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PWR's

NUCLEAR PERFORMANCE OF LARGE PRESSURIZED WATER REACTORS CONTROLLED BY SOLUBLE POISON

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DISCLAIMER

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INTRODUCTION

In order to obtain increased power capability from large pressurized water reactors of fixed thermal-hydrualic design, the maximum-to-average power density ratio of the core must be reduced, allowing more of the core to operate close to the thermal-hydraulic design limit. The nuclear contribution to this maximum-to-average power density ratio can be reduced by employing non-uniform loading of the fissionable fuel. For example, the J_0 variation in an uncontrolled, uniformly loaded, cylindrical reactor may be flattened substantially by preferential loading in several regions. When a nearly uniform power distribution is obtained in this manner, it is desirable to operate at power with a uniformly distributed control technique such as a soluble neutron poison (boric acid) dissolved in the moderator. If a non-uniformly distributed control technique such as neutron poison rods is employed, the improvement in power distribution due to non-uniform fuel loading could be virtually cancelled. Fuel management considerations which include cycling (partial core refueling) are considerably easier in cores controlled by soluble neutron poison because the effects of control rod programming need not be considered in fuel depletion studies, and, of possibly greater importance, it is not necessary to find a new control rod program for each non-equilibrium cycle as well as the equilibrium cycle. Because of the elimination of the requirement of matching the non-uniform loading and fuel cycling to a complicated non-uniform control technique, there is substantially increased freedom in the possible fuel management alternatives.

Another advantage resulting from the use of a soluble neutron poison is the reduction in the number of control rods, mechanisms, and associated control and instrumentation equipment which normally would be employed in a large PWR core. Since the soluble poison concentration requires a significant time for adjustment, it cannot be employed for compensation of rapid reactivity variations and some control rods are still required. However, soluble poison can be employed to compensate for fissionable material depletion and fission product generation. Even the variation in xenon poisoning can be followed by soluble poison. Therefore, there is the possibility of a factor of two or more reduction in the number of control rods required.

The reactivity requirements which must be controlled by rods include the variation with power resulting from Doppler broadening of U-238 resonances, the variation which may arise from rapid coolant temperature changes, the variation for a potential accidental boron dilution, as well as the normal shutdown margin with the assumption of a stuck control rod. These requirements are in excess of any operational control band requirements which may be imposed. In addition, the occurrence of power distribution disturbances or instabilities may require special prupose control rods to be employed for power shaping. Limited power shaping may also be desirable to resolve fuel management problems, particularly those involving non-equilibrium cycles.

Although the use of a soluble neutron poison at power is relatively new, it is common to compensa te for the reactivity variation with the temperature change from ambient to operating condition by means of soluble poison. This method of cold shutdown has been employed in the Yankee, BR-3, and Saxton power reactors as well as Indian Point.

Certain of the nuclear characteristics associated with chemical shim control are not considered desirable to the extent that extra precautions may be required to assure that core flexibility or capability is not adversely affected. The temperature coefficient becomes less negative with increased boron concentration, and thus with increased design burnup. Therefore, with high fuel burnup, care must be taken that this coefficient does not become sufficiently positive that core operation is unstable.

In specifying the number of control rods for a core controlled by chemical shim, there are several problems which are unique to this type of control. The rod worth decreases with increasing boron concentration, and, therefore, the number of rods must be specified for the maximum amount of boron which is expected to be employed in the core at power. During normal core operation all these rods will be at some predetermined position but not necessarily completely withdrawn from the core.

NON-UNIFORM FUEL LOADING FOR INCREASED CAPABILITY

The average power level in a reactor is determined to a large degree by the ratio of the peak power to the average power, the power capability being inversely proportional to this ratio. One means of lowering this maximum-to-average power density ratio is to load the fissionable material non-uniformly in the core. With a good choice of non-uniform loading, which amounts to placing fuel with lower fissionable material content (lower enrichment or higher burnup) in the core region of high neutron importance, it is possible to reduce this ratio by as much as 30% below that for a uniformly loaded core. Thus, in a core controlled by soluble poison dissolved in the coolant in which there will be no control rods inserted in the core to perturb this uniform power distribution, the power capability can be increased by as much as 30%.

There are several different methods of non-uniform fuel loading that can be employed to achieve a nearly uniform power distribution. The method that achieves the most uniform distribution for a given core depends on core size, fuel assembly size and the design burnup of the fuel. After specifying the fraction of core to be replaced at a time (say 1/3), several different schemes can be considered. The first, and intuitively the most obvious, is a three concentric region, equal volume loading with preferential fissionable material towards the outside of the core in the initial loading. Thereafter new fuel is introduced into the outer region, moved toward the center in successive cycles, and discharged from the center region. Another approach, which can be taken, is a dispersed or salt and pepper type loading which places fuel assemblies of varying burnup nearly uniformly throughout the core: Other types of loading can be obtained by considering combinations of these two. Figures 1, 2, and 3 show how the peak-to-average power is reduced, and thereby the capability increased, in going from a uniformly loaded core to a three region core or to a core with the salt and pepper type loading for a typical large PWR core. The normalized power distribution is plotted as a function of the square of the radius for a cylindrical core. By plotting against R^2 equal increments include equal core volumes. The maximum-to-average ratio of 2.0 for the uniform loading is reduced to 1.3 for the three-region loading or 1.4 for the salt and pepper loading which is of the Roundelay cycle type described by Mr. Dollard and Mr. Strawbridge in Session V* of this meeting. Of course, the relative merit of the two non-uniform loadings which are illustrated as well as the merit of other loading techniques is a function of core size and fuel burnup.

INCREASED BURNUP WITH CHEMICAL SHIM

In a core in which all of the control is supplied by control rods, the maximum burnup is limited by the maximum number of rods that can be inserted in the core. However, when a soluble neutron poison is used to control the excess reactivity required for burnup, this limitation no longer exists. For increased burnup in a chemical shim core the extra control is achieved by the addition of more boron, and the number of control rods is not affected except for a small decrease in rod worth with increasing boron concentration. Since the control restriction on high burnups has been changed from a control rod limit to a less restrictive temperature coefficient limit in a chemical shim core, much higher burnups are possible as will be indicated below.

As was noted before, the type of non-uniform loading necessary to give a uniform power distribution is dependent on the core burnup. For high burnups (nearly 25,000 MWD/MTU discharge), the three-region loading described earlier (Figure 2) with out-in furl movement does not appear to be desirable. This is because the ratio of fissionable material in the three regions that give the most uniform distribution at beginning of life causes the central region to become depleted so much for long burnups that the power sharing

*Fuel Management in Large Pressurized Water Reactors", by W. J. Dollard and L. E. Strawbridge (Westinghouse Atomic Power Division).

between regions one and two is not acceptable. Figure 4 shows the beginning of an equilibrium cycle of the three region core in which a single feed enrichment has been used. Because of the high burnup that the fuel in the center region has seen in its two previous locations, it is not sufficiently reactive to give adequate power generation in this region. The maximum-to-average power density has gone from less than 1.3 in the clean core (Figure 2) to 1.7 for the equilibrium core of Figure 4.

The salt and pepper type loading with Roundelay fuel cycling, or a combination of it with the three region out-in cycling scheme behaves better at high burnups. In the pure Roundelay type of fuel cycling the fuel is not moved from the time it is placed in the core to the time it is removed at the end of its cycle. Therefore only the depleted fuel need be moved when cycling is performed, instead of shifting all the fuel as is necessary in an out-in cycle scheme. In a core where the core diameter is very large, the Roundelay cycling scheme seems to give the most uniform power distribution. This method was employed to obtain the results shown in Figure 3. However, in practice, this fuel assembly size may be too small to be economically feasible. For a typical fuel assembly size (approximately eight inches square), the pure Roundelay cycling scheme loses its advantage. This is because the local ripple in power distribution from assembly to assembly becomes quite large.

