MOVABLE-MOLYBDENUM-REFLECTOR REACTIVITY EXPERIMENTS FOR CONTROL STUDIES OF COMPACT-SPACE-POWER-REACTOR CONCEPTS

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16. Abstract

An experimental reflector reactivity study was made with a compact cylindrical reactor using a uranyl fluoride - water fuel solution. The reactor was axially unreflected and radially reflected with segments of molybdenum. The reflector segments were displaced incrementally in both the axial and radial dimensions, and the shutdown reactivity of each configuration was measured by using the pulsed-neutron source technique. The reactivity effects for axial and radial displacement of reflector segments are tabulated separately and compared. The experiments provide data for control-system studies of compact-space-power-reactor concepts.

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MOVABLE-MOLYBDENUM-REFLECTOR REACTIVITY EXPERIMENTS FOR CONTROL

STUDIES OF COMPACT-SPACE-POWER-REACTOR CONCEPTS

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SUMMARY

Reactivity effects achieved by moving segments of a radial metallic reflector asso-
ciated with a compact solution-fuel reactor have been measured. The reference reactor
core was a cylinder 25.4 centimeters in diameter and 40.64 centimeters long which was
axially unreflected and radially reflected with molybdenum 10.14 centimeters thick.
The fuel was a water solution of 93 percent enriched uranyl fluoride with a hydrogen to
uranium-235 atom ratio of 447.

The molybdenum reflector segments were displaced incrementally in either the
axial or the radial direction. All reflector configurations started with the assembly in
the delayed critical condition, and reflector changes led to a loss in reactivity which
was measured by the pulsed-neutron source technique. Reactivity effects for displace-
ment of reflector segments in the two directions were separately measured and tabu-
lated.

The experiments provide data for control system studies of compact-space-power-
reactor concepts. Since the reactor is of simple geometry, the experimental reactivity
data may be used directly to estimate the capabilities of movable reflector systems and
to augment analytical conceptual designs.

INTRODUCTION

The use of movable reflectors as a means of reactor control has long been consid-
ered for fast-spectrum and compact thermal reactors. For example, the Los Alamos
Fast Reactor Clementine utilized reflector control rods that moved axially in vertical
holes (ref. 1). Another reactor with reflector control is the British Zero Energy Fast
Reactor (ZEPHYR). Over the years, a large number of concepts have considered

reflector manipulation for all or part of the reactivity control required.

Reactors recently proposed for space power systems have considered several kinds of reflector controls. Mayo, Whitmarsh, Miller, and Allen made a study of the characteristics of a fast-reactor concept with a nominal 40-centimeter-diameter core which used an axially movable reflector control system (ref. 2). This reactor was later considered with rotating drums of fuel and poison located in the radial reflector as the method of control (ref. 3). A reactor controlled by reflector segments which move radially away from the cylindrical core has been considered for use with a thermionic power system for electric propulsion (ref. 4). A zirconium hydride reactor system has been proposed in which the reflector control scheme involves reflector pieces that move axially and radially, simultaneously (ref. 5).

There is a need for definitive experiments to validate these movable-reflector control concepts and to provide data to compare with theoretical or analytical design studies. This report presents an experimental study of the reactivity effects of axially and radially movable reflector segments.

The experiments consisted of measuring a series of configurations of molybdenum reflector segments arranged around a cylindrical homogeneous-solution reactor core. Because of their basic simplicity, the experiments should lend themselves to an understanding of radial leakage phenomena and should provide definitive data with which to validate analytical models of the reflected configurations. The utility of such configurations for the purpose of checking calculational models and/or neutron cross section compilations has been demonstrated in prior studies such as reference 6.

EXPERIMENTAL ARRANGEMENT AND PROCEDURES

The NASA Zero Power Reactor I (ZPR-I) used in these tests had a 25.4-centimeter-inside-diameter cylindrical core tank that was about 75 centimeters long. Molybdenum blocks were used to form a 10.14-centimeter-thick radial reflector. The reference configuration chosen was a 40.64-centimeter tall, radially reflected, axially unreflected reactor (see fig. 1). This reference reactor was adjusted to be exactly at delayed critical with the reflector assembled in its maximum reactivity position. The reflector was then altered, and the shutdown reactivity worth was measured by means of the pulsed-neutron-source technique. Brief descriptions of the experimental arrangement and the experimental study are presented.

Reference Reactor Configuration

The ZPR-I used an aqueous solution of highly enriched (93.2 percent uranium-235)

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uranyl fluoride (UO_2F_2) as the fuel. A fuel solution hydrogen to uranium-235 atom ratio of 447 was required to achieve the delayed critical condition with a 40.64-centimeter-tall, 25.4-centimeter-diameter cylindrical reactor which was radially reflected with 10.14 centimeters of molybdenum. This fuel concentration was kept fixed, and the critical height of 40.64 centimeters was verified regularly during this study.

The physical arrangement of the reference core is shown in figure 1. The dimensions are presented in table I. The fuel solution was stored in geometrically safe storage tanks near a wall of the reactor test cell, and criticality was achieved by remotely transferring the fuel solution from storage to the reactor vessel. The reactor vessel was located near the center of the room to minimize effects of room return.

The molybdenum blocks used as the reflector were fabricated by pressing and sintering and were machine finished. The material was 99.95 percent pure molybdenum and had an average density of 9.88 grams per cubic centimeter (96.8 percent of theoretical density). The basic block was a 45$^{\text{o}}$ circumferential segment that was 20.32 centimeters tall. To construct the 40.64-centimeter-tall reference configuration reflector required a total of 16 blocks. Some of the experiments made use of two smaller blocks achieved by cutting one of the basic blocks in two lengthwise. This dissection gave two blocks which were about 22.5$^{\text{o}}$ segments and 20.32 centimeters long.

The reactor tank was constructed of type 304 stainless steel with a 0.16-centimeter-thick wall and an outside diameter of 25.72 centimeters. When stacked in a tight array the molybdenum blocks formed a cylindrical chimney with an inside diameter of 26.87 centimeters and an outside diameter of 47.15 centimeters. This left a gap of about 0.57 centimeter between the reactor tank and the molybdenum blocks. A more complete description of ZPR-I with a molybdenum reflector can be found in reference 6.

