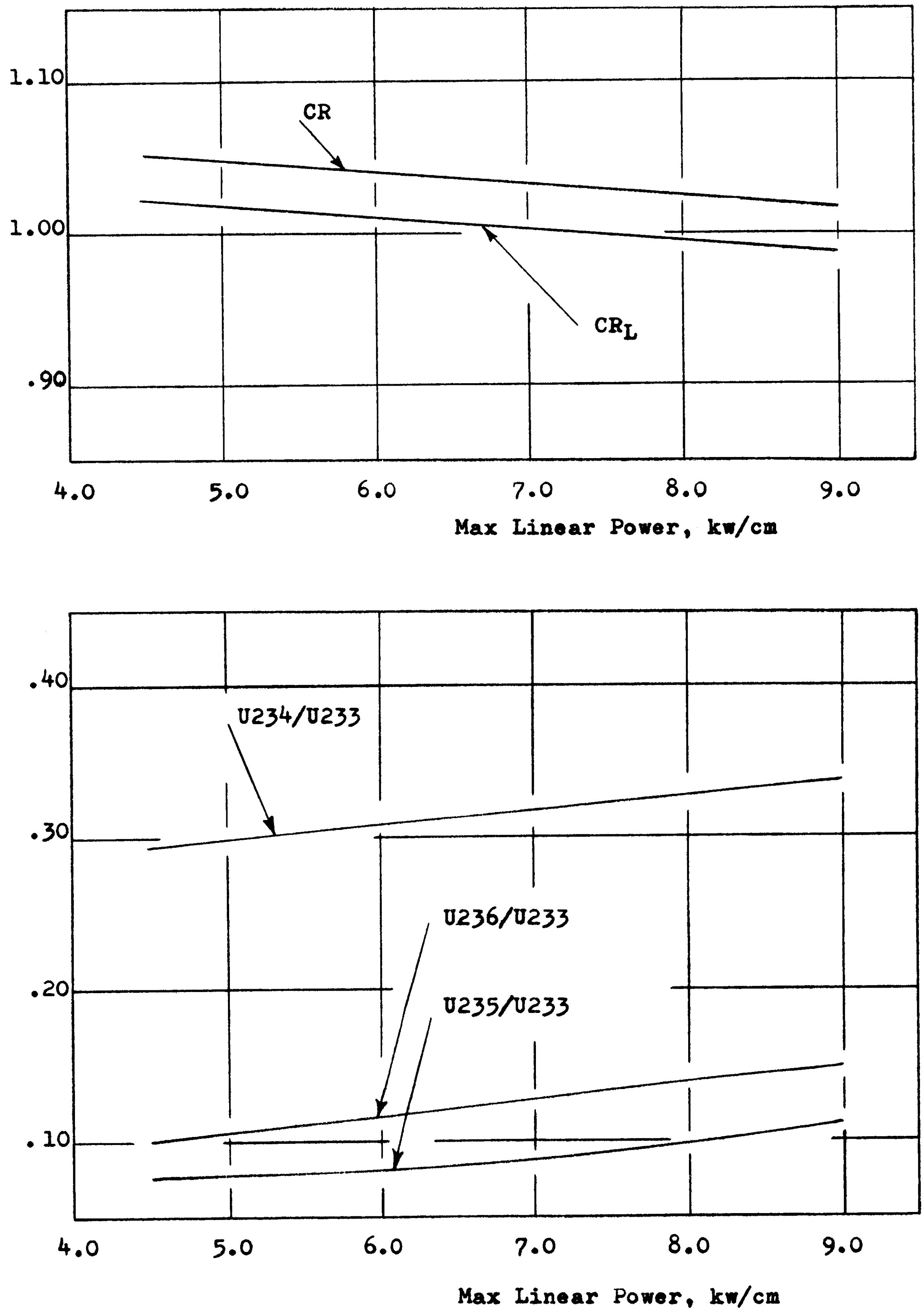


FIG. 4 CONVERSION RATIO AND ATOM RATIOS AS A FUNCTION OF