If a reference core ten feet in diameter with an eight-inch assembly is assumed with the fuel burnup objectives indicated in Table I, the distribution obtained by a pure Roundelay cycle is indicated in Figure 5. Expected neutron multiplication and boron concentration requirements are indicated in Table II for the first cycle. Note that this cycle is substantially longer in burnup than the succeeding ones. It is obvious that a pure Roundelay scheme is not adequate. We have also seen that the normal out-in cycling method is poor for long burnups, and therefore it becomes necessary to look at combinations of a three-region loading and a strict salt and pepper type loading. There are two ways to approach this problem. One can modify the three-region out-in method to obtain an acceptable power sharing between regions, or starting from the pure Roundelay method, consider modifications to obtain better power distributions.

In modifying the three-region core, the highly burned fuel must be moved more towards the outside of the core, and lesser burned fuel moved towards the center in order to get rid of the extreme "dishing" of the center region. Several examples of this type of modification are shown in Figures 6, 7, and 8 where three regions are retained but the boundaries are no longer concentric cylinders. The modifications shown in Figures 6 and 7 give an improvement in the maximum-to-average power density from 1.7 to 1.6 whereas the modification of Figure 8 gives an improvement to 1.5 over the core composed of concentric cylinders. One of the modifications considered for pure Roundelay is to combine multiregion loading with the Roundelay method of cycling. This involves having different fuel enrichments fed into each of several regions, as compared to a single enrichment in pure Roundelay. This method still has the advantage of not having to move all the fuel when cycling is performed, plus the advantage of a uniform power distribution afforded by multiregion loading. Figures 9 and 10 show how much the power distribution can be improved in a two and three region modified Roundelay cycling scheme. Note that the regions need not be of equal volumes in Roundelay cycling.

CONTROL RODS IN A CHEMICAL SHIM CORE

Since boron instead of control rods is used to control the excess reactivity for burnup and possible the reactivity associated with the equilibrium xenon swing in a chemical shim core, there is a large reduction in the required number of control rods. On the other hand, the rod worth is slightly less with boron in the core, and some rods must be added to compensate for this reduced worth. At the boron concentration required at beginning of life (approximately 2800 ppm), this defect in rod worth is only about 12 percent. We will see later that this is small compared to the possible reduction in the number of rods.

The control rods do serve an important function in a chemical shim core and some of the requirements of rods will now be discussed. The specific requirement of control for each of the categories mentioned will vary from core to core, and the ranges of values given are only approximate and the values given for the reference core are typical for a core of the size and burnup discussed above and in Table I. Control rods must be available to control the change in reactivity with a corresponding change in power level. The maximum change is in going from zero to full power, and this could vary between 1.5 and 2.5% Δk. A value of 2.0% has been assumed for the reference core. There must also be rods available to be inserted part of the way into the core to maintain a minimum ramp rate of reactivity for load reductions and to supply a boron dilution control band. This control band is provided because the chemical control system is not designed to meet precisely the boron concentration requirement and is also desirable to account for small temperature and pressure changes which would otherwise exceed limits specified for core operation. The amount of reactivity associated with the minimum ramp rate and control band is from 0.5 to 1.0% Δk, and 0.85 has been used for the reference core. Ordinarily, in a large PWR core the void content is very small and is restricted to statistical boiling. On the average this statistical boiling will give only about a third of one percent of void in the core. This could correspond to from zero to 0.1% Δk, and a value of 0.05% has been used for the reference core.

It may be desirable to make use of control rods to improve the power distribution in a chemical shim core. These rods could be employed to control local power peaks or power tilts which may occur in a large core. When rods are used for this purpose, the worth would range from zero to 2.0% Δk, with a value of 1% being assumed for the core under consideration until further work is performed to evaluate the desirability of power shaping. For a core in which the average temperature of the coolant is not constant with a change in power level, control rods must be supplied to control the reactivity change due to the change in temperature in going from zero to full power. The corresponding rod worth could be as much as 1.5% Δk. One percent is the nominal value chosen for the reference core. Although the reactivity requirements have been assumed to be additive, detailed study may indicate that this is not always the case and that some cancellation may be possible. For example, the boron control band is only necessary at the beginning of life when the moderator coefficient is nearly zero and the reactivity for temperature undershoot is only necessary at the end of life when the moderator coefficient is more negative.

In addition to the reactivity requirements for control rods that have been mentioned, rods must also be supplied for a concurrent reactivity insertion which might occur during an abnormal condition if the rate is too rapid to be controlled by poison. This condition could be a transient associated with the reactor system, or, a plant malfunction or credible operational error. The range of reactivity associated with such a concurrent insertion is from 0.5 to 2.5% Δk depending upon specific plant design. A reference value of 1.0% is used.

During a reactor scram it may be necessary to assure not only that neutron multiplication becomes less than unity buty also that it is sufficiently less than unity to assure a rapid decay of the neutron flux to terminate the power generation within a required time interval. An example of such a situation is a loss of coolant flow accident where the energy generation must fall rapidly relative to the coast-down of the coolant flow as it loses momentum. It has been found that approximately 2.0 percent shutdown in adequate to assure power decay and an increase in shutdown beyond this value will not appreciably decrease the energy generation following scram.

A slightly enriched UO_2 core has a characteristic which may help to eliminate the requirement for a shutdown margin. The Doppler broadening of U-235 resonances results in a hot-to-power reduction in reactivity which has been considered above. Because of the relatively low heat transfer from oxide to coolant (time constant or e-folding time of 5 to 10 seconds), at the time of scram roughly 2% additional shutdown is supplied. The neutron flux decays within the first few seconds before the oxide fuel has an opportunity to cool appreciably. Also, the probability of the shutdown being this low is very slight becasue this shutdown value assumes concurrent insertion <u>plus</u> a stuck rod. For these reasons no specific reactivity requirement has been assigned for the shutdown margin in the reference core.

The total range of reactivity requirements for control rods in a chemical shim core is from 2.5% to 9.6% Δk depending on the mode of operation and on the ground rules of control. For the core that has been considered as a reference, the rod worth requirements are 5.9% Δk. These requirements are summarized in Table III. In a completely rodded core with the same burnup characteristics, the control rods would have to be worth about 20% Δk, so that a savings in the number of control rods of more than a factor of 3 has been made in this particular chemical shim core.

EFFECTS OF BORON ON TEMPERATURE COEFFICIENT

The temperature coefficient in a core controlled by chemical shim is less negative than the coefficient in a rodded core. One reason for this is that control rods contribute a negative increment to the coefficient and, in a chemical shim core, the rods are nearly out of the core. Also, since water density decreases with an increase in temperature, the chemical poison density is decreased which gives rise to a positive component of the moderator temperature coefficient. This latter effect is directly proportional to the poison concentration and, since the chemical poison is used to control the excess reactivity for burnup, the beginning of life temperature coefficient becomes less negative as the design burnup is increased because of the consequent increase in beginning of life boron concentration. If sufficient boron is present, the coefficient can become positive, especially at lower temperatures where the core is less undermoderated than at operating temperature due to the higher water density.

