CONF-870102--15

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INTERACTION OF THE CONTROL SYSTEM WITH CORE NUCLEAR DESIGN FOR FAST SPECTRUM SPACE POWER REACTORS*

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CONF-870102--15

DE87 006987

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MANUSCRIPT prepared for:

OPEN SESSIONS
Fourth Symposium
on Space Nuclear Power Systems
Albuquerque, New Mexico
12-16 January 1987

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Title running head: INTERACTION OF THE CONTROL SYSTEM WITH CORE

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*Work supported by the U.S. Department of Energy, "Nuclear Energy Programs under Contract W-31-109-Eng-38.

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INTERACTION OF THE CONTROL SYSTEM WITH CORE NUCLEAR DESIGN FOR FAST SPECTRUM SPACE POWER REACTORS

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ABSTRACT

Generic features of the interaction between core nuclear and mechanical designs and reactor control system design for compact fast spectrum space power reactors have been examined. Reactivity worths of various control concepts were evaluated for representative fast spectrum cores. In addition, special characteristics of each control concept that significantly affect core nuclear and mechanical design were considered. Ex-core control methods based on reflector control and in-core control devices such as control rods lead to divergent core designs and to different types of design problems. Total control worth of ex-core control devices is limited and is strongly dependent on core size. Reflector control also results in unfavorable radial power shifts, but ex-core control does avoid unnecessary reactor vessel penetrations. Control rods have characteristics essentially opposite to those of ex-core devices. Design demands on the primary control system are shown to be reduced by including a slow-acting secondary system based on in-core dispersed poison.

INTRODUCTION

The reactor control system and operating strategy are essential factors in assessing reactor reliability and safety. The control system and its mode of operation also exert major influences on mechanical design of core components and on all aspects of nuclear design. Conversely, because the control system must control reactor operation, core nuclear and mechanical designs strongly influence control system design. This is especially true of reactors for space power applications because of imposed requirements regarding compactness, minimum mass, demanding duty cycles, and long-term operational reliability without external intervention or maintenance. This paper outlines generic features of the interaction between nuclear design and reactor control system design for compact fast spectrum space power reactors.

The reactors analyzed for this work were small fast spectrum reactors with uranium nitride (UN) fuel either in conventional pin form or in a cermet. The coolant was lithium; the cladding and/or structural material in the core was a W-Re alloy. Three cores designated A, B, and C in Table 1 were considered. However, the conclusions drawn here should be valid for compact fast spectrum reactors in general.

These reactors are generally characterized by a large control worth requirement. To minimize core mass and volume, space reactor designs tend toward maximum allowable fuel burnup levels and the associated high burnup reactivity swing. Reactivity requirements are increased by the large temperature defect resulting from very high operating temperatures and by significant Doppler reactivity associated with structural materials (Hwang, 1987). In addition, the control system must cope with very unconventional accident scenarios. All of these factors lead to a large control worth requirement.

Several basic control concepts were analyzed. These included ex-core control drums, in-core control rods, movable fuel and reflector segments, burnable poisons, and dispersed poisons in the core. The principal merits and defects of these concepts with regard to core design are considered below.

Cross sections for calculations were generated with MC^2-2 (Henryson et. al., 1976), and neutronics calculations were performed with the VIM Monte Carlo code (Blomquist et. al., 1980), ONEDANT (O'Dell et. al., 1982), and DIF3D (Derstine, 1984).

ANALYSIS

Ex-core control drums were (Kunze et. al., 1970) and are a common choice for space reactor control. Control drums offer three significant advantages for this application. First, mechanical aspects of drum design are relatively simple, at least compared to some of the alternatives. Second, drums can be located such that reactor vessel penetrations are avoided. Vessel penetrations pose significant design problems because they require reliable seals under very demanding physical conditions. Third, the drums can function as part of the radial shielding of external structures near the core.

Control drums also have several drawbacks for this application. First, the drums as a whole and the poison section in particular may require a special cooling system. Second, because of their location, it may be possible for the drums to separate from the core during certain types of launch accidents which complicates safety issues.

