NASA TECHNICAL NOTE

NASA TN D-4459

C. 1

NASA TN D-4459

REACTIVITY EFFECTS CAUSED BY RADIAL POWER FLATTENING IN A SMALL, FAST-SPECTRUM REACTOR

by C. L. Whitmarsh, Jr.
Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1968

REACTIVITY EFFECTS CAUSED BY RADIAL POWER FLATTENING IN A SMALL, FAST-SPECTRUM REACTOR

By C. L. Whitmarsh, Jr.

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

REACTIVITY EFFECTS CAUSED BY RADIAL POWER FLATTENING IN A SMALL, FAST-SPECTRUM REACTOR

by C. L. Whitmarsh, Jr.

Lewis Research Center

SUMMARY

The effect on criticality of flattening the radial power distribution in a small, reflector-controlled, fully enriched, fast-spectrum nuclear reactor was calculated. Power shaping was achieved by varying the U-235 enrichment in annular fuel zones of a cylindrical core (diameter = length = 32.6 cm). Compared to a uniformly fueled, fully enriched core, a decrease in reactivity occurred from reduced fuel inventory and an increase in reactivity occurred from enhanced reflector worth. To achieve a peak-to-average power ratio of 1.05 with a 5.08 cm beryllium oxide (BeO) radial reflector, an enrichment distribution varying from 57.9 percent in the central zone of the core to 93.2 percent in the peripheral zone was required. The reactivity loss caused by a reduced U-235 inventory was 12 percent, half of which (6 percent) was recovered by increased reflector worth. Fuel distributions were also calculated to indicate the effects of (1) changing the power ratio of 1.1, and (2) changing the reflector thickness to 7.62 cm. Change (1) resulted in a zoned core with an enrichment variation from 71.3 percent in the central zone to 93.2 percent in the peripheral zone; whereas, for change (2) these values were 67 and 93.2 percent, respectively. The net reactivity loss (fuel loss - reflector worth increase) based on a 93.2 percent enriched uniformly-fueled core was 3 percent for either of these zoned cores.

Power distortion in a reactor core is caused by reflector movement required to compensate for reactivity changes over the core lifetime. This effect in zoned cores was observed by calculating power shapes for the intial and the end-of-life reflector configurations for two zoned cores. One core was zoned to a peak-to-average power ratio of 1.05 for the initial reflector thickness of 5.08 centimeters, and the resulting power shape was then calculated for the end-of-life condition (7.62 cm of reflector). The other core was zoned to a peak-to-average power ratio of 1.05 for the end-of-life reflector thickness of 7.62 centimeters and the resulting power shape was calculated for the initial condition (5.08 cm of reflector). Maximum distortions were power ratio values of 1.08 in the peripheral zone of the first core design and 1.1 in the central zone of the second core design.

INTRODUCTION

High-temperature, long-lived, fast-spectrum, fully-enriched reactors are of interest for power generation in space. The small size of these systems generally necessitates using an external control system which is based on leakage, and/or absorptions of neutrons. Reactivity can be regulated either by a removable reflector (leakage control) or by a revolving drum (absorption control).

Reactor designers have used power flattening, i.e., uniform power generation per unit volume of core, in order to decrease the ratios of peak-to-average core temperature and fuel burnup. One method of flattening the power distribution is variation of fuel enrichment. Using a fully-enriched core with uniform fuel distribution as a basis for comparison, one can see that any variation of enrichment requires fuel removal, which, of course, decreases the reactivity of the core. When the reference core has a chopped-cosine radial power distribution, this fuel redistribution tends to increase the importance of the peripheral core region, thereby enhancing the reactivity worth of the radial reflectors. As part of a design study of a 1 megawatt reactor for Brayton cycle application, these neutronic effects were investigated and the results are presented herein. The present study was based on a cylindrical, fast-spectrum core with a diameter of 32.6 centimeters and a length-to-diameter ratio of one. The core consisted of 1.1 centimeter fuel pins composed of enriched uranium dioxide (UO_2) fuel clad with tungsten-25 volume percent rhenium alloy (W-25Re). The core was contained in a W-25Re pressure vessel and was controlled by axial movement of an external beryllium-oxide (BeO) radial reflector (leakage control by a removable reflector).

