REFLECTOR STUDIES FOR THE 600 MW(E) CANDU-PHW REACTOR

THE EFFECT ON BURNUP OF MODIFYING THE
600 MWe CANDU-PHW REFLECTOR

BY

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ABSTRACT

This report describes computer studies which were done to determine the effect on burnup of modifying the heavy water reflector in a 600 MWe CANDU-PHW reactor. It is shown that the burnup penalty increases rapidly as the reflector thickness is reduced. The burnup penalty is significantly lower for mixed reflectors in which some of the heavy water in the outer region of the reflector is replaced by graphite, an organic liquid, or light water, while maintaining the original reflector thickness.

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1. INTRODUCTION

In the 600 MWe CANDU-PHW reactor, the heavy water inventory constitutes a significant capital cost. The heavy water is used in the reactor core as both moderator and coolant, and it surrounds the core in the radial direction, serving as a neutron reflector. The expensive heavy water requirements could be reduced by decreasing the reflector thickness. However, in order to maintain a constant reactivity and a certain power distribution, it would be necessary to decrease the average burnup of the fuel to compensate for the greater radial leakage resulting from the decreased reflector thickness. This burnup penalty would result in higher fuel costs, which would offset the decrease in capital costs resulting from smaller heavy water requirements. In order to reduce the burnup penalty, instead of simply removing heavy water from the reflector, some of the heavy water in the outer region of the reflector could be replaced by another neutron reflecting material. Although the new material might be less efficient as a reflector, if it were cheaper than the heavy water that it replaced, the decrease in capital costs resulting from replacing some of the heavy water in the reflector by a less expensive material might more than offset the increase in fuel costs due to the burnup penalty.

Thus, there is a major incentive for determining the burnup penalty associated with changes to the CANDU-600 reflector. This report determines the burnup penalty that would result from either reducing the reflector thickness in a 600 MWe CANDU-PHW reactor, or from replacing some of the heavy water in the outer region of the reflector by graphite, light water, or an organic liquid known as HB40.

The definitions of some of the terms used in this report, and the symbols used to represent them are given in Appendix A, Section 1.

The Gentilly-2 600 MWe reactor has been used as the reference in this study (see Figure 1). The core contains 380 fuel channels arranged horizontally in a roughly circular array of radius 314 cm. To flatten the radial power distribution, the fuelling rate in the inner 124 channels is adjusted to give a larger fuel burnup than in the outer region. (The resultant core average burnup is defined in Appendix A, Section 2.) Power shaping, both radially and axially, is also attained through the use of 21 stainless steel adjuster rods, arranged in three rows in the radial plane in the inner region of the core. The adjuster rods have a worth of about 15 mk, and also provide about 30 minutes xenon override time in the event of a power shutdown. Six water filled zone control units, divided into 14 compartments and arranged in two rows in the radial plane in the inner region of the core, provide local reactivity control. Under normal operating conditions, the zone controllers have a reactivity worth of about 3 mk. The reactor core is surrounded radially by a heavy water reflector, contained within the calandria. The calandria consists of a main shell having a radius of 380 cm, with a smaller diameter sub-shell at each end. The reflector thickness in the main shell is about 65 cm. The notch in the calandria eliminates heavy water in a region of the core where the flux is low.

The Gentilly-2 reactor was simulated in a previous study using a detailed three-dimensional (rectangular geometry) computer code. However, the high computer costs ($200-$300 per run) and the inconvenience of making changes to the reflector size and composition in rectangular geometry precluded the use of the code in this study. Instead, a code called NMRB was used. This is an economical, two-dimensional (R-Z geometry), two energy group, finite difference neutron diffusion code. Lattice parameters were obtained from the cell homogenization code, POWDERPUFS-V.

The two-dimensional model of the Gentilly-2 reactor core used in NMRB was chosen in a preliminary study. Adjustments were made to the inner region radius, the inner and outer exposures, and the incremental thermal absorption cross sections ($\Delta\Sigma_{a2}$) of the adjuster rods and zone controllers (explained in Section 2.2.2) in order to obtain a reactor model which is representative of the real reactor. Values of the core parameters were chosen to ensure that the reactivity, radial form factor (the ratio of the average to maximum channel powers), and reactivity worths of the adjuster rods and zone controllers were comparable to the values determined using the detailed three-dimensional code. The core parameters for the reference case determined from this earlier study are listed in Table 1.

This model normalization was also necessary in the present study to ensure that the burnups of cores having different reflectors could be compared. Differences in reactivity, radial form factor, and the worths of the reactivity devices would result in differences in the core average burnup. Therefore, for each of the modified reflectors, the core parameters — inner region radius, inner and outer core exposures, $\Delta\Sigma_{a2}$ for the adjuster rods and zone controllers — were adjusted to satisfy certain constraints: that the reactivity, radial form factor, and reactivity worths of the adjuster rods and zone controllers be approximately the same for the modified reflector cases as for the reference case. Determining the core parameters which satisfied these constraints comprised the bulk of the work in this report. Small corrections were made to the final burnups of the modified reflector cases to account for small differences in the parameters from the reference case.

In this report, heavy water reflectors having thicknesses of 65.45 cm (the reference case), 55.45 cm, 45.45 cm, 35.45 cm and 25.45 cm were studied, as well as mixed reflectors containing 20 cm, 30 cm or 40 cm of graphite, HB40, or light water in the outer region of the reflector.

2. ANALYTICAL METHODS

2.1 Lattice Parameters

The lattice parameters for the homogenized fuel cell which were used as input to NMRB were obtained from the cell homogenization code, POWDERPUFS-V. The lattice parameters are burnup-averaged from zero burnup to the exit burnup in POWDERPUFS-V, to obtain a simple approximation to the spatial and time variations of burnup present in the core. The fuel data required as input to POWDERPUFS-V includes details of the lattice cell. These details, and hence the absolute values of the nuclear parameters, depend on the operating conditions in the reactor and are not important in this study.

The lattice parameters for the homogenized fuel cell determined using POWDERPUFS-V are shown in Table 2 for the range of exposures of interest. The values of parameters for exposures not in the table were obtained using linear interpolation between pairs of the tabulated parameters.

The lattice parameters for heavy water were also determined from POWDERPUFS-V. Multigroup cell calculations were used to derive the parameters for graphite and HB40 (1). The lattice parameters for water were obtained elsewhere (2). The lattice parameters for the various reflector materials are shown in Table 3.

2.2 NMRB

2.2.1 General Description of the Code

NMRB is a whole reactor physics code which solves the two-dimensional (R-Z geometry), two energy group, neutron diffusion equation using finite difference techniques. It is fast and economical (requiring about 3 seconds CPU time on the CYBER-175 computer for 756 mesh points), and thus is suitable for parametric surveys or optimization studies.

2.2.2 The Reactor Model

In the two-dimensional (R-Z) model used to represent the reactor core and reflector in NMRB, the Z-axis is in the center of the core, parallel to the fuel channels. The radial direction is therefore perpendicular to the fuel channels. It is assumed that the core has rotational symmetry about the Z-axis, and reflectional symmetry about the radial midplane. Only one-quarter of the reactor core in the axial midplane is represented, but with the symmetry about the Z-axis, this corresponds physically to half the core.

The adjuster rods and zone controllers are "smeared out" in this model: a row of adjuster rods or zone controllers is represented by a disc in the radial plane. In an R-Z model, a disc representing a row of adjuster rods or zone controllers appears as a rectangle. The adjuster rods and zone controllers are simulated by increasing the absorption cross section (Σ_{a2}) of the homogenized fuel cells where they are located by a small amount ($\Delta\Sigma_{a2}$), to give the appropriate reactivity worths of these devices. The only nuclear parameters affected by a change in the absorption cross section are the infinite medium multiplication constant and the thermal diffusion area, as shown in Appendix A, Section 3. The reactivity worth of the adjuster rods is simply the difference in reactivity of the core with and without the adjuster rods present (and with the zone controllers present); similarly for the reactivity worth of the zone controllers.

To represent the reactor core and reflector in NMRB, the R-Z plane is divided into rows and columns. To each of the resultant mesh rectangles, a number (material type) is assigned, which determines the lattice parameters and the dimensions of that mesh rectangle. The input to NMRB, then, includes a two-dimensional map of the core and reflector in which every mesh rectangle is indicated by a number, and the lattice parameters and R-Z dimensions associated with each number.

In NMRB, a black absorber (vacuum) surrounds the core and reflector. The flux is set to zero at the center of the mesh rectangles on external boundaries. Thus, three intervals of width 'w' in the reflector in the radial direction would correspond to a reflector thickness of 3.5 x w, rather than 3 x w. Internal boundaries are used as lines of symmetry in order to generate the flux in the rest of the core.

NMRB determines the flux at the midpoint of each of the mesh rectangles. A two-dimensional flux map is produced on output. For printout purposes the maximum flux is normalized to 1000. The power is determined in NMRB by multiplying the flux at each mesh point by the corresponding power to flux ratio (H), input as one of the lattice parameters. The radial power per unit volume is determined by summing the power over all the rows in a column for each column (ie. integrating the power in the axial direction) and dividing by the total volume of that column. The radial form factor is taken to be the ratio of the average to maximum power per unit volume in the columns. NMRB also determines the reactor eigenvalue, k_{eff}, from which the reactivity is determined using the relationship shown in Appendix A, Section 1.

As was mentioned previously, the model for the Gentilly-2 reactor core used as the reference in this study was chosen in an earlier study. The mesh sizes in the inner and outer burnup regions were chosen to give the correct sizes for these regions. The mesh sizes in the Z direction were chosen to approximate the correct locations of the zone controllers and adjuster rods. All mesh sizes were chosen to be less than the neutron migration length in a typical lattice cell (discussed in Appendix B, Section 1.2). The model that was chosen is shown in Figure 2.

The same model was used for the reactor core for all the modified reflectors. This eliminated errors in the burnup penalties which might result from comparing the burnups of cores which were modelled differently.

The models for the reflectors were chosen after investigating the sensitivity of the results to variations in the models, as described in the next section.

3. MODELLING THE REFLECTORS

It is important to reduce errors in the burnup penalties which are due to the modelling of the reference and modified reflector cases. Since the reactor core model is identical in all cases, these modelling errors are primarily due to the way in which the various reflectors are modelled.

3.1 Mixed Reflectors

Errors in the burnup penalty for the mixed reflector cases may arise if the reference reflector and the mixed reflectors are modelled differently. This problem was avoided by running a reference case for each different mixed reflector case, using the same model for the reference reflector as for the mixed reflector.

Another source of modelling errors stems from the fact that the sensitivity of the reactor parameters to variations in mesh size depends on the reflector material. For example, decreasing the mesh size in light water might result in a significant change in the reactivity or radial form factor, while the same change made in heavy water might have little effect.

Thus, the variation of the reactivity, radial form factor, and the average burnup with mesh size in graphite, HB40, and light water is important. Ideally, the mesh size should be chosen small enough so that a decrease in mesh size would not result in a significant change in these parameters. However, the mesh size (more exactly, the number of mesh points) is limited by code restrictions, cost, time and convenience. A maximum number of 40 radial mesh points was used in this study.

To determine the variation of reactivity, radial form factor, and average burnup with mesh size, mixed reflectors containing 45.45 cm of heavy water, and 20 cm of graphite, HB40, or light water were modelled, using various mesh sizes in the outer reflector material. The details of this sensitivity study, and the results, are given in Appendix B, Section 1. As a result of this study, increasingly smaller mesh sizes were used to model graphite, HB40, and light water. Also, an estimation of the errors in burnup resulting from the mesh sizes used was obtained.