For control drums, worth is a function of θ, the degree of rotation of the poison segment. Figure 1 shows the computed normalized worth curve for control drums. This curve is similar in shape to corresponding curves for control rods, so it is unlikely that drum rotation would introduce any special complications into the matter of reactivity insertion. However, motion of the drum poison section induces radial power shifts in the core. Figure 2 shows the effect of drum position on core radial power distribution. At 0° rotation, the poison segment is next to the vessel, as close to the core as possible. At 180° rotation, the poison segment is rotated outward as far from the core as possible. Such power shifts are highly undesirable because they complicate mechanical design, especially with regard to heat transfer. Also, such power shifts degrade core nuclear performance, affect core kinetics and safety parameters, and increase core mass requirements.

The fourth disadvantage of control drums is that their total worth is limited by radial leakage fraction and therefore depends strongly on core radius. Table 1 shows computed drum worths for three representative core configurations. Drum worth decreases as core radius increases because drum motion principally affects the outermost one or two rings of fuel elements (see Figure 2). A drum control system works best with a core of large height to diameter ratio.

Fifth, drums have limited total worth in a given core. Core geometry limits the number and location of the drums. Enriching the poison and increasing the poison section thickness are the only practical options for increasing drum worth. Table 2 shows the effect of changing the B-10 enrichment in the poison segment for two different core sizes. There is a practical (as well as a theoretical) limit to enrichment. In addition, as enrichment increases, total drum worth appears to approach an asymptotic value. Table 3 shows the effect of changing the poison thickness for fixed enrichment. In addition to the practical design limits on thickness, total drum worth appears to approach an asymptotic value as poison thickness increases.

The practical upper limit on control drum worth is a serious problem. The reactors considered here have high total reactivity requirements. For small core radii, computed drum worths are at best marginally adequate; as core radius increases, computed drum worths become inadequate to meet requirements.

In-core control rods are a common design alternative (or supplement) to control drums. Mechanically, rods have several unfavorable characteristics that affect core design. First, in-core rods require reactor vessel penetrations and, consequently, reliable seals. The issue of seals is important in space applications because of the consequences of failure and the difficulty or impossibility of maintenance under operating conditions in space. Second, relative to control drums, operation of control rods increases physical space requirements. Drums rotate in place without any other motion or change in core geometry. The axial motion of control rods requires spatial accommodation of the poison section and/or any follower section, depending on the degree of insertion of the poison segment. This accommodation affects design and layout of the core and other components along the core axis.

On the other hand, in-core rods improve on some of the unfavorable mechanical design attributes of control drums. For example, because control rods are distributed more or less uniformly throughout the core, computed radial power distributions are less affected by rod motion than by drum motion. Figure 3 shows a contour plot of the planar power distribution with control rods half inserted. There are local power depressions near the control rods, but these depressions affect a smaller volume than the depression in the outer half of the core that accompanies drum motion (see Figure 2). The reduced radial power tilt simplifies a number of mechanical design issues. Control rod motion does affect local axial power distributions. Figure 4 shows the effect of control rod motion on axial power profiles. This effect is not insignificant, but it is not likely to pose design problems as severe as those induced by radial power tilting.

For neutronics design purposes, control rods offer two significant advantages compared to control drums. Table 4 shows computed control rod worths for two core configurations. Despite differences in core size, the computed worths are nearly identical. This contrasts with the strong dependence of drum worth on core radius (see Table 1). Because of the flexibility in the number and location of control rods inserted, total available control rod worth can be made relatively insensitive to core size and shape. Use of control rods does not strongly influence core shape as drums do. Second, control rods can have much larger worth than drums. The drum worths shown in Table 1 are nearly maximum values because of the poison thickness and B-10 enrichment used and because of the limitation on total number of drums. The rod worths shown in Table 4 can easily be increased by increasing the number of rods used or by using a fueled follower with these rods. Rod worths can be made adequate to meet reactivity requirements without much difficulty. Figure 5 shows the worth curve of control rods as a function of insertion distance for Core A. This is the conventional worth curve and indicates that reactivity insertion would follow familiar patterns.

