APR 28 1972

BNL 16726
R2 1016

MASTER

REACTOR

PHYSICS

DIVISION

BROOKHAVEN NATIONAL LABORATORY

Control Cluster Worths and Other Aspects
of PWR Safety Analysis

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

David J. Diamond

September 1970

ABSTRACT

Several studies of reactor physics problems pertinent to the safety of a PWR are presented. The emphasis is on the obtaining of control cluster worths which are of interest in the analysis of abnormal operating conditions. This has included ejected rod, stuck rod and dropped rod studies as well as worth changes for a cluster left in the core. The effect of various quantities on control cluster worth has also been considered. These studies take into account soluble boron concentration, burnup, and the effect of other clusters. This latter topic includes the effect of part length clusters and adjacent clusters. A study of the nuclear enthalpy rise hot channel factor is also given.

Introduction

There are numerous physics problems that are associated with the safety of a PWR. This report summarizes work that has been completed on some of these problems. The bulk of this work has been concerned with understanding the effects of control rod clusters. Their reactivity worth under different control bank configurations has been of prime concern. However, other peripheral problems such as their effect on power peaking factors are considered.

The purposes of these studies have been varied. Of importance has been the gaining of a general understanding of how a control cluster's worth changes under different circumstances. All of the calculations in this report were performed for the Indian Point No. 2 (IP2) reactor. However, many of the trends and general results are applicable to any PWR of comparable design. For some of the studies the objective was to obtain quantitative results which were needed to ascertain the severity of an accident situation. An example of this is the obtaining of cluster worths which are of interest, in connection with the rod ejection accident.

It was also of interest to obtain some results which might be compared with the reactor vendor's safety analysis report. This provided a check of the applicability of results reported on in that document. One further use of this work has been to provide results which are used as input to kinetic studies of PWR's.

After a description of the calculational methods that were used, the results and discussion are broken up into six sections. In the first section control bank worths are discussed. The second section contains control cluster worths which are of interest for the analysis of the rod ejection accident. Both beginning-of-life (BOL) and end-of-life (EOL) cases are considered. The next section includes cases of interest for an assortment of reasons. It includes a discussion of the stuck rod and dropped rod problems. In addition, the effect of boron concentration and the use of core symmetry in the calculations are considered.

The fourth section pertains to the effect of the part-length clusters on the worth of control clusters. The next section discusses the effect on power peaking of different control cluster configurations. The last section considers how the worth of the central cluster changes with time after being inserted into the reactor. Since this study employs a different calculational method than that used for the bulk of the other studies, a discussion of this method is also included. Following these sections a summary is presented.

Method of Analysis

The calculational procedure consists of three basic parts. The first is the obtaining of four group cross sections for each of the basic cells which make up the reactor. These cross sections are obtained using the HAMMER system. The basic cells for IP2 contain either an Ag-In-Cd control rod, a burnable boron poison rod, or a fuel rod with one of the three (2.2%, 2.7%, 3.2%) different enrichments. In addition, a control rod cell with the rod replaced by water and a cell containing just water to represent the reflector are calculated.

The next step is to develop cross sections for those regions of an assembly where two types of cells must be homogenized. This must be carried out since the final representation of the core cannot afford the number of mesh points needed to represent each cell explicitly. The homogenization technique is a "three square ring" (3SR) representation that is suggested by a similar procedure used by Sha.¹

A typical fuel assembly is shown schematically in Fig. 1a. The 15 x 15 array of cells contains 21 positions that are not occupied by fuel rods. The central position (marked by an 0) is left empty in order to serve as an instrumentation channel. The twenty other positions (marked by x's) may be in one of five different configurations for IP2. They may all be occupied by either control rods or empty control rod positions filled with water or they may contain 16, 12 or 6 burnable poison rods with the remaining 4, 8, or 14 positions left empty.