One other consideration in the modelling of mixed reflectors was looked at briefly in Appendix B, Section 2.3. This lead to the conclusion that the difference in mesh size at the interface between the heavy water and the outer reflector material has little effect on the reactivity and radial form factor.

3.2 Heavy Water Reflectors

In order to establish a criterion for reducing modelling errors in the heavy water reflectors of reduced thickness, modelling studies were done using the reference reflector. As a result of these studies, described in Appendix B, Section 2, it was concluded that modelling errors in these reflectors could be reduced by using mesh intervals of approximately the same size (up to 18.7 cm) in the first 38 cm or so of the reflector. This guide was also used in modelling the heavy water part of the mixed reflectors, although this was not necessary since the same model was used for both the reference reflector and the mixed reflector in each case.

The models that were chosen for the modified reflectors are shown in Table 4.

4. ADJUSTING THE CORE PARAMETERS TO SATISFY THE CONSTRAINTS

4.1 General Approach

For each modified reflector, values were determined for the core parameters — the inner region radius, the inner and outer core exposures, and $\Delta\Sigma_{a2}$ for the adjuster rods and zone controllers — which resulted in approximately the same reactivity, radial form factor, and reactivity worths of the zone controllers and adjuster rods as in the reference case.

One way of visualizing this problem is to consider a two-dimensional map of the reactivity and radial form factor as a function of the inner and outer core exposures. For simplicity, the zone controllers and adjuster rods will be ignored for now. Every inner and outer exposure pair results in a certain flux and power distribution, radial form factor, and reactivity. Iso-reactivity and radial form factor contours could be drawn for such a map. Figure 3 shows what these iso-reactivity and radial form factor contours might look like for a hypothetical reactor (3). For every value of the radial form factor (except the maximum), there are two iso-radial form factor contours. Thus, a particular reactivity and radial form factor can be achieved with power and flux distributions which are either peaked (low inner exposure) or dished (high inner exposure) in the center of the core. For each modified reflector, there will be a different reactivity / radial form factor map for each inner region radius of interest. As the inner region radius increases, the maximum radial form factor achievable increases, reaches a maximum, then decreases (4). In the simpler problem where the zone controller and adjuster rods are ignored, one would first determine the inner region radius which would enable the desired radial form factor to be achieved. Then one would determine the inner and outer core exposures which would give the required reactivity and radial form factor.

One can use the same reactivity / radial form factor map to gain insight into the actual problem, by assuming that the incremental thermal absorption cross sections for the zone controllers and adjuster rods have been adjusted to give the required reactivity worths for these devices, for each pair of inner and outer exposures. Thus, if the zone controllers and adjuster rods have a total reactivity worth of say, 18 mk, then the 30 mk reactivity contour in Figure 4 would become a 12 mk reactivity contour.

Decreasing the effectiveness of the reflector — by decreasing the thickness of the heavy water reflectors, or, in the mixed reflectors, by increasing the amount of the outer material present in the reflectors at the expense of the heavy water, or by reducing the reflecting ability of the material in the outer region of the reflector — would result in greater neutron leakage from the core in the radial direction. As a result, the reactivity would decrease. As well, if the reactor power were held constant, the power in the center of the core would increase at the expense of the power in the outer region. To regain the original radial form factor (and radial power distribution), one could decrease the outer exposure, which would increase the reactivity, and flatten the flux. There could exist a value of the outer exposure for which the radial power distribution assumes its original shape, thereby allowing the original radial form factor to be achieved with no further changes. However, the decrease in outer exposure alone might not be enough to compensate for the increased radial leakage. It could happen that, while the power distribution in the center of the core can be matched with the original power distribution, the power in the outer region is too low. Since the number of fuel channels increases as R^2 in the radial direction, the radial power in the outer region of the core has considerable weight on the average channel power. Thus, the inability to increase the power in the outer region of the core may limit the maximum radial form factor achievable. If this is so, it might be possible to increase the maximum achievable radial form factor by increasing the inner region radius, which, for a suitable pair of inner and outer exposures, might result in a larger flattened power radius, and an increase in the power in the outer region of the core.

With this in mind, the following procedure was established for adjusting the core parameters for the modified reflectors to satisfy the various constraints. The choice of starting values for the parameters was based on the final values of the parameters for either the reference case, or a previously run case. The radial form factor was determined for several values of the outer exposure, and for the inner region radius and exposure chosen as starting values. The outer exposure giving the desired radial form factor was determined using interpolation or extrapolation. In Figure 3, this is equivalent to scanning the radial form factor contours in the verticle direction for the radial form factor contour of interest. If the desired radial form factor could not be achieved for the inner region radius and exposure under consideration, the radius of the inner region was increased by adding one more column to the inner region in the model.

In adjusting the core parameters to satisfy the constraints, it was convenient to make changes to the outer exposure, rather than the inner exposure, whenever possible, since changes to the outer exposure involved changes in the lattice parameters of only one material, while changes in the inner exposure involved changes in the lattice parameters of three materials (the homogenized fuel cell, and the lattice cells containing the zone controllers, and the adjuster rods). Since the flux is normalized to give a constant maximum flux, increasing the outer exposure has the same effect on the flux and power distributions as decreasing the inner exposure (not necessarily by the same amount), and vice versa. Of course, the effect on the core reactivity is not the same in both cases.

The reactivity worths of the zone controllers and adjuster rods are determined by the flux shape in the core, as well as $\Delta\Sigma_{a2}$ for the devices. Since the final flux shape was more or less known after the desired radial form factor was achieved, the worths of the reactivity devices were the next constraints which were satisfied. A small change in the worth of either of the reactivity devices could be achieved without a significant effect on the flux distribution or radial form factor, by making a small change to $\Delta\Sigma_{a2}$ for the device. In this case, the reactivity worth was approximately proportional to $\Delta\Sigma_{a2}$ from first order perturbation theory. However, a large change in $\Delta\Sigma_{a2}$ for either of the devices sometimes resulted in a significant change in the flux and radial form factor, so, in order to keep the same power distribution and radial form factor, the change in $\Delta\Sigma_{a2}$ was compensated by a change in the outer (or inner) exposure. For example, if the radial form factor was correct, but the worth of the adjuster rods was quite low, then simply increasing $\Delta\Sigma_{a2}$ for the adjuster rods would result in a decrease in the level of the flux in the center of the core, and hence, a change in the radial form factor. As well, the worth of the adjuster rods would be less than if the flux had remained constant. To ensure that the flux distribution remained unchanged after a change in $\Delta\Sigma_{a2}$ for the adjuster rods, it would be necessary to increase the outer exposure (or decrease the inner exposure).

The last constraint to be satisfied was the reactivity. A change in the reactivity, without a significant effect on the other parameters, could often be achieved by changing the inner and outer exposures by the same amount — increasing the exposures to decrease the reactivity, and vice versa. In Figure 3, this is equivalent to saying that the iso-radial form factor contours are about 45 degrees to the horizontal. An approximate rate of change of reactivity with exposure of -34 mk/(n/kb) was used to determine the required change in the exposures corresponding to a desired reactivity change. This number is the average value of 1000 x $(k_{eff}-1)/k_{eff}$, between 1.6 n/kb and 1.8 n/kb exposures; the effective multiplication constant (k_{eff}) was determined from POWDERPUFS-V.

If the other parameters did not change significantly as a result of equal changes to the inner and outer exposures, then all the constraints were satisfied, and this part of the procedure was finished. If the other parameters did change significantly, the procedure was repeated, until all the constraints were satisfied.

The procedure described above was generally used; however, the details varied from case to case.

4.2 Burnup Corrections due to Residual Differences in the Constrained Parameters

For each modified reflector, corrections were made to the calculated average burnup to account for small differences in the reactivity, the radial form factor, and the reactivity worths of the adjuster rods and zone controllers from the corresponding values for the reference case. Since these corrections were small, first order approximations were assumed to be valid: the difference in each of the parameters from the reference case was multiplied by the estimated rate of change of the average burnup with the parameter. It was assumed that adjustments could be made to any one of the parameters, while holding all the other parameters fixed. Thus, the total burnup correction is the sum of the burnup corrections due to adjustments made to each of the parameters individually.

4.2.1 Differences in Reactivity, Zone Controller and Adjuster Worths

A burnup correction of 120 (MWD/TeU)/mk was used to correct for differences in reactivity, and the reactivity worths of the zone controllers and adjuster rods, between the reference case and the modified reflector cases. This number was obtained in previous cell calculations, and implies that small changes in reactivity can be achieved through uniform changes in burnup throughout the core.

4.2.2 Differences in Radial Form Factor

POWDERPUFS-V has an option whereby a one-dimensional diffusion code can be used to determine the inner and outer exposures and the inner region radius which result in a certain radial form factor, specified on input. The resultant average burnup is also computed. In a previous study, this option was employed to determine the average burnup for several values of the radial form factor and various reflector thicknesses, modelling the same reactor that was used as a reference in this study. The results are shown in Figure 4, where the average burnup is plotted as a function of radial form factor, for reflector thicknesses of 65.45 cm, 55.45 cm and 45.45 cm. The tangent to each curve was drawn at a radial form factor of 0.8333 to give an estimate of the rate of change of burnup with radial form factor which was used to correct for differences in the radial form factor between the reference case and the modified reflector cases. The slopes of these tangents are given in Table 5. The rate of change of burnup with radial form factor was extrapolated to a reflector thickness of 35.45 cm in Figure 5.

There are a number of limitations in this method of determining the rate of change of burnup with radial form factor. POWDERPUFS-V employs a one-dimensional diffusion code, while a two-dimensional code was used in this study. POWDERPUFS-V achieves the specified radial form factor using only burnup flattening, wherease NMRB uses both burnup flattening and absorber flattening to shape the flux. It was assumed that the burnup correction did not depend on the composition of the reflector — the burnup correction for the mixed reflectors having a thickness of 65.45 cm was determined using a reflector containing 65.45 cm of heavy water. Finally, there is no constraint on the reactivity in the POWDERPUFS-V calculation. However, the method suffices to provide a rough approximation for small first-order burnup corrections.

5. RESULTS

The final values of the inner region radius, the inner and outer exposures, and $\Delta\Sigma_{a2}$ for the zone controllers and adjuster rods which satisfied the various constraints are tabulated in Table 6 for each of the modified reflectors. The corresponding values of the reactivity, radial form factor, and reactivity worths of the zone controllers and adjuster rods for each modified reflector and the corresponding reference reflector are shown in Table 7. The burnup corrections, the corrected average burnups, and the burnup penalties are also given in Table 7. The burnup penalties are plotted in Figure 6.

Two scales are used for the abscissa in Figure 6. The upper scale shows the thickness of the heavy water removed from the reflectors of reduced thickness, or the thickness of the outer reflector material in the mixed reflectors. The lower scale shows the thickness of the heavy water part of the reflectors, for all the modified reflectors; for the reflectors of reduced thickness, this is the total reflector thickness.

6. DISCUSSION

6.1 Burnup Penalties

The burnup penalties for the modified reflectors are shown in Table 7, and in Figure 6. The burnup penalties for the heavy water reflectors of reduced thickness are large, and increase rapidly as the reflector thickness is decreased. Reducing the thickness of the reflector by 10 cm, without replacing the heavy water lost, results in a burnup penalty of 141 MWD/TeU; a 20 cm reduction results in a burnup penalty of 484 MWD/TeU; if the thickness is reduced by 30 cm, the penalty jumps to 1548 MWD/TeU.

