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**3D DIFFUSION CALCULATIONS OF HIFAR  
INCLUDING THE COARSE CONTROL ARMS  
AND THEIR BURNUP**

by

**G. S. ROBINSON**

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AUSTRALIAN NUCLEAR SCIENCE  
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**3D DIFFUSION CALCULATIONS OF HIFAR  
INCLUDING THE COARSE CONTROL ARMS AND THEIR BURN-UP**

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**ABSTRACT**

A 3D model of HIFAR including the coarse control arms (CCAs) has been developed which is based on a 2-group, relatively coarse mesh, diffusion calculation. Comparison with recent measurements of the CCA reactivity calibration has shown good agreement as has limited comparison with measured axial neutron flux profiles. The reactivity errors in 2D burn-up calculations due to 3D effects have been established. Extension of the model to include the burn-up of the cadmium in the CCAs has provided the first calculation-based estimates of the loss of CCA effectiveness with time. Similar estimates of the worth of europium tipped control blades and their lifetime have been made.

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#### EDITORIAL NOTE

The Australian Nuclear Science and Technology Organisation (Ansto) replaced the Australian Atomic Energy Commission (AAEC) on 27 April 1987. Reports issued after April 1987 have the prefix ANSTO with no change of the symbol (E, M, S or C) or the numbering sequence.

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## 1. INTRODUCTION

HIFAR is a DIDO class research reactor operating at 10 MW. The 25 annular fuel elements are cooled and moderated by heavy water which also acts as the main reflector. The reactor is controlled by six signal-arm control blades, called coarse control arms (CCAs), which are lowered into the core between the fuel elements. The layout of fuel elements and CCAs is shown in Figure 1 which gives a plan view of the reactor for a typical CCA angle at startup. The presence of the CCAs is a considerable complication in attempting to perform detailed neutronic calculations of the reactor core and reflector. To date, neutronic models of HIFAR have been based on a combination of cell calculations and RZ plus XY diffusion calculations as described by Harrington [1983] and Harrington & Robinson [1985]. A rather crude representation of the CCAs in a 3D diffusion calculation was used by Robinson [1982] to deduce the effect on the reactivity worth of the CCAs of major differences in the reactor core loading for various CCA calibration measurements. The approach adopted in the present work is similar to that of Nonboel [1985] in that the CCA angle is an input parameter to the model which may be varied at will.

The development of a 3D diffusion model which includes the CCAs has been undertaken because the CCA effects, and the change in these effects throughout an operating cycle, are sufficiently large that XY models must be considered suspect.

In particular:-

- the effect of the CCAs on axial flux shapes in the core and throughout much of the reflector is very large;
- the increasing reliance on calculations to predict these fluxes requires a 3D model;
- there has been considerable uncertainty as to the magnitude of the effect on reactivity of interaction between the core loading and the CCAs;
- the effect on fuel burn-up of including the axial flux distribution rather than the uniform flux used in 2D models can be investigated;
- the model can be applied to many situations for which direct measurements would be difficult or impractical, and can be used for assessing proposals for reactor modifications.

Though the calculation of the burn-up of the cadmium in the CCAs was not considered in the original development of the model, a reasonable method of extending it to include burn-up of the control material has been developed. This has enabled the first assessment, based on calculation, of the lifetime of the blades to be made. The change in the reactivity worth of the CCA blades and their lifetime caused by replacing the standard cadmium blades by ones tipped with europium has also been calculated.

## 2. DESCRIPTION OF THE MODEL

### 2.1. General

The 3D model of HIFAR is a development of a 2D model with two neutron groups and a coarse mesh of 76.2 mm within the core. This 2D model was developed from the 5-group XY model of Harrington [1983] which has half the mesh spacing. The 2-group model, which is an order of magnitude quicker in computer time, was developed for HIFAR fuel management studies [Storr 1989] as well as this 3D application. The condensation to two groups is performed using both flux and adjoint flux from an RZ calculation.

The POW [Pollard 1974] and POW3D modules of the AUS code system [Robinson 1987a] which are used for the diffusion calculations have mesh points at the corners of boxes formed by the spatial subdivision. It was found that the flux depression in a fuel element caused by a rig could be well represented in the 76.2 mm mesh by using a point absorber at the centre of a fuel element. A set of artificial point absorbers on the radial core-reflector boundary was also included to correct the model for the error in power distribution caused by smearing fuel within the 152.4 mm square cell and, in the 2D case, for the average effect of the CCAs.

The 3D model was obtained from the 2D model by keeping the geometry constant over the core height and using essentially the RZ model of Harrington to represent the axial reflectors. The 2TAN horizontal facility which passes beneath the core was added. In the model, the z axis is vertical and the x axis goes through the fuel elements C1 to C5. Thus, the six signal arm control blades travel in planes represented by constant values of y in the model. The CCA blades are included by adding point absorber cross sections to points in the six planes. The value of the cross section at a point is assumed to depend on

the fraction of the xz rectangle about that point in which the control blade is present.

The most important requirement is to establish the correct cross section values to represent the control blades. This is considered in detail in the next subsection.

## 2.2. Derivation of Cross Sections for the CCAs

The effective section of the control blade consists of a 2 mm thick sheet of cadmium sheathed in stainless steel 0.9 mm thick. The cadmium in each blade has been modeled as a  $1091 \times 159$  mm rectangle which pivots about an (x,z) point ( $\pm 803, 1086$ ) mm, where the core centre has been taken as the origin and there are three pivots on each side. The pivot axis is offset (below) 54 mm from the centre of the cadmium and the cadmium extends 1421 mm from the pivot. When fully inserted, the CCA blades are at an angle of  $56^\circ$  below the horizontal. By convention, the CCA angle is quoted as the angle of the blades above this fully-in position. Thus,  $0^\circ$  is fully inserted and  $56^\circ$  is the horizontal, fully raised position.

Within the core, the CCA blade has been represented by adding a group-2 absorption cross section which matches the reactivity worth of the blade in cell calculations using POW and the 2D discrete ordinates code DOT [Rhoades & Mynatt 1973]. The POW calculations were performed in two groups as for the 3D model and the DOT calculations were multigroup with a high order angular quadrature. To obtain a 2D cell calculation, the CCAs were imagined to form an array of infinitely long, 152.4 mm wide blades hanging vertically between the fuel elements. Typical cells represented in the DOT and POW calculations are pictured in Figure 2. The DOT calculations were performed with two zones within the cell for cases with the CCA blade directly between two fuel elements (pictured) or with the blade offset 76.2 mm, and also with cell-average cross sections. Most calculations were performed using cell-average cross sections and the small difference for the two-zone models applied as a correction.

The spacing between CCA blades in the x direction was made sufficiently large to minimise interaction between the blades in the x direction. The y spacing represents the actual distance between blades. Because the cross section deduced for the CCA depends on the POW mesh spacing, this was set at 76.2 mm as in the 3D model. In Figure 2, one POW point has a fractional blade area (FBA) of unity and two have an FBA of 0.5. By increasing the x distance between blades by one mesh interval, the two central points have an FBA of unity. The cross section for FBA of 1 was established by matching the worth of the blade for this case in POW and DOT. Then a value for FBA of 0.5 could be established by matching worths for the pictured case. The deduced form for the variation of cross section with FBA was a polynomial with linear and cubic terms. This form was chosen because the variation was more than quadratic, and a linear component is appropriate for small values of FBA.

A check on cases with half the spacing between blades in the y direction showed that the interaction between blades was well represented by POW and that no correction was required where the two sets of blades overlap.

The cross section to be used for the CCA blade in the reflector was derived separately from cell calculations similar to those for the core but having neutrons slowing down in heavy water. In this case, the required cross section was obtained by matching the cell-average thermal cross section in the POW and DOT calculations. Preliminary 3D results indicated that the worth of the CCAs in the reflector was overestimated. Analysis of 1D reactor models with thermal poison in the core and reflector using 2-group diffusion and multigroup discrete ordinates calculations suggested an overestimate of the worth of large absorbers in the reflector but not in the core. This spectrum related effect was deduced to require a reduction of about 5 per cent in cases similar to the addition of CCA blades to the HIFAR reflector. This correction was applied.

## 3. VALIDATION OF THE MODEL

### 3.1. Comparison with Monte Carlo Calculation

The approximations used in the representation of the CCAs in the 3D diffusion calculation are quite considerable. Also, difficulties were experienced in establishing an appropriate cross section to represent those portions of the CCAs in the reflector which make a very important contribution. For angles greater than  $23^\circ$ , the CCAs are above the core. Even at  $15^\circ$ , calculations indicate that the reflector component is

about half the total. Monte Carlo calculations provide a method of representing the geometry in great detail and thus can provide a direct check of this aspect of the model.

A detailed model of HIFAR was established using the KENO-IV/CG Monte Carlo code [West et al 1979]. The model included an explicit representation of the fuel tubes in each fuel element, all facilities in the heavy water reflector (except 2TAN), most graphite facilities and the CCA blades. The calculations were performed for a uniform fuel burn-up throughout the core and a typical rig loading. The comparison with the 3D diffusion model for the same reactor state was made for the CCAs fully withdrawn and for an angle of  $11^\circ$ . This large angle range was used to ensure reasonable accuracy in the calculated CCA worth.

The calculated worth using the 3D diffusion model of 11.75% in reactivity was in excellent agreement with the Monte Carlo result of  $11.42 \pm 0.38\%$ . The computer times involved were 10 hours per case on the IBM 4381. This made it impractical to check the worth at  $23^\circ$  which is less than 3% so that even five per cent accuracy would require more than 60 hours per case.

### 3.2. Comparison with CCA Calibration Measurements

The most important requirement in modeling the CCAs is that the reactivity worth as a function of angle should be accurately calculated. The CCA calibration for HIFAR has been measured a number of times for a variety of fuel loadings. The most recent measurements [Storr 1987] were performed after the 1985 major shutdown. These measurements on an operational core with a  $^{235}\text{U}$  loading of about 2.7 kg used a variety of techniques including doubling time, inverse kinetics and subcritical multiplication. The results obtained were in excellent agreement with previous inverse kinetics measurements [Harries 1978] made over a limited range of angles for operational cores. Other HIFAR CCA calibrations were based on measurements of clean cores with large absorber loadings.