Three reactor designs were considered: case I, a peak-to-average power ratio of 1.1 and a radial reflector thickness of 5.08 centimeters; case II, a peak-to-average power ratio of 1.05 and a radial reflector thickness of 5.08 centimeters; and case III, a peak-to-average power ratio of 1.05 and a reflector thickness of 7.62 centimeters. These parameters cover the range of interest in the reactor study. In each case the specified power distribution was obtained by adjusting the U-235 enrichment in such a way that a minimum of fuel was removed from a fully enriched core design.

Because power distribution is dependent on radial reflector thickness, the use of a single reflector thickness in defining a power-flattened reactor design is complicated by the dynamic nature of the real situation, i.e., a changing reflector position over the operating life of the core. Operating control for the reference core required the reactivity change supplied by the addition of 2.54 centimeters of reflector to the initial condition of a 5.08 centimeters BeO reflector. Therefore, the resulting distortion of the power shape was observed by calculating the effects of changing the reflector thickness in the case II core design to 7.62 centimeters (case IIa) and of changing the reflector thickness in the case III core design to 5.08 centimeters (case IIIa). Case IIa thus represents the end-of-life condition of case II, and case IIIa represents the initial condition of case III.

ANALYTICAL PROCEDURE

A reference reactor was specified to have a uniform concentration of 93.2 percent enriched uranium-dioxide in the core and to have a BeO radial reflector. Fuel enrichment was then adjusted to provide a specified peak-to-average power ratio $P_p/\bar{P}$. The calculations were performed on a UO_2 fueled pin-type core controlled by the axial movement of radial reflectors. Dimensional and composition data for this reactor are listed in table I. In the calculational model (fig. 1) for this reactor, the cylindrical core was divided into six annular zones. The relative width of the zones was estimated from the power shape in the unzoned core with the widest spacing being used where the power shape was the flattest (zone 1 in fig. 2). Although preliminary calculations indicated that the selection of radial zone widths would influence the reactivity cost of power flattening, no attempt was made to optimize this parameter. Generally, one would expect the lower limits of these dimensions to be determined by fabrication procedures, and therefore the exact size of each zone was somewhat arbitrarily picked such that the zone would contain an integral number of fuel pins.

The method used to calculate the required fuel enrichment distribution to achieve a specified $P_p/\bar{P}$ was an iterative procedure and is listed below.

(1) The radial power distribution of the uniformly enriched core was normalized to the specified power ratio, either 1.05 or 1.1, at the region of least power generation (zone 6 in fig. 2). The U-235 atom density, $N_{U\text{-}235}$, in that zone will remain constant at the maximum value as the fuel enrichment is reduced in the other zones.

(2) Each fuel zone (excepting the peripheral zone) was then subjected to the following criteria:

(a) $N_{U\text{-}235} = N_{U\text{-}235}$ at 93.2 percent enrichment

and $\frac{P_p}{\bar{P}} \neq \frac{P_p}{\bar{P}}$ specified

(b) $N_{U\text{-}235} < N_{U\text{-}235}$ at 93.2 percent enrichment

and $\frac{P_p}{\bar{P}} \neq \frac{P_p}{\bar{P}}$ specified

(c) $\frac{P_p}{\bar{P}} = \frac{P_p}{\bar{P}}$ specified

and $N_{U\text{-}235} \leq N_{U\text{-}235}$ at 93.2 percent enrichment

If (a) or (b) applied, the fuel enrichment was adjusted by

$$N_{U\text{-}235} = \frac{P_p/\overline{P} \text{ specified}}{P_p/\overline{P} \text{ previous value}} \times N_{U\text{-}235}, \text{ previous value}$$

(3) A reactor calculation was performed and a new radial power distribution was determined.

Steps (2) and (3) were repeated until either $P_p/\overline{P} = P_p/\overline{P}$ specified or $N_{U\text{-}235} = N_{U\text{-}235}$ at 93.2 percent enrichment applied to each fuel zone.