Pulsed-Neutron-Source Experiments

The experimental arrangement used to conduct the pulsed-neutron-source experiments was the same as that described in reference 7. The pulsing head from the neutron generator was located on the axis of the reactor core directly beneath the tank, and the neutron detector was located in the core at a position found to be optimum for studying the fundamental prompt mode (see fig. 1). The neutron pulse generator was a small positive-ion sealed tube accelerator which produced 14.3-MeV neutrons by means of the deuterium-tritium reaction ^{3}H(d, n)^{4}He. The neutron pulse intensity was about 10^6 neutrons per pulse with the pulse width being 3.5 microseconds and the rate about 5 pulses per second. The neutron detector probe was a small 1/v gas proportional counter filled with helium-3 (^{3}He) gas. This probe was less than 1 centimeter in diameter and had a sensitive volume of 1 cubic centimeter which approximated a point detector. The pulses from the detector were fed through a preamplifier and an amplifier to a 400-channel

analyzer which was operated in a multiscalar mode using 50- to 400-microsecond chan-
nel widths. System resolution time has been measured as 1.12 microseconds with this
arrangement.

The output data from the 400-channel analyzer were reduced by using the digital
computer program GRIPE II developed by Kaufman (ref. 8). This program calculates
the fundamental prompt-mode decay constant and can be used to calculate the shutdown
reactivity of a subcritical solution system. The data reduction methods are described
in detail in reference 7.

The delayed critical reference case and each shutdown configuration were pulsed in
their static states by repetitively injecting short bursts of neutrons into the core and
measuring the time behavior of the thermal neutron level in the reactor. This measure-
ment produced the fundamental prompt mode decay constant α_o^p for each configuration.
Two techniques were then used to obtain shutdown reactivity from the decay constants.
The simplest and most direct technique is that of Simmons and King because it requires
no additional data. The reactivity is given by

$$\rho_s^{SK}(\$) = -\frac{\left(\alpha_o^p\right)_E}{\left(\alpha_o^p\right)_E^{DC}} + 1$$

where the superscript SK denotes Simmons and King, the subscript s denotes static
reactivity, α_o^p is the fundamental prompt mode decay constant, the subscript E denotes
experimental, and the superscript DC denotes delayed critical. The Simmons-King
technique is limited in use because it assumes a constant generation time. In most
cases of subcriticality this is not true, especially for systems more than a few dollars
below critical.

A more precise relation known as the in-hour technique gives

$$\rho_s^{IN}(\$) = \frac{\left(\alpha_o^p\right)_E}{\overline{\beta}_o/\Lambda_o} + 1$$

where the superscript IN denotes in-hour, $\overline{\beta}_o$ is the total effective delayed-neutron
fraction for the fundamental prompt mode, and Λ_o is the generation time for the prompt
mode. The ratio $\overline{\beta}_o/\Lambda_o$ is a calculated parameter which is identical to $-\alpha_o^p$ at de-
layed critical. The method of calculating this parameter is described in reference 7.
As these reactor configurations become more and more shutdown, $\overline{\beta}_o$ and Λ_o both vary
as functions of the overall neutron multiplication factor; $\overline{\beta}_o/\Lambda_o$ changes as shown in

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figure 2, where $\overline{\beta}_0/\Lambda_0$ has been normalized at delayed critical to match the experimentally determined value of -214 second^{-1} for α_0^p. The Simmons-King technique assumes that this factor remains constant; hence there is an error for large shutdown reactivities.

The area-ratio methods developed by Sjostrand, Gozani, and Garellis-Russell, which were used successfully to calculate reactivities with bare reactor systems (refs. 7 and 9), were not satisfactory for this reflector study. Two possible reasons were considered. First, in a two-region assembly, the neutron decay is the results of two exponential terms (see ref. 10). One exponential is due to the core decay, while the second is related to reflector decay. Analysis of the data did not reveal two exponentials. However, if the reflector decay was long or small, it could be masked or lost in the delayed neutron background and still cause the discrepancies found. Second, for a reflected thermal core assembly, each of the area methods needs a spatially dependent factor to account for the difference between delayed modes and the prompt modes caused by the reflector. This factor is known as the kinetic distortion factor and is discussed in detail by Preskitt, Nephew, Brown, and Van Howe in reference 11. Since the molybdenum primarily reflected fast-energy neutrons and the core was strongly thermalized because of the presence of hydrogen in high density, the distortion of the prompt and delayed modes near the core-reflector interface seems very likely.

EXPERIMENTAL PROGRAM

The experimental program was conducted in two general phases (1) reflector control using axial displacement of the molybdenum reflector blocks and (2) reflector control using radial displacement of the molybdenum reflector blocks. The first phase of the study had several parts which are treated in separate units. The second phase was limited to one unit. Both phases were curtailed somewhat prematurely by the cancellation of nuclear programs at NASA.

The same reference reactor was used throughout the study. Only the reference case was at delayed critical. All reflector geometric changes studied resulted in subcritical systems where the shutdown reactivity was measured by the pulsed-source technique. The reference reactor is described in the previous section Reference Reactor Configuration. This section describes the reflector changes made during the study.

Axial Displacement of Reflector Blocks

The study of reflector-control worths associated with axial displacement of the molybdenum reflector blocks is reported in three parts as follows:

(1) Displacement of one-half of the reflector

(2) Displacement of two quadrants of one-half of the reflector

(3) Displacement of various selected combinations of blocks

These particular units were selected for study in an effort to cover with a minimum number of experiments all of the axial displacement manipulations possible with this reactor configuration.

One-half of reflector. - When the molybdenum blocks were stacked in a tight chimney-like array and banded circumferentially with adjustable steel straps, the separate layers of the reflector could be handled as solid, one-piece sections, each 20.32 centimeters tall. The top layer (in this case the top half) was then raised in several steps from closed to 20.32-centimeter-spacing. A typical configuration with about 10-centimeter spacing is shown in figure 3. The spacing was maintained in each case by precisely cut lengths of thin-wall aluminum tubing. Two additional configurations were also measured. These were configurations with the top half completely removed and with the entire radial reflector removed.

Two quadrants of one-half of reflector. - Two opposite sets of two 45° blocks each were raised in selected intervals from closed to 20.32 centimeters (blocks 1, 2, 5, and 6 in fig. 4(a)). Use of the circumferential steel bands made it possible for the unraised quadrants to support the raised quadrants except at the fully raised position of 20.32 centimeters. The blocks were supported at the 20.32-centimeter position by lengths of thin-wall aluminum tubing.