The standard HIFAR reactivity scale [Duerden 1973] was based on the delayed neutron and photoneutron data of Keepin [1965] applied with a photoneutron effectiveness factor of 0.54. This scale, which was used by both Storr and Harries, was revised recently [Connolly et al 1988] by :-

- using delayed neutron fractions and emission spectra from ENDF/B V,
- calculating the importance of the delayed neutrons relative to prompt neutrons from RZ diffusion calculations to obtain effective delayed neutron fractions,
- obtaining a value of 0.63 for the delayed photoneutron effectiveness factor from coupled photon/neutron discrete ordinates calculations of a spherical model of HIFAR.

The ratios of reactivities for a given doubling time for the revised scale compared to that of Duerden are in the range  $1.074 \pm 0.001$  for doubling times between 10 and 45 seconds. The Storr calibration has been revised to account for this new reactivity scale.

The CCA worth as a function of angle has been calculated for the core state at the time of the measurements of Storr [1987]. The fuel burn-up distribution was calculated from 3D burn-up calculations (Section 4.). The calculated CCA calibration, normalized to a core loading of 2.75 kg of  $^{235}\text{U}$ , is compared to the fit to the measurements in Figure 3. The dependence of CCA reactivity on core  $^{235}\text{U}$  loading,  $M$ , was assumed to be  $M^{-0.7}$ . It can be seen that the agreement in integral worth is quite good. There is a slight lack of smoothness in the calculated integral worth but this is less than about one per cent of the worth at any angle. In order to compare the CCA sensitivity (reactivity per degree), the calculated worths have been fitted to the same Gaussian form as the measurements. The result in Figure 3 shows the calculation to be 6 to 7 per cent greater over the normal operating range.

To indicate the level of agreement between the calculation and the revised Storr calibration, a comparison with other CCA calibrations is given in the following table for a 2.75 kg core.

COMPARISON OF CCA SENSITIVITY ( per cent reactivity per degree)				
Angle	Calc.	Storr(rev.)	Fassbender[1965]	Duerden[1973]
28	0.220	0.204	0.242	0.176
24	0.371	0.349	0.392	0.331
20	0.572	0.541	0.567	0.562
16	0.803	0.763	0.747	0.890
12	1.020	0.963	0.895	1.096

The results of Fassbender [1965] for FRJ-2 with a core of new 115 g elements vary from 10 per cent higher to 12 per cent lower than the calculation. The current HIFAR calibration of Duerden [1973] varies from 20 per cent lower to 11 per cent higher than the calculation. These are in contrast to the uniform 6 to 7 per cent difference for the revised Storr results.

In summary, the calculated CCA calibration is in good agreement with the latest HIFAR measurements. Not only does this validate the calculation but provides some confirmation of the accuracy of those measurements.

### 3.3. Comparison with Axial Neutron Flux Measurements

Measurements of the axial thermal flux profile in the central C3 fuel element as well as a couple of other elements are made on a routine basis near the beginning and end of most HIFAR operating cycles. The comparisons made here are limited to the effect of the CCA movement on the axial flux distribution in C3. Since calculations indicate that the fuel element burn-up has a maximum effect of 4 per cent on the profile, the calculated distribution for the core used in the CCA calibrations has been compared with the average measurement for about six operating cycles in 1984-5. The measurements have a rather low accuracy and the best measurements near the two CCA angles of 26° and 20° were selected.

The comparison is given in Figures 4 and 5. It can be seen that the main features are well calculated. The calculated flux tends to increase more slowly than the measurements at the interface between the core and the top reflector. The agreement is better than might be expected in view of the representation of the CCAs by coarse mesh diffusion calculations.

### 4. COMPARISON OF 3D AND 2D BURN-UP CALCULATIONS

The effect of performing HIFAR burn-up with 3D calculations rather than 2D calculations which assume uniform axial fluxes has been checked for the operating cycles from 297 to 332. The CCA calibration measurements were performed at the beginning of cycle 332.

The comparison has been made using simple burn-up calculations in which it is assumed that macroscopic fuel element cross sections are a function of burn-up only. Thus the burn-up procedure consists of evaluating the power distribution, increasing the irradiation map for a given time interval and re-evaluating the fuel cross sections by interpolation. This method is thought to give accurate values for reactivity at shutdown but cannot be used for startup reactivity estimates because of the lack of a transient fission product treatment. A set of data giving the required fuel changes and absorber concentrations for rigs was available from a previous study [Robinson 1987c] which compared the 2D calculation with operating experience and the routine fuel management code HIFUEL [Robinson 1987b].

It was assumed in performing the 3D burn-up that the effect of the CCAs could be adequately represented by using flux distributions for a typical CCA angle of 21°. As one check on this assumption, the calculated ratios of the flux at the bottom and top to the centre of each fuel element were plotted as a function of angle. It was found that the variation was reasonably linear with angle except for a few outer elements at angles less than about 21°. Thus a constant CCA angle during burn-up should not introduce large errors and will certainly indicate the approximate magnitude of 3D effects.

Two main effects were studied. The first was the variation with operating cycle of the difference between the nominal excess reactivity (with CCAs withdrawn) between the 3D and 2D calculations. It was found that the range of variation of this difference over thirty cycles was 0.18% and the maximum difference between consecutive cycles was 0.11%. This indicates that 3D burn-up effects may produce errors of

this size in estimates of shutdown reactivity made with 2D calculations. Throughout this section, all reactivity worths have been normalized to a 2.75 kg core as in Section 3.2.

The second effect was the variation with operating cycle of the reactivity worth of the CCAs at 21° for the core state at shutdown. It was found that there was a range of 7 per cent in the CCA worth and a maximum difference between consecutive cycles of 5.7 per cent. In view of this large variation, the CCA worths at startup were compared for the operating cycles with the 5.7 per cent difference. For a CCA angle of 21° there was a 4.7 per cent difference and for a typical startup CCA angle of 15° there was a 3.8 per cent difference. The difference at 15° corresponds to a difference in reactivity of 0.3%. Thus the calculations indicate a maximum error of 0.3% in the startup reactivity estimate caused by the variation of the CCA worth with core loading. Since the variation was associated with an unusual fuel change in which the new fuel elements were all in the outer part of the core, it is possible that this startup reactivity error could be eliminated by correcting for the difference between the actual <sup>235</sup>U loading and an importance weighted <sup>235</sup>U loading.

## 5. LOSS-OF-CONTROL-ARM ACCIDENT STUDIES

A major concern in studies of the consequences of a possible loss of control arm is an accurate estimate of the reactivity injected when an arm swings from an initial position in the core to hanging vertically in the radial reflector. The few reactivity measurements available were made on cores with new fuel elements and heavy absorber loadings. The unusual configuration of the CCA bank required rather approximate experimental techniques in some cases. Hence, some doubt remains on the validity of the results when applied to operational cores. As the 3D calculations have been shown to accurately predict the variation of reactivity worth with CCA angle under normal operation, the calculated results for the loss-of-arm accident may be used to test the validity of the reactivity insertions used in the accident studies.

The calculated results have been compared with the reactivity insertions and the compilation of measurements of Connolly & Clark [1986]. The calculations have been performed for the same operational HIFAR core that was used for the CCA calibration. The arm #2 which is considered is one of the central pair of arms. The reactivities have been converted to values for a 2.875 kg core for the comparison.

The data on the reactivity gain on loss of arm #2 at any angle as a fraction of the reactivity control of the complete bank at that angle are compared in Figure 6. The comparison in these terms eliminates any problems with absolute reactivity worths. It can be seen that the results are in reasonable agreement. At high angles, one is comparing the small difference in reactivity for an arm above the core and hanging beside the core; hence the large experimental error. The HIFAR (1959) results were for a core with a heavily poisoned radial reflector. This may explain the calculated value being considerably lower.

Some of the data on the variation of reactivity as the angle of arm #2 is varied while the rest of the bank is held fixed at a given angle are given in Figure 7. There is quite good agreement with the HIFAR data for the bank at 27° but rather poor agreement with the FRJ-2 data for the bank at 10°, particularly for negative angles. However, the shape of these curves is a relatively minor consideration. Connolly & Clark used only a derived shape which was independent of the angle of the bank.

A comparison of the calculation with the conservative values derived by Connolly & Clark for the reactivity gain for loss of an arm by falling to vertical is given in the following table.

REACTIVITY GAIN ON LOSS OF CCA ARM		
Angle	Connolly & Clark	This Calculation
10	0.0219	0.0211
12	0.0191	0.0172
14	0.0151	0.0136

It can be seen that the calculation is less than the conservative value as required, but there is only a small margin at 10°. Thus, these calculations do lend support to the accident analysis.

## 6. BURN-UP OF CADMIUM IN THE CONTRL ARMS

### 6.1. Method of Calculation

The results presented in the previous sections were calculated using the cadmium loading of a new blade. Thus it was assumed that burn-up of the cadmium does not result in any change in the effectiveness of the blade. The effect of cadmium burn-up is now addressed. It is apparent that a straight forward calculation of burn-up in the 3D model is not possible because the control arm is represented only by an effective cross section appropriate for a coarse mesh. Therefore, the approach adopted has been to regard the burn-up of cadmium as a perturbation on the new blade case.