The k_{∞} for each type of assembly is calculated using the two dimensional diffusion theory code 2DB. This calculation employs several mesh points per cell. The assembly is then considered with the 3SR representation shown in Fig. 1b. Mesh points are taken at the axes of symmetry and at each of the boundaries of the three zones (delineated by the heavy lines) yielding a 6 x 6 representation for the assembly. The central square zone contains a mixture in which fuel cells and the central vacant cell are volume weighted. The outer zone utilizes cross sections for a fuel cell. The middle zone contains a mixture of fuel cells and cells which make up one of the five different configurations discussed above. The fuel cells are volume weighted so as to yield the correct amount of fuel in the assembly. The amount of other cells is obtained by performing a search calculation with 2DB in order to yield the k_{∞} calculated with the detailed representation.

Once this homogenization is done the final step is to run a reactor calculation with 2DB. Due to the symmetry of the reactor the calculations are done using a quarter core representation as shown in Fig. 2. Each assembly in the figure is marked by F1, F2, or F3 corresponding to the three different enrichments in increasing value. Assemblies with control clusters are marked by the bank they belong to. C1, C2, C3 and C4 are control banks and S1 and S2 are shutdown banks. XC are the clusters used to control possible xenon oscillations in the radial plane and PL are the part length clusters used for control of the axial flux distribution. Those assemblies marked by 16B, 12B and 6B contain the corresponding number of burnable boron poison rods. Each of the

assemblies has the 3SR representation previously discussed. The worth of a cluster or bank is obtained by running two 2DB problems with the required reactor configurations and with and without the cluster or bank of interest present. The reactivity is then given by $\Delta\rho = (k_1 - k_2)/k_1 k_2$ where k_1 and k_2 are the calculated eigenvalues.

The validity of the above procedure was ascertained by comparing a series of calculations with the corresponding measurements. Since measurements were not available for the IP2 reactor this comparison was made with data from the Connecticut Yankee (CY) reactor. The two reactors are similar. The comparison² showed that the calculational method was capable of giving agreement with the measurements that was within the experimental error involved.

Control Bank Worths

Results based on the above calculational scheme are shown in Table I for a number of control bank configurations. These and subsequent calculations refer to hot (500°F), zero power, beginning-of-life (BOL) conditions unless otherwise specified. Results at full power would be similar since the only parameter which changes is the fuel temperature. Some of the cases being considered are comparable to those reported on in connection with the FSAR³ for Indian Point No. 2. The worth of all control rods has been quoted as 8.50% at BOL. This compares favorably with the values of 8.74×10^{-2} and 8.88×10^{-2} given in Table I for two different soluble boron concentrations. Two values of k have been reported with all rods out and at boron concentrations of 0 and 1370 ppm. If these are converted to values at 450 ppm and 650 ppm respectively, the results are $k = 1.112$ and 1.071 . These values are to be compared with $k = 1.1138$ and 1.0892 as given in Table I.

The above adjustment of k was based on 89 ppm being equivalent to 1% in reactivity. This value is arrived at in connection with the FSAR. From Table I 0.01 in reactivity is found to be equivalent to 91 ppm and 81 ppm with all rods in and all rods out respectively. One other value for k quoted in the FSAR is for 650 ppm and all rods in. That value is 0.99 which compares well with the value of 0.9931 given in Table I.

The worths of the individual control rod banks given in Table I are for a situation where all control rods are initially inserted. The worth of the strongest bank is seen to be 2.61×10^{-2} .

TABLE I

Control Bank Worths

<u>Soluble Boron (ppm)</u>	<u>Control Banks Out</u>	<u>k</u>	<u>Reactivity₂ Worth x 10²</u>
450	All	1.1138	8.74
450	None	1.0150	
650	All	1.0892	8.88
650	None	0.9931	
650	C1	1.0132	2.00
650	C2	1.0063	1.32
650	C3	1.0194	2.60
650	C4	1.0133	2.01
650	S1	1.0132	2.00
650	S2	1.0101	1.69
650	XC	1.0195	2.61

Rod Ejection Studies at BOL and EOL

In this section control cluster worths which are of interest in the study of rod ejection accidents are considered. These are for situations where the last three control banks to be removed (C2, C3 and C4) remain in the core or the last two banks (C3 and C4) or just the C4 bank. Figure 3 shows the locations of the control clusters of interests.