Selected combinations of blocks. - In this part of the study various combinations of blocks in the top half of the reflector were raised 10.16 centimeters. A typical arrangement of two opposite blocks raised is shown in figure 5. To get some additional flexibility, one of the 45° blocks was cut in two vertically. Although the width of the saw cut reduced the actual size slightly, the resulting blocks were considered to be 22.5° segments. In this report a 45° segment is considered as a block and a 22.5° segment as a half block.

Configurations with the equivalent of one-half, one, two, four, five, six, and eight blocks were measured for shutdown worth at the 10.16-centimeter displacement (the worth of all eight blocks raised 10.16 cm had been measured before). As much as possible, the configurations were kept symmetrical with two equal and opposite segments raised. As described previously, the unraised blocks served as supports for the raised blocks when the entire array was tightly banded with steel straps.

Reflector Blocks Displaced Radially

In this portion of the study all reflector blocks were moved radially along lines projecting out from the center of the core. A typical arrangement is shown in figure 6.

The reference reactor radial position was considered as the zero position even though located about 0.57 centimeter from the reactor vessel. The blocks were then moved radially in small steps out to about 21-centimeter displacement from the reference reactor position. The gaps between blocks increased with radial displacement ΔR according to the relation

$$gap = \frac{2\pi \, \Delta R}{8}$$

and reached a maximum of about 16 centimeters at the 21-centimeter radial displacement.

EXPERIMENTAL RESULTS

The data from all parts of this study are reported in the same general format. In each case the parameter obtained by the GRIPE II code from the experimental data was the fundamental prompt mode decay constant $\left(\alpha_o^p\right)_E$, which has units of reciprocal time. The decay constants have a negative numerical value for all configurations either delayed critical or subcritical.

The shutdown reactivity $\rho_s(\$)$ was determined in a direct manner by using the fundamental prompt mode decay constant. The results of two techniques are reported. First, reactivity worths based on the Simmons-King technique are reported because these data can be derived solely from the experimental results. Second, results obtained by using the in-hour technique are reported because this technique does take into account the variation in the generation time with shutdown and has been demonstrated in previous work (refs. 7 and 9) as producing the best results.

Each part of this study had a number of data points repeated several times. It is possible to infer the reproducibility of the data from these repeated measurements. The standard deviation was consistently very near ±1 percent. Thus, a limit of ±2 percent can be assigned to each data point for a 95-percent confidence limit. This agrees well with previously reported data of this type. About half of this error is associated with counting statistics and half with the reproducibility of the experimental configuration.

It is noted that tests were made early in this study to assure that the measurements were not a function of detector position. The detector was traversed radially and axially within the core only because the reflector was solid and would not accommodate the detector. Three configurations were used: the reference core, the reactor with a 10-centimeter circumferential gap in the reflector, and the reactor with the top half of

the reflector removed. The only time a variation could be found that was greater than the error limits was when the detector was within a centimeter or two of the core boundaries. The detector was therefore fixed at a position that theoretically maximized the fundamental mode in comparison with higher order modes.

Axial Displacement Experiments

One-half of reflector displaced. - The results of displacing the top half of the reflector axially are listed in table II and plotted in figures 7 and 8. Enough different spacings were employed to define a complete curve from the closed position to 20.32-centimeter separation. As can be seen by examining the figures, the curves in both figures 7 and 8 follow a smooth line with an inflection at about 2-centimeter spacing. About 75 percent of the total worth is associated with the first 10 centimeters of displacement. These curves approach a limiting upper value represented by the case where the top half of the reflector was completely removed. This limit is shown in each instance as a horizontal line rather than a point since the appropriate reflector displacement distance was not defined by the experimental program.

Table II also presents the data for the case where the entire reflector was removed. The reactivity worth of removing the top half was a little more than half the reactivity worth measured when the entire reflector was removed.

Two quadrants of one-half of reflector. - The results of raising two opposite quadrants of the top half of the reflector from closed to 20.32-centimeter displacement are listed in table III and plotted in figures 9 and 10. These data follow a smooth curve similar in shape to that for the movement of the entire half of the reflector. In comparing the data of these two configurations (figs. 7 and 9), there are differences below 5-centimeter displacement, but the upper portions of the two curves are proportional within the error limits of the data. The reactivity worth of the two quadrants was 55 percent of the worth of the entire top half of the reflector for any displacement greater than 10 centimeters. For displacements of less than 2 centimeters, the worth of two quadrants was less than 50 percent of the worth of the entire half. Such differences would likely be of little practical significance, however.

Selected combinations of blocks displaced. - The data from this part of the study are given in table IV. The arrangements of molybdenum blocks in the reflector were as shown in the first three columns of the table. For configurations 2, 3, 5, 6, 8, and 9 refer to figure 4(a), and for configurations 1 and 4 refer to figure 4(b). The data for all blocks displaced were obtained from table II.

Data for configurations 1 to 5 are plotted in figures 11 and 12 along with those for the end points (no blocks and all blocks). These configurations were chosen because of their symmetrical or nearly symmetrical arrangement. The data appear to follow a reason-

ably smooth curve within the error bars determined. However, two points (configurations 1 and 4) were low and were investigated more thoroughly. These were the two configurations that were not quite symmetrical about the axis (180° apart). Additional work indicated that configuration 4 was low because of the nonsymmetry. However, additional cases (configurations 6 to 8) carried out to examine configuration 1 lead to some interesting effects that are discussed qualitatively in the paragraphs that follow.

First, the smaller 22.5° half block was worth less than half as much in shutdown reactivity as the full 45° segment. However, a 90° segment (configuration 8) was not worth twice as much as the 45° segment. This is similar to the effect observed in the other axial displacement experiments when an inflection in the curve of reactivity worth as a function of displacement was observed. There exists a spacing (different for each case) which gives a maximum reactivity worth per unit separation.

Second, the reactivity worth of 22.5°, 45°, and 90° segments raised on both sides is more than twice the worth of the segment of comparable size on one side only. Specifically, the in-hour derived values are

Segment, deg	One side	Two sides
	In-hour shutdown reactivity, $	
22.5	0.37	0.85
45	.87	1.79
90	1.64	3.41

This effect is small, but carefully repeated measurements verified that the results were valid.

One additional configuration (9) was measured in which four alternate 45° blocks were raised. This arrangement proved to be worth a few percent more in shutdown reactivity than four blocks raised as two 90° segments (configuration 3), but was not worth twice as much as two oppositely raised 45° blocks (configuration 2).