Control rods can be constructed with or without a fueled follower; similarly, a movable fuel segment can be constructed without a poison segment attached. The rod worths listed above are for the case with no fueled follower. The worths of fueled followers (or movable fuel segments) have also been computed for these configurations. For Core A, the worth of replacing three fuel assemblies at the control rod locations with coolant is 0.0522 Δk. For Core B, the worth of replacing six fuel assemblies at the control rod locations with coolant is 0.0597 Δk. If the control rods had used fuel elements as followers, total rod worth would be increased by an equivalent amount. Use of fueled followers or movable fuel segments complicates core mechanical and nuclear design because space is required to accommodate the follower or fuel segment when it is withdrawn from the core and because of problems with cooling the withdrawn fuel. Also, radiation doses and fluences would be affected by fuel motion.

While control drums and control rods are the most commonly considered methods for space reactor control, another method under consideration is reflector control. Drums are one type of reflector control; another type is to actually move the reflector in some way so as to change its albedo. One proposed type of motion is axial. Either the reflector is divided at the axial midplane and the two halves are moved apart, or the entire reflector is moved as one unit. The other proposed design for reflector control is to divide the reflector azimuthally into segments. These segments are hinged near the azimuthal dividing lines and rotate out away from the core about an axis parallel to the core vertical centerline.

Mechanically, these reflector control schemes have characteristics similar to control drums. No vessel penetrations are required, so requirements for seals are reduced. The mechanical design issues of reflector control elements are comparable to those of control drums, particularly for the second type that rotates azimuthally about a pivot point. Any required cooling may be more difficult because of the basic design of these control elements. The type of motion involved complicates design of a closed cooling system. For terrestrial reactors, this would not necessarily be a major problem, but for space applications, a closed system is necessary for these units unless radiative heat loss to space can be shown to be adequate. The potential for breakoff of reflector control units during launch accidents poses similar safety problems for moving reflectors and control drums.

Reflector motion causes power shifts similar to those induced by control drum motion, and similar mechanical design issues arise. Axial separation of two reflector halves (or motion of a single unit) could superimpose an axial power shift. In addition to changes in radial and/or axial power distribution, reflector motions will change neutron and gamma radiation fields outside the core with consequent changes in doses and fluences nearby.

Total worth of movable reflectors is strongly dependent on core radius. Worths for Cores A and B were computed for the design where the reflector is moved axially. For total removal, computed worths for Cores A and B are 0.2409 Δk and 0.1592 Δk respectively. For control drums in the same cores, computed worths were 0.1061 Δk in Core A and 0.0711 Δk in Core B. Total removal of the reflector has twice the worth of control drums. The worth difference occurs because removal of the reflector is equivalent to complete absorption of all incident neutrons whereas the control drums reflect a significant fraction of incident neutrons back into the core, even when the poison segment is next to the core. Total worth for the hinged reflector is intermediate between the worths of complete removal and of control drums. The worth of movable reflectors shows the same dependence on core radius that control drums exhibit.

The ideal control system would affect the reactor core uniformly rather than at specific locations. The obvious choice to effect this uniformity is a poison dispersed throughout the core. The concept of a burnable poison as applied in terrestrial thermal reactors would be ideal for this purpose. A poison is added to some part of each fuel element. This poison then burns out of the core just as the fuel burns. By a judicious choice of material and concentration, the poison can be burned out such that it compensates for the reactivity swing accompanying fuel burnup. If a similar concept can be applied to fast spectrum space reactors, control requirements can be eased considerably because burnup reactivity swing is a major portion of the entire reactivity requirement in these cores.

A number of conventional and unconventional poison materials were studied here, but none were satisfactory for this purpose. Core spectra in reactors considered here are so hard that no conventional poison material has the necessary fast spectrum absorption characteristics to match U-235 burnup. In order to match the burnup swing in these reactors, calculations indicated that a significant fraction of the core volume would be occupied by the poison. The presence of such material drastically reduced base reactivity and would impact many aspects of mechanical design.

Conventional burnable poisons offer the advantage of being a passive form of control, compensating for fuel burnup without active intervention from the control system. In addition, these burnable poisons affect the whole core uniformly (at least approximately), so power distributions are not distorted by their use. These same results can be achieved with a distributed poison which can be actively changed over time.

This distributed poison concept could be accomplished in several ways. One method involves changing the coolant isotopic concentration. The coolant for reactors considered here was lithium. Lithium consists of two principal isotopes, Li-6 which is strongly absorbing and Li-7 which is weakly absorbing. By varying the amount of Li-6 relative to Li-7 in the coolant, one can change the parasitic capture in the core. Table 5 shows the worth of Li-6 as a function of the Li-6 fraction in the core. It is quite possible to accommodate the burnup reactivity swing this way if the mechanism to adjust the Li-6 content can be designed. This approach also offers the advantage of having little effect on core power distributions. The principal drawbacks of this approach are the mechanical design of the device to change the Li-6 content and the possibility of large coolant void worth when the Li-6 content is high.