All reactor calculations were performed with the one-dimensional transport-theory code, DTF[1], utilizing the S_4P_0 approximation and 16-group cross sections generated by GAM-II[2] and TEMPEST-II[3] computer codes. The flux spectrum for these reactors was considered fast because the calculated median fission energy was about 0.7 million electron volts (0.1 pJ). The drastic spectral change occurring in the re lector region of a fast-core moderating-reflector configuration necessitated the use of two reflector regions for calculational purposes. The first region (nearest the core) was represented by cross sections weighted over the core spectrum and the second region by cross sections weighted over a BeO spectrum. The width of the first region was estimated to be about 2 inches (5.08 cm) by matching cadmium ratio foil data from a similar reactor system to calculations in which the width of the first region was varied.

Reactivity worth of a reflector was determined by criticality calculations of a reactor with and without the reflector. Reactivity worth, or change in reactivity, was then obtained from the equation

$$\Delta\rho = \frac{k_1 - k_2}{k_1 k_2} \times 100 \tag{1}$$

where k_1 and k_2 are the effective multiplication constants for the reflected and bare cases, respectively. In a real situation, however, the reflector is never completely absent and could reflect some neutrons even when fully open. Consequently, equation (1) represents an overestimate of reflector worth. The magnitude of this effect was assumed to be second order and therefore not calculated.

Total (or net) reactivity changes from the unzoned to the zoned core condition were calculated similarly by using the respective k values. The difference between the net reactivity change and increased reflector worth was considered to be the effect of fuel removal.

RESULTS

Results from the aforementioned calculations were categorized as follows:

(1) effects of $P_p/\overline{P}$ and total reflector thickness on fuel distribution, (2) reactivity changes caused by fuel distribution, (3) power distortion caused by reflector movement, and (4) reflector worth for zoned cores.

Effects of $P_p/\overline{P}$ and Total Reflector Thickness

Power shaping to attain a $P_p/\overline{P} = 1.10$ for a core with a 5.08 centimeter reflector (case I) was attained with a minimum enrichment of 71.3 percent in the central zone (table II). Reduction of $P_p/\overline{P}$ to 1.05 (case II) necessitated decreasing the minimum enrichment (central zone) to 57.9 percent with appropriate reductions in the other zones. Increasing the reflector thickness to 7.62 centimeters (case III) resulted in higher enrichments (and consequently less fuel removal) than for case II. This should generally be true because of the flux-flattening effect of increased reflector thickness.

Maximum power was not achieved in the outer zone, thereby indicating a nonoptimum width for this region. However, no attempt was made to vary zone dimensions because any effect on net reactivity was considered to be small. Another feature of the power shape was the absence of any power peaking near the core-reflector interface for both the zoned and unzoned cores. Although such peaking often occurs in fast-reactor design, the problem can be alleviated by using relatively thin reflectors and a thermal neutron absorber (W-25Re pressure vessel) between the core and the reflector.

Reactivity Changes Caused by Fuel Distribution

The effect on criticality of these fuel distributions (cases I, II, and III) to attain power flattening is expressed in table III as a reactivity change from the fully-enriched, uniformly-fueled condition. The overall effect is a net reactivity loss of 3 percent for case I ($P_p/\overline{P} = 1.1$ with a 5.08 cm reflector), 6 percent for case II ($P_p/\overline{P} = 1.05$ with a 5.08 cm reflector, and 3 percent for case III ($P_p/\overline{P} = 1.05$ with a 7.62 cm reflector).

This overall reactivity loss represents the net result of two opposing effects, viz., increased reflector worth and fuel removal. The increased reflector worth, 2 percent reactivity for case I, 6 percent reactivity for case II, and 4 percent reactivity for case III, is directly related to the relative power output of the peripheral core zone, as can be seen by comparing the power distributions in table II with reflector worths in table III. The general implication is that the flatter the power distribution the greater the increase in reflector worth.

The difference between the overall reactivity effect and the increased reflector worth was assumed to be caused by the removal of fuel from the fully-enriched core to achieve a given power shape. The reactivity loss was approximately proportional to the reduction in fuel inventory (table III).