The results of this study show that this burnup penalty can be greatly reduced by replacing the heavy water that is saved when reducing the reflector thickness by graphite, HB40, or light water, thus maintaining the original reflector thickness. Furthermore, the burnup penalty increases at a slower rate for the mixed reflectors as the amount of heavy water removed from the core is increased. The burnup penalty is smallest for graphite: replacing 20 cm of heavy water by graphite results in a burnup penalty of only 9 MWD/TeU. The penalty rises to 52 MWD/TeU when 40 cm of heavy water are replaced. The burnup penalties are greater for HB40 and light water mixed reflectors, but are still substantially lower than the penalties for the corresponding pure heavy water reflectors of reduced thickness. Replacing 20 cm of heavy water by HB40 or light water results in a burnup penalty of about 9 MWD/TeU. (This number approximately doubles when the sensitivity of the results to mesh size is considered, as discussed in the next section.) The burnup penalty increases to 535 MWD/TeU for HB40, and 588 MWD/TeU for light water, when the outer 40 cm of heavy water in the reflector are replaced.

For the core having a heavy water reflector with a thickness of 25.45 cm, a radial form factor of 0.8333 could not be achieved — the severe radial neutron leakage could not be compensated for by either increasing the reactivity of the fuel in the outer region of the core, or by increasing the radius of the inner burnup zone. If the reflector thickness were reduced too much, one might not even be able to achieve criticality. Severe radial neutron leakage also accounts for the large variations in the reactor parameters for the heavy water reflector of thickness 35.45 cm, as compared to the parameters for the other modified reflectors in Table 6.

6.2 Discussion of Errors

Table 7 shows the final values of the optimized parameters, and the burnup corrections used to account for differences in these parameters from the reference case. The magnitude of the burnup correction for any of the parameters, and the final correction, never exceeds 15 MWD/TeU, and the average final correction is about 8 MWD/TeU.

One may wonder what error would have resulted if, instead of having run a separate reference case for each mixed reflector, a single reference case had been used. The largest variation in the reactivity in the reference cases is 0.045 mk (0.113-0.068 mk). This is the largest error in the reactivity of the reference case that could have resulted from running only a single reference case, and corresponds to an error in the average burnup (and burnup penalty) of 5.4 MWD/TeU, assuming a correction of 120 (MWD/TeU)/mk. Similarly, the largest variations in the worths of the adjuster rods and zone controllers are 0.02 mk and 0.011 mk respectively, and correspond to errors in the average burnup of the reference case of 2.4 MWD/TeU, and 1.3 MWD/TeU respectively. The largest variation in radial form factor is 3.3×10^{-4}, corresponding to a 3.3 MWD/TeU burnup correction. Since the largest value of each of the four parameters does not occur for the same mixed reflector, and similarly for the smallest value, it follows that the largest possible error in the average burnup due to errors in each of the parameters is smaller that the sum of the largest errors possible for each parameter individually. Thus, the error in the average burnup of the reference case (and the resultant burnup penalty) that would have resulted had only one reference case been used for the mixed reflectors would have been less than 12 MWD/TeU. Of course, the reason why this error is so small is that care was taken in choosing the models for the mixed reflectors: the fact that mesh intervals of approximately the same size were used in the heavy water part of the mixed reflectors reduced the resultant differences in the parameters between the various reference models. This is discussed in Appendix B, Section 2.1.

The effect of mesh size on the convergence of the reactivity and radial form factor is discussed in Appendix B, Section 1. As is noted there, had sensitivity studies been done for all the mixed reflectors used, corrections could have been applied to the burnup to account for the mesh size used in each case. However, these studies were done only for mixed reflectors containing 45.45 cm of heavy water. For consistency, corrections were not applied to the average burnup to account for the mesh size used in the mixed reflectors containing 20 cm of graphite, HB40 or light water, in Table 7. One is justified in doing so, however. The corrected burnup penalties become 3 MWD/TeU, 20 MWD/TeU, and 16 MWD/TeU for mixed reflectors containing 20 cm of graphite, HB40 and light water respectively. To obtain a rough estimate of the error in the average burnup for mixed reflectors containing different thicknesses of heavy water, one can assume that the same relationship exists between mesh size and sensitivity of the parameters for these reflectors. The resultant errors in burnup are shown for the mesh sizes used in Table B2. The burnup correction for graphite is small at all mesh sizes used, and reduces the burnup penalty — by about 7 MWD/TeU for a mixed reflector containing 40 cm of graphite. The possible errors in the burnup penalties are considerably larger for the HB40 and light water mixed reflectors, but then again, the burnup penalties are much larger. For mixed reflectors containing 40 cm of HB40, the error in the average burnup is about 14 MWD/TeU; for 40 cm of light water, the error is about 27 MWD/TeU. Both these errors are in the direction of increasing burnup penalty. Again, it must be emphasized that these corrections are only estimates; the actual corrections due to the mesh sizes used may be larger or smaller for mixed reflectors containing 35.45 cm or 25.45 cm heavy water than the corrections for mixed reflectors containing 45.45 cm of heavy water.

One source of error that has not been considered at all is due to the fact that a two-dimensional model has been used to represent a three-dimensional core and reflector. One would expect that there would be less effect on the burnup penalty than on the burnup itself, since the burnup penalty involves differences in burnup between a modified reflector case and a reference case, so that systematic errors would compensate to a certain extent. However, it would be difficult to estimate the size of these errors without running at least two three-dimensional cases — one for a modified reflector case, and one for the reference case.

6.3 Further Studies

One objective of further studies would be to reduce the uncertainties in the burnup penalties. This could be accomplished by using finer mesh sizes in the outer region of the mixed reflectors, and by doing mesh-size sensitivity studies for each of the reflectors of interest. Once the uncertainty in burnup was reduced as far as desired, and a reasonable estimation of the errors was obtained for the two-dimensional models, then a few three-dimensional cases could be run. The results of the three-dimensional studies could be used to scale the burnup penalties determined using the two-dimensional models. Of course, three-dimensional studies could be done from the start, but the high cost, and large computer requirements for three-dimensional codes usually preclude their use except for final design work.

Another area for further study would be the determination of the xenon override time of the modified reflector cores, using a time dependent xenon dynamics code. The xenon override time depends not only on the reactivity worth of the adjuster rods, which was kept constant at about 15 mk for all the modified reflectors studied, but also on the flux shape. However, the differences in flux shape from case to case were small with the exception of the 35.45 cm thick heavy water reflector case, so one would expect that differences in the xenon override time would be small.

In the final assessment of the modified reflectors, the engineering feasibility of a two region reflector would have to be considered. One would have to determine a means of separating the graphite, HB40 or light water from the heavy water, and the effect of the means of separation on the neutronics would have to be considered.

7. CONCLUSIONS

This study has determined the burnup penalty that would result from either reducing the thickness of the 600 MWe CANDU-PHW heavy water reflector, or from replacing some of the heavy water in the outer region of the reflector by graphite, HB40, or light water while maintaining the original reflector thickness. The burnup penalty increases rapidly as the thickness of the reflector is reduced, and is significantly lower for the mixed reflectors. As an indiciation of the relative effectiveness of the modified reflectors considered, the burnup penalty resulting from reducing the reflector thickness by 30 cm is 1548 MWD/TeU; if the 30 cm of heavy water saved in reducing the reflector thickness is replaced by light water, HB40, and graphite, the burnup penalty is reduced to 195 MWD/TeU, 166 MWD/TeU, and 11 MWD/TeU respectively.

The burnup penalties determined in this study, along with the costs and volumes of the materials used in the modified reflectors, could be used to optimize the reflector with respect to capital and fuel costs. The results of such a cost optimization study would indicate whether further studies on the burnup penalties for the modified reflectors are warranted.

TABLES

Table 1 Core Parameters and Properties for the Gentilly-2 Reference Core *

Inner Exposure (n/kb)	1.718
Outer Exposure (n/kb)	1.598
Inner Region Radius (cm)	180.0
$\Delta\Sigma_{a2}$ Adjuster Rods ($\times10^{-4}$ cm^{-1})	5.166
$\Delta\Sigma_{a2}$ Zone Controllers ($\times10^{-4}$ cm^{-1})	2.055
Reactivity (mk)	0.08
Radial Form Factor	0.8333
Average Burnup (MWD/TeU)	6776.1
Adjuster Rod Worth (mk)	14.94
Zone Controller Worth (mk)	2.99

* The core was modelled as in Figure 2; the reflector was modelled using one mesh interval of size 10.7 cm before the notch, and four intervals of sizes 18.7 cm, 8.05 cm, 8.0 cm and 8.0 cm after the notch.

Table 2 POWDERPUFS-V Lattice Parameters for the Homogenized Fuel Cell

Exposure (n/kb)	Burnup (MWD/TeU)	k_∞	p	L^2 (cm^2)	D_2 (cm)	H
0.0	0.00	1.07676	.906072	255.500	.941062	.239180
0.2	781.37	1.07486	.906105	252.795	.941104	.239066
0.4	1598.40	1.07790	.906138	248.725	.941204	.241229
0.6	2436.52	1.07739	.906172	245.401	.941271	.242330
0.8	3282.08	1.07425	.906205	242.763	.941311	.242510
1.0	4126.27	1.06941	.906239	240.661	.941331	.242025
1.2	4963.52	1.06347	.906272	238.971	.941336	.241071
1.4	5790.48	1.05686	.906306	237.597	.941330	.239794
1.6	6605.31	1.04984	.906340	236.465	.941317	.238298
1.8	7407.32	1.04264	.906373	235.521	.941298	.236664
2.0	8196.51	1.03529	.906407	234.721	.941275	.234949

$$\left.\begin{aligned} L_s^2 &= 156.207\ cm^2 \\ D_1 &= 1.27396\ cm \end{aligned}\right\}\ \text{for all exposures}$$

Table 3: Lattice Parameters for the Reflector Materials

Material	D_1 (cm)	D_2 (cm)	L_s^2 * (cm^2)	L^2 * (cm^2)	Σ_{a2} ($x10^{-3}$ cm^{-1})	Σ_{r1} ($x10^{-2}$ cm^{-1})
D_2O	1.31706	0.878703	130.092	10534.1		
Graphite	1.0590	0.8980	308.746	2963.70	0.3030	0.3430
HB40	1.4570	0.1960	67.767	16.3333	12.0	2.15
H_2O	1.2130	0.15341	34.1498	8.67213	17.69	3.552

In all cases, $p=1.0$

$k_\infty=0.0$

$H=0.0$

* For graphite, HB40 and H_2O, L^2 and L_s^2 were calculated using $L^2 = D_2/\Sigma_{a2}$, and $L_s^2 = D_1/(\Sigma_{a1}+\Sigma_{r1})$. $\Sigma_{a1}=0.0$.

Table 4 Reflector Models

Mixed Reflectors

45.45 cm D_2O, 20 cm Gr	18.7 / 18.7, 8.05; 2(8.0)
45.45 cm D_2O, 20 cm HB40	18.7 / 18.7, 8.05; 10(1.90476)
45.45 cm D_2O, 20 cm H_2O	18.7 / 18.7, 8.05; 18(1.08108)
35.45 cm D_2O, 30 cm Gr	2(9.35) / 2(8.375); 3(8.57143)
35.45 cm D_2O, 30 cm HB40	2(9.35) / 2(8.375); 14(2.06897)
35.45 cm D_2O, 30 cm H_2O	2(9.35) / 2(8.375); 18(1.62162)
25.45 cm D_2O, 40 cm Gr	3(6.2333) / 6.75; 6(6.15385)
25.45 cm D_2O, 40 cm HB40	3(6.2333) / 6.75; 18(2.16216)
25.45 cm D_2O, 40 cm H_2O	3(6.2333) / 6.75; 18(2.16216)

Heavy Water Reflectors of Reduced Thickness

55.45 cm D_2O	2(9.35) / 3(10.5)
45.45 cm D_2O	2(9.35) / 3(7.64286)
35.45 cm D_2O	4(4.675) / 3(4.78571)

NOTE:

a) The location of the notch is indicated by a slash, '/'. In all cases the reflector in the 18.7 cm before the notch consists of heavy water.

b) The boundary between the heavy water and the outer material in the mixed reflectors is indicated by ';'.

c) The exterior black absorber which surrounds the core is not included in the models above. Half the width of the last interval must be included when determining the reflector thickness.

d) n intervals of size x are indicated by n(x).