Table II lists the results for both BOL and EOL. The BOL cases were done with a soluble boron concentration of 1250 ppm. The EOL cases were done using nuclide concentrations derived from a SIZZLE burnup calculation⁴ and were for a temperature of 550°F. The burnup calculation was for a one-dimensional mock-up of the Maine Yankee reactor. However, by a proper interpretation of the results they were extended to yield the fuel and boron poison depletion and fission product build-up expected for the IP2 reactor.

The coordinates of the clusters considered refer to Figure 3. Due to the symmetry of the core only those clusters in a one-eighth section need be considered. The largest worth of an ejected cluster is found to be 0.0024 at BOL and 0.0028 at EOL. Certain clusters are omitted from the list since it is known that their worths will be smaller than the maximum worth for that configuration. For example, at BOL with three banks in clusters C4(A,A) and C3(F,F) need not be considered. The region in which C4(A,A) is located is shielded by the C3 bank clusters surrounding it and C3(F,F) is near the core boundary. Their lower worths are borne out by the calculations done with just banks C3 and C4 initially in.

With the exception of case 8 all EOL values are higher than the BOL values. This is consistent with findings reported by Westinghouse in the IP2 FSAR. All of the worths are well below the conservative values of 0.8% Δk for EOL and 0.75% Δk for BOL used in the rod ejection accident analysis presented in the IP2 FSAR. These values were obtained for three and two banks initially in respectively.

Table II

Control Cluster Worths

<u>Case</u>	<u>Banks In</u>	<u>Clusters Removed</u>	<u>$\Delta p \times 10^2$, EOL</u>	<u>$\Delta p \times 10^2$, BOL</u>
1	C2, C3, C4	C3 (C, A)	0.19	0.17
2	C2, C3, C4	C2 (E, A)	0.27	0.24
3	C2, C3, C4	C4 (G, C)	0.28	0.22
4	C2, C3, C4	C3 (F, F)	0.15	-
5	C3, C4	C4 (A, A)	-	0.077
6	C3, C4	C3 (C, A)	0.20	0.18
7	C3, C4	C4 (G, C)	0.23	0.18
8	C3, C4	C3 (F, F)	0.096	0.11
9	C4	C4 (A, A)	0.27	0.21

Stuck Rods, Dropped Rods, and Other Cases

Table III lists additional cases at hot, BOL conditions which provide further insight into the effect of control clusters. Cases 1, 2 and 3 give the worth of the central cluster with all banks out and demonstrate the insensitivity of this configuration to soluble boron concentration. Case 4 shows that the worth of an off-center cluster is similar to that for the central cluster in this same configuration. This is an indication that the flux is relatively flat in the central region of the core with all banks out. These cases correspond to the accident situation wherein a central cluster drops into the core during normal operation. Kinetic studies reported on in the IP2 FSAR use values of $\Delta\rho = 0.0023$ and 0.0012 for dropped rod worths.

Case 5 gives the worth of the central cluster after ejection with banks C1 and C4 initially in. These two banks are not expected to be in the core during normal operation. The case is of interest, however, since it demonstrates how the worth of the central cluster increases as more of the core is effectively shut down. With all banks out (case 3) the worth of the central cluster is 0.0011. With banks C1 and C4 in, the outer region of the core is heavily poisoned and the worth of this cluster is now 0.0033. This trend continues with the entire core uniformly poisoned as in case 6. In this case one can think of the core as being defined by the unpoisoned nine assemblies in the central region. The worth of the central cluster is now 0.0065. This figure is not directly comparable to the previous two due to a different