Summary of axial data. - A composite plot of all axial fundamental prompt mode decay constant data is presented in figure 13. The data measured for the four- and eight-block arrays are complete enough that continuous curves for 0- to 20.32-centimeter displacement can readily be inferred. In addition, a reasonable estimated curve can be produced for arrays of two, five, and six blocks because of the similarity of the entire family of curves. Some uncertainty exists in the 0- to 2-centimeter displacement range for these arrays but does not affect the curves in general.

The displacement of one block (two 22.5° segments) is a unique case. Although the

single data point is included on the graph, it is not recommended that a curve be estimated on the basis of the other data.

Radial Displacement Experiments

The data derived from this part of the study are listed in table V and plotted in figures 14 and 15. A smooth curve has been drawn through each set of data. Some of these data points were measured only once and show somewhat more scatter than the repeated cases reported. When an error limit typical of this kind of experiment is assigned, the data in figure 14 follow a smooth curve within the error bars.

The inflection found in all the curves during this study was present in this curve near a radial displacement of 1 centimeter. In general, the reactivity worth per centimeter is nearly uniform for the first 5 centimeters of radial movement, and about 60 percent of the total reactivity worth of the entire reflector can be realized with such a movement.

Comparison of Radial and Axial Movement of Reflector Blocks

A comparison of reactivity control worth of the integral radial and axial movement of reflector blocks is made in table VI and figure 16. For this comparison it was assumed that the reactivity worth (determined by the in-hour technique) of moving both halves of the reflector axially away from the midplane should be worth twice that of moving the top half only. This was not quite true near maximum displacements, and a small adjustment was made to provide an adequate normalization for this comparison.

With the assumption that the movement of one block through a 1-centimeter distance required the same amount of work regardless of the direction of motion, a unit called the block-centimeter (number of reflector blocks times centimeters of movement) was calculated for the following:
  (1) Radial movement of all blocks
  (2) Axial movement of all blocks
  (3) Axial movement of top half
A comparison of the relative reactivity worths of these arrangements as a function of the integral reflector movement is made in figure 16.

Examination of figure 16 indicates that the radial movement of reflector blocks achieved a more rapid change in total reactivity worth through the initial portion of the movement, for example, the first 5 centimeters that all 16 blocks were moved. On the other hand, after about the first centimeter of axial movement of all blocks, the change in the total reactivity worth was nearly linear over the range of movement considered.

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The two kinds of reflector displacements must eventually merge to the same value of maximum shutdown worth, that is, the bare or unreflected configuration. This comparison covered only about a 10-centimeter integral movement of all blocks. The results of the displacement of the top half axially also have been presented to demonstrate the effect when a configuration approaches its maximum limiting value of reactivity.

SUMMARY OF RESULTS

Movable-molybdenum-reflector reactivity experiments for control studies of compact-space-power-reactor concepts produced the following results. Although the homogeneous fuel solution reactor used is unique, many of the qualitative reactivity effects should be generally applicable.

1. Each of the series of configurations dealing with a range of successive displacements of reactor arrays produced an S-shaped curve of the integral reactivity as a function of displacement that has similarities to a representative integral reactivity worth curve determined for a control rod in a reactor core. For reflector control displacements the curve was distorted asymmetrically because the maximum rate of change occurred in an early portion of the movement and the differential worths tended to be reduced with successive reflector displacement.

2. The integral displacement of all reflector blocks radially produced a much more rapid change in reactivity in the first few centimeters of movement than a comparable integral axial movement of the same blocks.

3. Removal of the top half of the reflector was worth more in reactivity than 50 percent of that for the removal of the entire reflector.

4. Displacements of equal and symmetrically opposite segments varying from 22.5° to 90° of the top half of the reflector were always worth more than twice the reactivity change produced by the displacement of one side only. There is no reason to believe this would not be true for similar segments displaced over the full length of the reflector.

5. The total worth of the reflector approached $16, of which at least $8 to $10 should be practical for control in an actual application. The use of reflector movement for reactor control is feasible for compact reactors such as the one used in this study because large amounts of reactivity are controllable in high leakage cores.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, July 26, 1973,
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TABLE I. - RADIAL DIMENSIONS OF NASA

ZPR-I REFERENCE REACTOR FOR

MOLYBDENUM REFLECTOR

CONTROL STUDY

	Inside radius, cm	Outside radius, cm
Fuel solution[a]	-----	12.70
Type 304 stainless-steel tank	12.70	12.86
Void region	12.86	13.43
Molybdenum reflector	13.43	23.57

[a]Fuel was UO_2F_2 salt in water solution with concentration fixed at hydrogen to uranium-235 atom ratio of 447; reactor height for delayed critical at 20° C was 40.64 cm.

TABLE II. - FUNDAMENTAL PROMPT MODE

DECAY CONSTANTS AND SHUTDOWN

REACTIVITIES FOR AXIAL DIS-

PLACEMENT OF ONE-HALF

OF MOLYBDENUM

REFLECTOR

Reflector spacing, cm	Fundamental prompt mode decay constant, $-\left(\alpha_o^p\right)_E$, sec^{-1}	Simmons-King	In-hour
		Shutdown reactivity, $-\rho_s$, \$	
0 (critical)	214±2	-----	-----
.635	287±3	0.34	0.34
1.27	361±4	.69	.69
2.54	559±6	1.61	1.63
5.08	945±9	3.42	3.48
7.62	1289+14	5.02	5.16
10.16	1537±16	6.18	6.38
15.24	1822±22	7.51	7.81
20.32	1924±30	7.99	8.32
No top half	1976±20	8.23	8.58
Bare core	3380±40	14.79	15.93

TABLE III. - AXIAL DISPLACEMENT OF TWO

OPPOSITE QUADRANTS OF TOP HALF OF

RADIAL MOLYBDENUM REFLECTOR

Reflector spacing, ΔH, cm	Fundamental prompt mode decay constant, $-\left(\alpha_o^p\right)_E$, sec^{-1}	Simmons-King	In-hour
		Shutdown reactivity, $-\rho_S$, \$	
0 (delayed critical)	214	----	----
.635	238	0.11	0.11
1.27	281	.31	.31
2.54	385	.80	.80
5.08	598	1.79	1.82
10.16	932	3.36	3.42
15.24	1100	4.14	4.23
20.32	1192	4.57	4.68

TABLE IV. - DATA FOR 10.16-CENTIMETER AXIAL DISPLACEMENT

OF VARIOUS MOLYBDENUM REFLECTOR BLOCKS OF

RADIALLY REFLECTED REACTOR

Configuration	Number of 45° segments raised	Block number (from fig. 4)	Fundamental prompt mode decay constant, sec^{-1}	Simmons-King	In-hour
				Shutdown reactivity, $-\rho$, \$	
Critical	0	-------------	214±2	0	0
1	1	8,9	393±4	.84	.85
2	2	2,6	593±6	1.77	1.79
3	4	1,2,5,6	930±7	3.35	3.41
4	5	1,2,5,6,8,9	1091±8	4.10	4.19
5	6	1,2,4,5,6,8,9	1257±10	4.87	5.00
6	1/2	8	294±2	.37	.37
7	1	2	397±5	.86	.87
8	2	1,2	561	1.62	1.64
9	4	1,3,5,7	949	3.43	3.49
[a]All blocks	8	All blocks	1537±16	6.18	6.38

[a]Data taken from table II.