MAXIMUM LINEAR POWER

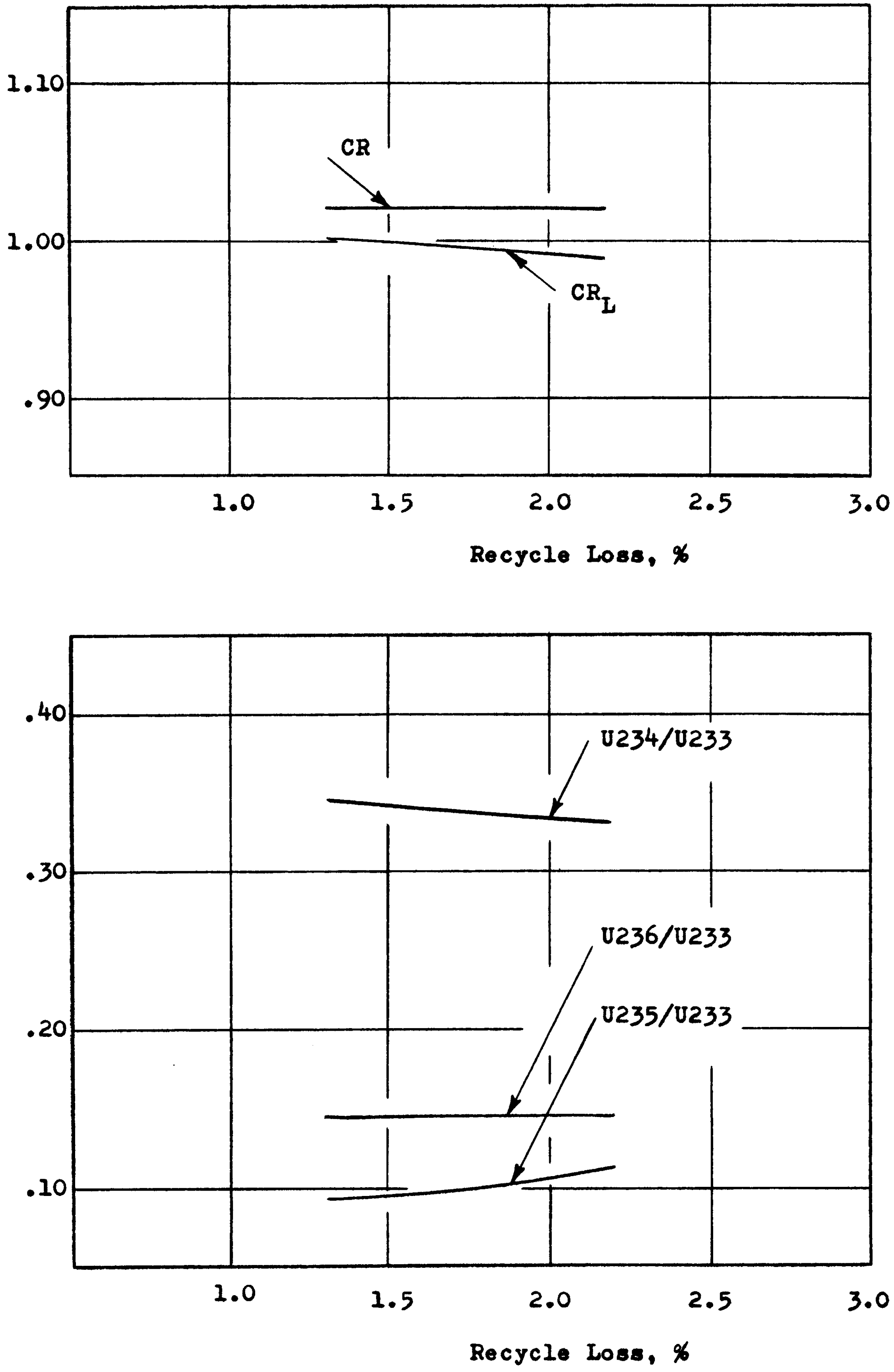
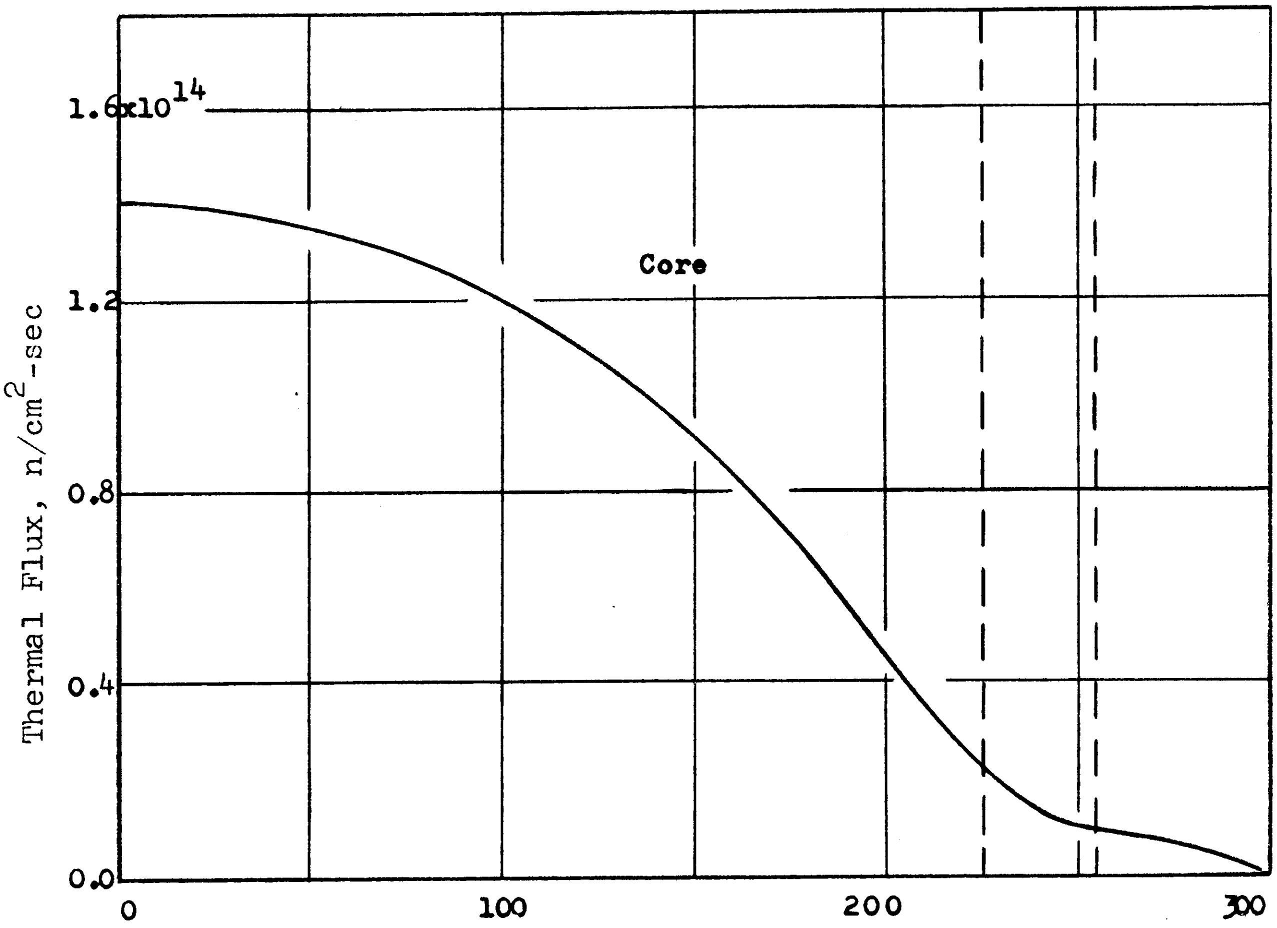