Firstly, the change in effectiveness of a portion of the blade with irradiation was obtained from a 1D slab calculation. The geometry consisted of the cadmium, the steel sheath and a zone consisting of a mixture of reactor core material and moderator. The mixture was adjusted to give the spectrum required to make reasonable comparisons between cadmium and europium (see Section 7). Burn-up of this cell was performed at a constant power which gave an initial cadmium reaction rate of  $2 \times 10^{13} \text{cm}^{-2}$  which is typical of those at the tip of the blade for operation at a power of 10 MW. The calculation was performed using the ANAUSN [Clancy 1982] and CHAR [Robinson 1986c] modules of AUS. The relative effectiveness of the blade was taken as the ratio of the reactivity worth of the blade in the cell to that of a new blade. The result is plotted as a function of time in Figure 8. It can be seen that there is an abrupt drop in worth as the last of the  $^{113}\text{Cd}$  burns out. When this occurs the other cadmium isotopes and the steel sheath still provide about 37 per cent of the initial worth, though their contribution to the initial worth is insignificant. It was necessary to adjust the time scale to achieve a linear variation in the reaction rate between time steps rather than the constant flux for each time step used in the CHAR module. These results have been used by taking the relative effectiveness to be a function of the product of time and initial reaction rate. They have been applied in the 3D calculations by assuming that each of a number of subdivisions of a blade burns out independently at a rate determined by the reactions in each subdivision for a new blade.

The core state using in these calculations was the same as that used for the CCA calibration. Reactivities are quoted as %p in a core with 2.75 kg of  $^{235}\text{U}$ . The results for the reaction rate distribution within a new blade at a given angle have been calculated from the POW3D fluxes in a straight forward manner which is consistent with the representation of the CCA in POW3D and thus reproduces the total cadmium reaction rate. However the accuracy of this distribution is questionable because the POW3D mesh is coarse and the method was designed to give the correct worth rather than the correct reaction rate distribution. Also, the results are sensitive to the details of this distribution because the abrupt loss of effectiveness makes the results sensitive to the initial reaction rate in any zone. In practice, subdivision of the blade into approximate squares of side 80, 40 and 32 mm was tested and the last was chosen because this maximised the calculated effect of burn-up. This choice was made to be conservative even though some non-physical variation in the reaction rate was apparent. An example of the calculated reaction rate distribution and the resulting loss of relative effectiveness of subdivisions at the tip of an arm is given in the table below.

Reaction Rates ( $10^{13}\text{cm}^{-2}$ ) in Arm 2 at Angle 22													
1.13	1.21	1.10	0.81	0.90	0.95	0.72	0.67	0.72	0.64	0.46	0.44	0.45	0.32
1.38	1.43	1.38	1.32	1.17	1.06	1.07	1.00	0.81	0.78	0.77	0.60	0.47	0.47
1.83	1.86	1.59	1.41	1.39	1.36	1.18	1.11	1.18	1.05	0.79	0.84	0.82	0.54
2.03	1.97	2.05	1.93	1.54	1.74	1.84	1.46	1.41	1.50	1.33	0.99	0.98	0.97
2.02	2.06	2.11	2.16	1.91	1.78	1.91	1.71	1.49	1.50	1.43	1.30	1.10	1.00
Fractional Loss in Effectiveness of Arm 2 at Angle 22 and Irradiation 170000 MWh													
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
0.09	0.14	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
0.63	0.63	0.63	0.56	0.02	0.04	0.11	0.02	0.01	0.02	0.01	0.01	0.01	0.01
0.63	0.63	0.63	0.63	0.43	0.05	0.44	0.03	0.02	0.02	0.01	0.01	0.01	0.01

Calculations of control blade worths by perturbation methods can be very inaccurate because of the large flux changes involved. Therefore, the perturbation method has been checked by comparison of the results with direct calculations for several situations in which a blade or a section of a blade was removed. The section removed from the blade was 79.5 mm wide by 156 mm long from the bottom of the tip. The results for perturbation calculations using the flux calculated with the complete CCA bank inserted in combination with either the adjoint for the same case (CCA in) or the case with the CCA bank at 56° (CCA out) are given in the table below.

Case	Reactivity Worth (% $\rho$ )			Ratio CCA out to direct
	Direct	CCA in	CCA out	
Total bank at 15°	8.05	2.04	8.05	1.00
Arm #5 at 15°	1.48	0.50	1.89	1.27
Bit from all arms at 15°	1.98	0.93	2.62	1.33
Bit from arm #5 at 15°	0.477	0.226	0.619	1.30
Total bank at 0°	24.02		24.02	1.00
Bit from arm #5 at 0°	1.232		1.441	1.17

It can be seen that the use of the adjoint for the CCA-out case gives perfect results as expected for the total bank cases and a reasonable, conservative estimate for the cases of most interest. Hence, this method was adopted to estimate the worth of CCA burn-up.

## 6.2. Results and Discussion

It was considered that the limiting condition on CCA burn-up is that undue errors should not be introduced into reactivity accounting through the use of the CCAs to estimate reactivity worths and measure excess reactivity. Thus, the possible error at start-up angles is the main concern and results have been given at 15° to represent typical, low start-up angles. Results are also given at the fully-in position of 0° to show the effect on shut-down capability. The results for these two cases are given in Tables 1 and 2 respectively as a function of the exposure measured in MWh and the average CCA angle during burn-up. Examination of HIFAR shut-down angles since Program 250 and calculating an average angle for six of these programs suggests that average angles have been mainly in the range from 22° to 23°. Thus, an angle of 22° is the most appropriate to use for past operation. The results for blades 1, 2 and 3 at 15° and a burn-up angle of 22° are also displayed in Figure 10. The variation with irradiation is not completely smooth but this is of no consequence. It can be seen that the results are quite sensitive to irradiation because of the abrupt loss of effectiveness of a portion of the tip as the  $^{113}\text{Cd}$  is fully burnt out. This sensitivity means that the small degree of conservatism built into the results is not sufficient to provide a final conservative result. An additional margin on the exposure of about 10 per cent would be required to do so. However, the consequences of exceeding the reactivity losses of up to 0.18 % $\rho$  at 15° calculated for the current exposure limits [Carlson 1990] of 150000, 180000 and 200000 MWh for arms 2 & 5, 3 & 6, and 1 & 4 respectively are not severe and such a margin is not warranted. It is of interest to note that if the worth of the steel and other cadmium isotopes is neglected the 0.18 % $\rho$  increases to 0.30 % $\rho$ .

The effect of the chosen core state on the calculated reaction rates in the CCA blades was checked by repeating the reaction rate calculation at 23° for a core with a uniform burn-up distribution. The increases in peak reaction rates were 3 per cent for an outer blade and 1.5 per cent for an inner blade. These changes are insignificant. The effect on reaction rates of an increase in mass of  $^{235}\text{U}$  to 4 kg which approximates recent DIDO operation with 205 g elements was to decrease reaction rates by about 20 per cent. The dependence on  $^{235}\text{U}$  mass was deduced to be  $M^{-0.6}$ .



further emphasizes the insensitivity of the effectiveness results to details of the calculation. To quantify the effect of epithermal to thermal ratio on effectiveness, the calculations were repeated for a cell with one third the ratio, which is that calculated in the reflector about 200 mm from the core boundary. The results (labeled thermal) are compared with the standard results in Figure 8 and show only very minor differences. Thus the attention paid here to an accurate representation of resonance events was unnecessary.

To calculate the worth of a europium tipped blade relative to a new cadmium blade, the perturbation method used for cadmium burn-up was applied here in a very similar way. The europium insert consists of an oblong shape with a width 6.6 mm less than that of the cadmium blade and extending 486 mm along the bottom and 102 mm along the top of the blade. The tip is also slightly tapered. All this detail was modeled approximately by first calculating the fraction of each subdivision of a cadmium blade which is occupied by europium, cadmium or neither in a europium blade and then performing the perturbation estimates as before. Thus it was assumed that the subdivisions do not interact and nor do the cadmium and europium components of a subdivision.

### 7.3. Results and Discussion

Tables 3 and 4 give results for the loss in worth of the europium blades relative to a new cadmium blade as a function of irradiation and burn-up angle for insertion angles of  $15^\circ$  and  $0^\circ$  respectively. It can be seen that the calculated difference between the worth of new europium and cadmium would not be detectable. The loss in worth is approximately 1.5 per cent only of the cadmium blade worth. The results for blades 1, 2 and 3 at  $15^\circ$  for a burn-up angle of  $22^\circ$  are also compared with the equivalent results for cadmium blades in Figure 10. As a further check on the spectrum effects, calculations of the slab cell were repeated using cross sections from a normal HIFAR fuel cell calculation to represent the spectrum at the centre of the core. This gave a relative worth for europium to cadmium of 1.111 rather than 1.049 for the standard result. Using this value for the europium insert in the perturbation calculation at  $0^\circ$  gave a gain in worth of 3 per cent over the cadmium blade compared to the 1.5 per cent loss for the standard result. Thus the calculations indicate that the europium and cadmium blades are extremely well matched. The europium blade lifetimes are much longer and there is no abrupt loss of worth as the poison burns out. It is also interesting that the calculations estimate that the burn-up of the europium tip and the cadmium in the rest of the blade contribute about equally to the reactivity loss.

## 8. CONCLUSIONS

A 3D model of HIFAR which includes the coarse control arms has been developed which is based on a 2-group, relatively coarse mesh, diffusion calculation. Appropriate absorption cross sections to represent the signal arm control blades were obtained by comparison with multigroup discrete ordinates cell calculations. An integral test of the CCA worth using the model showed excellent agreement with a geometrically detailed Monte Carlo calculation. Comparison with the most recent measurement of the CCA reactivity calibration showed good agreement and, in particular, a constant difference of about 6 per cent between calculation and measurement in change of reactivity with arm movement over the normal operating range. Limited comparisons with measurement for variation in the axial thermal flux profile showed good agreement. Burn-up calculations in 3D with a constant CCA angle of  $21^\circ$  showed that 2D burn-up calculations are capable of giving shutdown reactivity estimates to an accuracy of about 0.1% in reactivity. However, the error in startup reactivity estimates due to variation in CCA worth with core loading may be about 0.3%. Calculations of reactivity additions due to loss of a control arm were in reasonable agreement with measurement and confirmed the reactivity additions used in the study of the loss-of-arm accident on HIFAR.