TABLE V. - DATA FOR RADIAL DISPLACEMENT OF

MOLYBDENUM REFLECTOR BLOCKS OF

RADIALLY REFLECTED REACTOR

Reflector spacing, ΔR, cm	Fundamental prompt mode decay constant, $-\left(\alpha_{o}^{p}\right)_{E}$, $\sec^{-1}$	Simmons-King Shutdown reactivity, $-\rho$, \$	In-hour Shutdown reactivity, $-\rho$, \$
0 (delayed critical)	214	----	----
.635	441	1.06	1.07
1.27	758	2.54	2.58
1.91	1047	3.89	3.98
4.45	1972	8.21	8.56
6.99	2517	10.76	11.36
9.55	2870	12.41	13.21
12.07	3030	13.16	14.06
14.63	3192	13.92	14.92
17.15	3215	14.02	15.04
20.96	3325	14.54	15.64

TABLE VI. - COMPARISON OF SHUTDOWN REAC-

TIVITY WORTH OF RADIAL AND AXIAL

DISPLACEMENT OF MOLYBDENUM

REFLECTOR BLOCKS

Integral displacement, blocks×cm	All blocks displaced axially	Top half displaced axially	All blocks displaced axially
	Shutdown reactivity, $-\rho$, \$		
5.08	----	0.34	----
10.16	0.68	.69	1.07
20.32	1.38	1.63	2.58
30.48	----	----	3.98
40.64	3.26	3.48	----
71.20	----	----	8.56
81.28	6.96	----	----
111.84	----	6.38	11.36
121.92	a10.2	----	----
152.80	----	7.81	13.21
162.56	a12.4	8.32	----

aValue adjusted to normalize data to top half data at end limits.

(a) Plan view.   (b) Elevation.
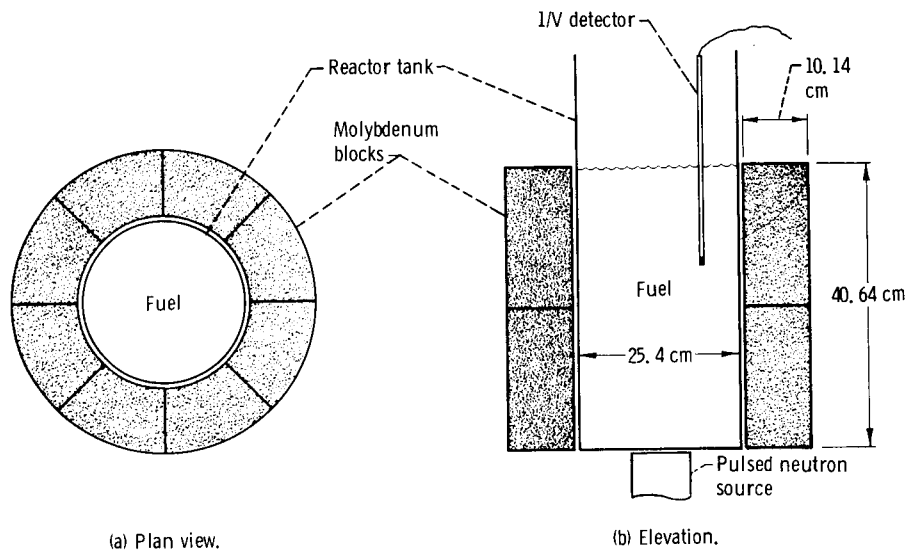
Figure 1. – Reference reactor, ZPR-I.
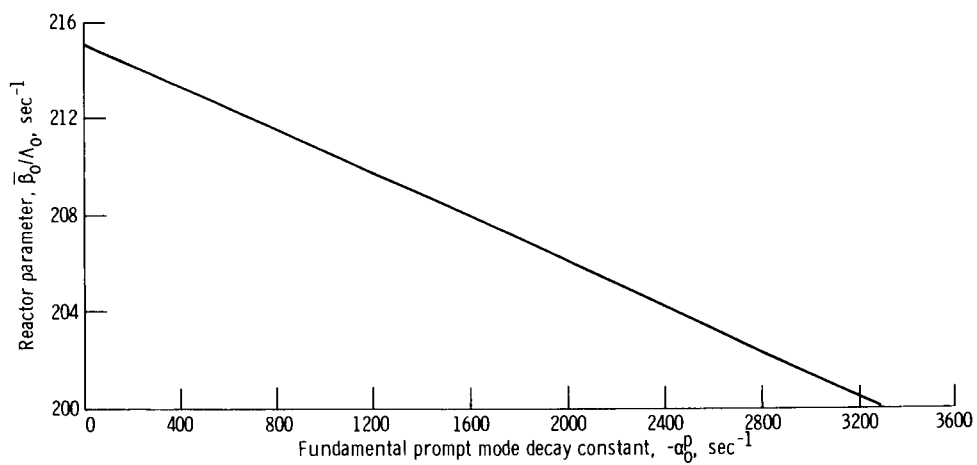
Figure 2. – Variation of reactor parameter $\bar{\beta}_0/\Lambda_0$ with fundamental prompt mode decay constant.
Variably reflected reactor with 25.4-centimeter diameter and 40.64-centimeter height; ratio of
hydrogen to uranium-235 atoms in fuel solution, 447.
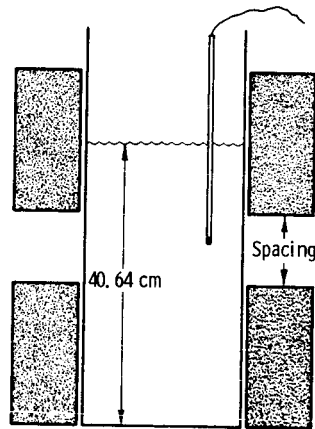
Figure 3. - Typical shutdown configuration where top half of reflector is moved axially as a unit.
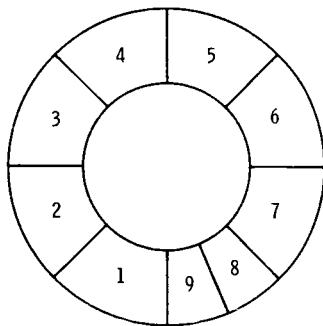
(a) Even number of blocks raised.
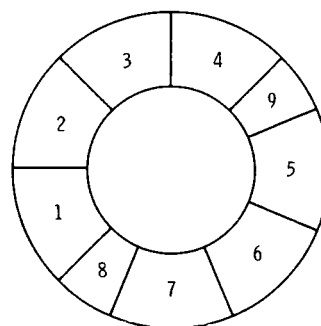
(b) Odd number of blocks raised.