Table 5: Burnup Corrections due to Residual Differences in the Radial Form Factor

Reflector Thickness (cm)	Burnup Correction * (MWD/TeU)/(10^{-4})
65.45	-1.00
55.45	-1.43
45.45	-2.44
35.45	-5.20 +

* This is the slope of the tangent in Figure 4 at a radial form factor of 0.8333.

\+ Extrapolated in Figure 5.

Table 6 Final Core Parameters

Case	Exposure (n/kb)		$\Delta\Sigma_{a2}$ ($\times 10^{-4}$ cm^{-1})		Inner Region Radius (cm)
	Inner	Outer	Adjuster Rods	Zone Controllers	
45.45 cm D_2O 20 cm Gr	1.718	1.598	5.166	2.055	180.0
45.45 cm D_2O 20 cm HB40	1.718	1.598	5.166	2.055	180.0
45.45 cm D_2O 20 cm H_2O	1.701	1.589	5.094	2.021	199.18
35.45 cm D_2O 30 cm Gr	1.705	1.588	5.076	2.028	199.18
35.45 cm D_2O 30 cm HB40	1.709	1.514	5.076	2.028	199.18
35.45 cm D_2O 30 cm H_2O	1.709	1.500	5.076	2.028	199.18
25.45 cm D_2O 40 cm Gr	1.705	1.570	5.076	2.028	199.18
25.45 cm D_2O 40 cm HB40	1.713	1.303	5.076	2.028	218.36
25.45 cm D_2O 40 cm H_2O	1.713	1.280	5.103	2.028	218.36
65.45 cm D_2O	1.718	1.598	5.166	2.055	180.0
55.45 cm D_2O	1.709	1.520	5.101	2.008	199.18
45.45 cm D_2O	1.709	1.324	5.101	2.008	218.36
35.45 cm D_2O	1.762	0.935	5.414	2.110	218.36
25.45 cm D_2O	A radial form factor of 0.8333 could not be achieved.				

Table 7a Burnup Corrections for Mixed Reflectors Containing 45.45 cm D_2O

	Case	ρ (mk)	ρ_{adj} (mk)	ρ_{zc} (mk)	RFF	Burnup (MWD/TeU)	Corrected Burnup * (MWD/TeU)	Burnup Penalty* (MWD/TeU)
	20 cm Gr	-0.012	14.984	3.007	0.83272	6776.4	6767.0	9.1
	Reference	0.079	14.942	2.991	0.83326	6776.1		
Δ*		-0.091	0.042	0.016	-0.00054			
ΔB*		-10.9	5.0	1.9	-5.4	-9.4 (total)		
	20 cm HB40	0.032	14.960	2.999	0.83299	6776.1	6766.5	9.3
	Reference	0.108	14.933	2.990	0.83347	6775.8		
Δ		-0.076	0.027	0.009	-0.00048			
ΔB		-9.1	3.2	1.1	-4.8	-9.6 (total)		
	20 cm H_2O	0.083	14.957	2.993	0.83346	6769.0	6767.6	8.4
	Reference	0.113	14.937	2.990	0.83352	6776.0		
Δ		-0.030	0.020	0.003	-0.00006			
ΔB		-3.6	2.4	0.4	-0.6	-1.4 (total)		

* NOTE: Δ - the difference in ρ, ρ_{adj}, ρ_{zc} or the RFF between the reference case and the modified reflector case.

ΔB - the corresponding burnup correction to account for the above difference in Δ (MWD/TeU)

Corrected Burnup - the average core burnup of the modified reflector case, including ΔB.

Burnup Penalty - the difference in the core average burnup of the modified reflector case from the reference case.

Table 7b Burnup Corrections for Mixed Reflectors Containing 35.45 cm D_2O

	Case	ρ	ρ_{adj}	ρ_{zc}	RFF	Burnup	Corrected Burnup	Burnup Penalty
		(mk)	(mk)	(mk)		(M W D / T e U)		
	30 cm Gr	0.023	14.920	2.993	0.83321	6773.9	6765.4	10.8
	Reference	0.068	14.953	2.988	0.83319	6776.2		
Δ		-0.045	-0.033	0.005	0.00003			
ΔB		-5.4	-4.0	0.6	0.3	-8.5 (total)		
	30 cm HB40	0.104	14.936	3.010	0.83318	6610.8	6610.4	165.7
	Reference	0.100	14.950	2.984	0.83341	6776.1		
Δ		0.004	-0.014	0.026	-0.00023			
ΔB		0.5	-1.7	3.12	-2.3	-0.4 (total)		
	30 cm H_2O	0.141	14.938	3.013	0.83310	6577.9	6581.5	194.6
	Reference	0.104	14.946	2.983	0.83344	6776.1		
Δ		0.037	-0.008	0.030	-0.00034			
ΔB		4.4	-1.0	3.6	-3.4	3.6 (total)		

Table 7c Burnup Corrections for Mixed Reflectors Containing 25.45 cm D_2O

	Case	ρ (mk)	ρ_{adj} (mk)	ρ_{zc} (mk)	RFF	Burnup (MWD/TeU)	Corrected Burnup (MWD/TeU)	Burnup Penalty (MWD/TeU)
	40 cm Gr	0.063	14.931	2.996	0.83285	6733.2	6724.0	52.1
	Reference	0.092	14.948	2.983	0.83338	6776.1		
Δ		-0.029	-0.017	0.013	-0.00053			
ΔB		-3.5	-2.0	1.6	-5.3	-9.2 (total)		
	40 cm HB40	0.128	14.893	3.010	0.83395	6237.6	6240.8	535.3
	Reference	0.113	14.947	2.980	0.83352	6776.1		
Δ		0.015	-0.054	0.030	0.00043			
ΔB		1.8	-6.5	3.6	4.3	3.2 (total)		
	40 cm H_2O	0.148	14.931	3.006	0.83354	6182.3	6187.9	588.2
	Reference	0.113	14.947	2.980	0.83352	6776.1		
Δ		0.035	-0.016	0.026	0.00002			
ΔB		4.2	-1.9	3.1	0.2	5.6 (total)		

Table 7d Burnup Corrections for Reflectors of Reduced Thickness

	Case	ρ	ρ_{adj}	ρ_{zc}	RFF	Burnup	Corrected Burnup	Burnup Penalty
		(mk)	(mk)	(mk)		(M W D / T e U)		
	55.45 cm D_2O	0.069	14.991	2.983	0.83362	6624.8	6635.0	141.2
	Reference*	0.068	14.953	2.988	0.83319	6776.2		
Δ		0.001	0.038	-.005	0.00043			
ΔB		0.1	4.6	-0.6	6.1	10.2 (total)		
	45.45 cm D_2O	0.081	14.988	2.993	0.83343	6280.4	6292.7	483.5
	Reference*	0.068	14.953	2.988	0.83319	6776.2		
Δ		0.013	0.035	0.005	0.00024			
ΔB		1.56	4.2	0.6	5.9	12.3 (total)		
	35.45 cm D_2O	-0.031	14.974	2.966	0.83362	5229.4	5228.2	1548
	Reference+	0.092	14.948	2.983	0.83338	6776.1		
Δ		-0.123	0.026	-.017	0.00024			
ΔB		-14.8	3.12	-2.0	12.5	-1.2 (total)		

* The same reference as for the mixed reflector containing 30 cm graphite was used.

\+ The same reference as for the mixed reflector containing 40 cm graphite was used.