Power Distortion Caused by Reflector Movement

Since a reflector-controlled reactor must necessarily have a varying amount of reflectivity over the core lifetime in order to compensate for reactivity changes, the effect of changing the radial reflector thickness around a zoned core was investigated. Two situations, cases IIa and IIIa (table IV) respectively, were considered: (1) the core was power flattened to the initial reflector configuration of 5.08 centimeters (case II) and 2.54 centimeters of reflector were added to simulate the end-of-life condition; and (2) the core was power flattened to the end-of-life reflector configuration of 7.62 centimeters (case III) and a 2.54 centimeters of reflector were removed to simulate the initial condition. The results in table IV show power peaks exceeding the design value of 1.05 in the peripheral zones for increased reflector thickness (case IIa) and in the interior zones for decreased reflector thickness (case IIIa). However, it seems reasonable to assume that a fuel distribution could be obtained, either by adjusting zone dimensions, or by zoning at an intermediate reflector thickness, such that the required $P_p/\overline{P}$ is not exceeded in the central zone for the initial reactor conditions and in the peripheral zone for the end-of-life condition.

A more complete description of how power shapes change over the core lifetime is shown in figure 3. The beginning and end-of-life power distributions for a zoned core (case II and IIa) indicate the shape of the power distribution within each fuel zone and the degree to which this shape is flattened within each fuel zone by increasing reflector thickness over the core lifetime.

Reflector Worth For Zoned Cores

An obvious extension of the increased reflector worth data in table III is the fact that the worth per unit width of reflector is increased when the power distribution is flattened. Reflector worth data plotted in figure 4 indicate that the peripheral 2.54 centimeters thick region was worth 3 percent for a zoned core (case II fuel distribution) and 2 percent for a uniformly-fueled core. Therefore, if 2 percent reactivity were the requirement for operating control (temperature changes, fuel burnup, etc.) for a reactor design, the required reflector thickness could be reduced accordingly.

SUMMARY OF RESULTS

Neutronics effects of radially flattening power of a small, gas-cooled, fast-spectrum, reflector-controlled nuclear reactor by fuel-enrichment variation from the fully enriched condition are summarized below. All conclusions were based on a cylindrical core (length = diameter = 32.6 cm) with a beryllium oxide (BeO) radial reflector.

1. For a core with a 5.08 centimeter reflector, power shaping to a peak-to-average power ratio of 1.05 was accomplished by varying the uranium-235 (U-235) enrichment from 57.9 percent at the core center to 93.2 percent at the edge. The reactivity cost of removing U-235 from a uniformly-fueled, fully-enriched core to obtain this distribution was 12 percent, but half of this (6 percent) was recovered by increased worth of the reflector.

2. Increase of the peak-to-average power ratio to 1.1 required lesser changes in U-235 distribution (71.3 percent at the center to 93.2 percent at the edge) from the uniformly-fueled situation and resulted in a 5 percent reactivity loss from fuel removal and a 2 percent gain from increased reflector worth.

3. Power flattening to a peak-to-average ratio of 1.05 but with a 7.62 centimeter BeO radial reflector required less fuel removal (greater enrichments) than for the 5.08 centimeter reflected core. Reactivity loss from fuel removal was 7 percent of which more than half (4 percent) was regained from increased reflector worth.

4. For each of the three power-flattened cores, about half of the reactivity lost by fuel removal was regained by increased reflector worth. This recovery in reactivity was directly dependent on the absence of a power spike near the core edge in any of the reactor designs considered.

5. Power shapes are distorted by reflector movement which is required to compensate for reactivity changes during the core lifetime. As reflector thickness increases, the peak-to-average power ratio decreased in the interior core zones and increases in the peripheral zones. When the core was initially zoned to a peak-to-average power ratio of 1.05 for a radial reflector 5.08 centimeters thick, the power ratio increased to 1.08 in the peripheral fuel zone for an end-of-life reflector 7.62 centimeters thick. Alternately, in a core zoned to a peak-to-average power ratio of 1.05 for a 7.62 centimeters reflector thickness (end-of-life condition), the ratio in the central zone was 1.10 for the initial reflector thickness of 5.08 centimeters.

6. The worth of the outer 2.54 centimeters of a 7.62 centimeter BeO radial reflector was increased from 2 percent reactivity (fully enriched fuel) to 3 percent reactivity by fuel-enrichment variation to achieve power flattening to a radial peak-to-average power ratio of 1.05.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 5, 1967,
120-27-06-05-22.