Extension of the model to include the burn-up of the CCA control material has provided the first calculation-based estimates of the loss of CCA effectiveness with time. These estimates are consistent with the current CCA lifetime limits which have been based on anecdotal evidence. Similar estimates of the worth of europium tipped control blades and their lifetime have been made. This confirmed that blades of this type have almost identical initial reactivity worth to all-cadmium blades and that their lifetime is very much longer.

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Table 1 Loss in Reactivity Worth at 15° for Cd CCA Blade

burn-up angle	blade no. irrad.(MWh)	1	2	3	4	5	6
		Loss in blade worth (%p)					
22°	140000	0.0048	0.0280	0.0144	0.0040	0.0244	0.0144
22°	150000	0.0053	0.0679	0.0169	0.0043	0.0421	0.0169
22°	160000	0.0057	0.2201	0.0231	0.0047	0.1339	0.0229
22°	170000	0.0063	0.3463	0.0595	0.0051	0.2900	0.0574
22°	180000	0.0070	0.4381	0.1801	0.0055	0.3928	0.1764
22°	190000	0.0079	0.4911	0.2333	0.0060	0.4686	0.2347
22°	200000	0.0098	0.5118	0.3069	0.0065	0.4917	0.3073
22°	220000	0.0434	0.6216	0.3700	0.0084	0.5920	0.3736
22°	240000	0.0964	0.7823	0.4162	0.0195	0.7275	0.4199
22°	260000	0.1371	0.8230	0.5238	0.0774	0.8001	0.5229
22°	280000	0.1631	0.8849	0.5932	0.1220	0.8502	0.5985
22°	300000	0.1859	0.9433	0.6192	0.1528	0.9070	0.6208
20°	140000	0.0060	0.1836	0.0682	0.0047	0.1534	0.0674
20°	150000	0.0070	0.3124	0.1042	0.0052	0.2678	0.1051
20°	160000	0.0101	0.3762	0.1498	0.0057	0.3429	0.1514
20°	170000	0.0341	0.4751	0.2338	0.0064	0.4387	0.2360
20°	180000	0.0421	0.5395	0.2720	0.0078	0.5126	0.2742
20°	190000	0.0489	0.5826	0.3369	0.0125	0.5470	0.3392
20°	200000	0.0623	0.6794	0.3923	0.0340	0.6312	0.3961
20°	220000	0.1208	0.7933	0.4636	0.0595	0.7658	0.4666
20°	240000	0.1437	0.8741	0.5621	0.1021	0.8306	0.5663
20°	260000	0.1859	0.9252	0.6031	0.1380	0.8933	0.6052
20°	280000	0.2101	0.9695	0.6570	0.1691	0.9419	0.6621
20°	300000	0.2387	1.0020	0.6978	0.1880	0.9789	0.7025
24°	140000	0.0041	0.0195	0.0118	0.0035	0.0182	0.0118
24°	150000	0.0044	0.0234	0.0131	0.0037	0.0212	0.0131
24°	160000	0.0048	0.0370	0.0148	0.0040	0.0283	0.0148
24°	170000	0.0052	0.1020	0.0176	0.0043	0.0735	0.0175
24°	180000	0.0056	0.1859	0.0260	0.0046	0.1361	0.0253
24°	190000	0.0060	0.2740	0.0658	0.0050	0.2301	0.0640
24°	200000	0.0065	0.4335	0.1222	0.0053	0.3340	0.1159
24°	220000	0.0079	0.5033	0.2641	0.0061	0.4847	0.2579
24°	240000	0.0120	0.5910	0.3551	0.0073	0.5576	0.3588
24°	260000	0.0458	0.7041	0.3884	0.0106	0.6535	0.3914
24°	280000	0.0964	0.7983	0.4708	0.0335	0.7556	0.4726
24°	300000	0.1362	0.8326	0.5519	0.0720	0.8024	0.5498
26°	140000	0.0036	0.0160	0.0101	0.0031	0.0151	0.0101
26°	150000	0.0039	0.0179	0.0110	0.0033	0.0168	0.0110
26°	160000	0.0042	0.0208	0.0121	0.0035	0.0190	0.0121
26°	170000	0.0045	0.0283	0.0134	0.0038	0.0231	0.0134
26°	180000	0.0048	0.0741	0.0154	0.0040	0.0406	0.0152
26°	190000	0.0051	0.1288	0.0197	0.0043	0.0973	0.0191
26°	200000	0.0055	0.1623	0.0423	0.0046	0.1464	0.0359
26°	220000	0.0063	0.3198	0.1123	0.0052	0.2555	0.1117
26°	240000	0.0075	0.4673	0.1769	0.0059	0.4280	0.1735
26°	260000	0.0109	0.5708	0.3089	0.0069	0.5308	0.3052
26°	280000	0.0381	0.6483	0.3760	0.0092	0.6131	0.3740
26°	300000	0.0549	0.7500	0.4470	0.0260	0.7055	0.4452

Table 2 Loss in Reactivity Worth at 0° for Cd CCA Blade

burn-up angle	blade no. irrad.(MWh)	Loss in blade worth (%ρ)					
		1	2	3	4	5	6
22°	140000	0.0130	0.0697	0.0358	0.0103	0.0653	0.0358
22°	150000	0.0141	0.1523	0.0415	0.0111	0.1049	0.0413
22°	160000	0.0154	0.4585	0.0540	0.0120	0.2933	0.0535
22°	170000	0.0168	0.7461	0.1240	0.0129	0.6521	0.1196
22°	180000	0.0184	0.9822	0.3595	0.0139	0.9099	0.3503
22°	190000	0.0207	1.0996	0.4770	0.0151	1.1093	0.4781
22°	200000	0.0250	1.1491	0.6534	0.0164	1.1669	0.6495
22°	220000	0.0951	1.4249	0.7897	0.0204	1.4307	0.7941
22°	240000	0.2208	1.8728	0.8935	0.0417	1.8275	0.8979
22°	260000	0.3276	1.9999	1.1729	0.1578	2.0467	1.1632
22°	280000	0.3842	2.2019	1.3705	0.2557	2.2210	1.3735
22°	300000	0.4386	2.4103	1.4558	0.3314	2.4261	1.4445
20°	140000	0.0158	0.3974	0.1297	0.0119	0.3480	0.1284
20°	150000	0.0182	0.6639	0.2147	0.0131	0.6030	0.2165
20°	160000	0.0248	0.8129	0.3065	0.0144	0.7777	0.3096
20°	170000	0.0731	1.0374	0.4732	0.0160	1.0107	0.4767
20°	180000	0.0963	1.2011	0.5619	0.0187	1.1969	0.5642
20°	190000	0.1166	1.3108	0.7066	0.0275	1.2963	0.7072
20°	200000	0.1456	1.5632	0.8314	0.0657	1.5248	0.8361
20°	220000	0.2788	1.9010	1.0051	0.1251	1.9313	1.0065
20°	240000	0.3416	2.1547	1.2717	0.2105	2.1436	1.2728
20°	260000	0.4371	2.3353	1.3962	0.2896	2.3653	1.3897
20°	280000	0.4963	2.5004	1.5635	0.3644	2.5562	1.5637
20°	300000	0.5664	2.6272	1.7053	0.4112	2.7028	1.7029
24°	140000	0.0111	0.0506	0.0298	0.0090	0.0501	0.0297
24°	150000	0.0120	0.0592	0.0329	0.0096	0.0573	0.0328
24°	160000	0.0129	0.0848	0.0367	0.0104	0.0725	0.0365
24°	170000	0.0139	0.2083	0.0425	0.0111	0.1575	0.0421
24°	180000	0.0149	0.3840	0.0577	0.0119	0.3025	0.0562
24°	190000	0.0161	0.5800	0.1265	0.0127	0.4995	0.1223
24°	200000	0.0174	0.9608	0.2412	0.0135	0.7683	0.2283
24°	220000	0.0206	1.1287	0.5558	0.0155	1.1503	0.5369
24°	240000	0.0293	1.3508	0.7566	0.0182	1.3444	0.7617
24°	260000	0.0968	1.6577	0.8337	0.0246	1.6141	0.8374
24°	280000	0.2173	1.9210	1.0438	0.0655	1.9128	1.0415
24°	300000	0.3240	2.0369	1.2557	0.1417	2.0569	1.2411
26°	140000	0.0097	0.0416	0.0254	0.0079	0.0416	0.0253
26°	150000	0.0104	0.0462	0.0277	0.0085	0.0459	0.0276
26°	160000	0.0112	0.0523	0.0302	0.0091	0.0511	0.0301
26°	170000	0.0120	0.0661	0.0332	0.0097	0.0599	0.0329
26°	180000	0.0128	0.1406	0.0371	0.0103	0.0911	0.0367
26°	190000	0.0137	0.2393	0.0449	0.0110	0.1902	0.0437
26°	200000	0.0146	0.3122	0.0801	0.0117	0.2934	0.0718
26°	220000	0.0166	0.6514	0.2039	0.0131	0.5479	0.2020
26°	240000	0.0193	1.0166	0.3407	0.0148	0.9610	0.3321
26°	260000	0.0261	1.2942	0.6262	0.0169	1.2632	0.6107
26°	280000	0.0749	1.5028	0.7962	0.0213	1.4940	0.7867
26°	300000	0.1135	1.7786	0.9769	0.0481	1.7569	0.9664