Table III

Control Cluster Worths

<u>Case</u>	<u>Soluble Boron (ppm)</u>	<u>Banks In Initially</u>	<u>Clusters Moved</u>	<u>$\Delta\rho$/Cluster $\times 10^2$</u>
1	450	None	C4 (A, A)	0.11
2	650	None	C4 (A, A)	0.11
3	1250	None	C4 (A, A)	0.11
4	1250	None	C3 (C, A)	0.11
5	1250	C1, C4	C4 (A, A)	0.33
6	750	All	C4 (A, A)	0.65
7	750	All	C3 (C, A) or C3 (A, C)	0.69
8	750	All	C4 (A, A) and, C3 (C, A) or C3 (A, C)	0.88
9	750	All ^a	C3 (C, A) or C3 (A, C)	1.00 ^a
10	750	All ^b	C4 (A, A)	1.26 ^b
11	650	All	C4 (A, A)	0.74

^aWith C4 (A, A) out

^bWith C3 (C, A) or C3 (A, C) out

soluble boron concentration, however, it is indicative of how the worth of cluster increases as the effective core size diminishes.

Before further consideration of the cases with all banks in it should be noted that with bank S1 as one of the banks inserted there is an asymmetry in the core. If the upper right quadrant is considered in Fig. 4 it is seen that the assembly at coordinate (B,D) contains a control cluster whereas there is none at coordinate (D,B). The effect of assuming quarter core symmetry for purposes of the calculation is then to represent two of the clusters in bank S1 at incorrect positions. The correct positions for bank S1 clusters are shown in Fig. 2 and the shift for calculational purposes is indicated in Fig. 4.

The result of this is that if a cluster such as $C3(C,A)$ which is near this asymmetry is being considered it will have a different worth than its symmetric counterpart; $C3(A,C)$ in this case. To circumvent this difficulty and present a worth which is representative of the true physical configuration the worths given in cases 7 - 10 are arithmetic averages of the worths calculated using either $C3(C,A)$ or $C3(A,C)$ and hence are only approximate figures.

The worths with all banks in are of interest for the stuck rod problem. This is the situation wherein all banks are inserted into the reactor except for one or two clusters which remain stuck out of core. The worths of these clusters should be known in order to insure that adequate shutdown margin is present. Clusters $C4(A,A)$ and $C3(C,A)$ [or $C3(A,C)$] were studied since it was felt that the central region of the reactor would have the clusters

with the largest worth. Cases 6 and 7 show that the worths of those clusters is similar.

Cases 8 - 10 give the worth of these clusters when the adjacent cluster is also stuck out. In case 8 clusters $C4(A,A)$ and $C3(C,A)$ or $C3(A,C)$ are withdrawn simultaneously. The worth per cluster of 0.0088 implies that together the two clusters are worth 0.0176. In case 9 $C3(C,A)$ or $C3(A,C)$ is withdrawn with $C4(A,A)$ already out and in case 10 the roles of these clusters is reversed. The greater worth in case 10 is probably due to the fact that the calculation is done for a core quadrant.

The quadrant calculation means that the removal of a single cluster corresponds to the removal of four clusters from the reactor if the cluster is wholly within the quadrant and two clusters from the reactor if the cluster is on the x or y axes. The worth per cluster is obtained from the calculated worth by dividing by the appropriate number. This assumes that each cluster has a worth which is independent of the position of its symmetric counterparts. This is true in most circumstances and will be discussed further below. With all banks in, however, the effective core size is small and the effect of symmetric clusters may not be independent. For case 10 this becomes apparent. The removal of $C4(A,A)$ not only removes control material from the core center but also allows a coupling between the two non-poisoned regions of the core which were initially present due to the absence of $C3(C,A)$ (or $C3(A,C)$) and its symmetric counterpart. This coupling effect is not present in case 9 where the removal of $C3(C,A)$ (or $C3(A,C)$) just enlarges the central region of the reactor which is unpoisoned.

The last case in Table III gives the central cluster worth at a different boron concentration again with all banks in. By comparing this result with that for case 6 it is seen that the amount of boron in the reactor can affect cluster worth when the effective core size is small.

Table IV gives additional worths for clusters removed while two banks are in the reactor. They are primarily of interest for studying the symmetry in the core which allows the use of quadrant calculations to mock up the core. The first five cases are for banks C1 and C2 initially in. This is not expected to be a normal operating pattern but does provide additional control worth information.