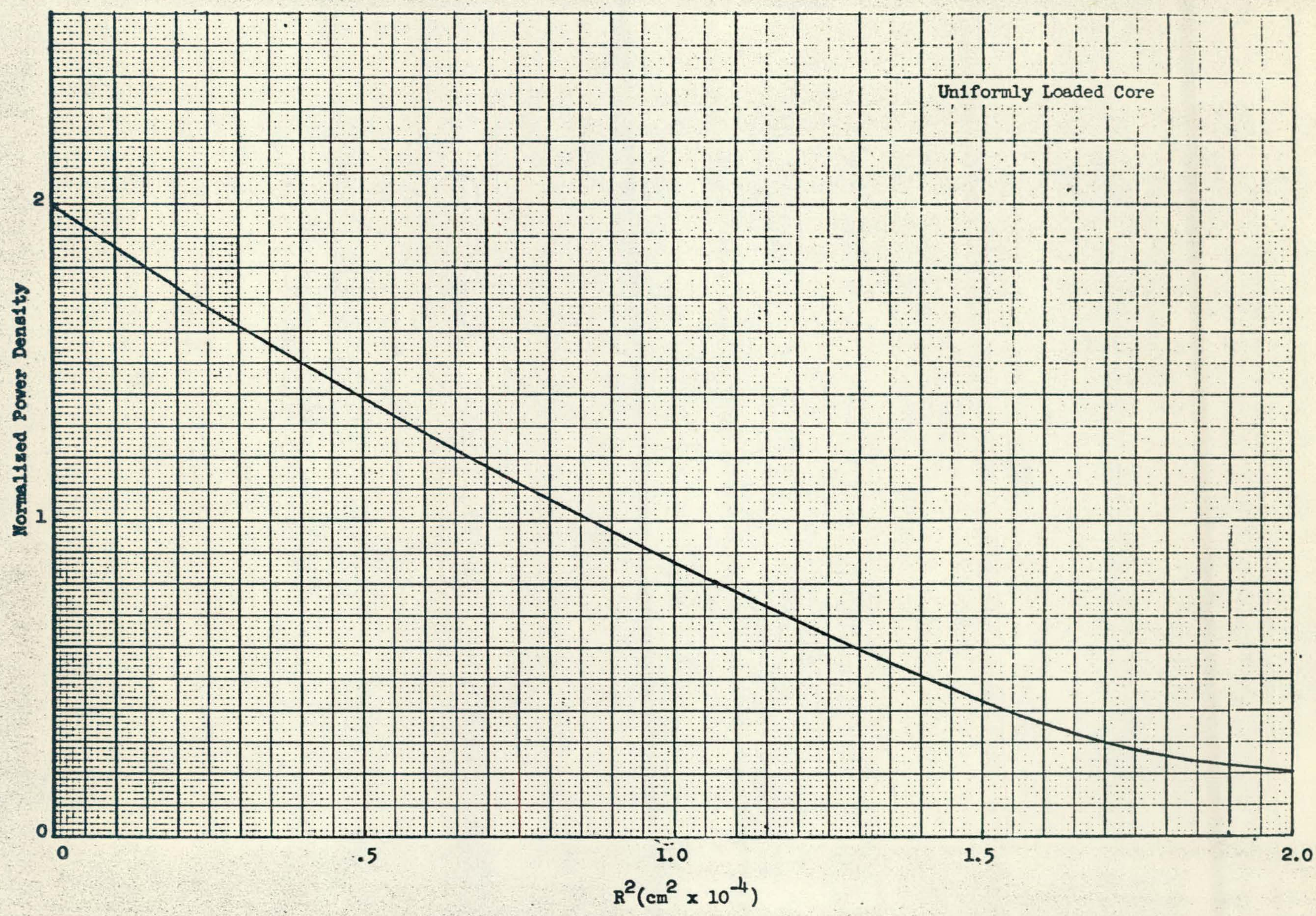
Figure 11 shows the behavior of this coefficient with temperature for several different boron concentrations. The Doppler contributions to the coefficient are included. From Table II we see that there is about 2800 ppm of boron in the core at beginning of life in cycle one. At this concentration the coefficient is approximately zero although slightly positive ($\sim 4 \times 10^{-5}$/°F) at the operating temperature of 575°F. Note that if the equilibrium xenon swing were controlled by rods instead of boron, as was considered above, the beginning of life boron concentration would be about 2300 ppm. For this case the coefficient is approximately zero when the effect of xenon on the neutron spectrum contribution to the coefficient ($\sim 10^{-5}$(°F)$^{-1}$) has been considered. In cores with higher burnup which therefore contain more boron, the temperature coefficient would be more positive yet. However, it is not anticipated that this situation is likely to be of interest since a 12,000 MWD/MTU cycle can be controlled with these boron concentrations and, in equilibrium, the discharge burnup for this cycle is 36,000 MWD/MTU. This is believed to be beyond the value of burnup which will yield optimum fuel cost. It is significant to note in this discussion that the net contribution of xenon, samarium, and plutonium to the moderator coefficient per unit of reactivity holddown is less positive than that of the dissolved boron and may well be negative. Therefore the least negative coefficient occurs at the beginning of the fuel cycle and becomes more negative in magnitude as fuel burnup proceeds.

It has been found that even with a zero or positive moderator temperature coefficient the stability of the core is not adversely affected as long as the net coefficient (Doppler plus moderator) remains only slightly positive. One case has been studied with a net coefficient of $+ 1 \times 10^{-4} (°F)^{-1}$ with no serious problems resulting. The trend towards an algebraically more positive moderator coefficient affects plant operation in two fashions. Normally, part of the reactivity insertion due to a partial load reduction is compensated by the negative temperature coefficient of the moderator. As this coefficient becomes ineffectively small or slightly positive, more rapid rod motion is required to compensate for load reduction. A failure to compensate does not indicate a non-safe situation as the most adverse consequence is to initiate a scram and shut the plant down. Secondly, at full power, it is desirable to maintain a small moderator temperature control band to establish a high value of coolant average temperature because of its effect on secondary system steam conditions. If a stepping type control rod mechanism is employed, the finite reactivity insertion per step will result in the temperature overshooting the control band if the temperature coefficient is too small in magnitude or positive. The consequence of this condition is hunting in which the rod group alternates back and forth between two step positions. The very large thermal inertia of the PWR primary loop results in the period of this oscillation to be of the order of several minutes and no undue hardship is imposed upon the stepping mechanism.

The safety of the plant is not affected by the moderator temperature coefficient if it is not substantially more positive than the Doppler because of the large time delay in heat transfer from oxide fuel to the coolant. The time constant is of the order of 5 seconds or more. The scram process can be completed in the order of 2.5 seconds so that the uncontrolled response to a transient is determined by the prompt Doppler coefficient which is unaffected by the boron addition and always remains negative.

SUMMARY

The majority of the information on the nuclear performance of large pressurized water reactors which are controlled by soluble poison has been developed during the Large Reactor Development Program which is funded by the Atomic Energy Commission under Contract Number AT(30-1)-3064. Many of the studies are still in progress and will continue over the next 15 months. The cycling studies that have been reported here were performed in one-dimension. These will be done in two dimensions and some effort will be made to study the effect of three-dimensional burnup. The use of control rods to control power distribution disturbances as well as the nature of these disturbances is an object of continued study.



Uniformly Loaded Core
Normalized Power Density
2
1
0
0
.5
1.0
1.5
2.0
R^2(cm^2 x 10^{-4})