An alternative to adjusting the Li-6 content of the coolant is to maintain separate channels in the core. These channels could be filled with any strongly absorbing fluid material to produce a reasonably uniform poison dispersion in core. By changing the poison content of these channels over time, total capture in the core can be changed to accommodate the burnup swing. This concept was previously studied with He-3 (Davison et. al., 1967). Present calculations with boron carbide and Li-6 have shown that this concept would be neutronically feasible for the cores considered here (see Table 5). This system is actively controlled, assuring required changes as needed. The mass and volume penalties associated with these dispersed poison concepts are small compared to the benefits achieved. The time scale for required changes is quite slow and requirements are not extremely precise, so control of the dispersed poison device is unlikely to be particularly demanding. In addition, only welds are required for the device.

SUMMARY

Nuclear design of a fast reactor core for space applications is strongly affected by control system design strategy. Ex-core control drums and in-core control rods, two commonly proposed primary control devices for space reactors, lead to divergent core designs and different types of problems. Total drum worth is limited and depends strongly on core radius. The limited total drum worth may require inclusion of a secondary control device if reactivity requirements are high. Because of the core-size dependence, drum control leads to a core design of small radius and large height. Drum motion induces undesirable radial power tilts which complicate mechanical design. Control through movable reflector segments raises the same design issues as control drums do, but the larger worth of movable reflectors reduces problems associated with limited total drum worth. The virtue of drum or reflector control is the reduction of required vessel penetrations.

Compared to control drums, the worth of control rods is much less dependent on core shape. A rod control system does weakly favor a core of large radius because the increased number of element locations provide greater freedom in choosing the number and location of control rods. The much higher worth available with rods (as compared to drums) is an important advantage for current long life core designs with large reactivity control requirements. Rod motion induces smaller power shifts than drum motion causes. Finally, the number and complexity of mechanical design problems varies considerably between drum and rod systems.

Dispersed poisons cannot replace the primary control system, but a dispersed poison system can reduce design demands on the primary system by compensating for burnup swing and other reactivity changes. A dispersed poison system slightly reduces the worth of the primary control system, but the dispersed poison significantly reduces operational demands on the primary system. Most importantly, a dispersed poison system does not induce undesirable power shifts. Conventional fixed burnable poisons as used in terrestrial thermal reactors do not seem to be practical. However, an actively controlled system using the coolant or separate passages in the core appears neutronically feasible. To counterbalance its virtues, the dispersed poison concept may, under certain circumstances, introduce an unfavorable power coefficient of reactivity.

No single control concept or system is free of problems. The present study has attempted to illustrate the advantages and tradeoffs among some of the leading choices.

Acknowledgements

Work supported by the U.S. Department of Energy, Nuclear Energy Programs under Contract W-31-109-Eng-38.

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Table 1. Control Drum Worth as a Function of Core Size

Core	Number of Fuel Elements	Radius (m)	Drum Worth, Δk
A	19	0.17	0.1061
B	37	0.24	0.0711
C	61	0.31	0.0562

Table 2. Control Drum Worth as a Function of B-10 Enrichment - B_4C Thickness of 2.54 cm

Enrichment, %	Drum Worth, Δk Core A, 19 Elements	Core B, 37 Elements
20	0.0675	0.0453
40	0.0842	0.0565
60	0.0949	0.0637
80	0.1028	0.0689
90	0.1061	0.0711

Table 3. Control Drum Worth as a Function of B_4C Thickness in Poison Section - B-10 Enrichment 90%

B_4C Thickness, cm	Drum Worth, Δk Core A, 19 Elements	Core B, 37 Elements
0.5	0.0684	0.0463
1.0	0.0865	0.0583
1.5	0.0965	0.0649
2.0	0.1024	0.0687
2.54	0.1061	0.0711

Table 4. Comparison of Control Drum and Control Rod Worths for Cores A and B - Three Rods in A, Six Rods in B