**Table 3 Loss in Reactivity Worth at 15° for Eu Tipped CCA Blade  
(Relative to New Cd Blades)**

burn-up angle	blade no. irrad.(MWh)	1	2	3	4	5	6
		Loss in blade worth (%p)					
22°	0	0.0130	0.0347	0.0253	0.0113	0.0339	0.0256
22°	100000	0.0142	0.0449	0.0309	0.0121	0.0434	0.0311
22°	200000	0.0208	0.0898	0.0560	0.0172	0.0851	0.0564
22°	300000	0.0336	0.1564	0.0989	0.0268	0.1493	0.0996
22°	350000	0.0417	0.2072	0.1216	0.0334	0.1985	0.1226
22°	400000	0.0495	0.2574	0.1559	0.0405	0.2466	0.1565
22°	450000	0.0577	0.3085	0.1885	0.0477	0.2955	0.1902
22°	500000	0.0716	0.3506	0.2248	0.0603	0.3384	0.2255
22°	550000	0.0859	0.3920	0.2532	0.0712	0.3782	0.2546
22°	600000	0.1021	0.4341	0.2757	0.0868	0.4182	0.2775
22°	650000	0.1140	0.4785	0.3028	0.0984	0.4594	0.3046
22°	700000	0.1288	0.5277	0.3334	0.1112	0.5070	0.3354
20°	0	0.0130	0.0347	0.0253	0.0113	0.0339	0.0256
20°	100000	0.0149	0.0485	0.0330	0.0126	0.0468	0.0333
20°	200000	0.0242	0.1067	0.0663	0.0195	0.1012	0.0669
20°	300000	0.0408	0.1892	0.1149	0.0324	0.1817	0.1158
20°	350000	0.0495	0.2486	0.1480	0.0402	0.2397	0.1491
20°	400000	0.0581	0.3064	0.1866	0.0478	0.2963	0.1878
20°	450000	0.0731	0.3491	0.2253	0.0609	0.3372	0.2271
20°	500000	0.0889	0.4008	0.2528	0.0739	0.3869	0.2545
20°	550000	0.1082	0.4464	0.2867	0.0917	0.4293	0.2887
20°	600000	0.1211	0.4886	0.3156	0.1037	0.4714	0.3178
20°	650000	0.1363	0.5433	0.3456	0.1170	0.5263	0.3481
20°	700000	0.1506	0.5759	0.3746	0.1285	0.5594	0.3774
24°	0	0.0130	0.0347	0.0253	0.0113	0.0339	0.0256
24°	100000	0.0137	0.0421	0.0293	0.0118	0.0407	0.0295
24°	200000	0.0186	0.0760	0.0483	0.0156	0.0722	0.0485
24°	300000	0.0279	0.1341	0.0840	0.0227	0.1276	0.0844
24°	350000	0.0344	0.1667	0.1032	0.0278	0.1587	0.1037
24°	400000	0.0417	0.2105	0.1260	0.0337	0.2002	0.1275
24°	450000	0.0489	0.2541	0.1555	0.0401	0.2445	0.1560
24°	500000	0.0587	0.3026	0.1846	0.0480	0.2907	0.1856
24°	550000	0.0684	0.3344	0.2196	0.0577	0.3231	0.2203
24°	600000	0.0834	0.3754	0.2398	0.0697	0.3618	0.2408
24°	650000	0.0947	0.4216	0.2640	0.0817	0.4060	0.2653
24°	700000	0.1085	0.4564	0.2913	0.0942	0.4388	0.2927
26°	0	0.0130	0.0347	0.0253	0.0113	0.0339	0.0256
26°	100000	0.0133	0.0399	0.0280	0.0115	0.0387	0.0282
26°	200000	0.0172	0.0656	0.0426	0.0145	0.0625	0.0428
26°	300000	0.0242	0.1132	0.0706	0.0200	0.1072	0.0707
26°	350000	0.0291	0.1401	0.0879	0.0238	0.1332	0.0881
26°	400000	0.0350	0.1697	0.1057	0.0285	0.1626	0.1063
26°	450000	0.0414	0.1992	0.1255	0.0338	0.1900	0.1259
26°	500000	0.0491	0.2439	0.1447	0.0400	0.2333	0.1453
26°	550000	0.0575	0.2820	0.1757	0.0483	0.2716	0.1762
26°	600000	0.0637	0.3226	0.2028	0.0538	0.3081	0.2033
26°	650000	0.0758	0.3642	0.2307	0.0632	0.3515	0.2306
26°	700000	0.0872	0.3985	0.2551	0.0738	0.3834	0.2560

**Table 4 Loss in Reactivity Worth at 0° for Eu Tipped CCA Blade  
(Relative to New Cd Blades)**

burn-up angle	blade no. irrad.(MWh)	Loss in blade worth (%ρ)					
		1	2	3	4	5	6
22°	0	0.0281	0.0748	0.0530	0.0238	0.0753	0.0535
22°	100000	0.0315	0.1015	0.0669	0.0262	0.1014	0.0674
22°	200000	0.0486	0.2124	0.1264	0.0385	0.2103	0.1268
22°	300000	0.0810	0.3854	0.2293	0.0614	0.3851	0.2297
22°	350000	0.1018	0.5603	0.2914	0.0773	0.5605	0.2922
22°	400000	0.1224	0.7396	0.4064	0.0947	0.7401	0.4050
22°	450000	0.1452	0.9425	0.5207	0.1132	0.9431	0.5224
22°	500000	0.1886	1.0871	0.6626	0.1510	1.1037	0.6586
22°	550000	0.2391	1.2207	0.7572	0.1867	1.2400	0.7553
22°	600000	0.2985	1.3434	0.8235	0.2407	1.3637	0.8227
22°	650000	0.3425	1.4724	0.9006	0.2816	1.4898	0.9003
22°	700000	0.3937	1.6424	0.9889	0.3245	1.6590	0.9896
20°	0	0.0281	0.0748	0.0530	0.0238	0.0753	0.0535
20°	100000	0.0333	0.1102	0.0717	0.0273	0.1102	0.0724
20°	200000	0.0569	0.2527	0.1497	0.0437	0.2511	0.1504
20°	300000	0.0990	0.4869	0.2701	0.0745	0.4902	0.2708
20°	350000	0.1218	0.7026	0.3746	0.0934	0.7111	0.3749
20°	400000	0.1452	0.9213	0.5074	0.1128	0.9369	0.5070
20°	450000	0.1920	1.0714	0.6517	0.1518	1.0906	0.6519
20°	500000	0.2511	1.2393	0.7457	0.1954	1.2612	0.7447
20°	550000	0.3206	1.3635	0.8538	0.2575	1.3826	0.8532
20°	600000	0.3632	1.4855	0.9266	0.2972	1.5086	0.9268
20°	650000	0.4139	1.6915	1.0112	0.3416	1.7215	1.0124
20°	700000	0.4581	1.7858	1.1021	0.3762	1.8220	1.1035
24°	0	0.0281	0.0748	0.0530	0.0238	0.0753	0.0535
24°	100000	0.0301	0.0944	0.0630	0.0252	0.0944	0.0636
24°	200000	0.0429	0.1783	0.1083	0.0347	0.1766	0.1085
24°	300000	0.0665	0.3240	0.1928	0.0517	0.3228	0.1927
24°	350000	0.0830	0.4204	0.2404	0.0638	0.4176	0.2404
24°	400000	0.1016	0.5664	0.3075	0.0781	0.5604	0.3109
24°	450000	0.1206	0.7288	0.4036	0.0938	0.7333	0.4020
24°	500000	0.1486	0.9251	0.5089	0.1150	0.9287	0.5086
24°	550000	0.1772	1.0272	0.6495	0.1431	1.0446	0.6459
24°	600000	0.2292	1.1570	0.7120	0.1808	1.1729	0.7096
24°	650000	0.2706	1.3204	0.7842	0.2227	1.3377	0.7830
24°	700000	0.3236	1.4170	0.8734	0.2680	1.4347	0.8723
26°	0	0.0281	0.0748	0.0530	0.0238	0.0753	0.0535
26°	100000	0.0292	0.0886	0.0599	0.0246	0.0887	0.0604
26°	200000	0.0390	0.1513	0.0942	0.0320	0.1501	0.0944
26°	300000	0.0565	0.2676	0.1589	0.0449	0.2650	0.1586
26°	350000	0.0689	0.3396	0.2005	0.0540	0.3376	0.2000
26°	400000	0.0836	0.4295	0.2471	0.0649	0.4305	0.2479
26°	450000	0.1000	0.5216	0.3053	0.0776	0.5189	0.3048
26°	500000	0.1210	0.6854	0.3633	0.0933	0.6841	0.3627
26°	550000	0.1444	0.8283	0.4732	0.1166	0.8365	0.4719
26°	600000	0.1619	0.9820	0.5750	0.1311	0.9775	0.5722
26°	650000	0.1994	1.1241	0.6777	0.1588	1.1410	0.6712
26°	700000	0.2392	1.2369	0.7592	0.1938	1.2493	0.7570