Figure 1

Three Region Core - Out-In Cycling

First Core

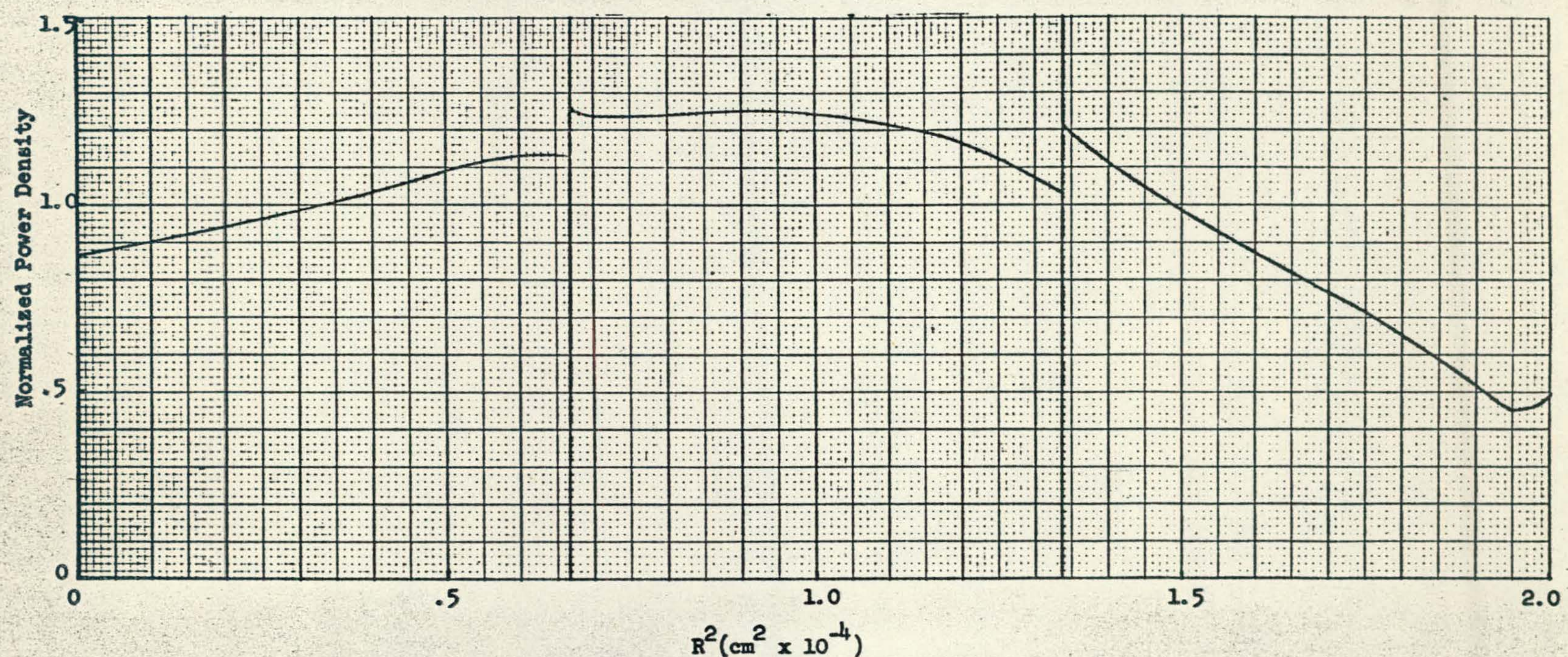


Figure 2

Salt and Pepper Type Loading - Roundelay Cycling

Small Fuel Assembly

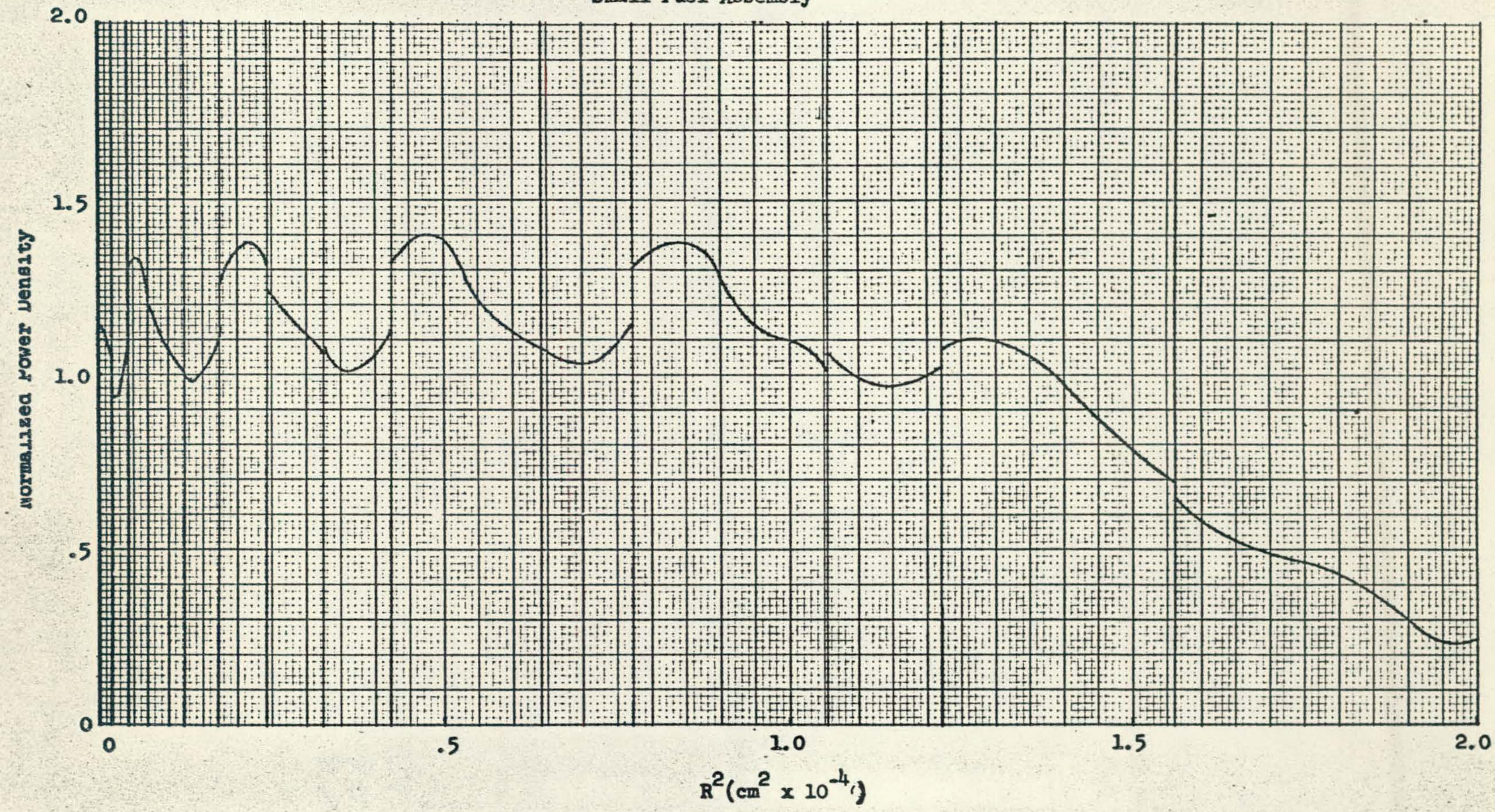
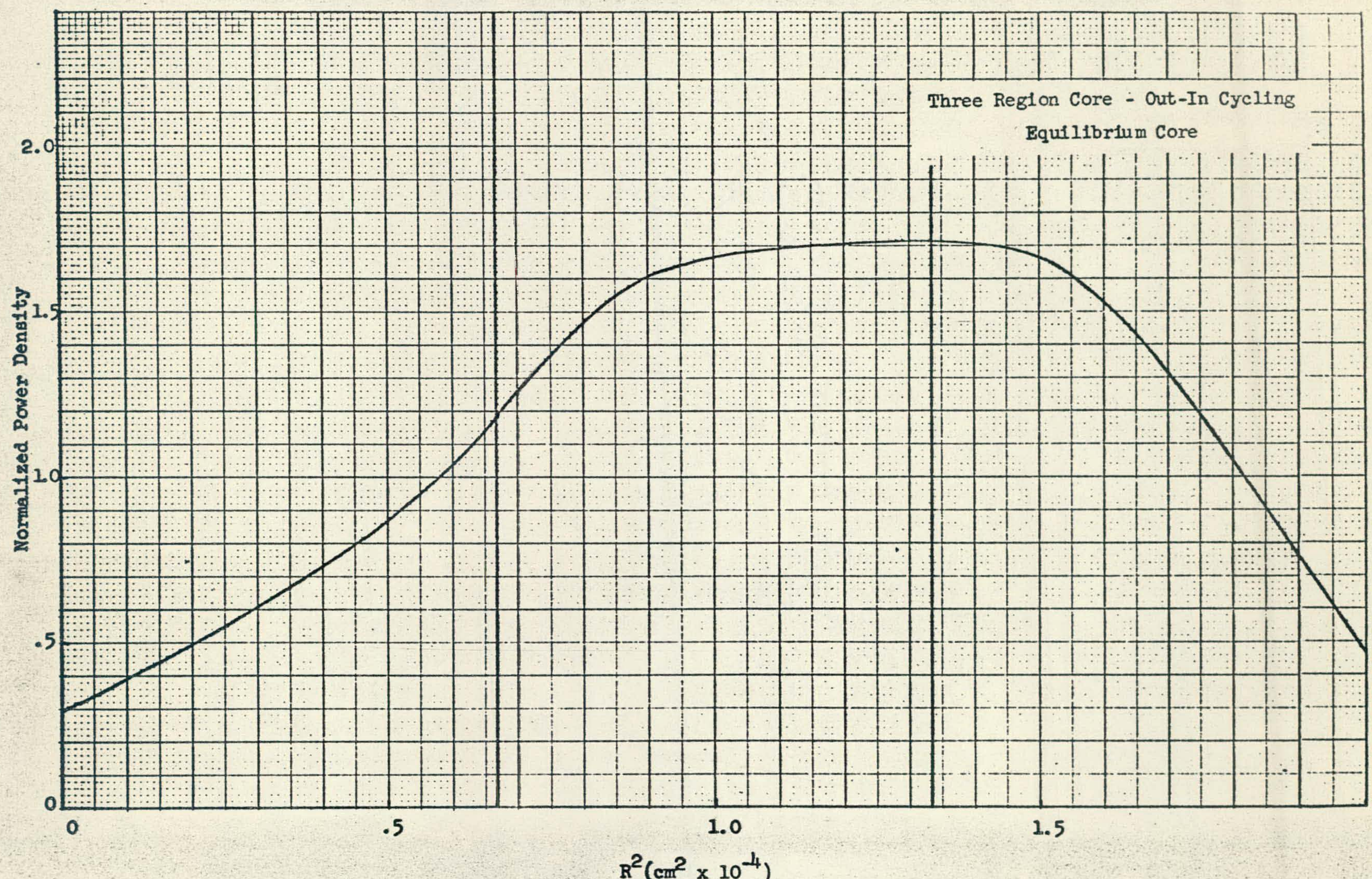
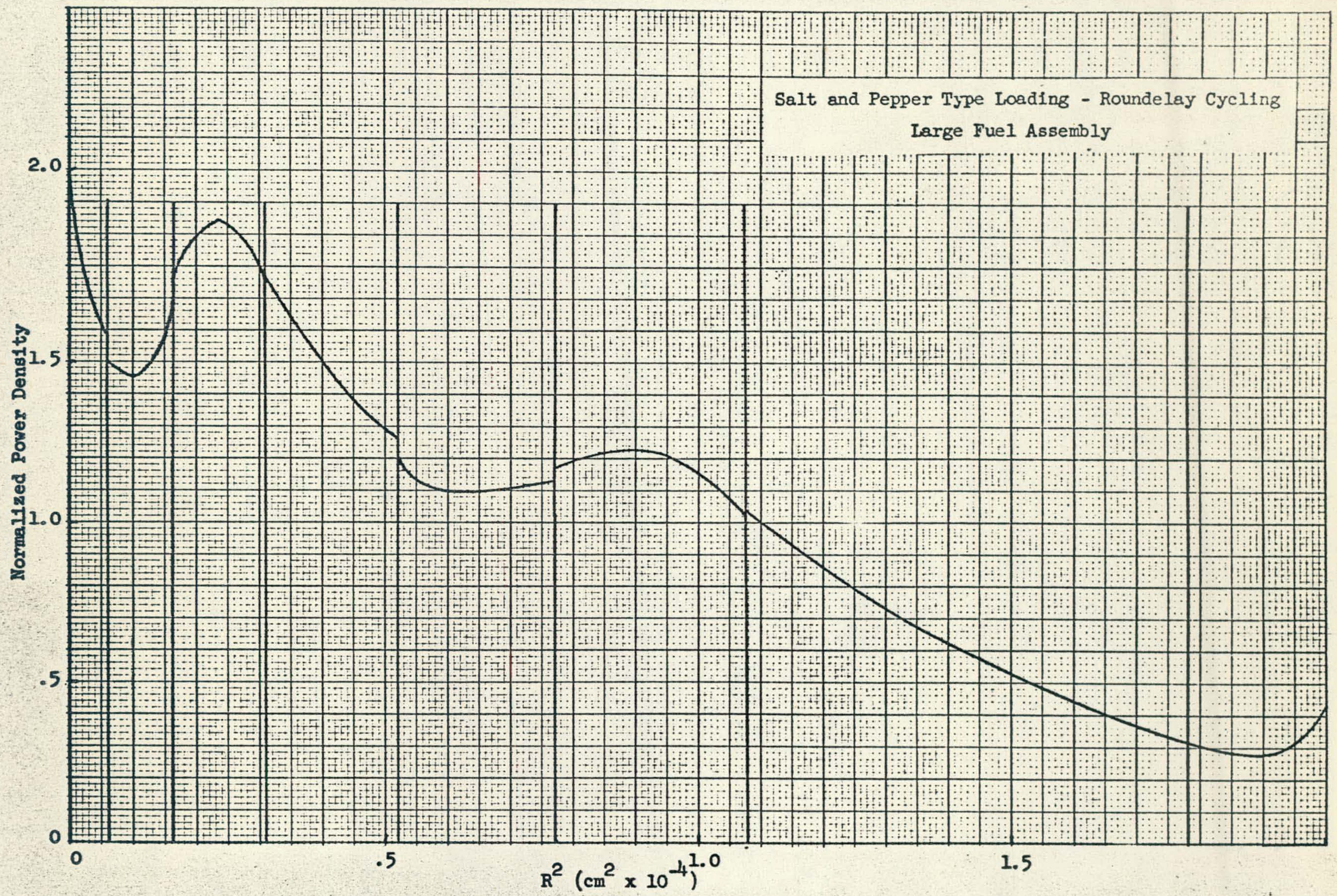