FIGURES

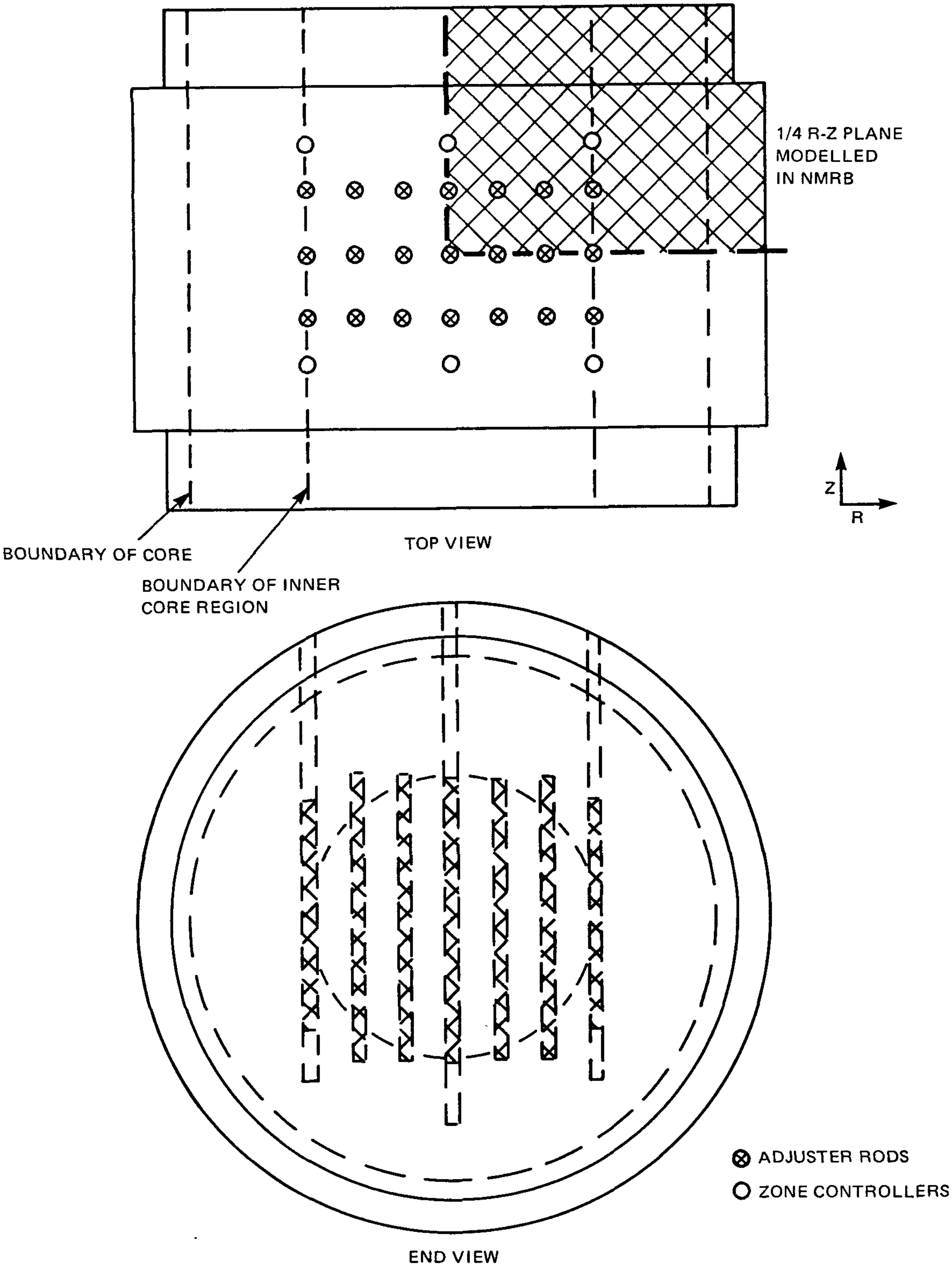

FIGURE 1 SCHEMATIC REPRESENTATION OF GENTILLY-2 REACTOR

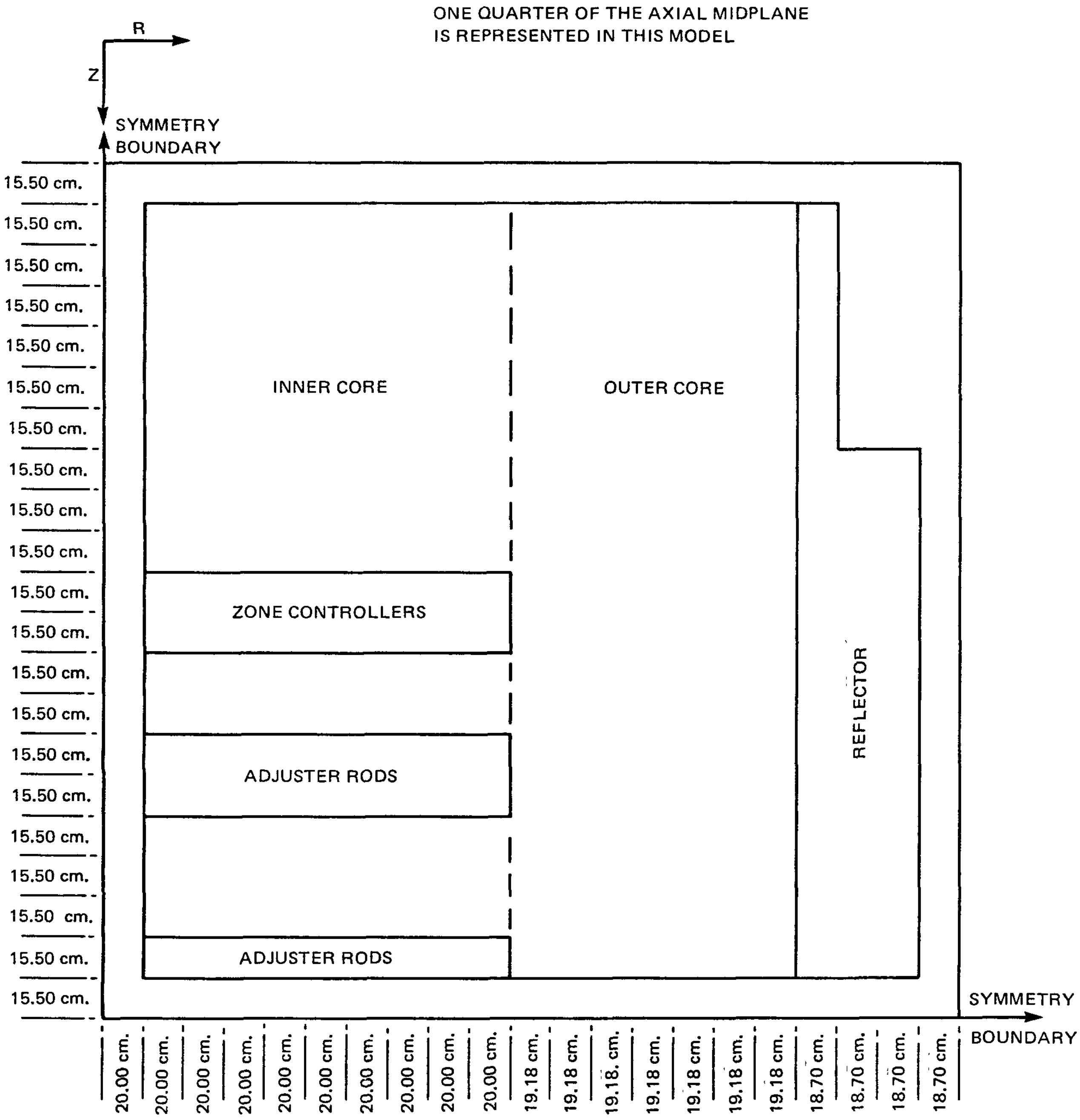

FIGURE 2 MODEL USED TO REPRESENT THE GENTILLY-2 REACTOR

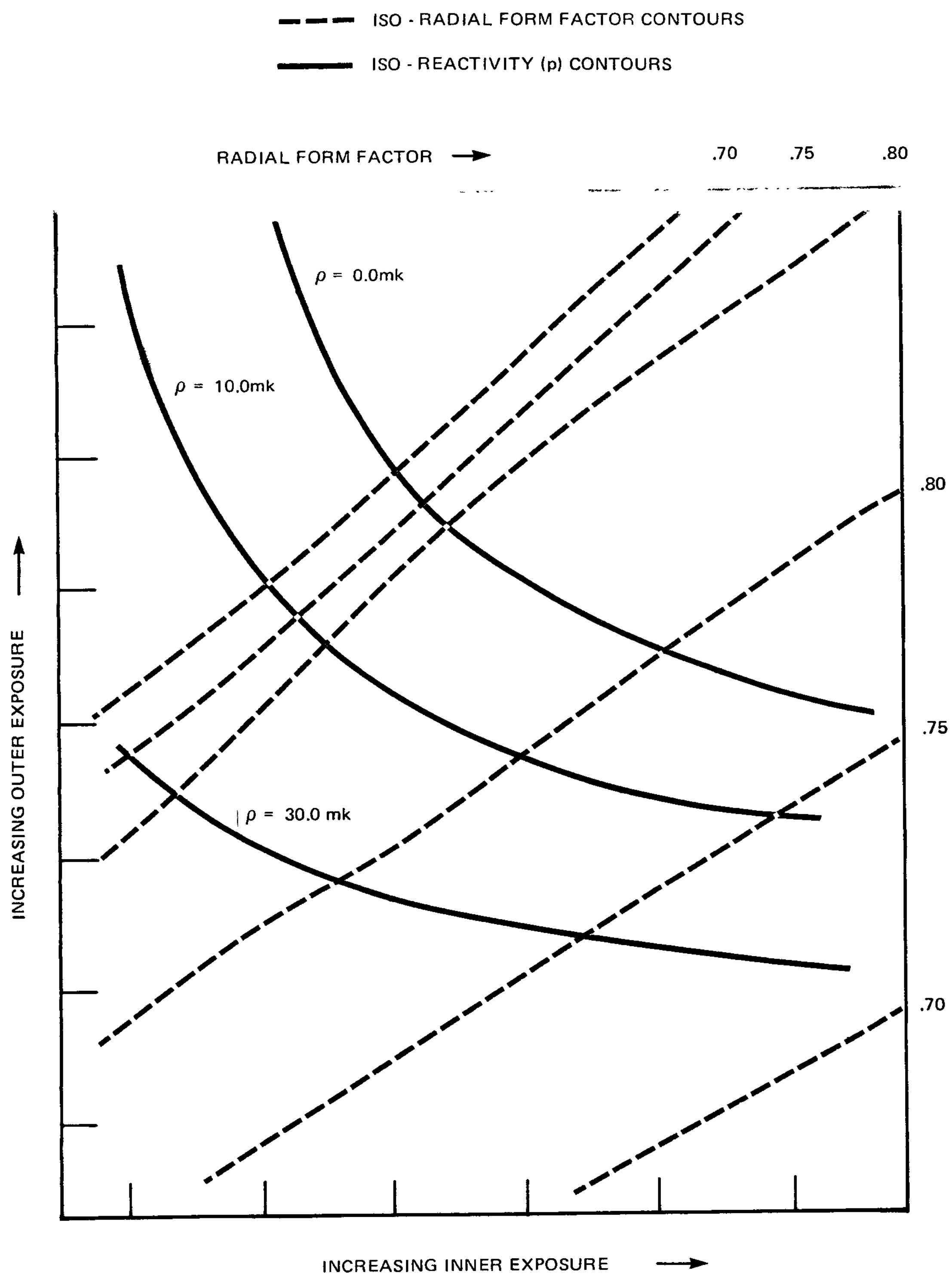

FIGURE 3 TYPICAL ISO-RADIAL FORM FACTOR & REACTIVITY CONTOURS FOR A HYPOTHETICAL REACTOR

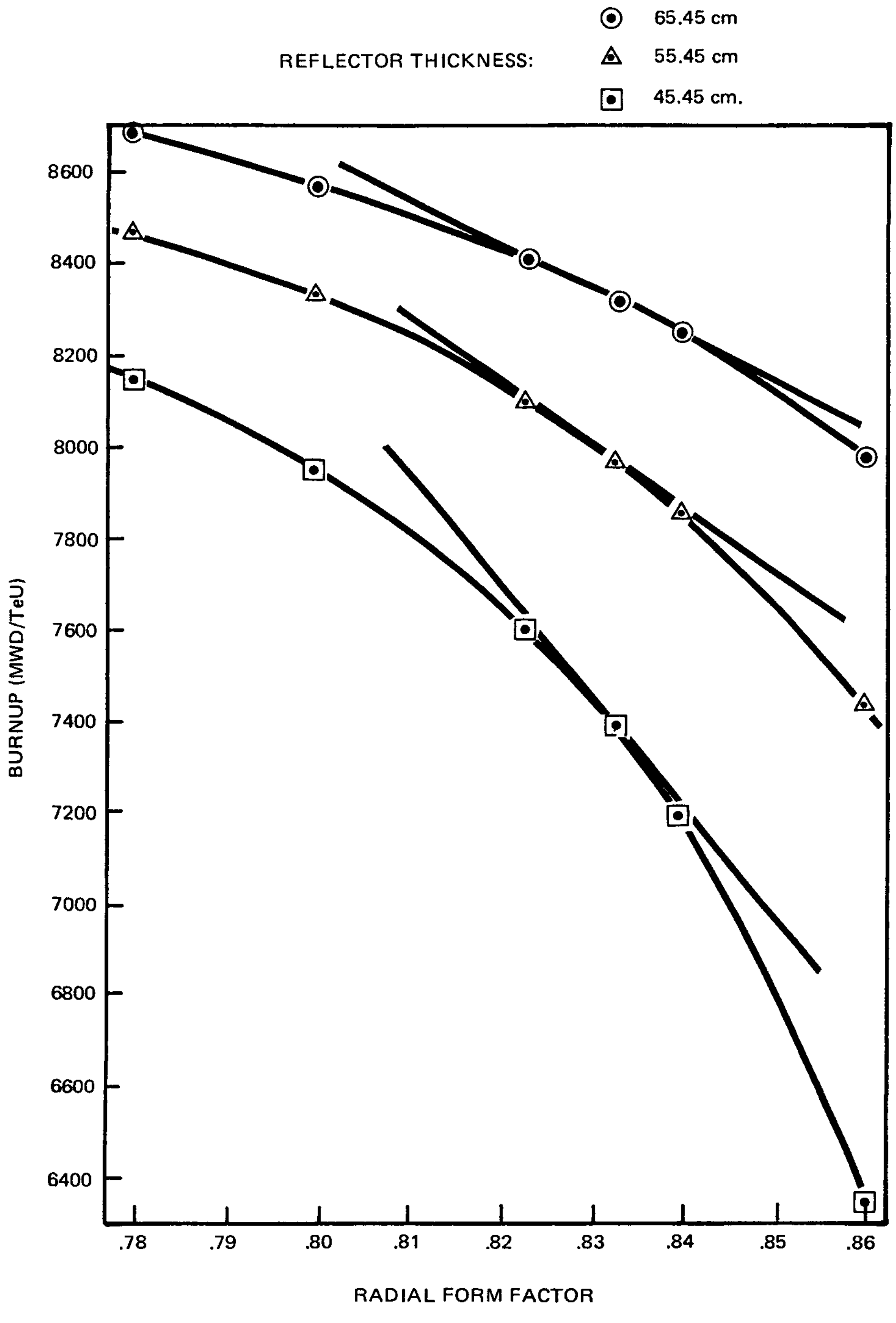

FIGURE 4 VARIATION OF BURNUP WITH RADIAL FORM FACTOR (USING POWDERPUFS - V)