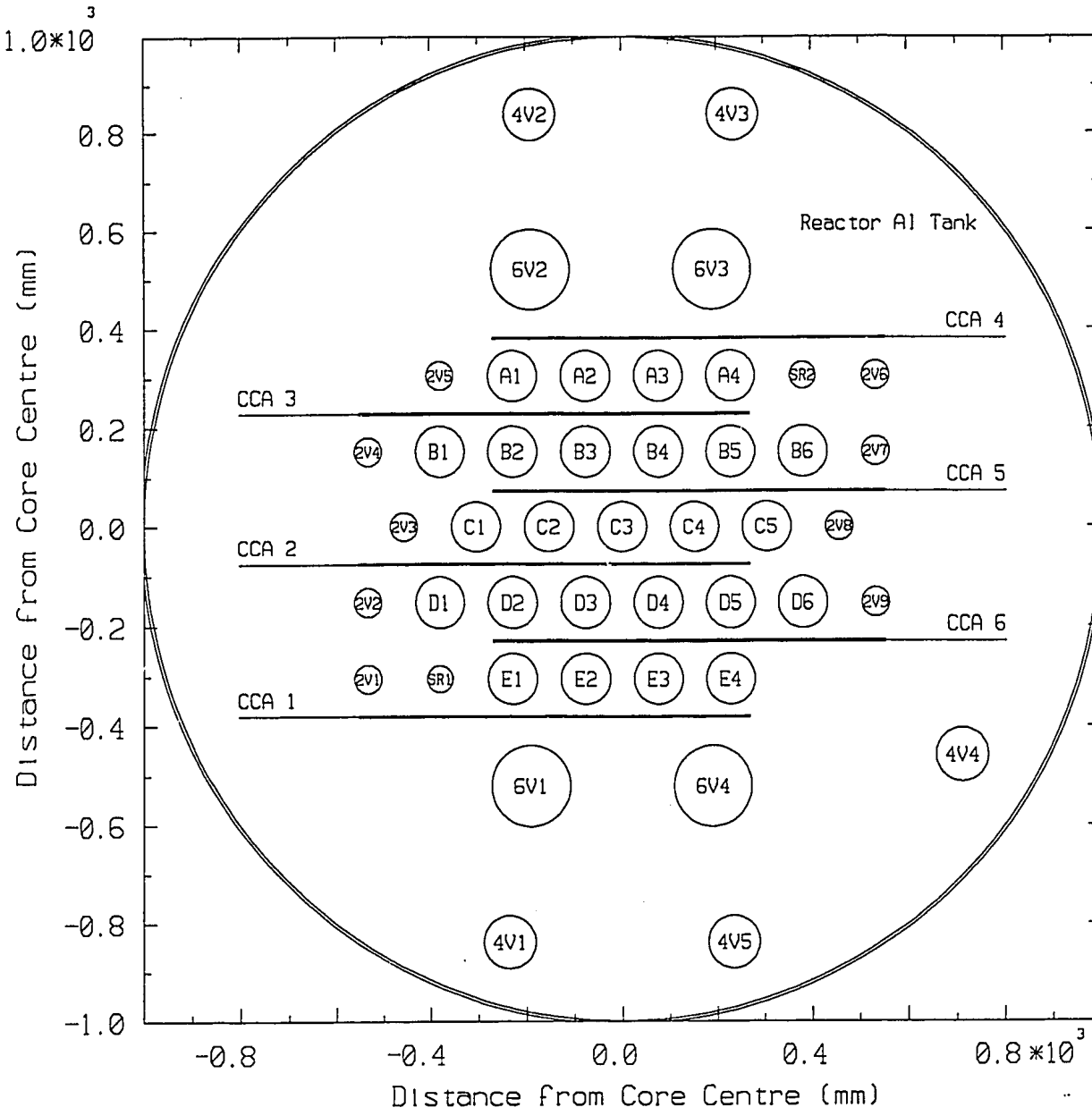


Figure 1 Location of Fuel Elements, CCA Blades and Vertical Facilities

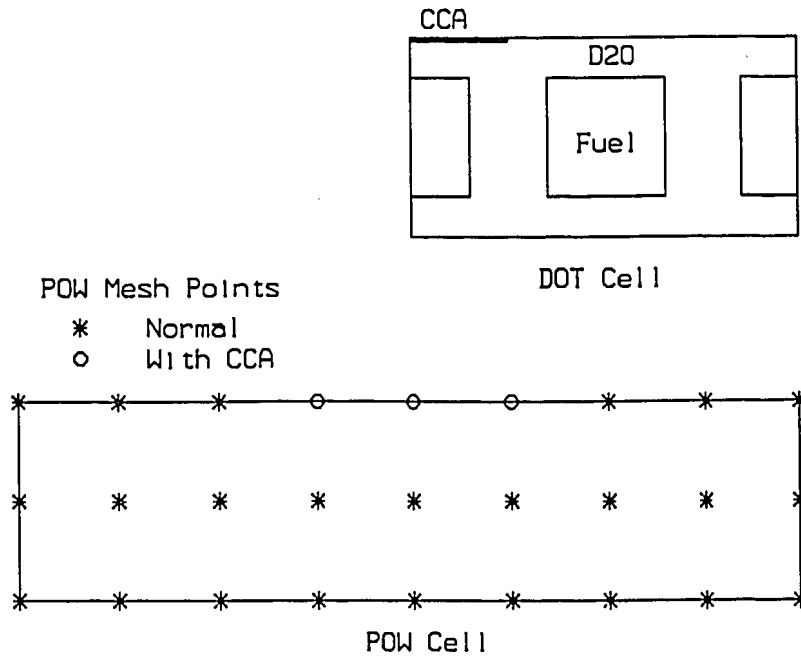
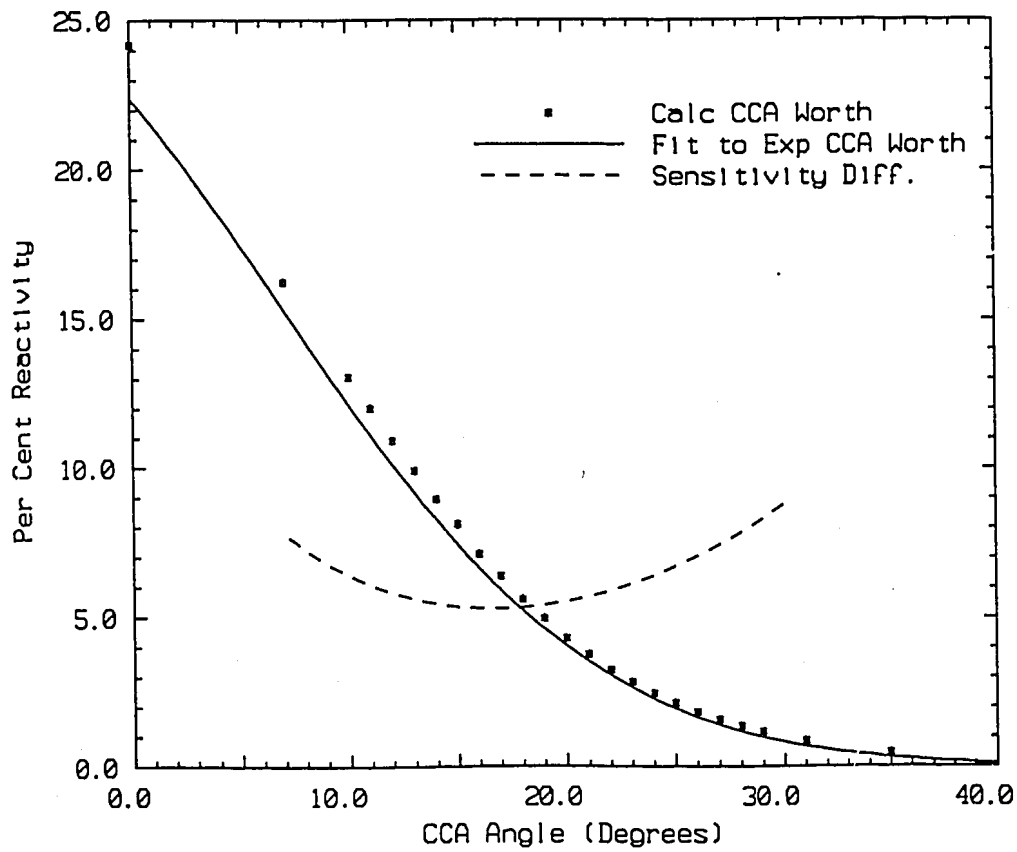