Figure 4. - Block arrays showing number schemes used with different reflector arrangements for axial movement of blocks.
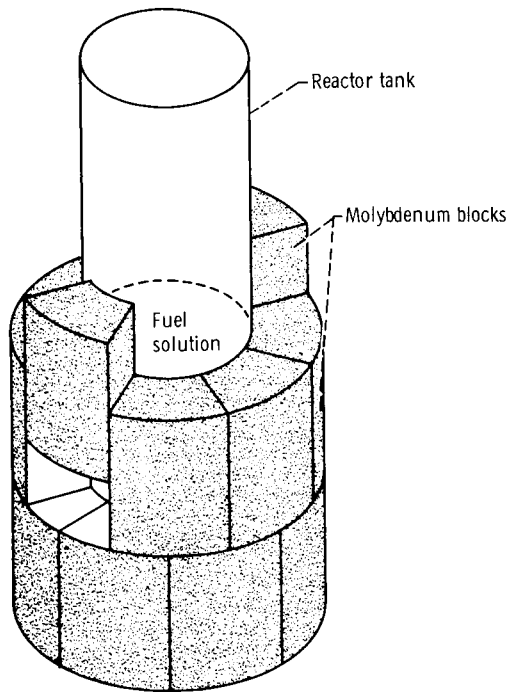
Figure 5. – Typical reflector configuration showing
two blocks raised 10. 16 centimeters.
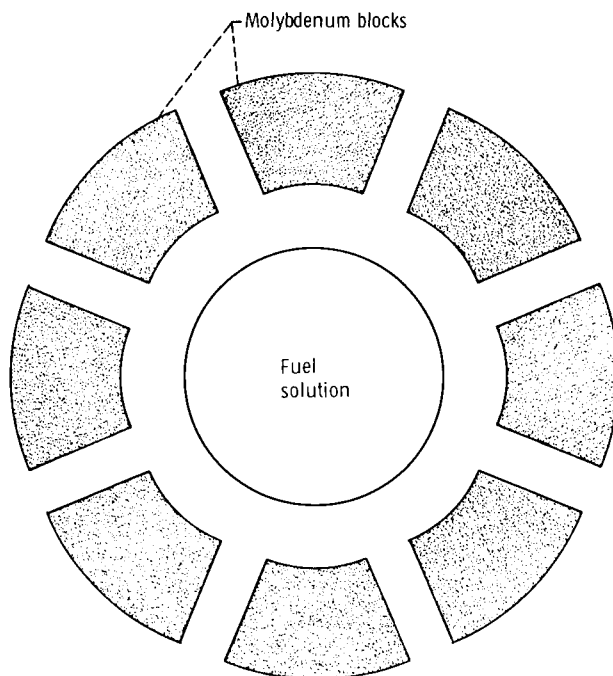
Figure 6. – Typical reflector arrangement showing radial displacement
of molybdenum blocks.

Figure 8. - Shutdown reactivity as function of reflector spacing for axial displacement of top half of radial molybdenum reflector.
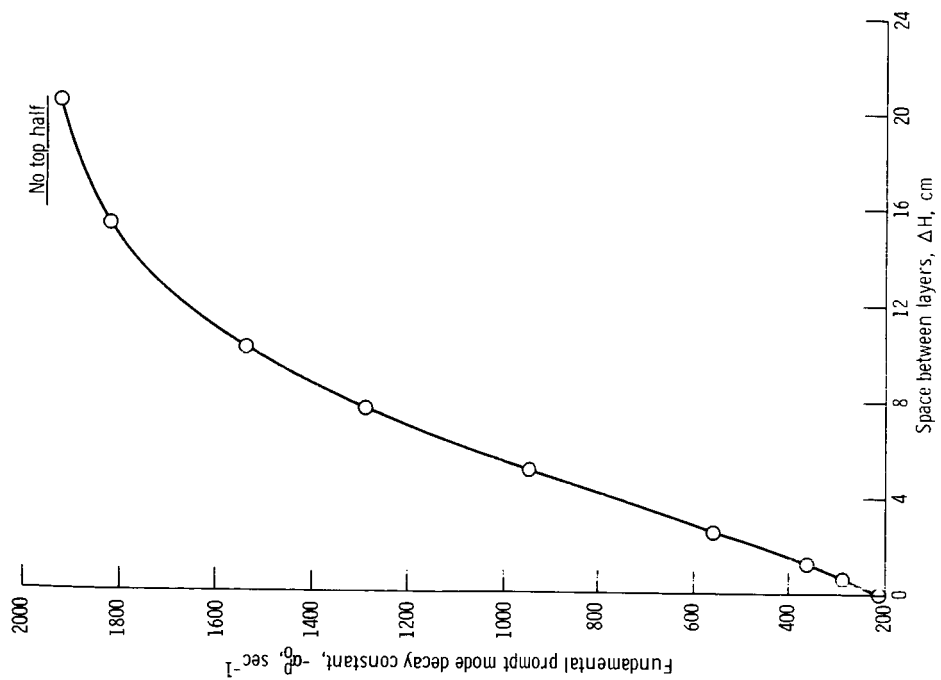
Figure 7. - Fundamental prompt mode decay constant as function of reflector spacing for axial displacement of top half of radial molybdenum reflector.

Figure 10. - Shutdown reactivity worth as function of axial displacement of two quadrants of top half of radial molybdenum reflector.