FIG. 5 CONVERSION RATIO AND ATOM RATIOS
AS A FUNCTION OF RECYCLE LOSS

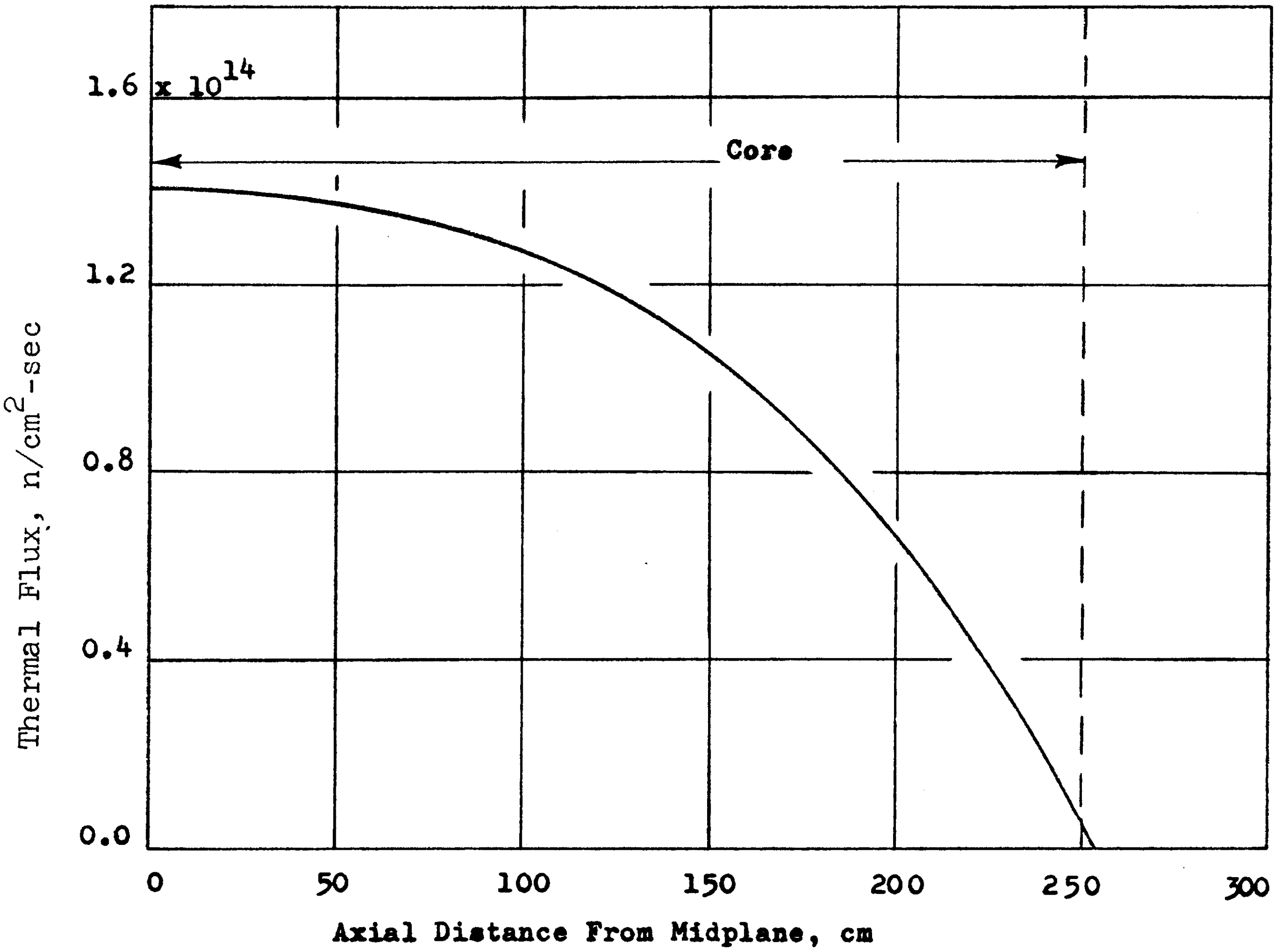


Radius, cm

Reactor Characteristics:

Core Radius	= 225.61 cm
Blanket Radius	= 255.00 cm
Reflector Radius	= 299.70 cm
Core Height	= 500.40 cm
Constant Fuel Velocity	