Figure 2 Geometry for CCA Cell Calculations



Sensitivity Comparison - (Calc-Exp)/Exp %

Figure 3 Comparison of Calculated and Measured CCA Worth

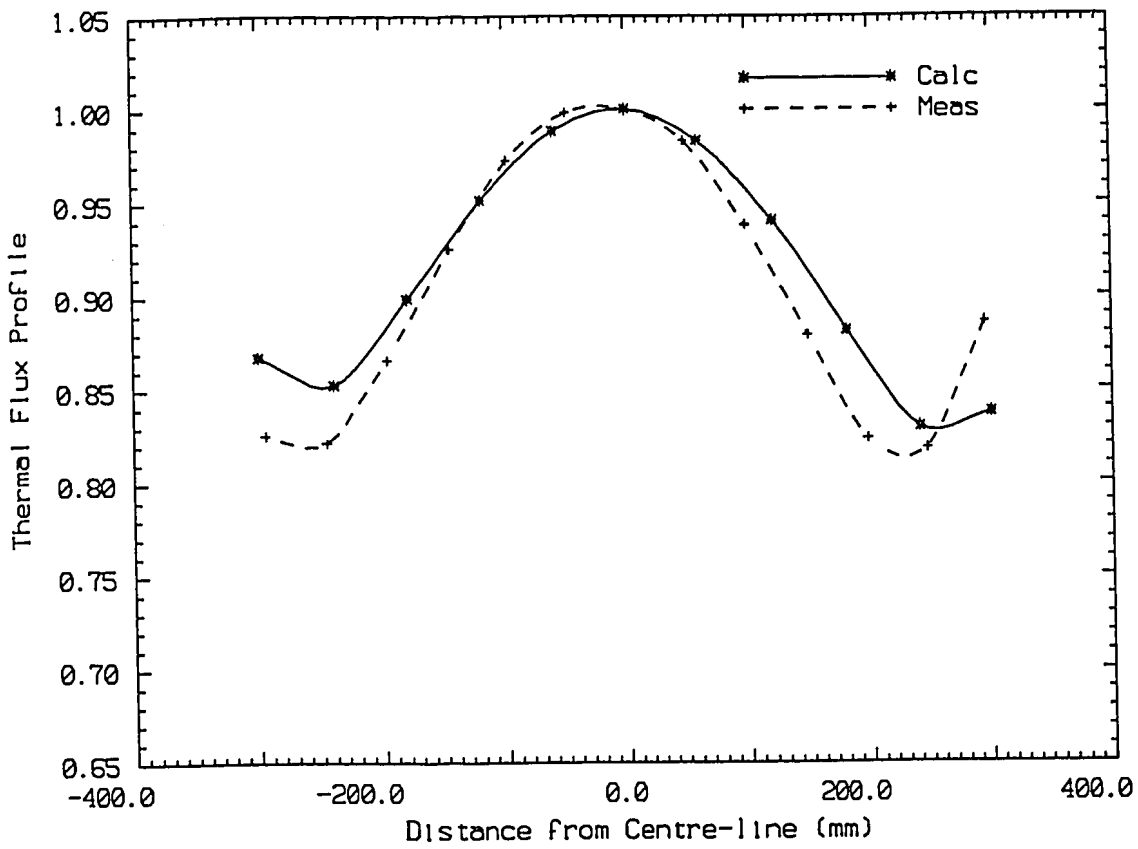


Figure 4 Flux Profile in C3 Facility for CCA Angle of 26°

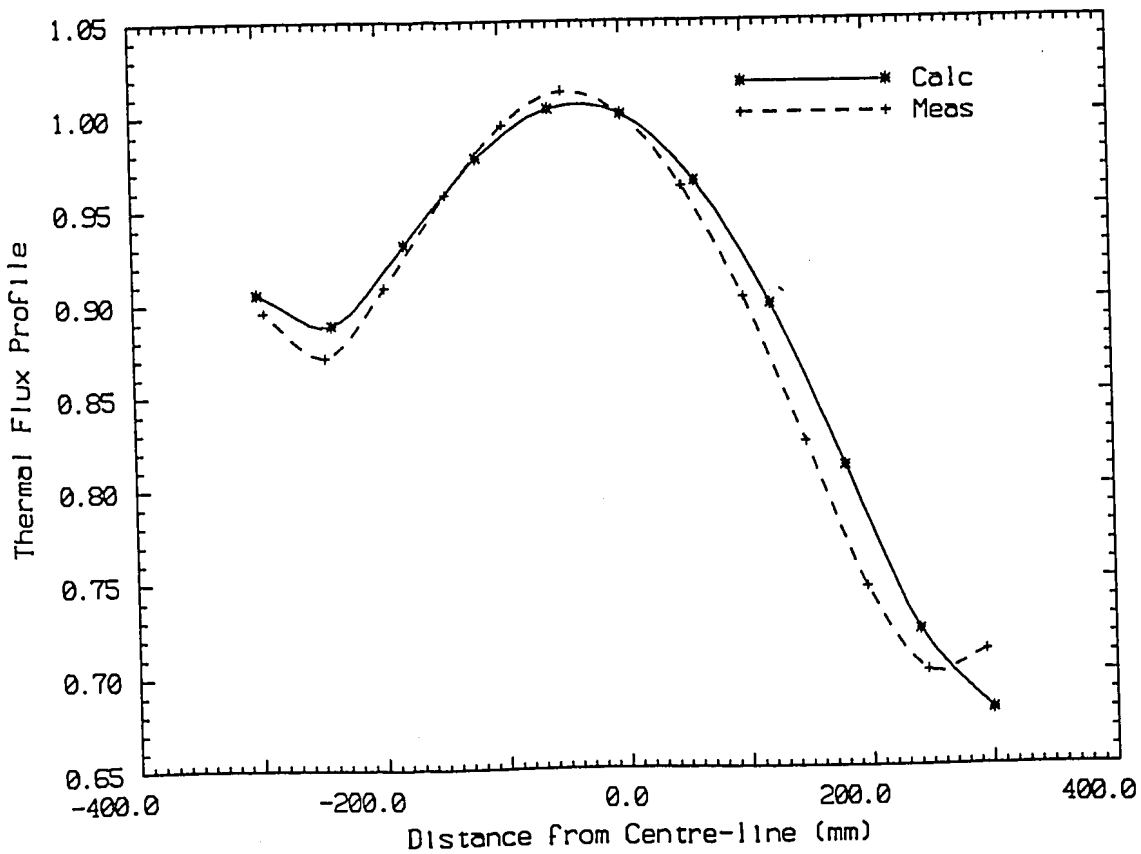


Figure 5 Flux Profile in C3 Facility for CCA Angle of 20°

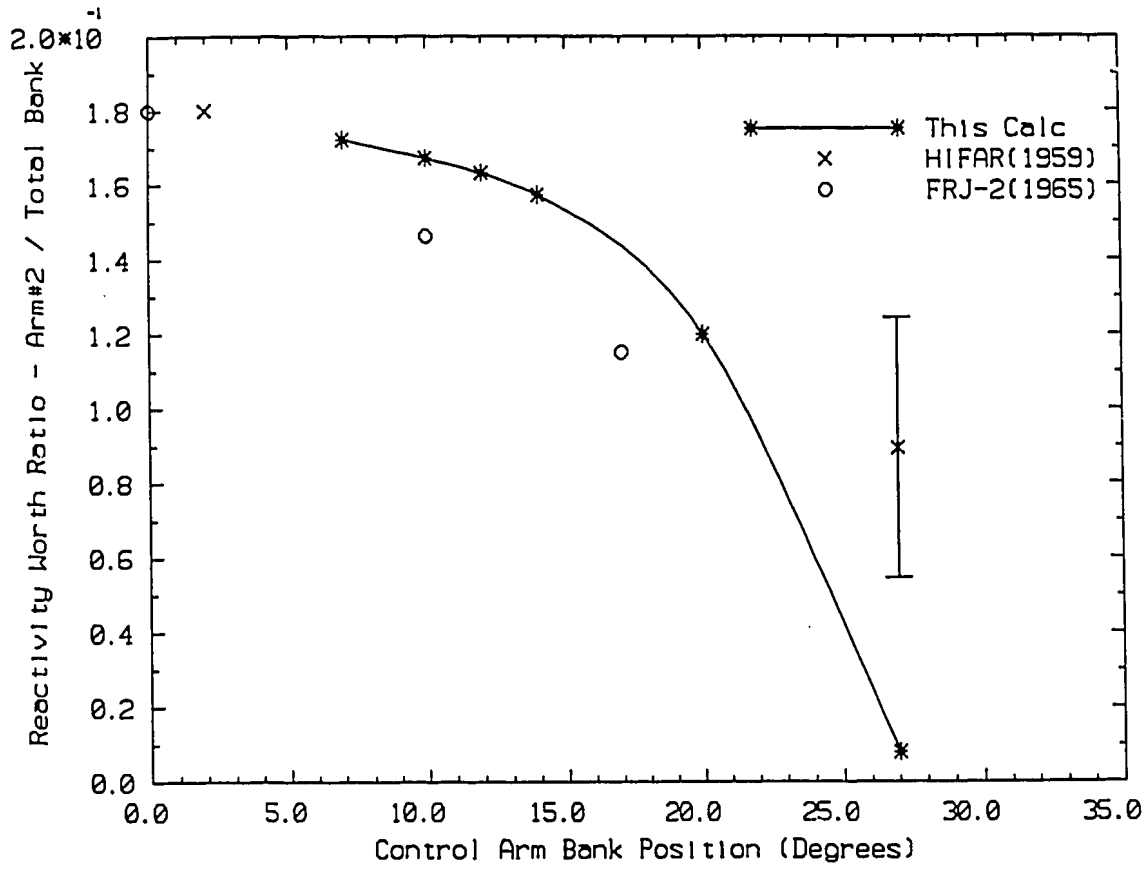


Figure 6 Ratio of Reactivity Gained on Moving Arm #2 to Vertical to Total CCA Bank Worth at Given Angle

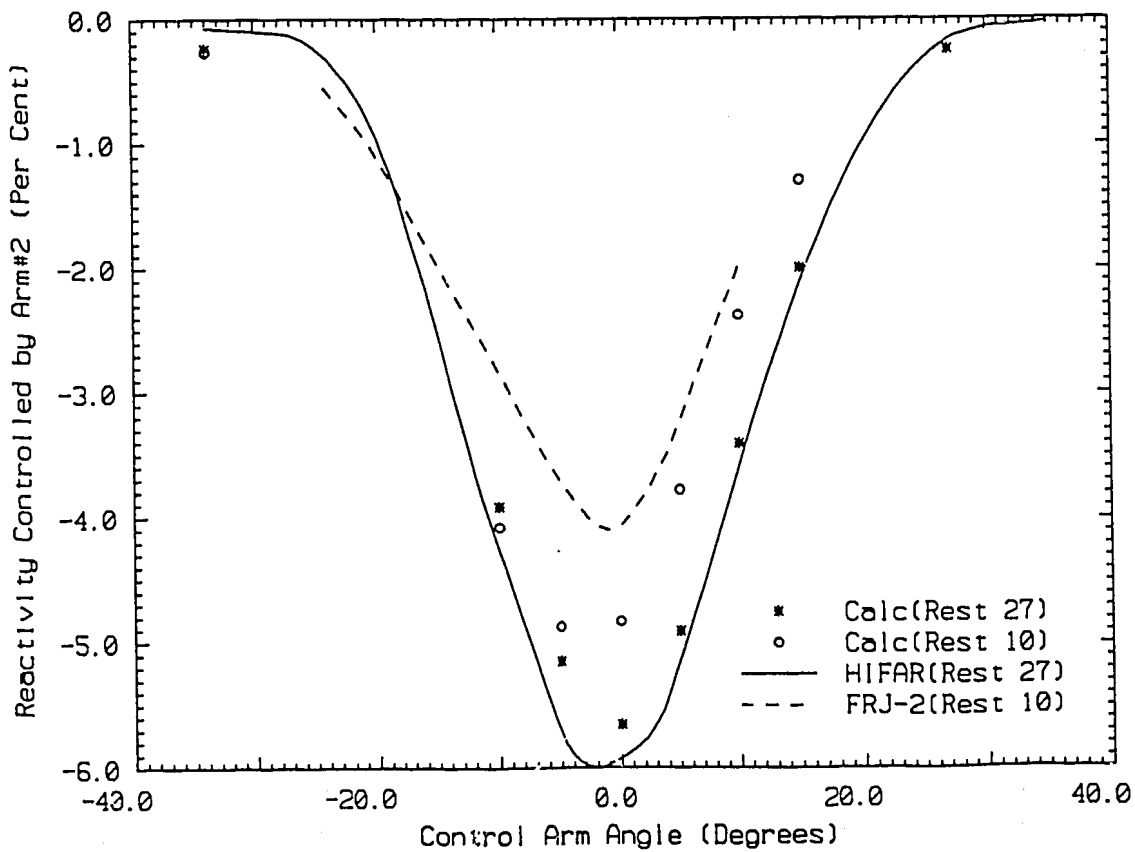


Figure 7 Reactivity Controlled by Arm #2 as Function of Angle, with Angle of Remaining Arms as a Parameter