Figure 9. - Fundamental prompt mode decay constant as function of axial displacement of two quadrants of top half of radial molybdenum reflector.
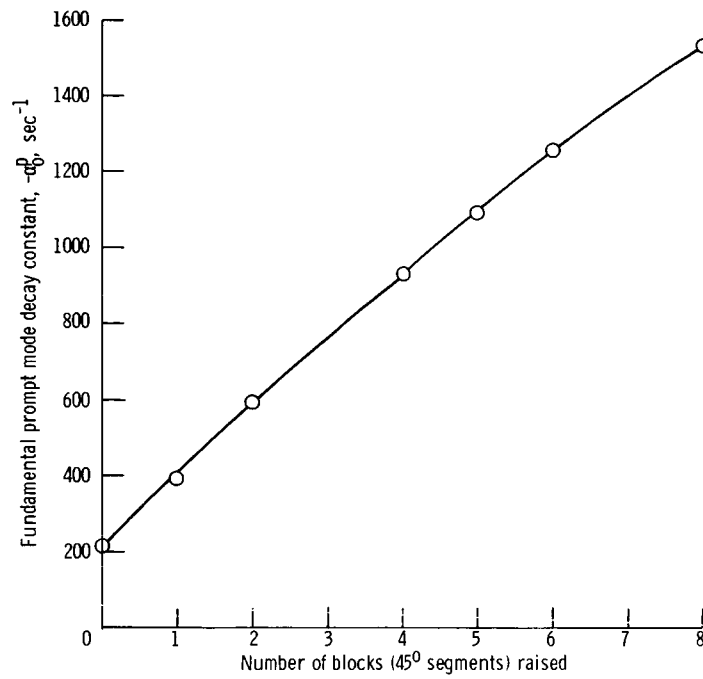
Figure 11. - Fundamental prompt mode decay constant as function of number of blocks displaced axially 10.16 centimeters.
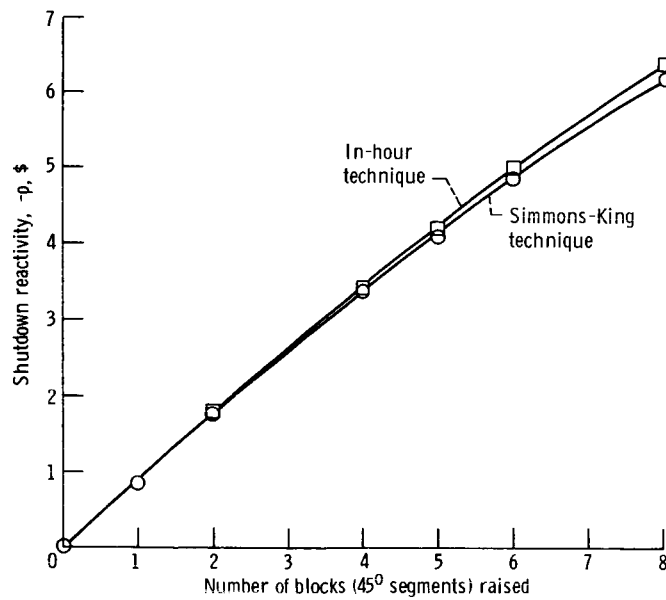
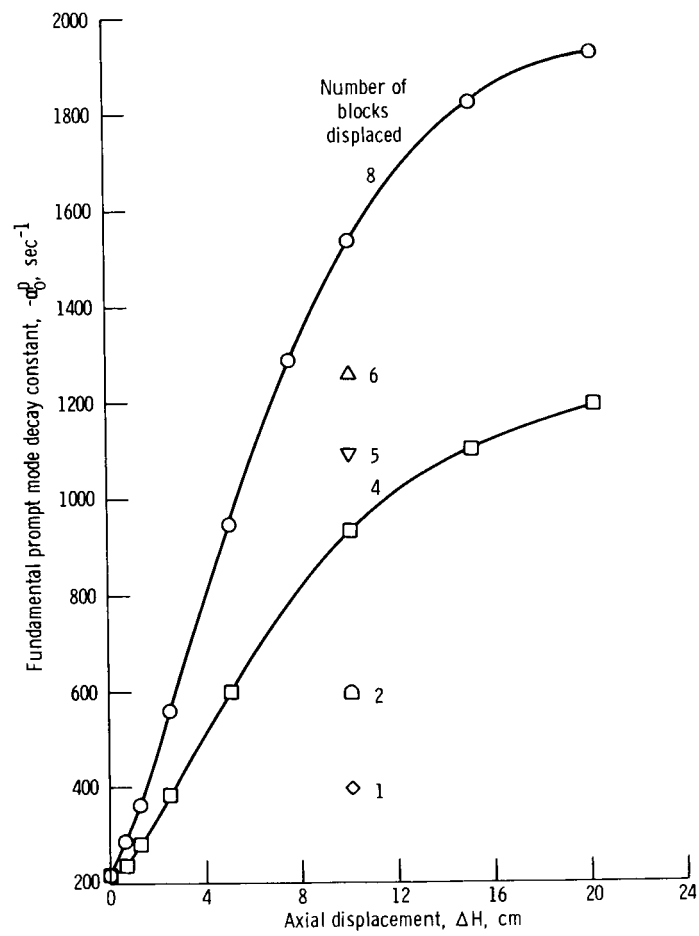Figure 12. - Shutdown reactivity as function of number of blocks displaced axially 10.16 centimeters.