REFERENCES

1. Carlson, B. G.; Worlton, W. J.; Guber, W.; and Shapiro, M.: DTF Users Manual. Vol. I. Rep. No. UNC Phys/Math - 3321, United Nuclear Corp., Nov. 1963.
2. Joanou, G. D.; and Dudek, J. S.: GAM-II. A B_3 Code for the Calculation of Fast-Neutron Spectra and Associated Multigroup Constants. Rep. No. GA-4265, General Atomic Div., General Dynamics Corp., Sept. 16, 1963.
3. Shudde, R. H.; and Dyer, J.: TEMPEST-II, A Neutron Thermalization Code. Rep. No. TID-18284, Atomics International, June 1962.

TABLE I. - REFERENCE REACTOR CHARACTERISTICS

Component	Material	Configuration	Composition volume fraction
Core		Cylinder, 32.6 cm diam. by 32.6 cm length	
Fuel	UO_2		0.721
Clad	W-25Re		.073
Coolant	60Xe-He		.206
Pressure vessel	W-25Re	0.953 cm wall	
Radial reflector			
Initial	BeO	5.08 cm thick	
End-of-life	BeO	7.62 cm thick	
Axial reflector (fuel end-plate)	W	1.27 cm thick	

TABLE II. - ENRICHMENTS AND POWER RATIOS IN REACTORS WITH ZONED FUEL DISTRIBUTIONS

Radial zone	Fraction of total core volume	Case I 5.08 cm BeO reflector k = 1.125, $P_p/\overline{P} = 1.10$			Case II 5.08 cm BeO reflector k = 1.036, $P_p/\overline{P} = 1.05$			Case III 7.62 cm BeO reflector k = 1.124, $P_p/\overline{P} = 1.05$		
		Enrichment percent U-235	$P_p/\overline{P}$	$P_{min}/\overline{P}$ (a)	Enrichment percent U-235	$P_p/\overline{P}$	$P_{min}/\overline{P}$	Enrichment percent U-235	$P_p/\overline{P}$	$P_{min}/\overline{P}$
I	0.081	71.3	1.10	1.06	57.9	1.05	1.02	67.0	1.05	1.02
II	.169	74.3	↓	1.02	60.2	↓	.97	69.4	↓	.98
III	.131	81.3	↓	1.02	65.8	↓	.97	75.1	↓	.98
IV	.237	89.0	↓	.98	71.8	↓	.95	80.9	↓	.95
V	.245	93.2	1.02	.88	81.0	↓	.92	89.2	↓	.94
VI	.137	93.2	.88	.80	93.2	1.03	.94	93.2	.98	.93

[a] $P_{min}/\overline{P}$ ≡ minimum to average power ratio.

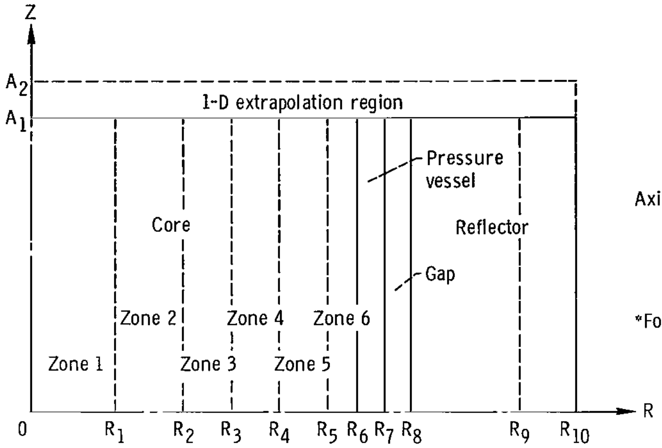
TABLE III. - REACTIVITY COST TO RADIAL POWER FLATTEN A CYLINDRICAL, FAST REACTOR WITH A 32.6 CM DIAMETER AND LENGTH

Case	Reflector	$P_p/\bar{P}$	Reduction of U-235		Reactivity,[a] percent		
			kg	Fraction of initial inventory	Loss from fuel removal	Increased reflector worth	Net loss
I	5.08 cm BeO	1.10	14	0.08	5	2	3
II	5.08 cm BeO	1.05	36	.21	12	6	6
III	7.62 cm BeO	1.05	22	.13	7	4	3

[a] For the unzoned core with a 7.62 cm reflector, k = 1.215, and with a 5.08 cm reflector, k = 1.188.