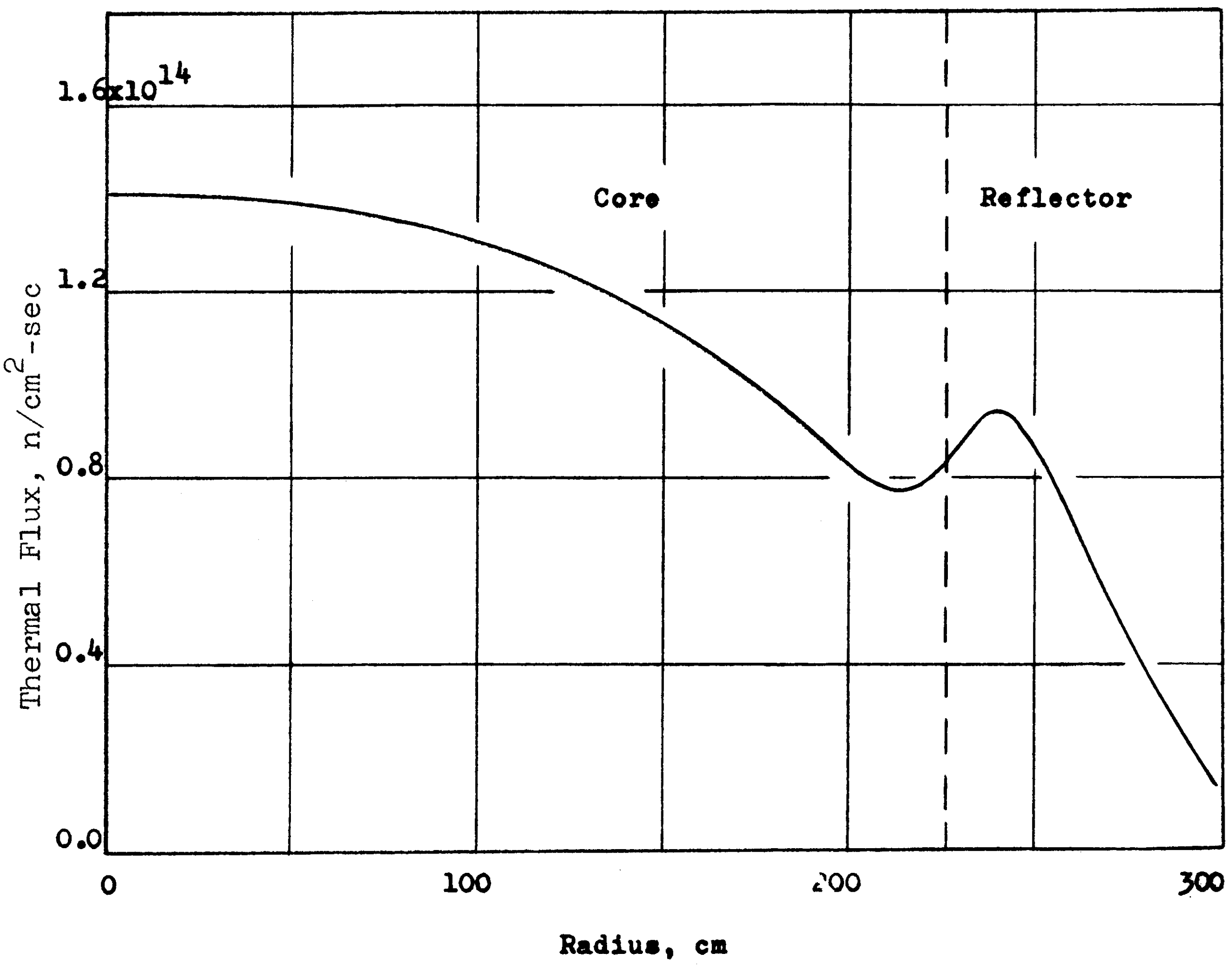
FIG. 6 RADIAL FLUX DISTRIBUTION AT REACTOR MIDPLANE WITH BLANKET



Reactor Characteristics:

Core Radius	= 225.61 cm
Blanket Radius	= 255.00 cm
Reflector Radius	= 299.70 cm
Core Height	= 500.40 cm
Constant Fuel Velocity	

FIG. 7 AXIAL FLUX DISTRIBUTION
ALONG REACTOR CENTERLINE



Reactor Characteristics:

Core Radius = 225.61 cm
No Blanket
Reflector Radius = 299.70 cm
Core Height = 500.40 cm
Constant Fuel Velocity