Core	Control Worth, Δk Drums	Rods, No Follower	Rods, Fueled Follower
A	0.1061	0.1291	0.1813
B	0.0711	0.1350	0.1947

Table 5. Dispersed Poison Worth as a Function of Core Volume Fraction in Cores A and B

Volume Fraction, %	Poison Worth, Δk Core A Li-6	 Core A B_4C	 Core B Li-6	 Core B B_4C
1.0	0.0123	0.0261	0.0140	0.0285
2.0	0.0241	0.0490	0.0273	0.0539
3.0	0.0354	0.0700	0.0401	0.0772
4.0	0.0463	0.0896	0.0524	0.0989

FIGURE 1. Control Drum Worth as a Function of Insertion Angle θ for Core A.

FIGURE 2. Effects of Control Drum Rotation on Radial Power Distribution for Core B.

FIGURE 3. Effect of Control Rod Insertion on Planar Power Distribution for Core B-Axial Midplane Contour with Rods Half Inserted and 60° Symmetry.

FIGURE 4. Effect of Control Rod Insertion on Axial Power Distribution in Core A-Rods Half Inserted.

FIGURE 5. Control Rod Worth as a Function of Insertion for Cores A and B.

FIGURE 1. Control Drum Worth as a Function of Insertion Angle θ for Core A.