The one-eighth core symmetry is demonstrated by comparing results for C2(E,A) vs. C2(A,E) and C1(D,F) vs. C1(F,D) which are seen to be similar. The differences that do arise are due to the numerical nature of the calculation. These results also provide an example of how clusters close to one another may affect reactivity independently. The worth per cluster when both C1(D,F) and C1(F,D) are removed is the same (within $1.0 \times 10^{-4} \Delta\rho$) as when each is removed separately. From Fig. 2 it is seen that these clusters are only separated by a single assembly diagonally between them.

Cases 6 - 10 are for banks C3 and C4 initially in. Cases 6 and 9 were previously reported in Table II. The remaining cases were obtained using a half-core representation which would correspond to the upper half of the core shown in Fig. 3. The removal of cluster C3(C,A) in the quadrant calculation had

Table IV

Control Cluster Worths

<u>Case</u>	<u>Soluble Boron (ppm)</u>	<u>Banks In Initially</u>	<u>Clusters Removed</u>	<u>Δp_2 $\times 10^2$</u>	<u>$\Delta p/\text{cluster}$ $\times 10^2$</u>
1	1300	C1, C2	C2 (E, A)	0.35	0.18
2	1300	C1, C2	C2 (A, E)	0.32	0.16
3	1300	C1, C2	C1 (D, F)	0.48	0.12
4	1300	C1, C2	C1 (F, D)	0.47	0.12
5	1300	C1, C2	C1 (D, F) , C1 (F, D)	0.98	0.12
6	1250	C3, C4	C3 (C, A)	0.36	0.18
7	1250	C3, C4	C3 (C, A)	0.20 ^a	0.20 ^a
8	1250	C3, C4	C3 (A, C)	0.37 ^a	0.19 ^a
9	1250	C3, C4	C4 (G, C)	0.71	0.18
10	1250	C3, C4	C4 (C, G)	0.31 ^a	0.16 ^a

^a Half-core representation

implied the removal of two clusters. With the half-core representation the removal of this single cluster gives a worth of $\Delta p = 0.0020$ whereas the quadrant calculation gives $\Delta p = 0.0018$. The difference is within the error involved in this type of problem. It should be noted that the half-core problem was not an exact doubling of the quadrant problem. Due to the limitations of computer storage the central region of each assembly which previously had been represented by four mesh boxes, had only a single mesh box representation in the half-core problem.

The removal of $C3(A,C)$ provides another example of the effect of symmetric clusters on the calculation. Due to the one-eighth core symmetry the worth of $C3(A,C)$ should be the same as for $C3(C,A)$. With the half-core representation $C3(C,A)$ is removed by itself to give a worth of $\Delta p = 0.0020$ whereas $C3(A,C)$ is removed with its symmetric counterpart in the lower half core and gives a worth of $\Delta p = 0.0019$.

An additional example is provided by the calculations given for cases 9 and 10. The half-core calculation of $C4(C,G)$ implies the removal of two clusters whereas the quadrant calculation for $C4(G,C)$ implies the removal of four clusters. Again the worth per cluster for these cases is similar.

Effect of Part-Length Rods

In addition to the normal control clusters the IP2 reactor has eight part-length (PL) clusters. These clusters differ from the others in having an active length of only one-fourth of the fueled height of the core. They are used for control of the axial power distribution. In order to see how these clusters affect the worth of the control clusters it would be desirable to have a three dimensional calculation of the reactor. However, since this is not possible, the usual two dimensional representation was used to provide an upper bound on the worths with the PL bank in.

The effect of the PL clusters is to enhance the worth of other clusters since the flux depression due to the PL bank is compensated for by an increase in flux in other regions of the reactor. The calculations whose results are shown in Table V have the positions of the PL bank represented by full clusters. The calculation then represents an axial region in the reactor where all the PL clusters are positioned and overemphasizes their effect. The actual worth of a control cluster is some appropriately weighted average of the worths given with and without the PL bank in.