Figure 3



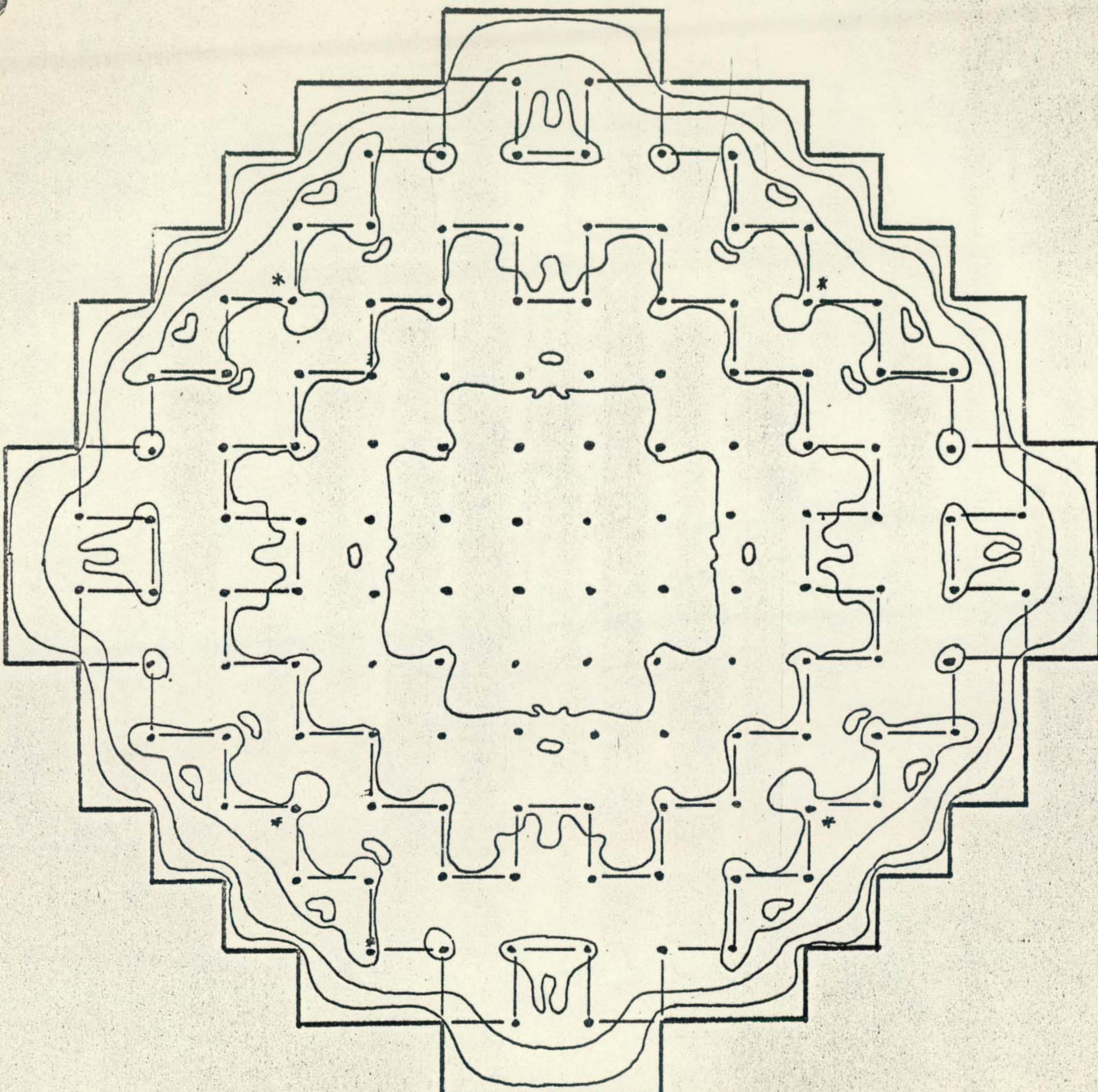
Three Region Core - Out-In Cycling
Equilibrium Core
Normalized Power Density
2.0
1.5
1.0
.5
0
0
.5
1.0
1.5
R²(cm² x 10⁻⁴)