TABLE IV. - EFFECT OF REFLECTOR THICKNESS ON THE POWER DISTRIBUTION IN ZONED CORES

Radial zone	Case II 5.08 cm BeO reflector k = 1.036 $P_p/\bar{P}$	Case IIa 7.62 cm reflector k = 1.068 $P_p/\bar{P}$	Case IIIa 5.08 cm reflector k = 1.092 $P_p/\bar{P}$	Case III 7.62 cm BeO reflector k = 1.124 $P_p/\bar{P}$
I	1.05	1.00	1.10	1.05
II	↓	1.00	1.09	↓
III	↓	1.02	1.08	↓
IV	↓	1.04	1.06	↓
V	↓	1.06	1.04	↓
VI	1.03	1.08	.93	.98



Radial dimensions, cm	
R_1 = 4.664	Core zone 1, t = 4.664
R_2 = 8.162	Core zone 2, t = 3.498
R_3 = 10.494	Core zone 3, t = 2.332
R_4 = 12.826	Core zone 4, t = 2.332
R_5 = 15.158	Core zone 5, t = 2.332
R_6 = 16.324	Core zone 6, t = 1.166
R_7 = 17.277	Pressure vessel, t = 0.953
R_8 = 17.912	Gap, t = 0.635
R_9 = 22.992	Reflector zone 1, t = 5.08
R_{10} = 25.532*	Reflector zone 2, t = 2.54 (for a 7.62 cm reflector)

Axial dimensions, cm	
A_1 = 16.324	Core
A_2 = 17.956	Extrapolated dimension to approximate reflector savings effect of end plate and pressure vessel

*For calculations with reflectors other than 7.62 cm thick, this value was changed accordingly.

Figure 1. - Model for one dimensional calculations with cylindrical geometry.

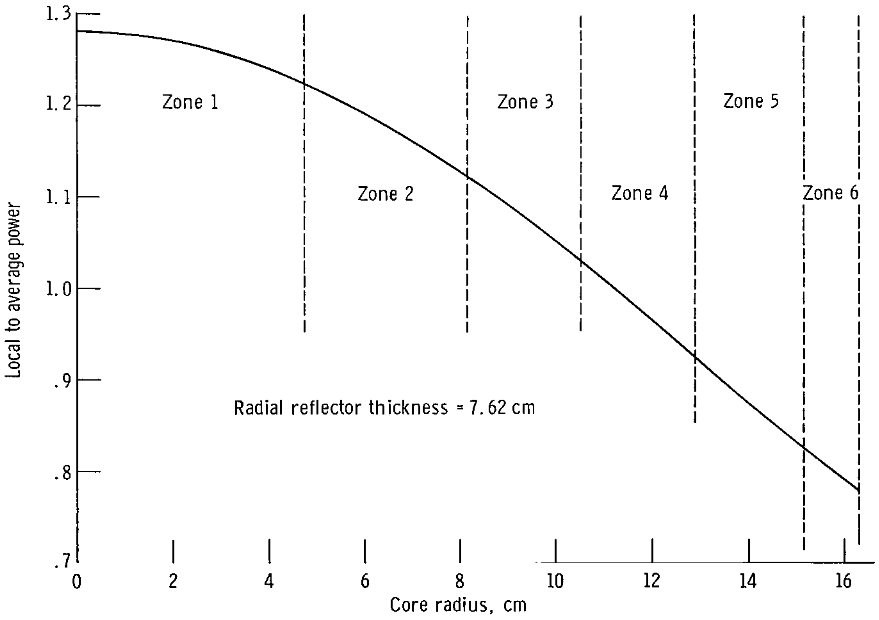


Figure 2. - Radial power distribution in a small, fast spectrum, uniformly fueled, fully enriched reactor.