The results given in Table V are for clusters with the highest worths for the two bank patterns considered. The reactor configuration with the C3, C4 and PL banks in is shown in Fig. 5. Although the effect of the PL bank is to increase the worth of a control cluster, the upper bounds shown are not excessive. It is expected that the most important effect of the PL clusters will be related to the axial flux shape which was not investigated here.

Table V

Effect of Part-Length Rods

<u>Case</u>	<u>Banks In Initially</u>	<u>Cluster Removed</u>	$\Lambda_p/\text{cluster} \times 10^2$	
			<u>Without PL Bank</u>	<u>With PL Bank</u>
1	C3, C4	C3 (C, A)	0.18	< 0.25
2	C3, C4	C4 (G, C)	0.18	< 0.29
3	C4	C4 (A, A)	0.21	< 0.38

Power Peaking

Another parameter of interest with regard to reactor safety is the nuclear enthalpy rise hot channel factor $F_{\Delta H}^N$. Since a large number of reactor calculations had been performed for the analysis of cluster worths it was decided to use these same calculations to supply information on this quantity. Although not the optimum scheme for obtaining $F_{\Delta H}^N$, it was felt that these calculations could supply reasonable estimates of the hot channel factor.

A disadvantage in using the usual 2DB representation is that each fuel cell within an assembly is not represented explicitly. The 15 x 15 rod assembly is homogenized to a 6 x 6 array using the 3SR technique as depicted in Fig. 1. This means that the power density for a 2DB mesh box is actually an average over four or more fuel cells. In order to obtain a more accurate $F_{\Delta H}^N$ two steps were necessary. The first involved the obtaining of the maximum power density from the reactor calculation. The ratio of this maximum power to the core average power then gave a "gross" power peaking factor F^{Gross} . In order to obtain a correction factor which would take into account the variation in power across a 2DB mesh box the type of assembly and the location within that assembly where the maximum power occurred were noted. The correction factor of "local" power peaking factor F^{Local} was then obtained from a separate 2DB calculation of the appropriate assembly type. These detailed assembly calculations had already been run as part of the 3SR homogenization technique and involved the use of six mesh points per lattice pitch. The average

power for the region of the assembly which corresponded to the 2DB mesh box with the maximum power density in the reactor problem was calculated. In addition the power density within this region for the fuel cell with the highest power was calculated. The ratio of these powers was then F^{Local} .

The above scheme was applied to the IP2 reactor with 1250 soluble boron. The cases considered are given in Table VI. The coordinates of the position of peak power are represented by both letters and numbers. The letters correspond to the core quadrant shown in Fig. 2 and the numbers correspond to the assembly representation shown in Fig. 1b.

The results indicate that for all banks out, either for normal operation or with a single cluster inadvertently left in, the nuclear enthalpy rise hot channel factor $F_{\Delta H}^N$ does not exceed the design limit of 1.75. With bank C4 in, either fully or with a cluster inadvertently left out, $F_{\Delta H}^N$ exceeds the above limit. The reactor, however, is not expected to be operated with any bank fully in.

The calculations do not take into account the power flattening effect of Doppler broadening and equilibrium xenon. In addition, those calculations for a single cluster left in the core will tend to overestimate the power peaking due to the fact that they are done for a core quadrant. With the exception of the case for the central cluster, the insertion of a control cluster in the 2DB core quadrant implies the inserting of the symmetric clusters in the other quadrants. This means the core is poisoned in several locations and hence

Table VI

Power Peaking Factors

A) All Banks Out

<u>Cluster In</u>	<u>F^{Gross}</u>	<u>F^{local}</u>	<u>F^N_{ΔH}</u>	<u>Peaking Position</u>
-	1.38	1.05	1.45 ^a	(E3, E3)
C4 (A, A)	1.43	1.05	1.50	(E3, E3)
C3 (C, A)	1.48	1.05	1.55	(E3, E3)
XC (C, C)	1.54	1.02	1.57	(B1, G1)
C3 (F, F)	1.55	1.02	1.58	(B6, C1)
C4 (G, C)	1.69	1.02	1.72	(B1, G1)

B) Bank C4 InCluster Out

-	1.72	1.02	1.75 ^b	(C1, D1)
C4 (A, A)	1.87	1.02	1.91	(B6, C1)
C4 (G, C)	1.77	1.02	1.81	(G1, B1)

a) FSAR Value = 1.41

b) FSAR Value = 1.70

the power peaking will be increased. This assumption has been tested and substantiated by performing a number of calculations with a half-core representation.