Figure 4



Salt and Pepper Type Loading - Roundelay Cycling
Large Fuel Assembly
Normalized Power Density
2.0
1.5
1.0
.5
0
0
.5
1.0
1.5
R^2 (cm^2 x 10^{-4})

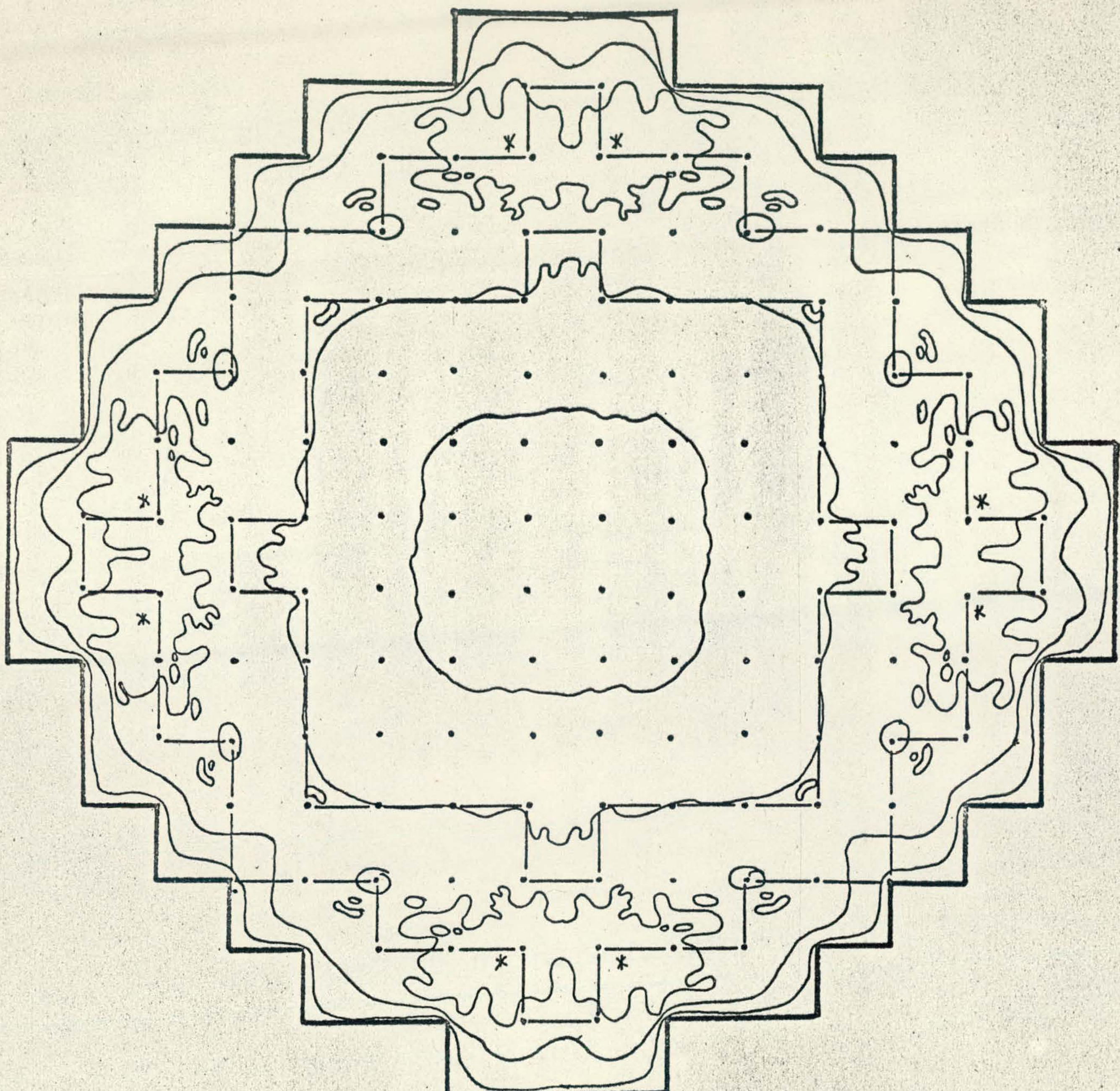
Figure 5



Modified Three Region Core

F = 1.6 (*)