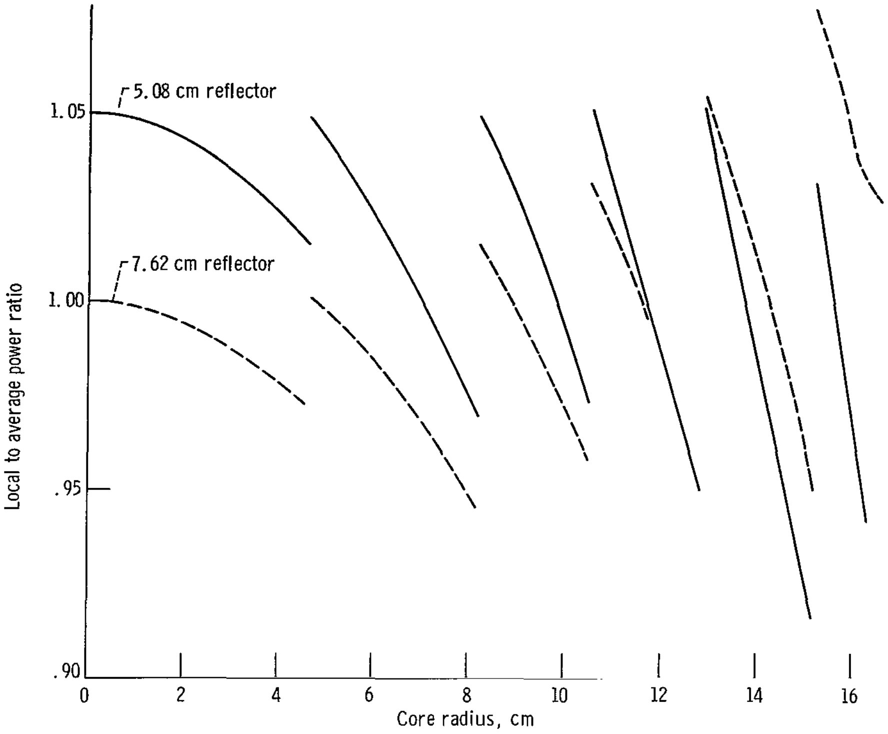


Figure 3. - Effect of reflector thickness on the radial power distribution of a small, fast spectrum, cylindrical reactor with a zoned fuel distribution.

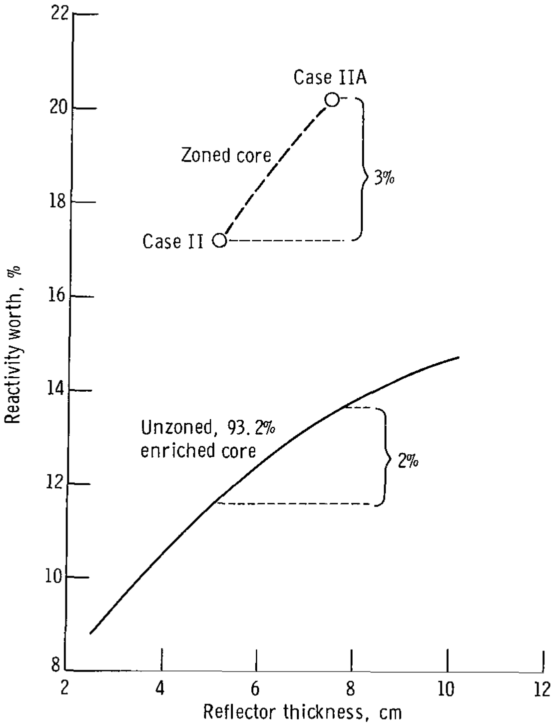


Figure 4. - Reactivity worth of radial BeO reflectors on a small, cylindrical, fast reactor core.

NASA-Langley, 1968 —— 22

National Aeronautics and Space Administration
WASHINGTON, D. C.

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

040 001 47 51 30S 68074 00903
AIR FORCE WEAPONS LABORATORY/AFWL/
KIRTLAND AIR FORCE BASE, NEW MEXICO 87117

ATT MISS MADELINE F. CANOVA, CHIEF TECHNI
LIBRARY /WLIL/

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

---

> *"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*
>
> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546