FIG. 8 RADIAL FLUX DISTRIBUTION AT REACTOR MIDPLANE - NO BLANKET

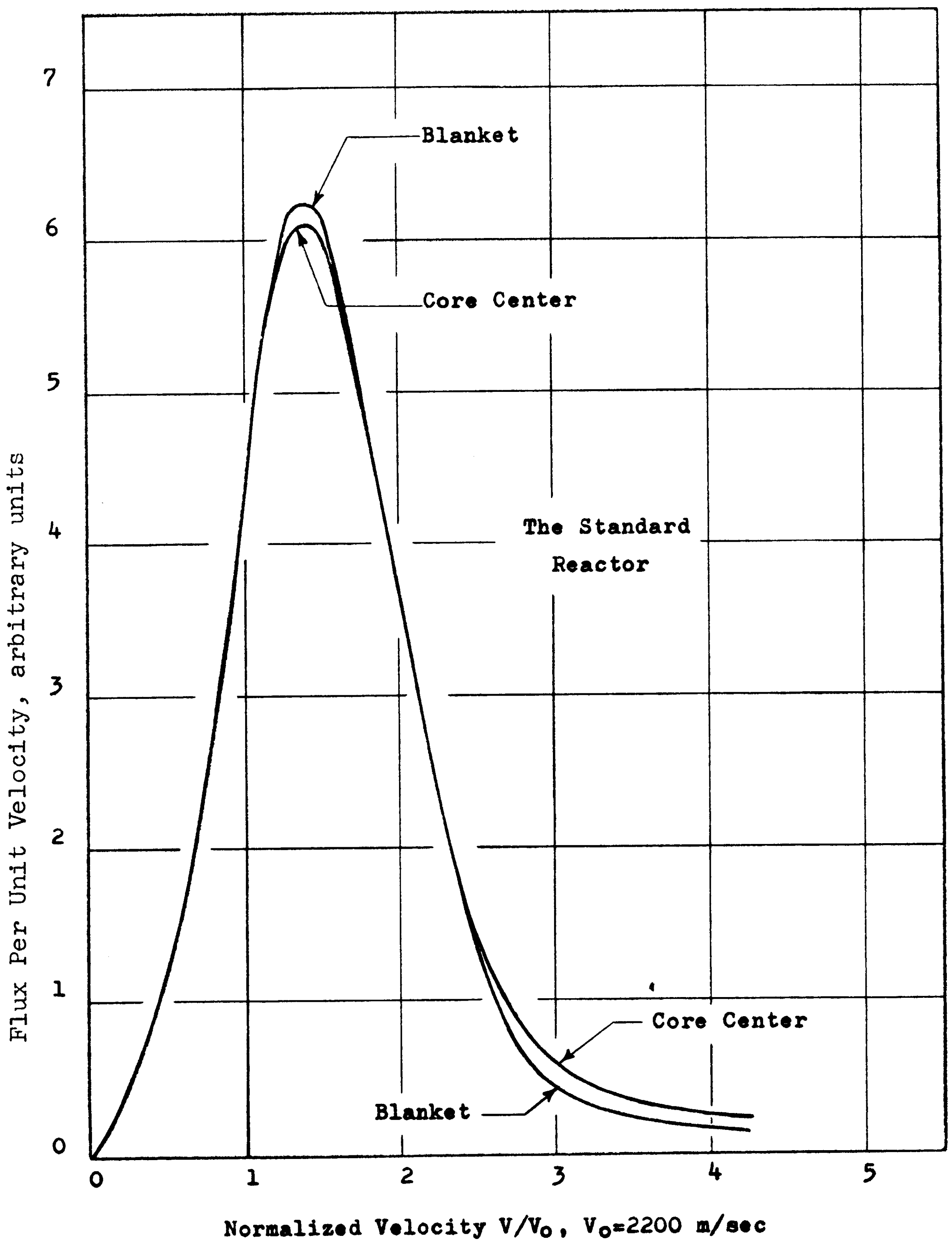


FIG. 9 COMPARISON OF FLUX SPECTRA AT CORE CENTER AND IN THE BLANKET

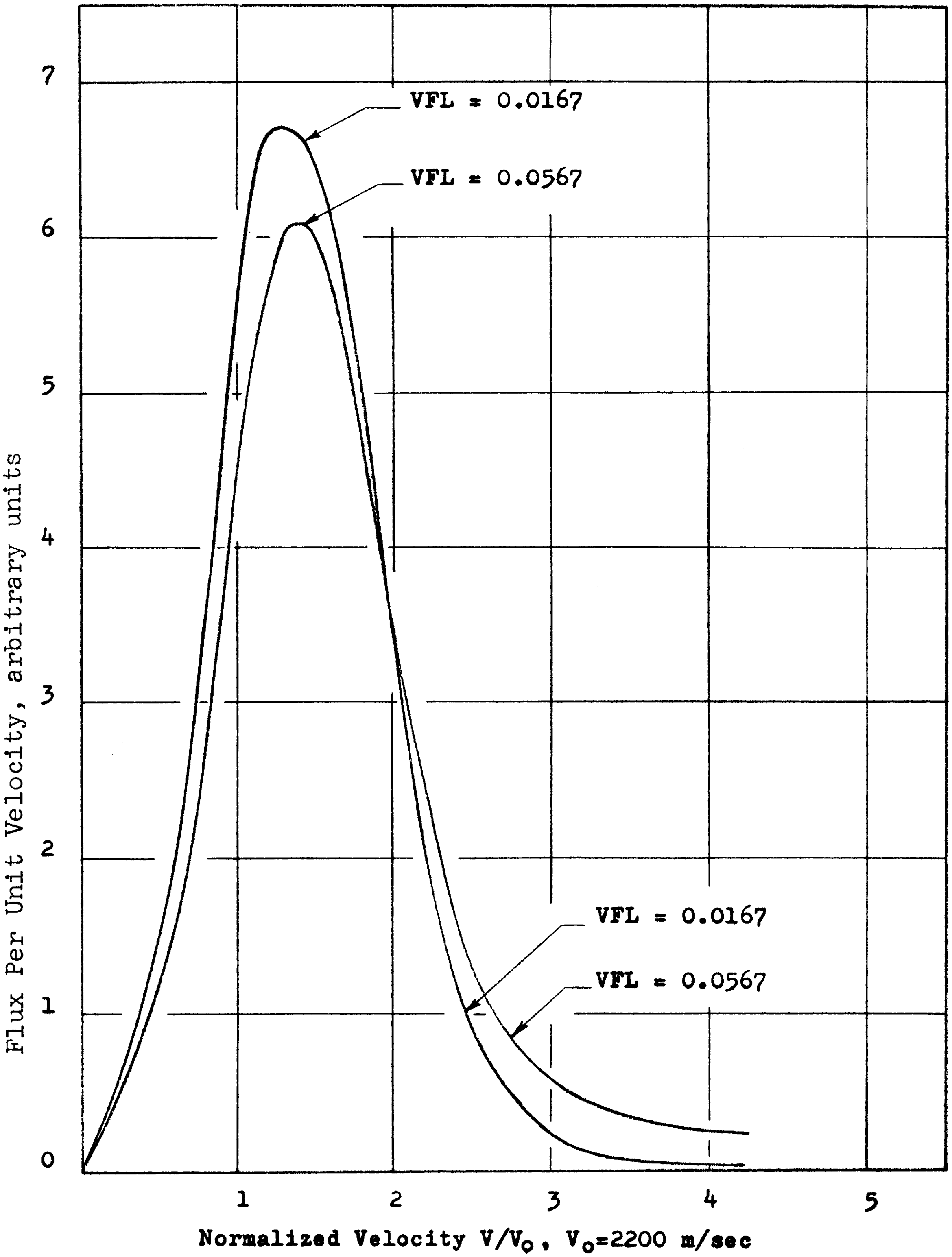


FIG. 10 COMPARISON OF FLUX SPECTRA FOR TWO FUEL VOLUME FRACTIONS

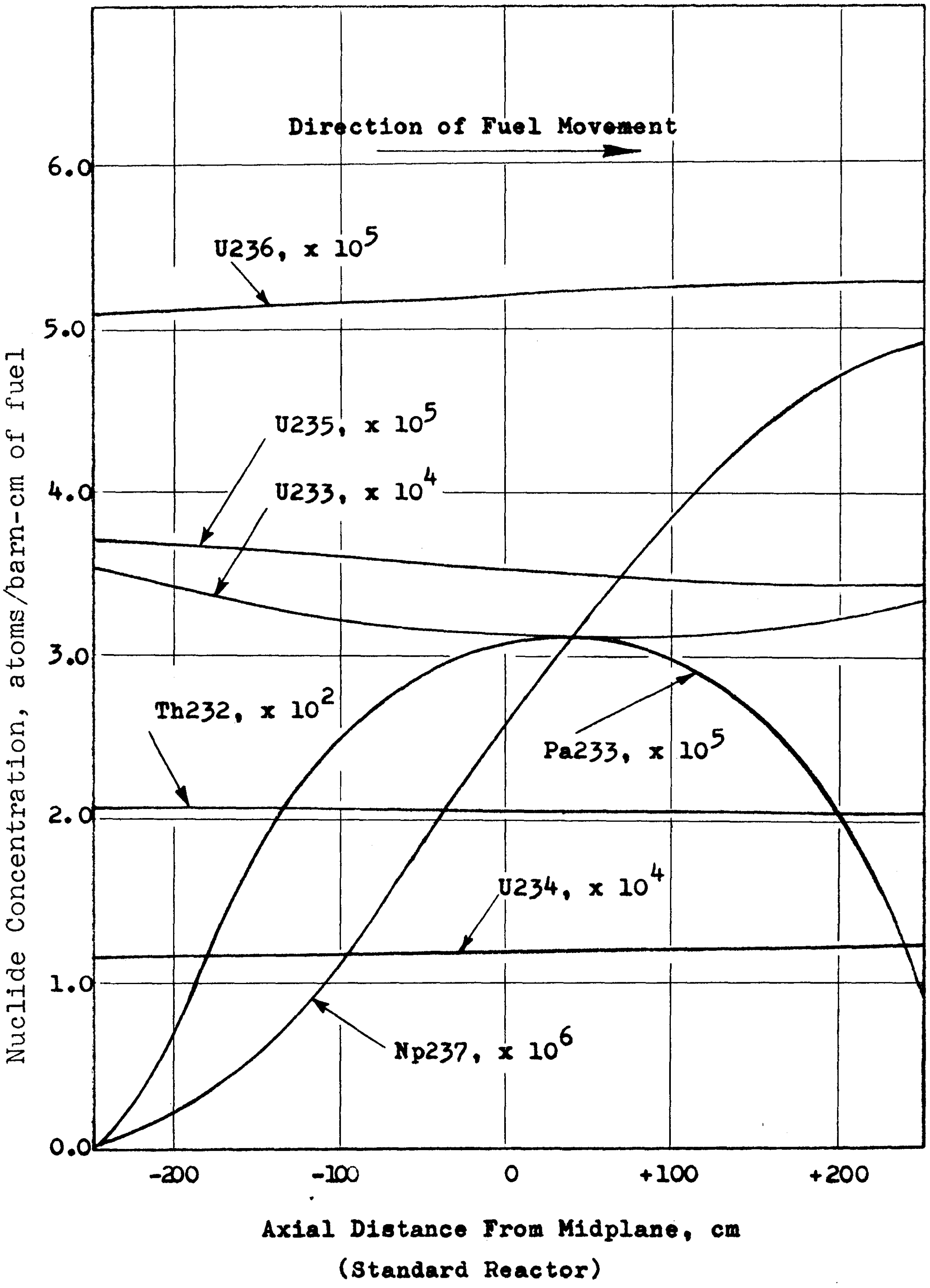


FIG. 11 NUCLIDE CONCENTRATIONS ALONG THE CENTER FUEL CHANNEL

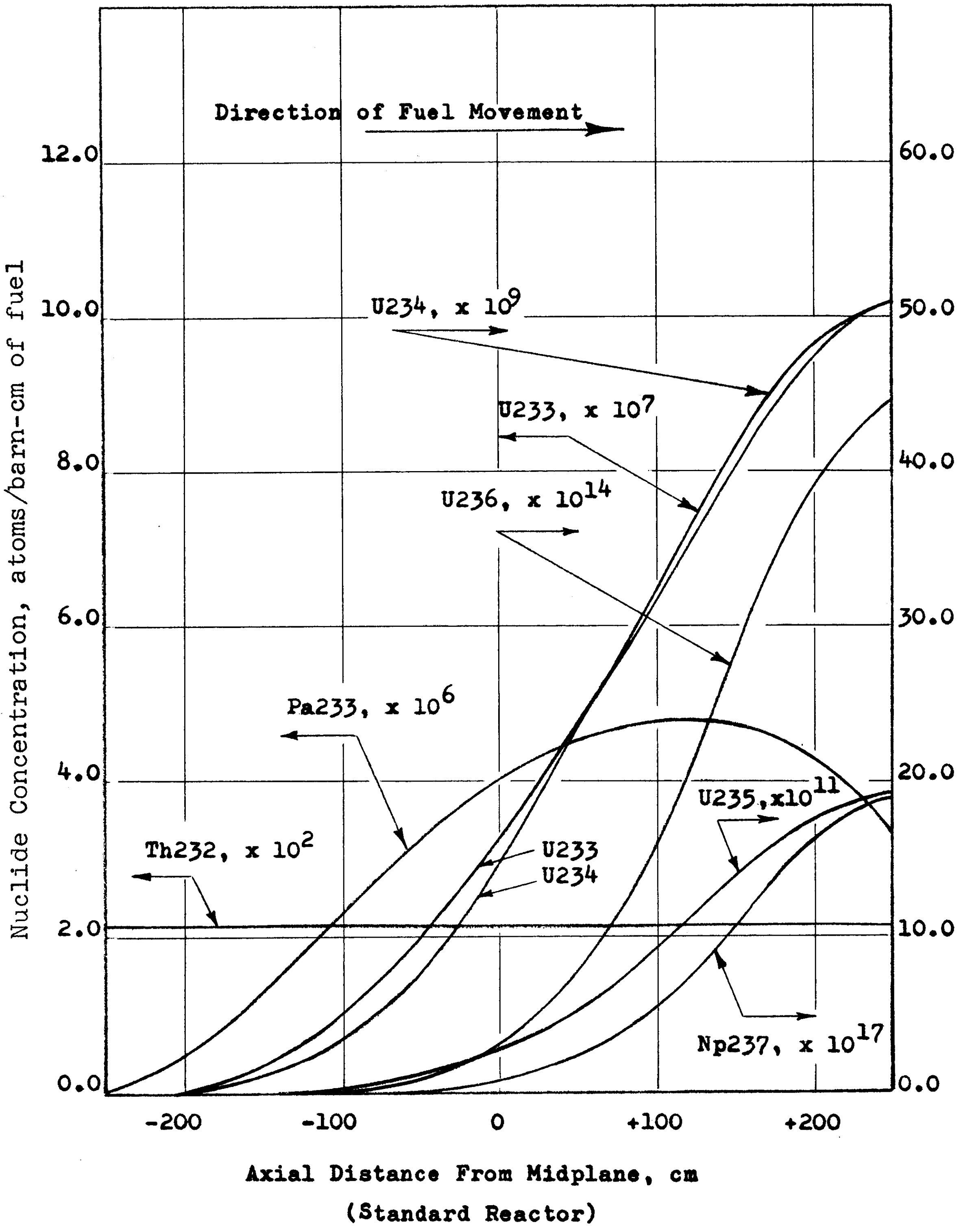


FIG. 12 NUCLIDE CONCENTRATIONS ALONG THE BLANKET CHANNEL

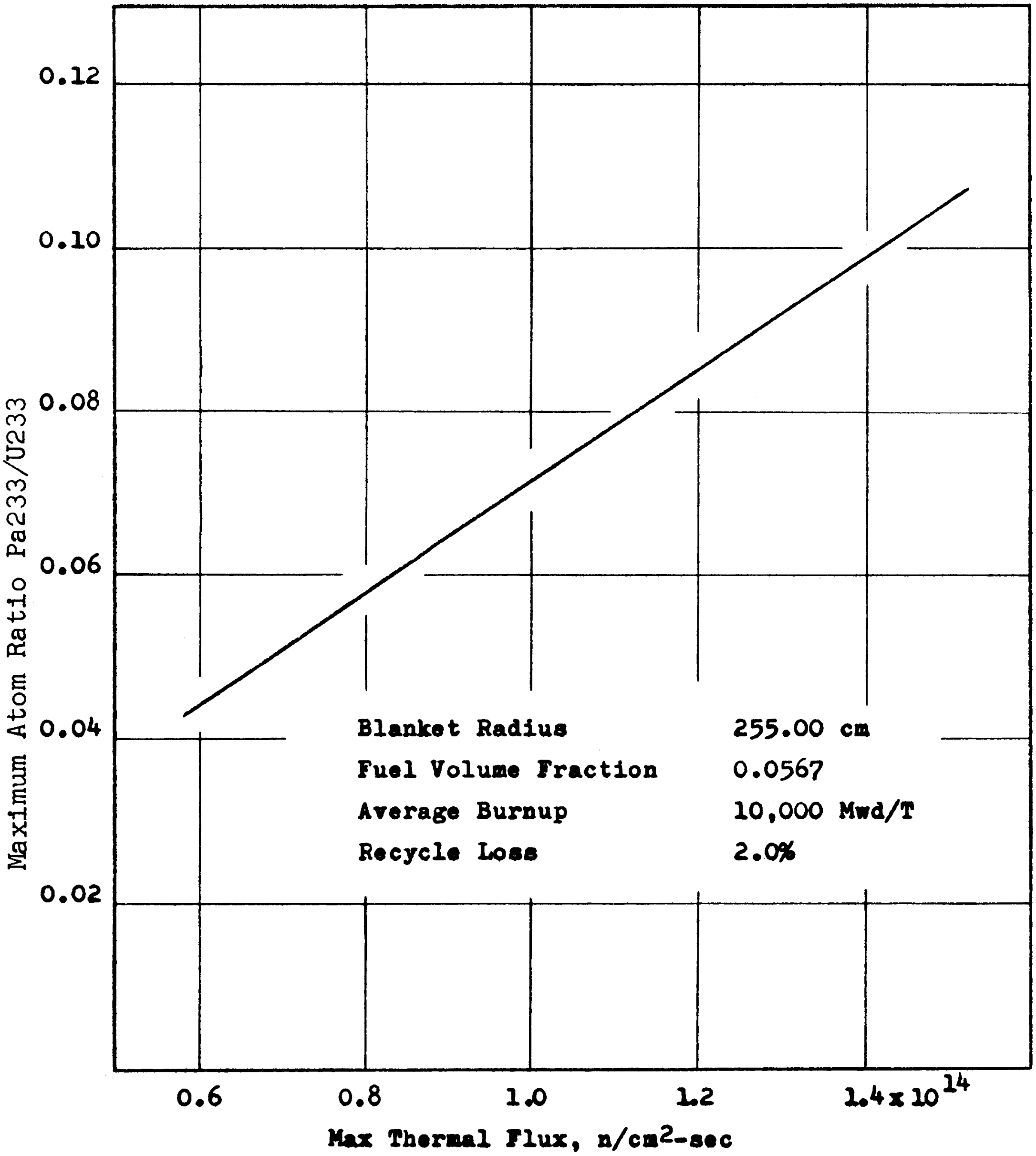


FIG. 13 MAXIMUM ATOM RATIO Pa233/U233 AS A FUNCTION OF MAXIMUM THERMAL FLUX IN THE CENTER FUEL CHANNEL

DISCUSSION AND CONCLUSIONS

The results of the correction are encouraging. Although the reactor parameters used in this study were not optimized for breeding on the thorium cycle, conversion ratios greater than unity were achieved.