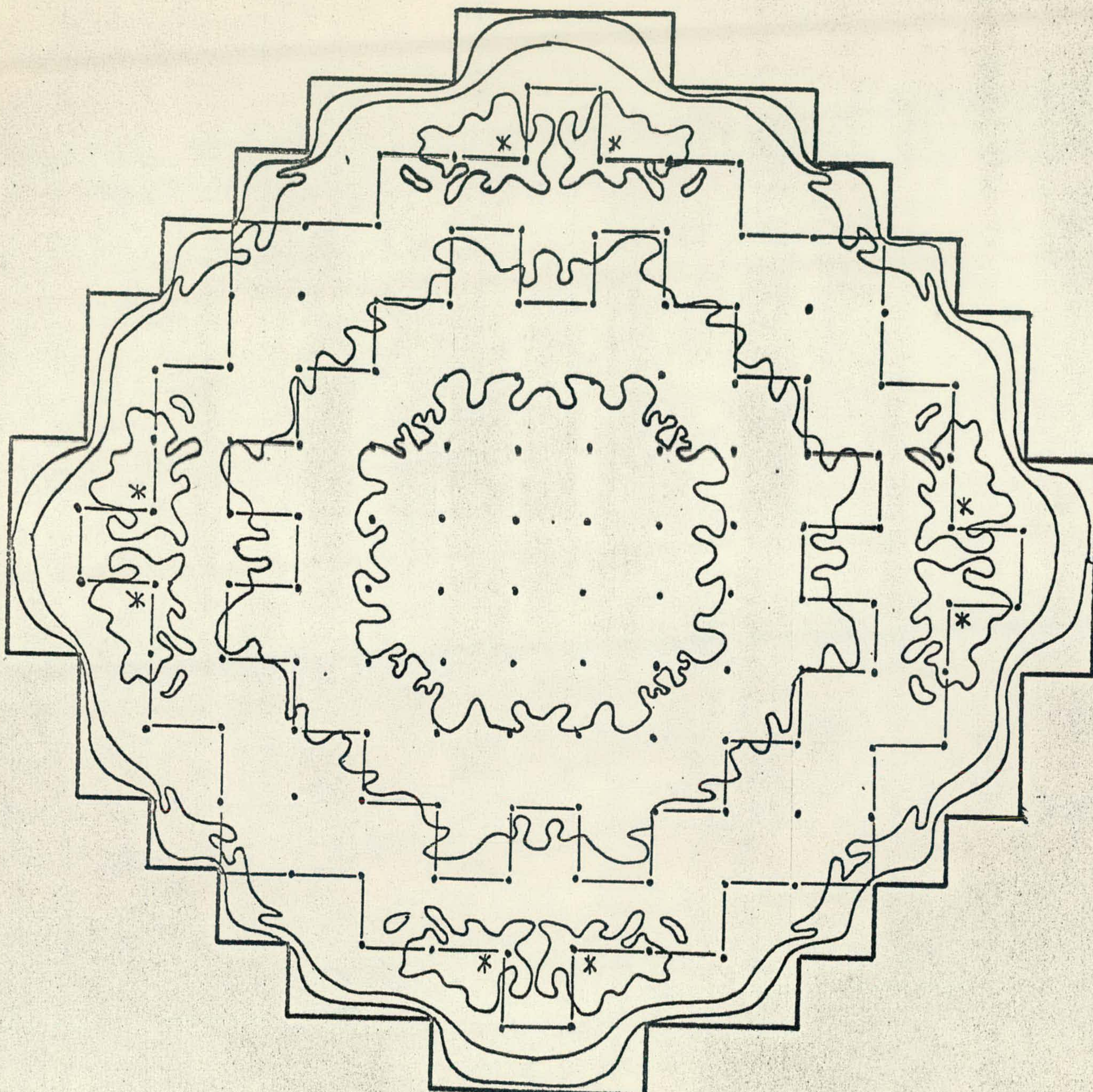
Figure 6



Modified Three Region Core

F = 1.6 (*)

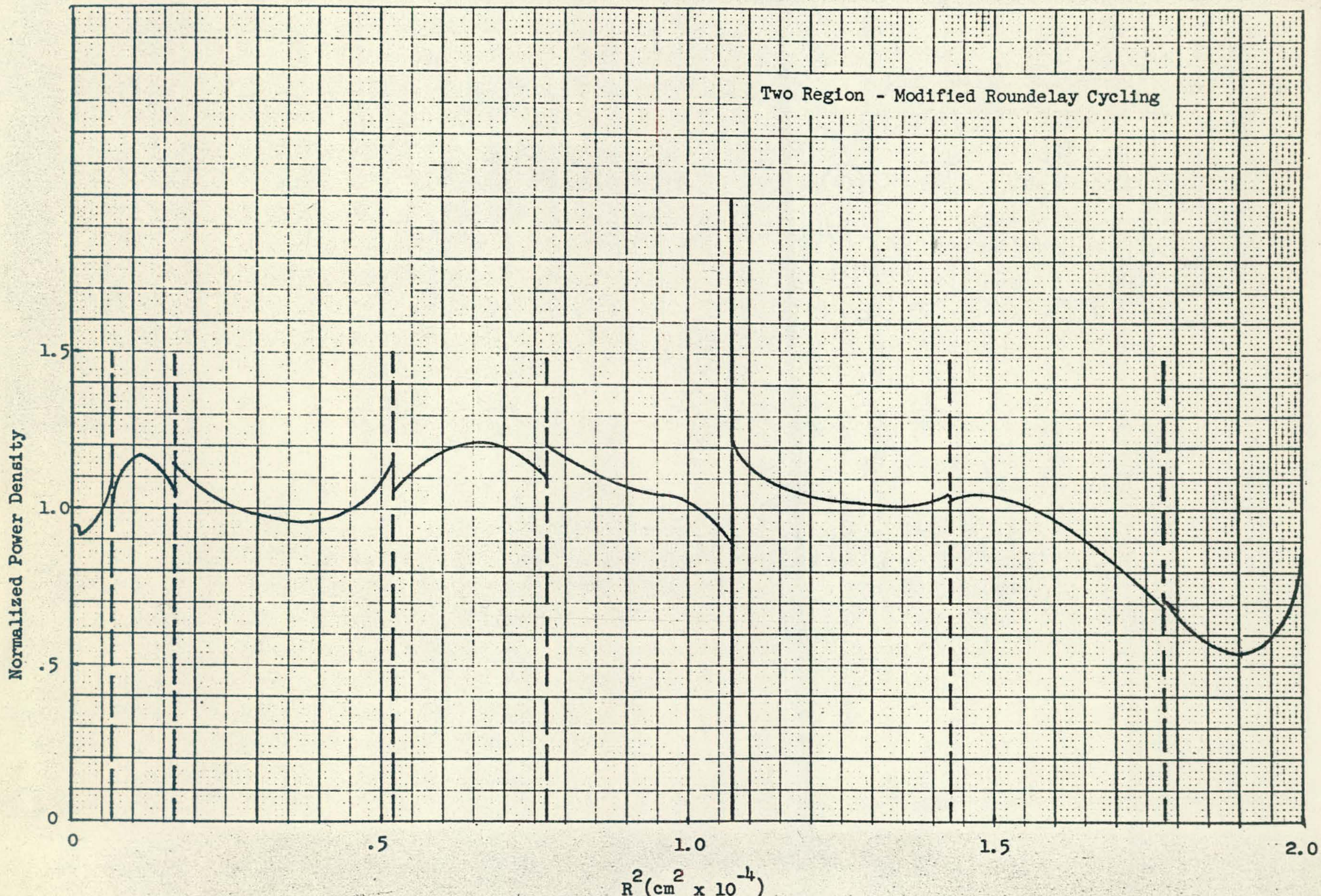
Figure 7



MODIFIED THREE REGION CORE

F = 1.5 (*)

Figure 8



Two Region - Modified Roundelay Cycling
Normalized Power Density
1.5
1.0
.5
0
0
.5
1.0
1.5
2.0
R²(cm² x 10⁻⁴)