It is difficult to assess the accuracy of the above calculations due to the many approximations inherent in the analysis. A comparison of two of the power peaking factors with numbers quoted in the Indian Point No. 2 FSAR³ is shown in Table VI. The present analysis gives results about 3% higher than those given by Westinghouse. Two cases for a single cluster left in the reactor were run using a half-core representation. These cases considered the same number of clusters as are implied inserted in the quadrant calculation as being in. The only difference between the half-core and quadrant problems was in the mesh size; a difference necessitated by the greater computer storage requirements for the half-core problem. The differences in $F_{\Delta H}^N$ due to this slight change in the analysis was $\pm 6\%$. In conclusion, it is felt that the present results are sufficiently accurate to say that the radial power peaking will not be excessive with a single cluster inadvertently left in the core.

Worth Change of Cluster Left in Reactor

It was also of interest to see how the worth of a control cluster changes with time after being inserted and left in the reactor. In order to do this a simple one-dimensional model of the IP2 reactor was employed and the central cluster was chosen for study. Since this analysis necessitated a different calculational model than that used for the previously discussed studies, a brief description of the calculational method follows.

The one-dimensional model of the IP2 reactor is shown in Fig. 6. The central three regions represent the central assembly of the reactor. They are the cylindricalized version of the 3SR representation used in the two dimensional studies. The first and third regions contain fuel cells while the second region contains the appropriate homogenization of fuel cells and either control rod cells or the same cells with water replacing the control rods. The fourth region is a volume weighted homogenization of the remaining assemblies with the two lowest enrichments. The fifth region is a similar homogenization of the assemblies with the highest enrichment and the outermost region represents the reflector.

Burnable boron poison rods as well as water filled control rod positions are taken into account in the homogenization. All control rods (with the exception of the central cluster) are considered fully withdrawn. The four group microscopic and macroscopic cross section were obtained from HAMMER calculations.

In order to assess how good this representation of the

reactor was, the worth of the central cluster was obtained at BOL using the diffusion theory burnup code SIZZLE. The result was $\Delta\rho = 0.00071$ which differs somewhat from the value of 0.0011 obtained using the two dimensional representation with 2DB. The difference is not unexpected due to the gross homogenization of the core. However, since it is the changes in worth with burnup that are of interest it was felt that the representation with SIZZLE would be adequate for that purpose.

A SIZZLE calculation for 21 days without the central cluster was first run in order to obtain the nuclide concentrations in the reactor with equilibrium xenon. The reactor was assumed to be at 2758 Mwt. With these new concentrations another SIZZLE run was performed for up to 21 days with the central cluster in. Each of these runs was broken up into smaller time steps in order to obtain the nuclide concentrations as a function of time. The code automatically adjusted the soluble boron concentration at each time step to keep $k = 1.0$. The concentrations at a particular time step were then used to run SIZZLE calculations with and without the central cluster inserted in order to obtain the worth at that particular time.

The results are shown in Fig. 7 where for convenience the lower end of the time scale has been expanded. After 21 days of operation with no control clusters the worth of the central cluster (shown at $t = 0$ on Fig. 7) has increased to $\Delta\rho = 0.00093$ from 0.00071 at BOL. This is the result of an increase in the flux level in the central assembly which occurs as part of a general flux flattening due to burnup. Fig. 8 shows the source density as a function of position at BOL and after 21 days. From the graph it is readily seen

that the higher flux level in the outer region of the core at EOL leads to increased burnup in this region and thence to the flux flattening.