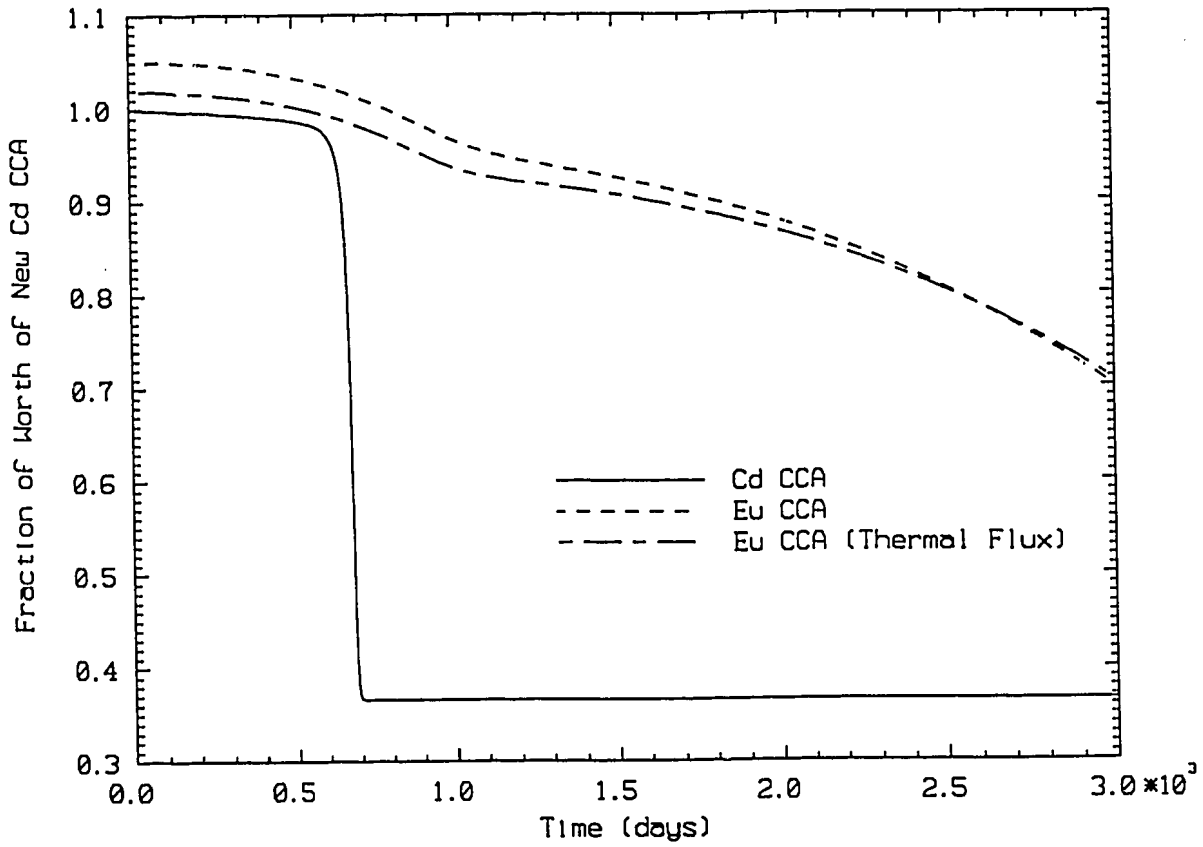


Figure 8 Variation in Relative CCA Reactivity Worth with Time

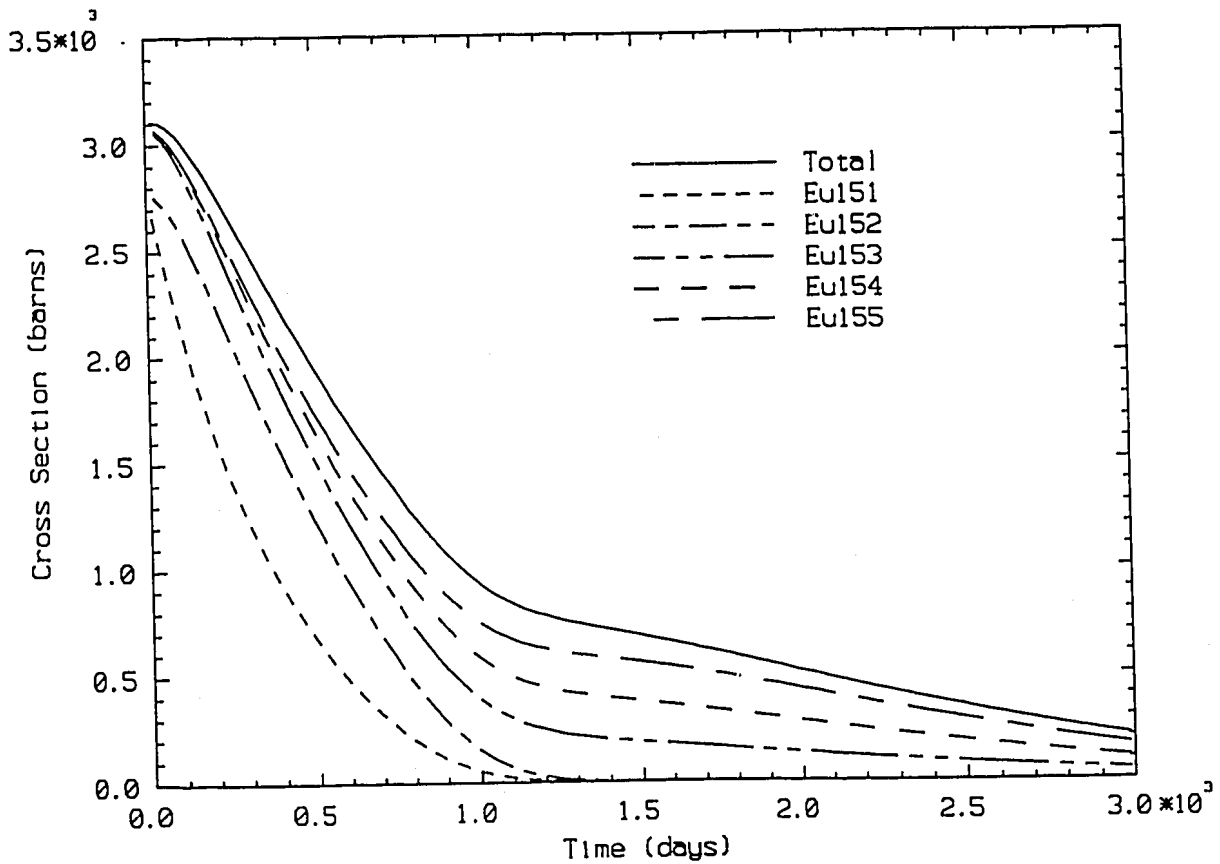


Figure 9 Components of Effective Eu Cross Section

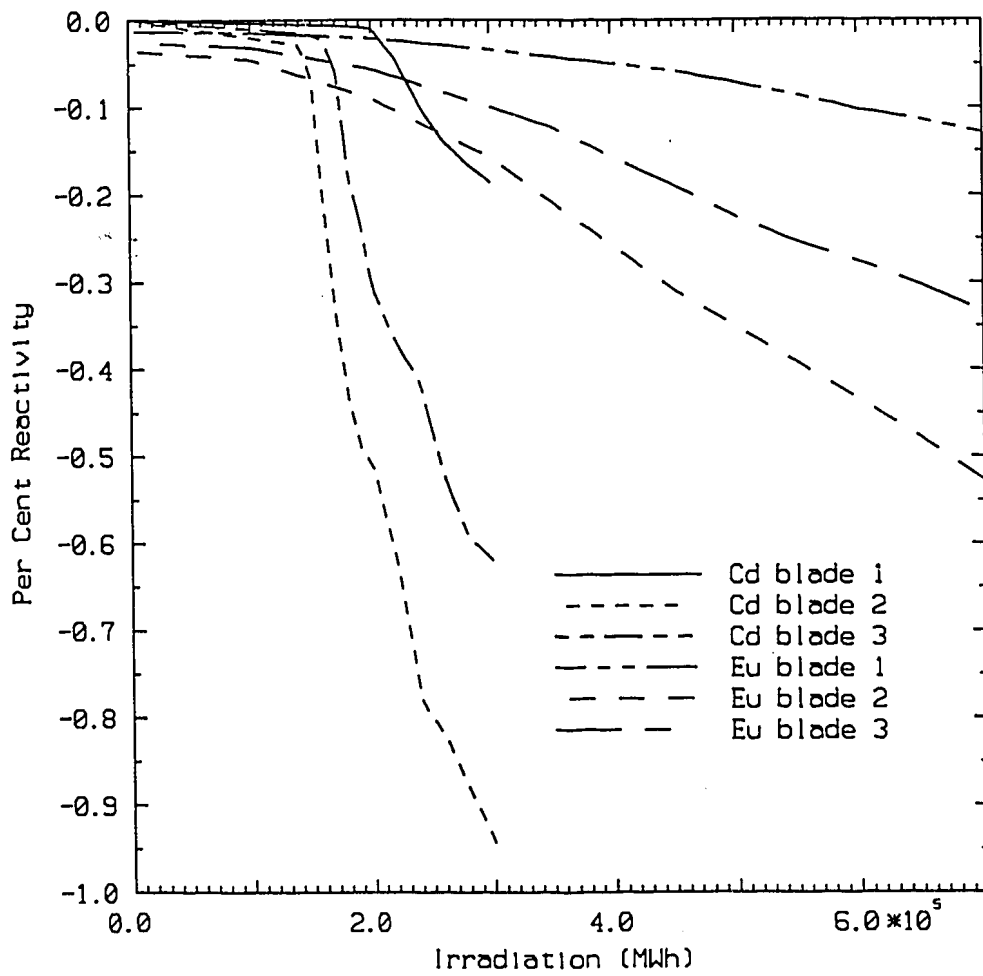


Figure 10 Loss in Reactivity Worth at 15° Relative to New Cd Blade for 22° Burn-up Angle