Figure 9

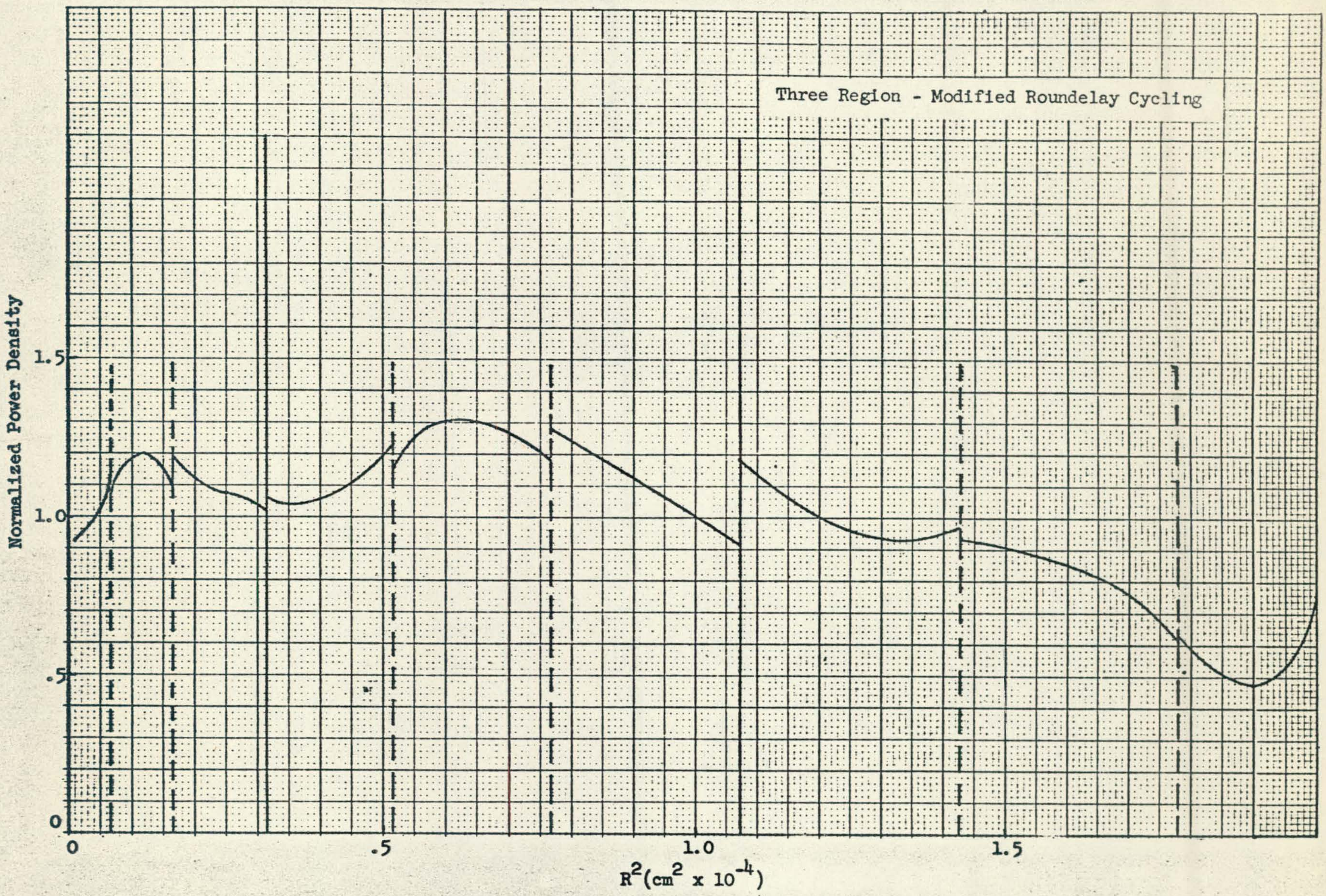
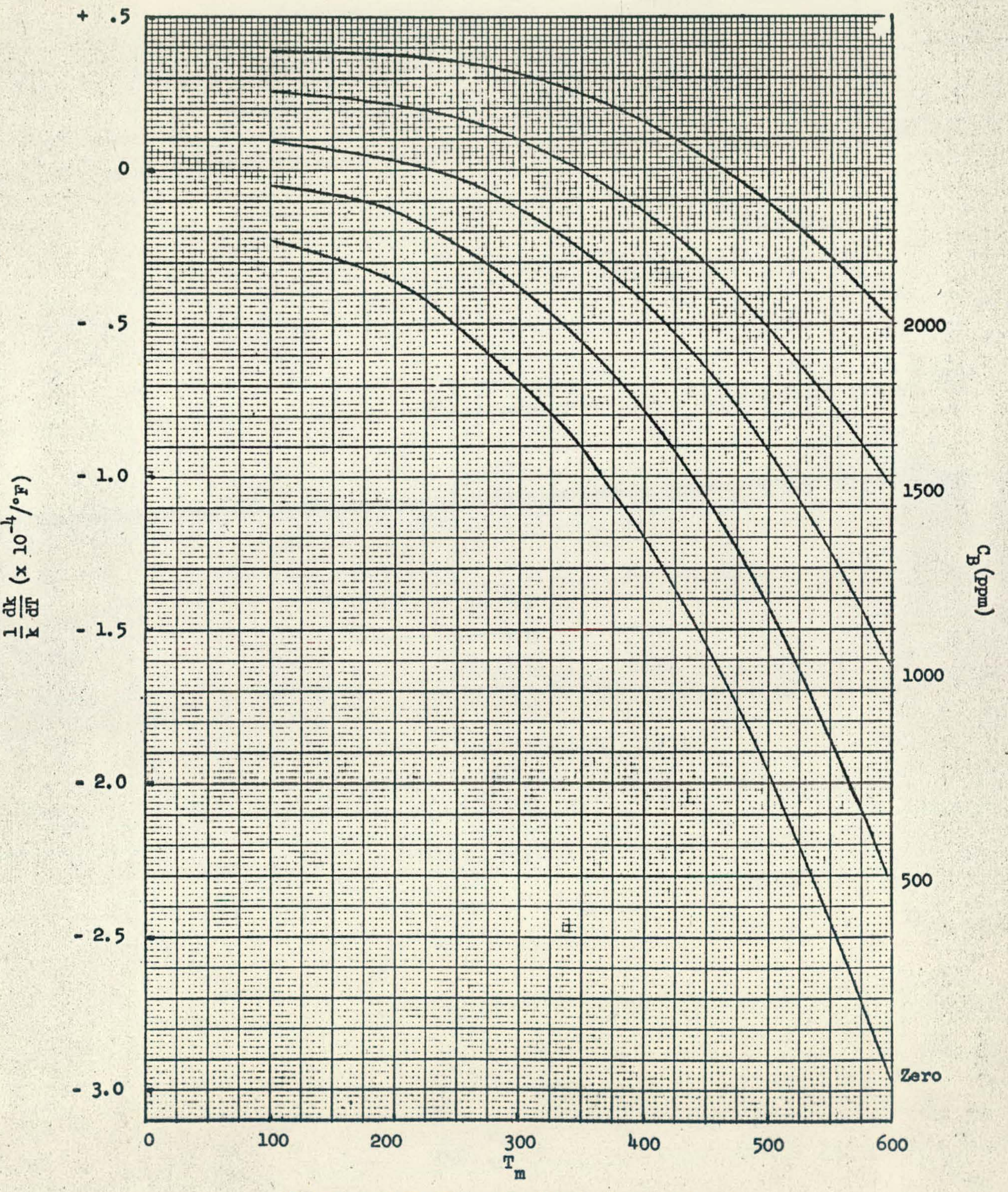

Three Region - Modified Roundelay Cycling
Normalized Power Density
1.5
1.0
.5
0
0
.5
1.0
1.5
$R^2(cm^2 \times 10^{-4})$

Figure 10



Moderator Temperature Coefficient vs. Moderator Temperature at Different Boron Concentrations

Figure 11

TABLE I

BURNUP CHARACTERISTICS FOR A LARGE PRESSURIZED WATER REACTOR CONTROLLED BY CHEMICAL SHIM

CYCLE	CYCLE BURNUP MWD/MTU	DISCHARGE BURNUP MWD/MTU
1	11,100	12,000
2	8,800	20,000
3	8,500	28,000
4	8,000	24,000

TABLE II

CONTROL CHARACTERISTICS OF FIRST CORE

EFFECTIVE MULTIPLICATION (BEGINNING OF LIFE)	
HOT, POWER, EQUILIBRIUM POISON	1.15
HOT, POWER, UNPOISONED	1.19
HOT, NO POWER, UNPOISONED	1.21
COLD, NO POWER, UNPOISONED	1.26
BORON CONCENTRATIONS, PPM	
TO SHUT REACTOR CORE DOWN TO k = 0. 97 WITH NO RODS INSERTED	
COLD	3500
HOT	3600
TO CONTROL AT POWER WITH NO RODS INSERTED	
UNPOISONED	2800
POISONED	2300
APPROXIMATE CONCENTRATION FOR WORTH OF ONE (1) PERCENT	
HOT	150
COLD	120

TABLE III

CONTROL ROD REQUIREMENTS FOR A CHEMICAL SHIM CORE

REQUIREMENT	PERCENT Δk	
	APPROXIMATE RANGE	REFERENCE CORE
HOT TO POWER	1.5 - 2.5	2.0
BORON DILUTION CONTROL BAND	0.5 - 1.0	0.85
VOID CONTENT	0 - 0.1	0.05
POWER SHAPING	0 - 2.0	1.0
VARIABLE TEMPERATURE	0 - 1.5	1.0
CONCURRENT INSERTION	0.5 - 2.5	1.0
TOTAL	2.5 - 9.6	5.9