Richardson, using more recent nuclear data in a generalized study of the breeding potential of large D_2O moderated power reactors fueled with thorium and uranium, has suggested that these results are somewhat optimistic, but the indication is that breeding on the thorium cycle may be possible with a reactor of the CANDU-type design.

It is of interest to calculate the maximum conversion ratio predicted by the performance of the five variables. The conversion ratio can be written in terms of the function F as:

$$CR = F(BR,\ VFL,\ BURNUP,\ PDNLM\ ROSS)$$

where

BR = blanket outside radius, cm
VFL = fuel volume fraction
BURNUP = avg. fuel burnup, MWD/T
PDNLM = max. linear power, kw/cm
ROSS = recycle loss, %

Assuming that there are no interactions between the variables, the function F can be written

$$\begin{aligned} &F(BR,\ VFL,\ BURNUP,\ PDNLM,\ ROSS) \\ &\quad = CR_o + f_1(BR) + f_2(VFL) + f_3(BURNUP) \\ &\qquad + f_4(PDNLM) + f_5(ROSS) \end{aligned} \tag{2}$$

where CR_o is the conversion ratio of the standard reactor and each function f expresses the change in conversion ratio caused by changing one of the variables from its standard value, all other variables remaining constant. The maximum value of F is found by simply inserting the maximum value of the f's, obtained from figures 1-5, into equation (2).

The maximum conversion ratio of the reactor alone, CR_{max}, is

CR_o = 1.020 (fig 1)
f_1,max = CR(BR=257) - CR_o = 0.000 (fig 1)
f_2,max = CR(VFL=0.0497) - CR_o = 0.003 (fig 2)
f_3,max = CR(BURNUP=6000) - CR_o = 0.009 (fig 3)
f_4,max = CR(PDNLM=4.712) - CR_o = 0.030 (fig 4)
f_5,max = CR(ROSS=1.5) - CR_o = 0.002 (fig 5)

CR_{max} = 1.064

The maximum conversion ratio with the recycle loss included, $CR_{L,max}$, is

$CR_{L,o}$ = 0.990 (fig 1)
$f_{1,max}$ (BR = 260) = 0.000 (fig 1)
$f_{2,max}$ (VFL = 0.0486) = 0.004 (fig 2)
$f_{3,max}$ (BURNUP = 12,000) = 0.001 (fig 3)
$f_{4,max}$ (PDNLM = 4.712) = 0.031 (fig 4)
$f_{5,max}$ (ROSS = 1.5) = 0.009 (fig 5)

$CR_{L,max}$ = 1.035

It should be noted that the set of variable values for both maximum conversion ratios contain the lowest maximum linear power considered, and that both conversion ratios are essentially inverse linear functions of the maximum linear power (no maxima or minima - fig 4). The overall conversion ratio, CR_L, drops below unity at

7.5 kw/cm. This is the conversion ratio penalty to be expected as the maximum linear power is increased.

The conclusion that may be drawn now is that it is probably possible to breed on the thorium cycle in a reactor of the CANDU-type design. The next logical step is to include economics in the study, and determine the dollar penalty of the low maximum linear power required for breeding.