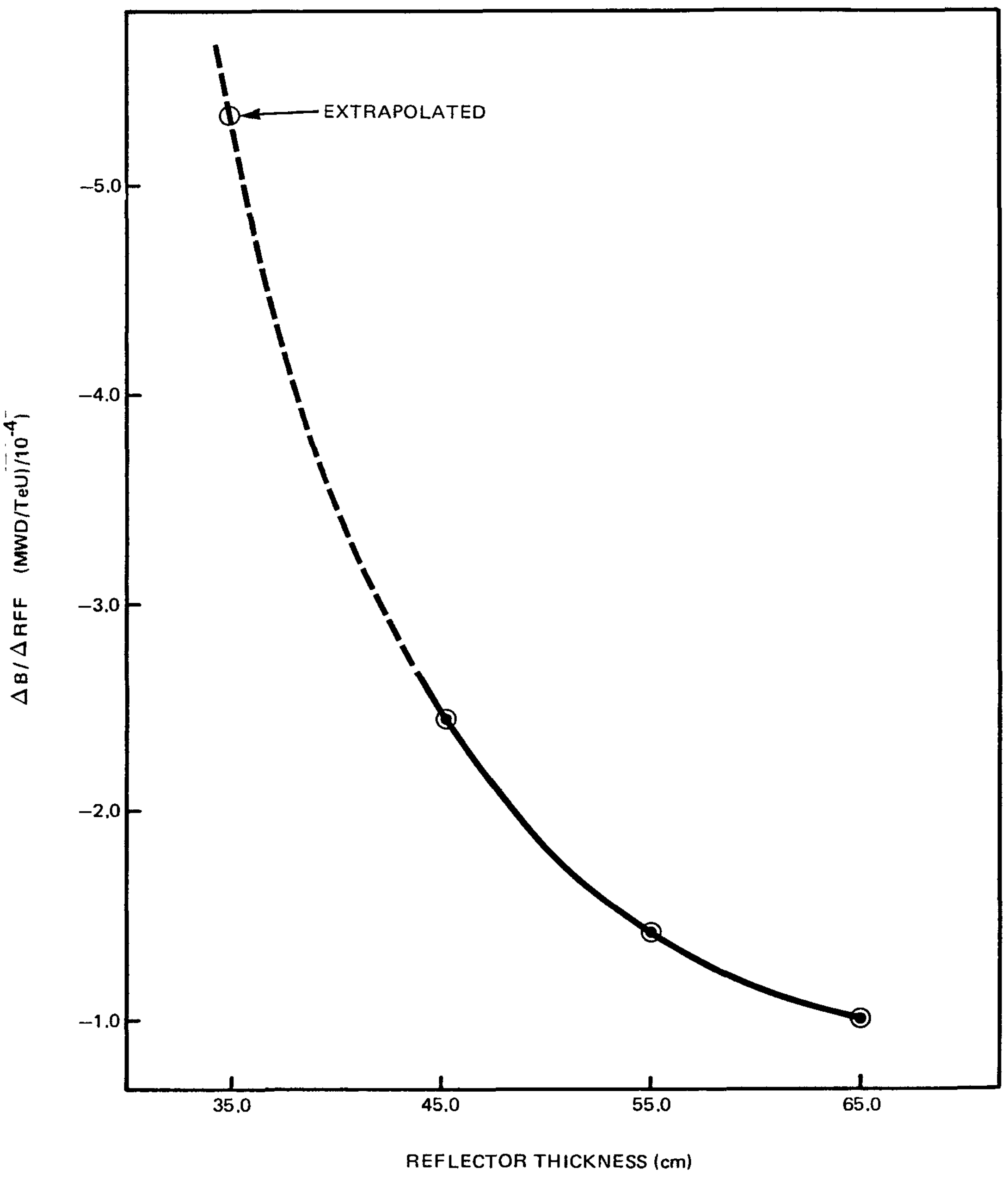

FIGURE 5 RATE OF CHANGE OF BURNUP (B) WITH RADIAL FORM FACTOR (RFF) - Δ B/Δ RFF - AS A FUNCTION OF REFLECTOR THICKNESS

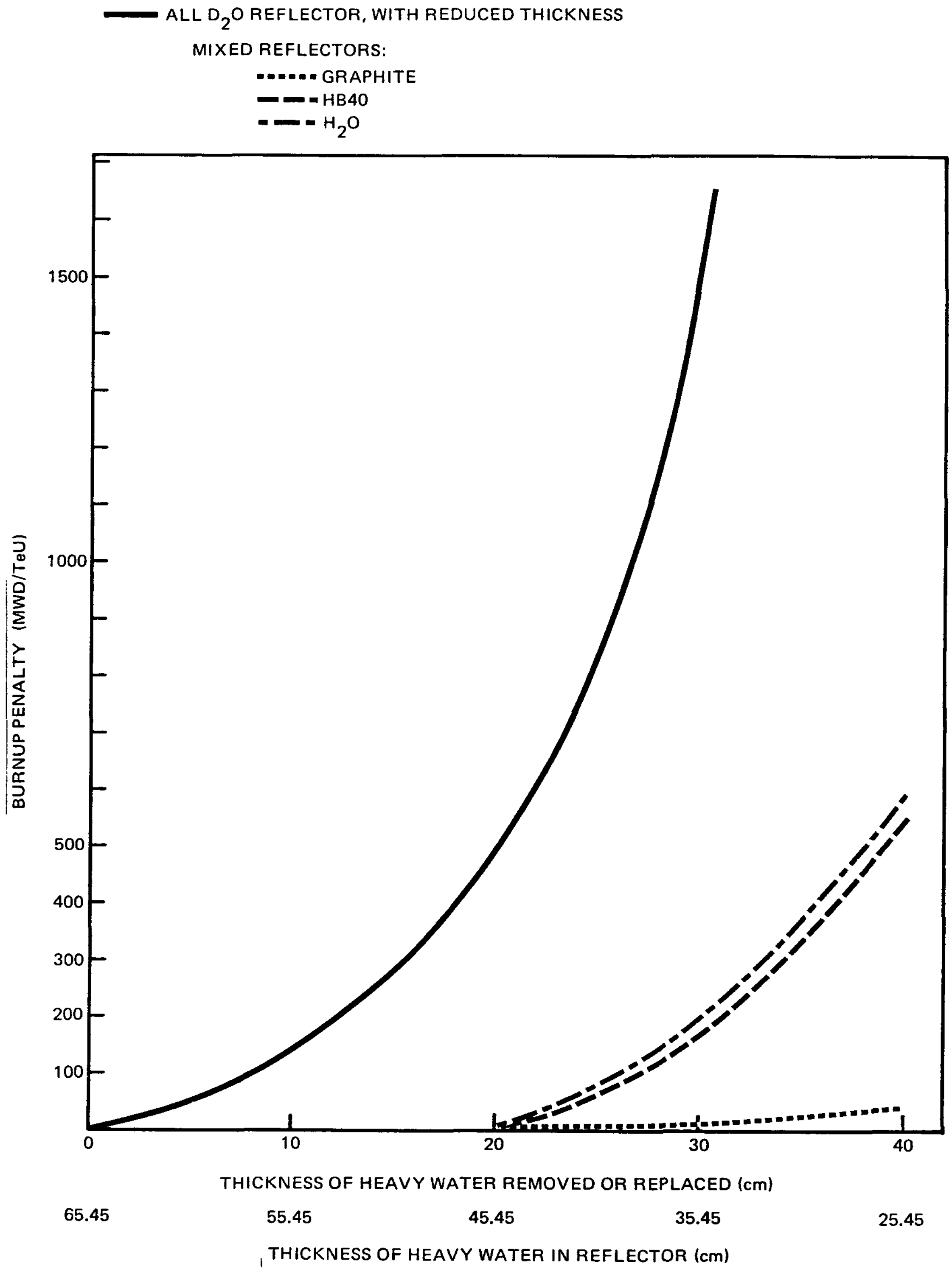

FIGURE 6 BURNUP PENALTIES FOR THE MODIFIED REFLECTORS

APPENDICIES

APPENDIX A

A 1 Symbols and Definitions

It is important to understand the meaning of the following terms:

Exposure (n/kb) - A measure of the exposure to which the fuel has been subjected is the integral over energy and time of the flux. The unit of exposure used in this report is neutrons/kilo-barn (n/kb), where 1 barn = 10^{-24} cm^2.

B - Burnup (MWD/TeU) - The burnup is a measure of the fission energy released by the fuel as a result of a certain exposure. The unit of burnup is megawatt-day per tonne of uranium. A tonne is 1000 kg. The uranium refers to the U-238 present in the fresh fuel.

k_{eff} - Effective multiplication constant - A measure of the criticality of a reactor is k_{eff} - the ratio of the total rate of neutron production to the total rate of neutron loss (through absorption and leakage) in the core.

k_{∞} - Infinite medium multiplication constant - This is a measure of the degree of criticality of a material alone, rather than the entire reactor. It is equal to k_{eff} for an infinite amount of the material.

ρ - Reactivity (mk) - This quantity is related to k_{eff} by $\rho = 1000x(k_{eff}-1)/k_{eff}$. A critical reactor has zero reactivity, a subcritical reactor has a negative reactivity, and a super critical reactor has a positive reactivity.

ρ_{adj}, $\{\rho_{zc}\}$ - Reactivity worth of the adjuster rods {zone controllers} (mk) - This is the change in reactivity of the reactor when the adjuster rods {zone controllers} are removed.

RFF - Radial Form Factor - This is the ratio of the average channel power to the maximum channel power. If the maximum channel power is limited to prevent fuel failure, then the total reactor power is proportional to the RFF.

As well, the following symbols were used in the report:

L^2 - Thermal diffusion area (cm^2).

L_s^2 - Slowing down area (cm^2).

p - Resonance escape probability.

D_1 - Diffusion constant for energy group 1 (cm).

D_2 - Thermal diffusion constant (cm).

Σ_{a1} - Macroscopic absorption cross section for energy group 1 (cm^{-1}).

Σ_{a2} - Macroscopic thermal absorption cross section (cm^{-1}).

$\Delta\Sigma_{a2}$ - Incremental thermal absorption cross section (cm^{-1}), used in the simulation of the reactivity devices.

Σ_{r1} - Macroscopic slowing down cross section from energy group 1 to energy group 2.

H - Ratio of the fission power to the average cell flux (arbitrary units).

A 2 Average Burnup

It can be shown that the average burnup (B) of a two region core having a total power P_T is related to the burnups - B_1, B_2 - and powers - P_1, P_2 - in regions 1 and 2 of the core respectively, by the following relationship: $\frac{P_T}{B} = \frac{P_1}{B_1} + \frac{P_2}{B_2}$. This relationship is used in NMRB to calculate average core burnup.

A 3 Lattice Parameters for the Adjuster Rods and Zone Controllers

The adjuster rods and zone controllers were modelled by increasing the thermal absorption cross section (Σ_{a2}) of the lattice cells where they were located, to give the required reactivity worths for these devices. The only lattice parameters affected by a change in Σ_{a2} are the infinite medium multiplication constant (k_∞) and the thermal diffusion area, L^2.