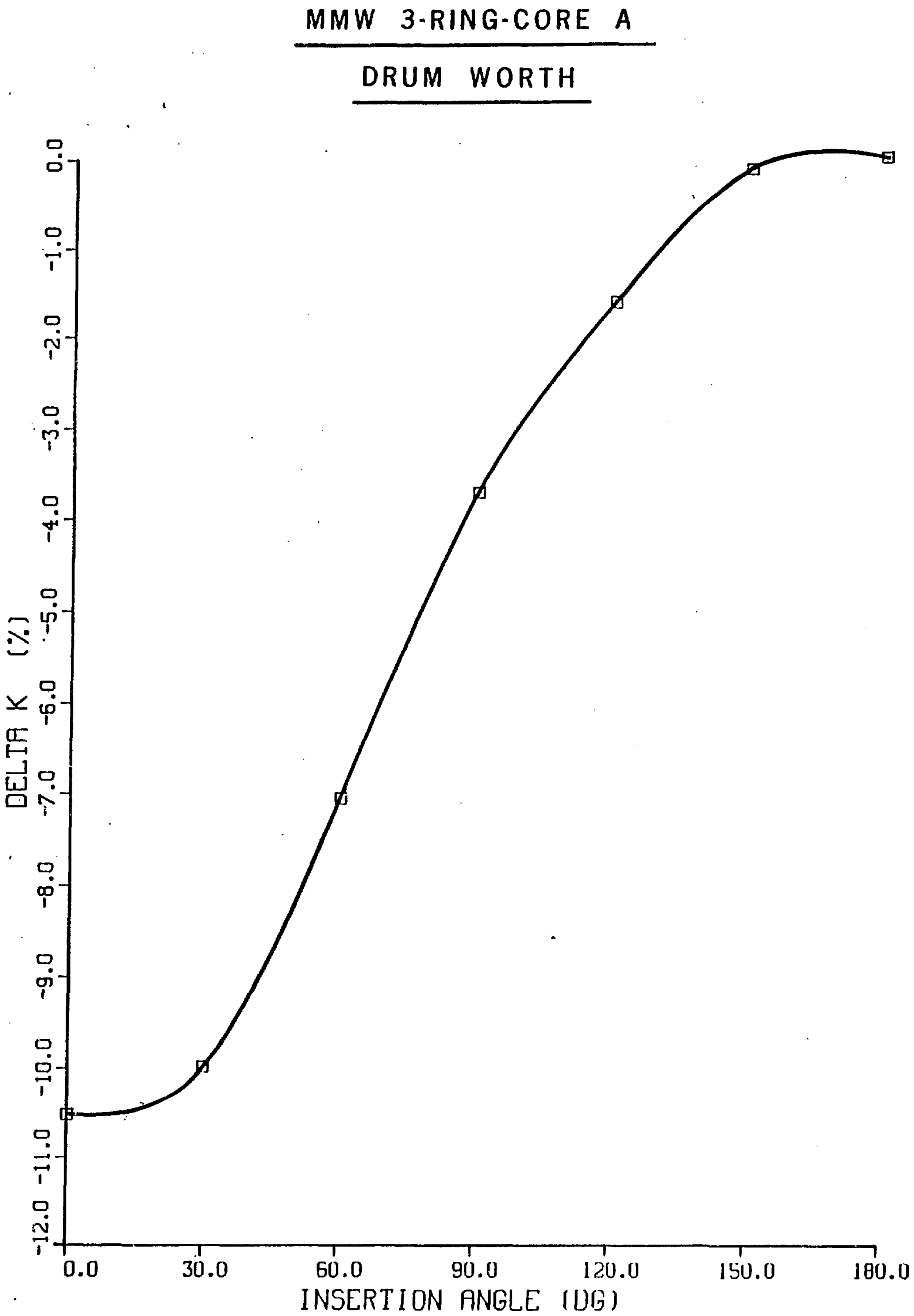

FIGURE 2. Effects of Control Drum Rotation on Radial Power Distribution for Core B.