Figure 13. - Composite of data for fundamental prompt mode decay constant as function of displacement and number of blocks displaced with molybdenum radial reflector.
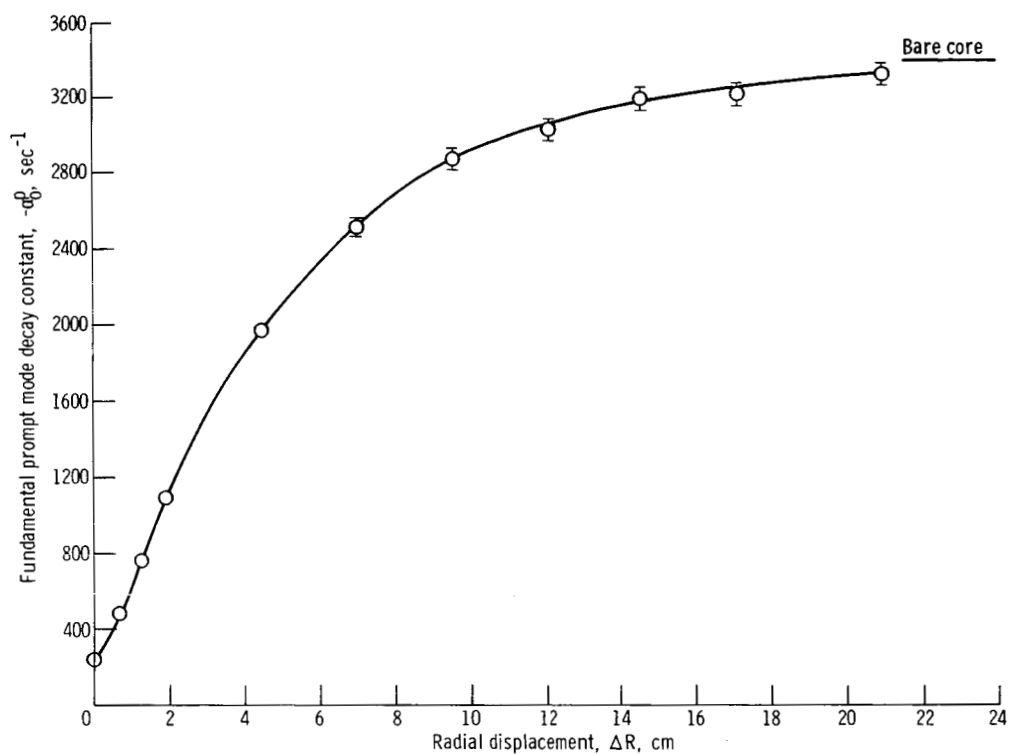
Figure 14. - Fundamental prompt mode decay constant as function of radial displacement of radial molybdenum reflector.
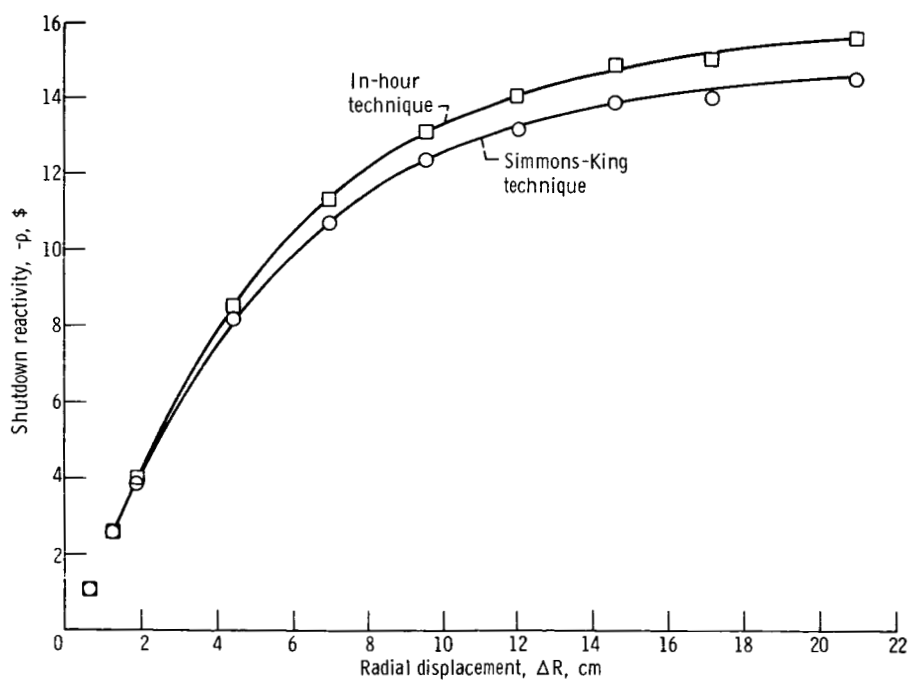

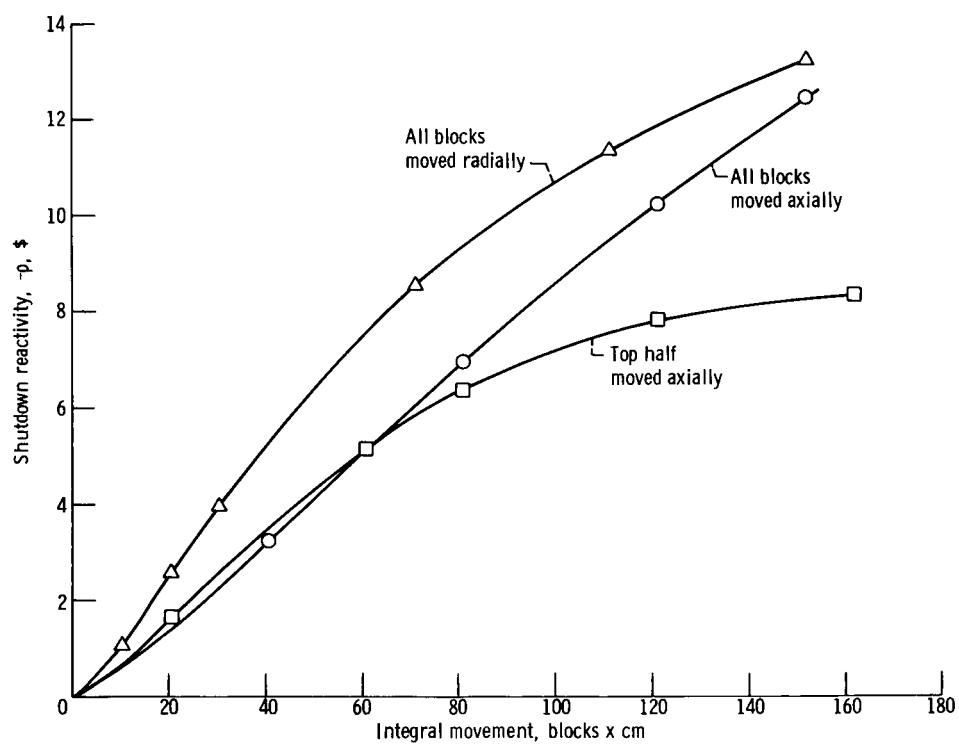Figure 15. - Shutdown reactivity as function of radial displacement of radial molybdenum reflector.

Figure 16. – Comparison of shutdown reactivity worth as function of integral block movement for axial and radial displacements.