If the symbols representing the lattice parameters of the reactivity device being modelled are primed, and those of the fuel cell are unprimed, and if the reactivity device is simulated by increasing Σ_{a2} of the fuel cell by $\Delta\Sigma_{a2}$, then $\Sigma_{a2}' = \Sigma_{a2} + \Delta\Sigma_{a2}$. Since k_∞ is proportional to $(1/\Sigma_{a2})$, then $\Sigma_{a2} \times k_\infty = \Sigma_{a2}' \times k_\infty'$ so $k_\infty' = (\Sigma_{a2} / \Sigma_{a2}') \times k_\infty$. Similarly, $L^{2\prime} = L^2 \times (\Sigma_{a2} / \Sigma_{a2}')$.

APPENDIX B

B 1 Sensitivity Studies for Mixed Reflectors

B 1.1 Method

In order to investigate the sensitivity of the reactivity, radial form factor, and average burnup to mesh size in the various reflector materials, mixed reflectors containing 45.45 cm of heavy water and 20 cm of graphite, HB40 or light water were modelled using different mesh sizes in the outer reflector material.

Except for the outer reflector, the reactor was modelled in the same way in all cases. The heavy water part of the reflector was modelled using three mesh intervals: 18.7 cm before the notch, and 18.7 cm and 8.05 cm after the notch. The outer 20 cm of the reflector was modelled using from one (13.3333 cm) to nineteen (1.02564 cm) mesh intervals. The core parameters used are shown in Table B1.

B 1.2 Results and Discussion

In Figures B1, B2, and B3 the reactivity and radial form factor are plotted as a function of mesh size for the graphite, HB40, and light water mixed reflectors respectively. The values of the reactivity and radial form factor for zero (infinitesimally small) mesh size, and for the mesh sizes that were finally chosen were obtained through interpolation or extrapolation. A burnup correction was computed in each case to account for the adjustments that would have to be made to the parameters to change them from their actual values (at zero mesh size) to the desired values (at the mesh sizes considered). For example, the reactivity resulting from using a mesh size of 8.6 cm in graphite is -0.018 mk for the core parameters used. This is 0.039 mk lower than the actual reactivity of 0.021 mk at zero mesh size. One could decrease the reactivity from 0.021 mk to -0.018 mk by increasing the average burnup of the fuel by 4.7 MWD/TeU, assuming a burnup correction of 120 (MWD/TeU)/mk. The burnup corrections are shown for the mesh sizes of interest in Table B2.

The figures and the table of burnup corrections show that in going from graphite, to HB40, to light water, increasingly smaller mesh sizes must be used in order to achieve convergence of the reactivity and radial form factor to within certain limits. For the mixed reflector containing 20 cm of graphite, decreasing the graphite mesh size from 8.6 cm to 0.0 cm results in an increase in the reactivity and radial form factor for only 0.04 mk and 1.8×10^{-4} respectively. In HB40, decreasing the mesh size from 2.2 cm to 0.0 cm results in a decrease in reactivity and radial form factor of 0.06 mk and 7×10^{-4} respectively — equivalent to a burnup correction of -14 MWD/TeU. So, even though the mesh size in HB40 is a quarter of that in graphite, the magnitude of the burnup correction is twice as large. Similarly, there is an even greater sensitivity of reactivity and radial form factor to mesh size in light water. For a mesh size of 2.2 cm in light water, the burnup correction is -27 MWD/TeU.

For all three mixed reflectors considered, the average burnup is esentially independent of mesh size (although the burnup corrections are not).

The conclusion that the mesh size must be reduced in going from graphite, to HB40, to light water can also be deduced from a consideration of the neutron migration area in these materials. (The neutron migration length is equal to the square root of the migration area.) The migration area is equal to the sum of the diffusion area, L^2, and the slowing down area, L_s^2. Physically, it is equal to one-sixth the average distance from the point where a fast neutron is born to the point where it is absorbed as a thermal neutron (5). The number of mesh points required for the accurate determination of the flux and related parameters increases as the migration area decreases. The migration area is tabulated in Table B3 for the reflector materials of interest in this study, and for the homogenized fuel cell (where L^2 was averaged from 1.2 to 1.8 n/kb exposures).

If sensitivity studies were carried out for each of the mixed reflectors considered, corrections could be applied to account for the mesh size used in each case. Since these studies were done only for mixed reflectors containing 45.45 cm of heavy water, the results were used only to estimate the error in the burnup resulting from the mesh sizes used, by assuming the same relationship between the parameters and the mesh size applies for mixed reflectors containing different amounts of heavy water.

B 2 Further Modelling Studies

B 2.1 Modelling Studies for Heavy Water Reflectors

In order to establish a criterion for reducing modelling errors in the heavy water reflectors of reduced thickness, various models were used to represent the first 38 cm of the 65.45 cm thick reflector in the reference case. The reflector models used, and the resultant reactivities, radial form factors and average burnups are shown in Table B4, Cases 1 through 8.

In the first four cases, mesh intervals of the same size were used in the first 38 cm of the reflector, with the mesh sizes ranging from 18.7 cm to 4.675 cm. The parameters showed little sensitivity to mesh size, indicating that a mesh size of 18.7 cm is adequate in heavy water.

In cases 5 and 6, the mesh size in the 18.7 cm of the reflector before the notch was chosen to be either half or double the mesh size in the 18.7 cm after the notch. Large differences resulted in the reactivity and radial form factor.

The conclusion from the first six cases is that modelling errors in the heavy water reflector can be reduced by choosing mesh intervals in the 18.7 cm before and after the notch which are of approximately the same size.

This guide was also used in choosing reflector models for the heavy water part of the mixed reflectors. Although this was unnecessary, because the same model was used for both the reference reflector and the mixed reflector, differences in the reactivity and radial form factor between the reference models were reduced. Cases 7 and 8 show two models that could be used for the 30 cm graphite mixed reflector, and the resultant reactivities and radial form factors for the reference reflector cases. In Case 7, where mesh intervals of approximately the same size were used in the heavy water part of the mixed reflector, the reactivity and radial form factor are comparable to the first four cases. In Case 8, where widely varying mesh sizes were used in the heavy water part of the mixed reflector, the reactivity and radial form factor are quite different from Case 7 and the first four cases.

B 2.2 Flux Convergence Criterion

The flux convergence criterion used in all cases was 10^{-5}; i.e. in NMRB the flux iteration was terminated when the difference between successive iterations on the flux was less than 10^{-5}, for each of several mesh points. In Case 9, the convergence criterion was decreased to 10^{-6}, using the same reactor model as in Case 1. Comparing the results of these two cases shows that the 10^{-5} flux convergence criterion ensures an accuracy in the reactivity and radial form factor of no better than 0.004 mk and $2\text{x}10^{-5}$ respectively.

B 2.3 The Importance of Mesh Size at the Boundary of the Inner and Outer Reflector Materials for Mixed Reflectors

There was some question as to the importance of avoiding a large difference in the mesh size at the interface between the inner and outer reflector materials, where there is an abrupt change in the lattice parameters of the reflector. To look at this question, two reflector models were considered for a mixed reflector containing light water in the last 20 cm of the reflector. The two models were identical, except at the interface of the heavy water and the light water. In Case 10, the mesh sizes in the heavy water and the light water at the interface were 8.05 cm and 1.08108 cm respectively. In Case 11, the 8.05 cm interval in the heavy water was broken into two intervals, of sizes 6.96892 cm and 1.08108 cm, so that the mesh sizes at the interface were the same in the heavy water and the light water. Inner and outer exposures of 1.718 n/kb and 1.628 n/kb respectively were used, and incremental thermal absorption cross sections of 5.24×10^{-4} and 2.051×10^{-4} cm^{-1} were used for the adjuster rods and zone controllers respectively. (A mistake was made inputting the outer region burnup, so the absolute value of the average burnup is wrong in both cases, but this has no effect on the conclusions.)

There is negligible difference between the parameters in Cases 9 and 10. Since there were no larger differences in mesh size at the interface than the difference considered here, it was concluded that the mesh sizes at the boundary of the inner and outer reflector materials are not important for the mesh sizes used in this study.

Table B1: Core Parameters used in the Sensitivity Studies for Mixed Reflectors

Outer Reflector Material	Exposure (n/kb)		$\Delta\Sigma_{a2}$ ($\times 10^{-4}$ cm^{-1})	
	Inner	Outer	Adjustor Rods	Zone Controllers
Graphite	1.718	1.598	5.166	2.055
HB40 H_2O	1.718	1.627	5.200	2.051

The inner burnup region radius is 180 cm.

Table B2: Burnup Corrections as a Function of Mesh Size for Mixed Reflectors Containing 45.45 cm D_2O

Outer Reflector Material	Mesh Size (x) (cm)	$\rho(x)$* (mk)	$\rho(0)-\rho(x)$ (mk)	RFF(x)*	RFF(0) -RFF(x) ($\times 10^{-4}$)	Burnup Correction (MWD/TeU)		
						ρ^{+}	RFF^{+}	Total
Graphite	0.0	0.021	0.0	0.83290	0	0	0	0
	6.2	-0.007	0.028	0.83274	2	3	2	5
	8.6	-0.018	0.039	0.83272	2	5	2	7
HB40	0.0	-0.74	0.0	0.8331	0	0	0	0
	1.9	-0.70	-0.04	0.8336	-6	-5	-6	-11
	2.2	-0.68	-0.06	0.8338	-7	-7	-7	-14
H_2O	0.0	-0.90	0.0	0.8322	0	0	0	0
	1.1	-0.86	-0.04	0.8325	-3	-5	-3	-8
	1.6	-0.82	-0.08	0.8328	-6	-10	-6	-16
	2.2	-0.76	-0.14	0.8332	-10	-17	-10	-27

* The values of ρ and RFF were obtained from Figures B1, B2 and B3, using interpolation or extrapolation.

\+ A correction of 120(MWD/TeU)/mk was used to correct the burnup for differences in ρ; 1 (MWD/TeU)/10^{-4} was used to correct for differences in the RFF.