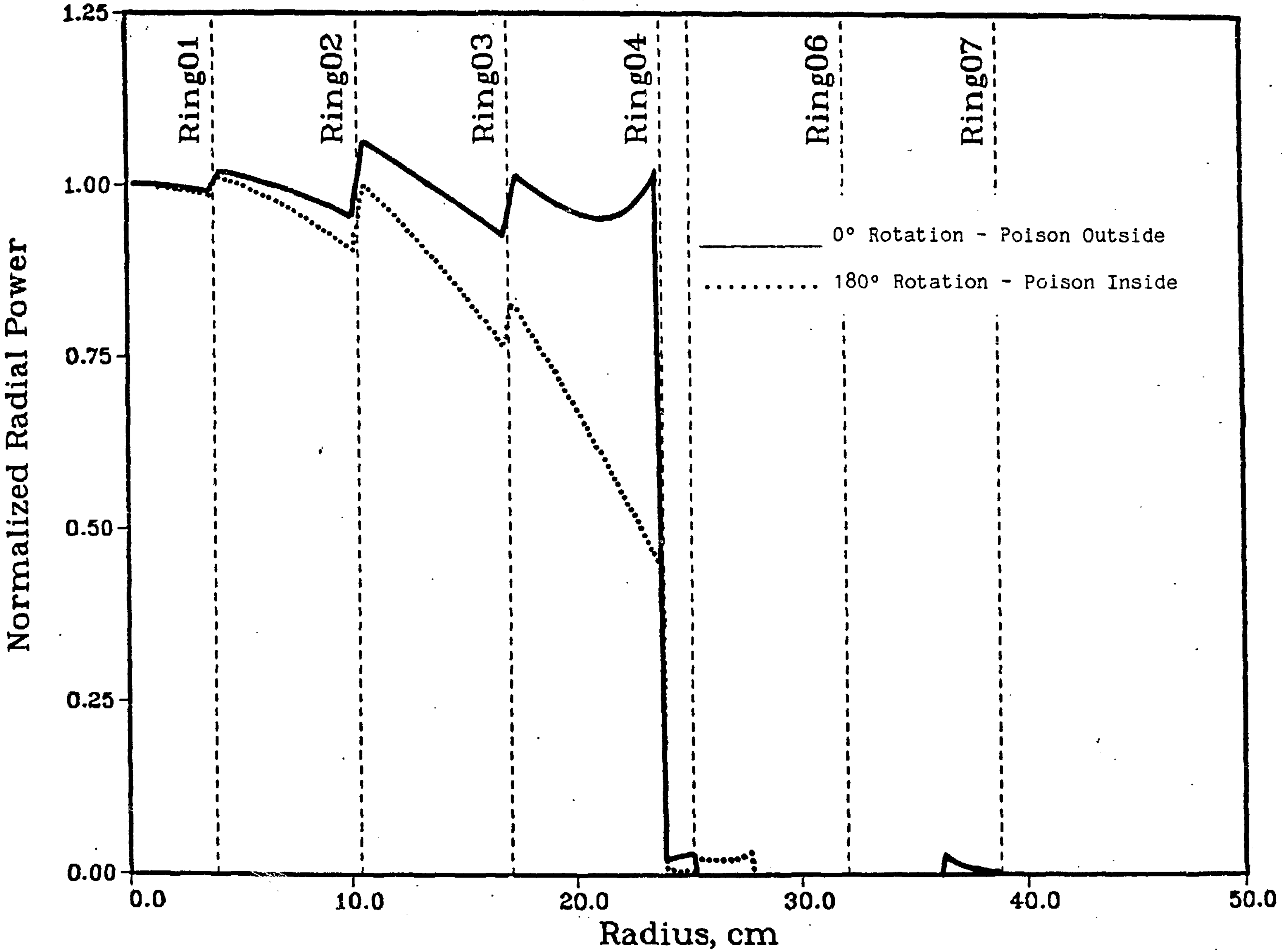

FIGURE 3. Effect of Control Rod Insertion on Planar Power Distribution for Core B-Axial Midplane Contour with Rods Half Inserted and 60° Symmetry.

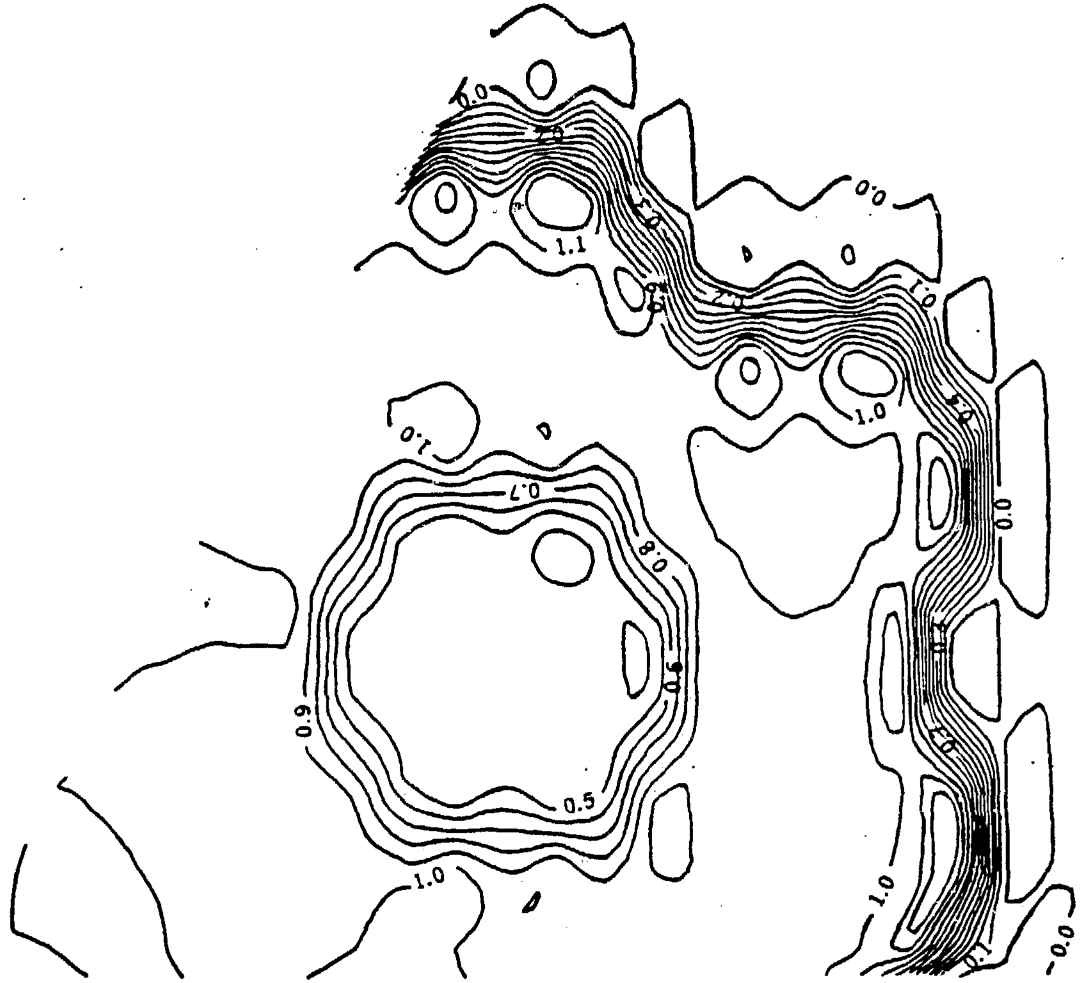

FIGURE 4. Effect of Control Rod Insertion on Axial Power Distribution in Core A-Rods Half Inserted.