Table B3: Neutron Migration Areas

Material	Migration Area (cm^2)
D_2O	10664
Graphite	3272
HB40	84
H_2O	43
Homogenized Fuel Cell	393

Table B4 Further Modelling Studies

Case	Reflector Model	ρ (mk)	RFF	Average Burnup (MWD/TeU)
1	18.7/18.7, 8.05; 2(8.0)	.079	.83330	6776.18
2	2(9.35)/2(9.35), 8.05; 2(8.0)	.088	.83338	6776.13
3	3(6.23)/3(6.23), 8.05; 2(8.0)	.075	.83323	6776.20
4	4(4.675)/4(4.675), 8.05; 2(8.0)	.065	.83310	6776.25
5	18.7/2(9.35), 8.05; 2(8.0)	-.074	.83176	6776.86
6	2(9.35)/18.7, 8.05; 2(8.0)	.246	.83500	6775.41
7	2(9.35)/2(8.375); 3(8.571)	.068	.83319	6776.22
8	18.7/11.1667, 5.5833; 3(8.571)	-.056	.83202	6776.73
9*	18.7/18.7, 8.05; 2(8.0)	.075	.83328	6776.17
10	18.7/18.7, 8.05; 18(1.08108)	-.864	.83255	6852.03
11	18.7/18.7, 6.96892, 1.08108;18(1.08108)	-.862	.83252	6852.02

* Flux convergence criterion = 10^{-6}

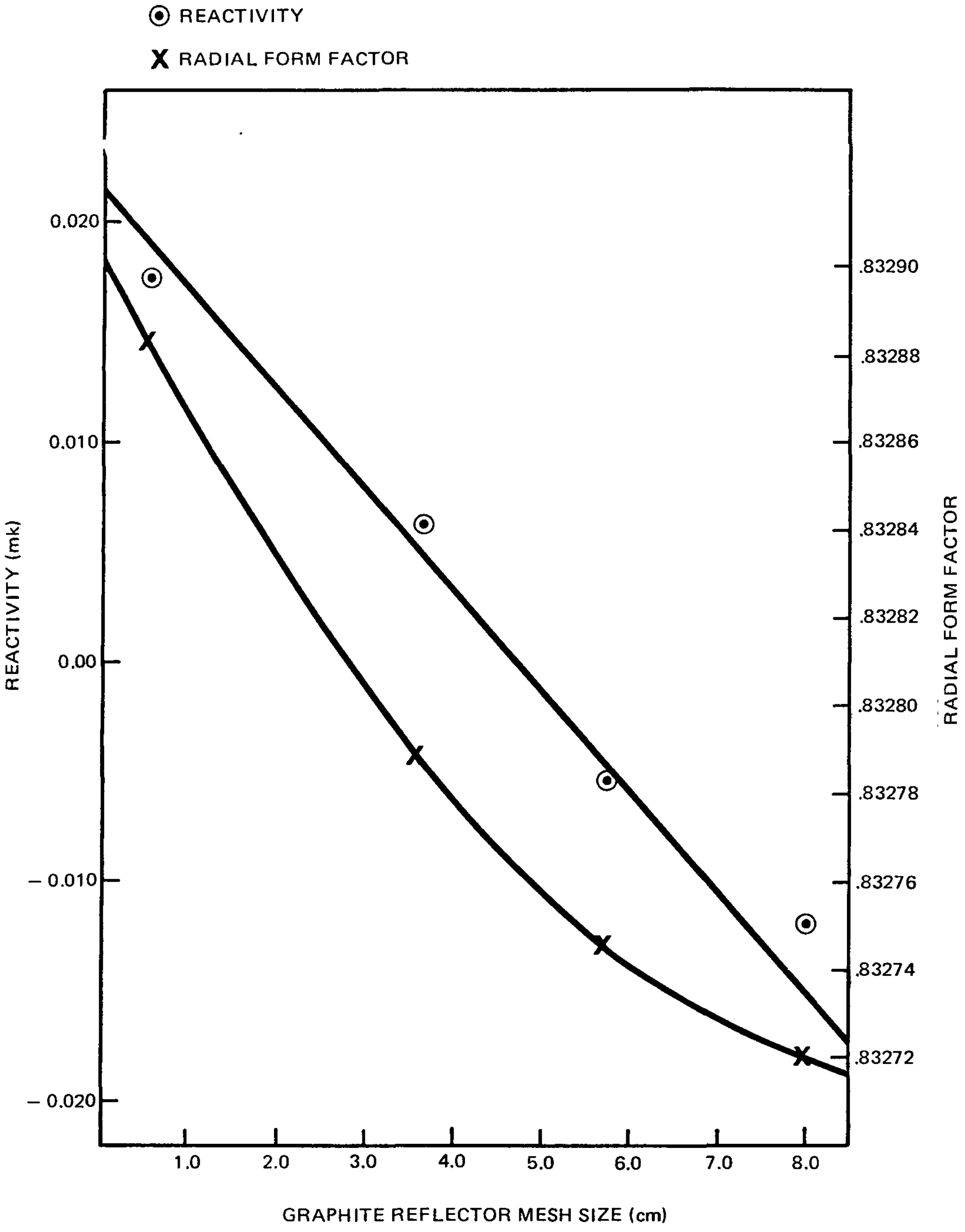

FIGURE B1 VARIATION OF REACTIVITY AND RADIAL FORM FACTOR WITH GRAPHITE REFLECTOR MESH SIZE

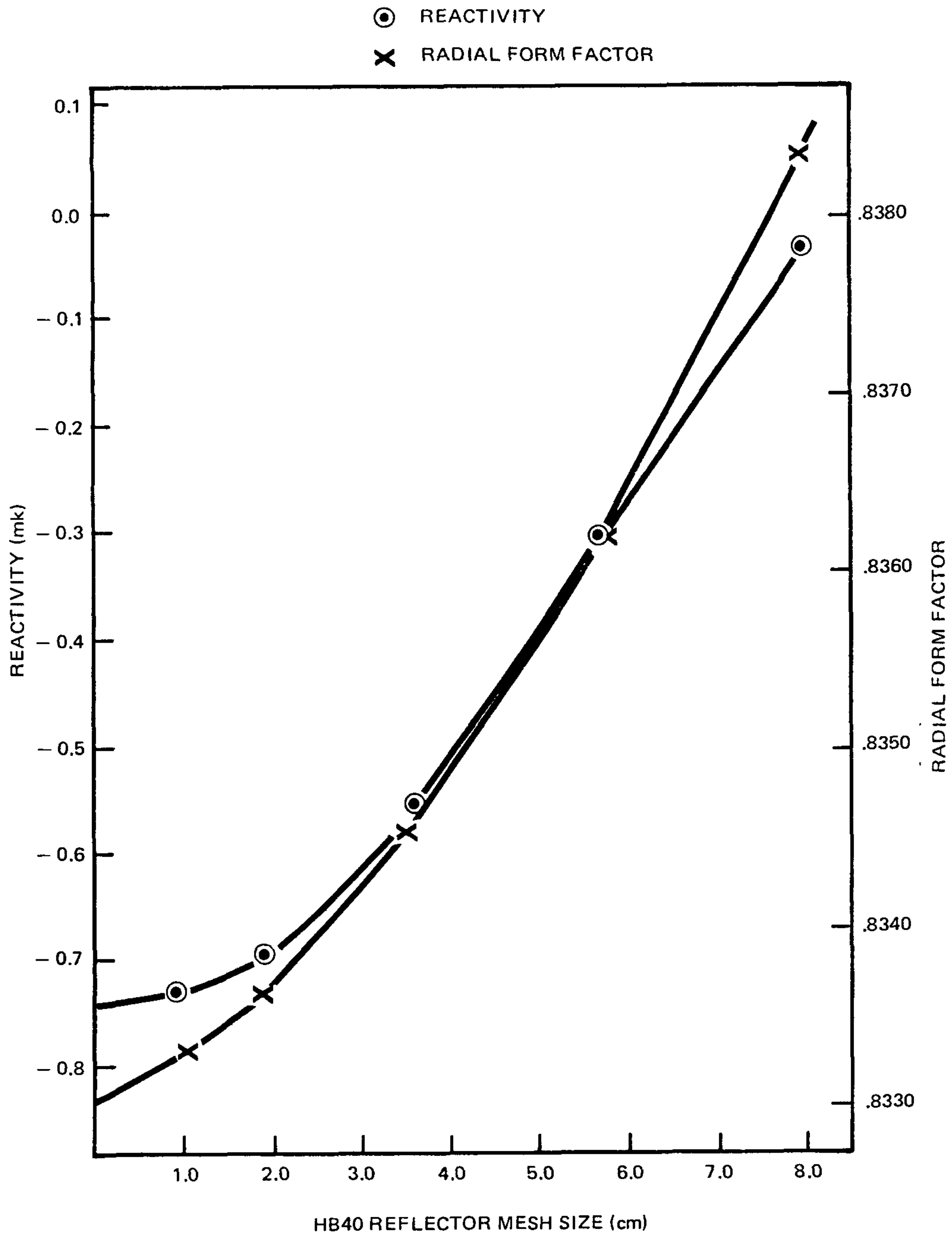

FIGURE B2 VARIATION OF REACTIVITY AND RADIAL FORM FACTOR WITH HB40 REFLECTOR MESH SIZE

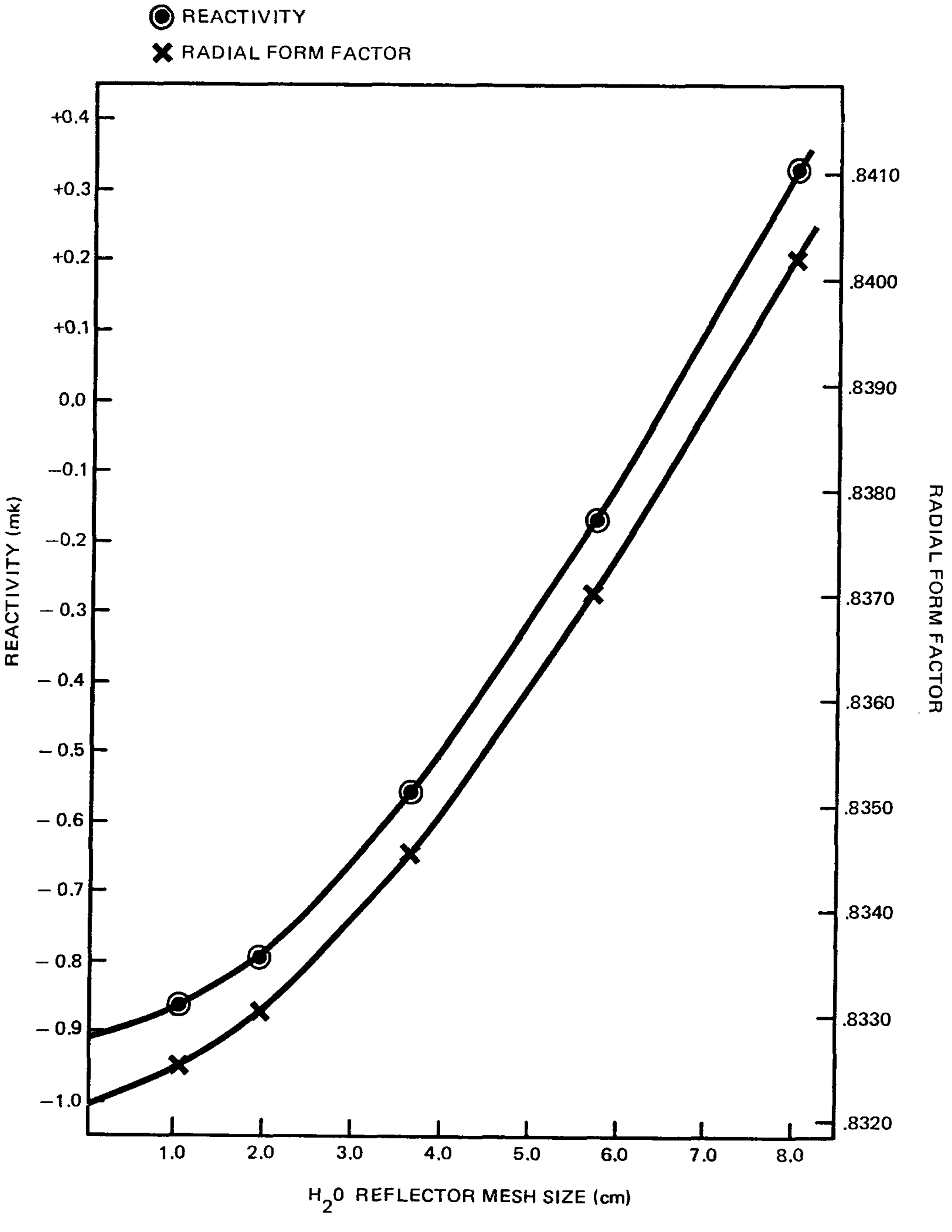

FIGURE B3 VARIATION OF REACTIVITY AND RADIAL FORM FACTOR WITH H_2O REFLECTOR MESH SIZE

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