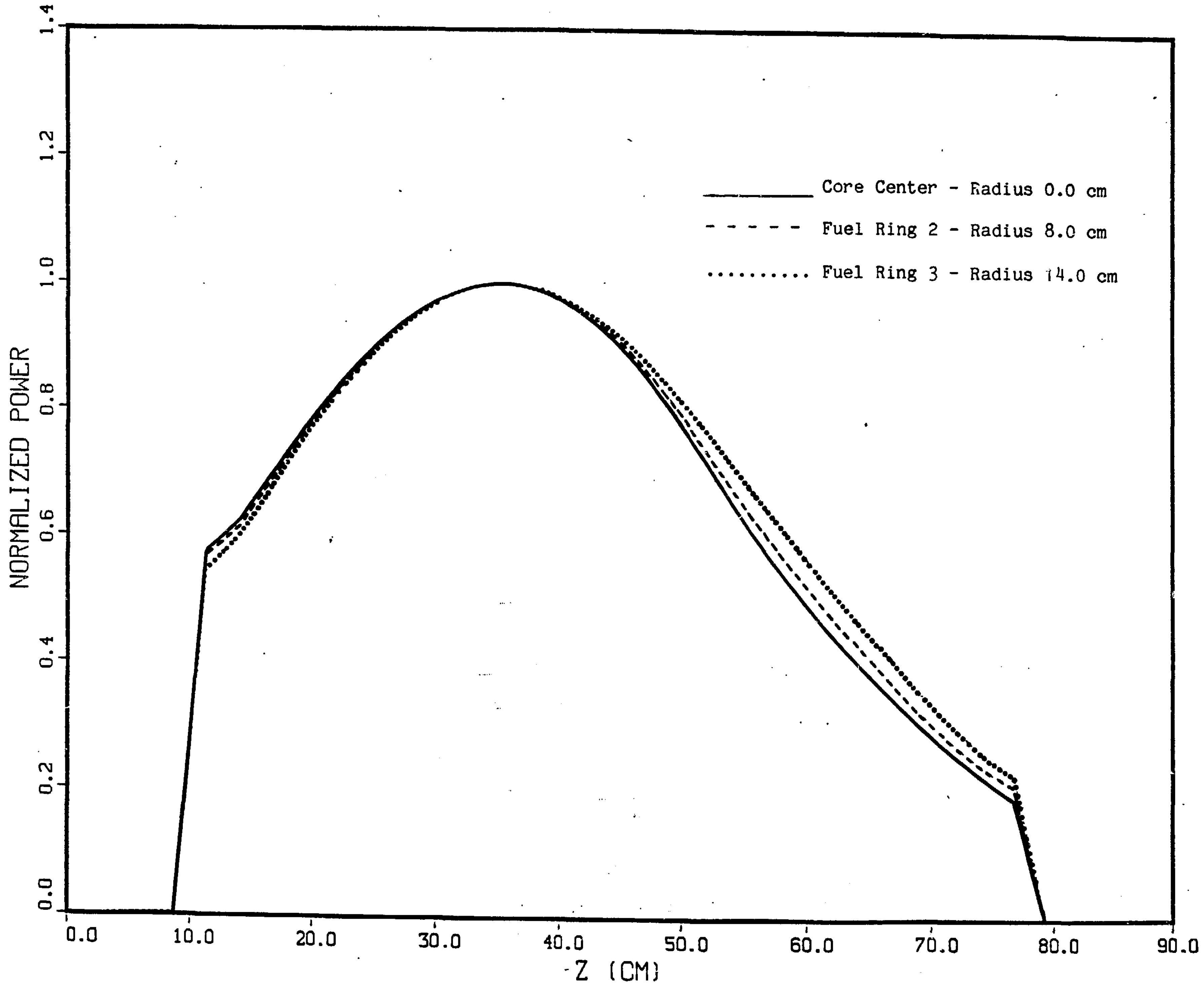

FIGURE 5. Control Rod Worth as a Function of Insertion for Cores A and B.