From Fig. 7 it is seen that within the first eight hours the worth drops slightly. This is due to the buildup of xenon within that time interval. The xenon concentration increases since with the reduced flux in the assembly due to the presence of the control cluster there is less burnup. At the same time, there is still xenon being produced from the decay of the iodine whose concentration is determined from the flux level prior to insertion. (Recall that the half-life of I^{135} is 6.7 hrs.) The increased xenon means that when the cluster is removed the flux is still relatively depressed and hence the worth is diminished.

As time increases the xenon concentration in the central assembly again equilibrates but at a lower level due to the presence of the control rods. There is a continuing buildup of non-saturating fission products and a depletion of fissile material. However, since the flux is depressed in this assembly this occurs to a lesser degree than in the rest of the reactor. This means that when the control cluster is removed the flux in this assembly will be increased relative to the flux in the other regions, hence, as can be seen on Fig. 7 the worth of the central cluster increases with time after the first half day. After 21 days the worth has increased by 16%.

In order to see if this effect is enhanced by having a stronger control cluster an additional calculation was performed. This new calculation was similar to the one just

discussed but had the control cluster replaced by a material with an absorption cross section ten times the value for the original cluster. Since the original cluster was "black" to begin with, the worth at zero time only goes from $\lambda_p = 0.00093$ to 0.00120. After being inserted for 21 days the new cluster increases its worth by 22%. This increase over the 16% figure for the original cluster is indicative of the stronger effect on burnup that this cluster has. The results for the new cluster are also shown in Fig. 7.

Summary

This report is itself a summary of several studies of reactor physics problems pertinent to the safety of a PWR. The emphasis has been on the obtaining of central cluster worths which are of interest in the analysis of accident or abnormal operating conditions. Those cases have included ejected rod, stuck rod and dropped rod studies as well as worth changes for a cluster left in the core. The results of these studies gave quantitative values for these worths and showed that the worths were not excessive relative to the situation being studied.

In addition these results were compared where possible with values given in the IP2 FSAR. General agreement was found for the cases cited above as well as for an assortment of other cases. These latter problems included bank worths and individual cluster worths which were of interest for gaining a better understanding of the effect of control rods. The effects on cluster worths of soluble boron concentration, part length clusters, adjacent clusters, and the diminishing of effective core size by the insertion of control banks have been considered. Discussions of the interdependence of clusters and the use of core symmetry in the calculations are also given.

Power peaking was also studied and the nuclear enthalpy rise hot channel factor was calculated. The design limit was found not to be exceeded under normal operating conditions.

References

1. W. T. Sha, "An Analysis of Reactivity Worth of the Rod Cluster Control (RCC) Elements and Local Water-Hole Power Density Peaking", WCAP-3269-47, Westinghouse Atomic Power Divisions, Pittsburgh (1965).
2. D. J. Diamond, "Some Comments on the Stuck Rod Measurement", BNL RP-1015, August (1970).
3. Consolidated Edison Co. of N.Y., Inc., Indian Point Nuclear Generating Unit No. 2, Final Facility Description and Safety Analysis Report, USAEC Docket No. 50-247 (1968).
4. L. Epel, Personal Communication (May 1970).

1a. Fuel Assembly

1b. Assembly 3SR Representation

Figure 1

LY

H	6B F3	F3	6B F3	F3				
G	XC F1	16B F2	C4 F1	12B F3	F3	6B F3		
F	12B F2	S2 F1	12B F2	C1 F1	16B F2	C3 F3	6B F3	
E	C2 F1	12B F2	PL F1	16B F2	S1 F2	16B F2	F3	
D	16B F2	S1 F1	12B F2	F1	16B F2	C1 F1	12B F3	F3
C	C3 F1	12B F2	XC F1	12B F2	PL F1	12B F2	C4 F1	6B F3
B	16B F2	F1	12B F2	F1	12B F2	S2 F1	16B F3	F3
A	C4 F1	16B F2	C3 F1	16B F2	C2 F1	12B F2	XC F1	6B F3
	A	B	C	D	E	F	G	H

Core Quadrant

Figure 2

Banks C2, C3 and C4

Figure 3

A B C D E F G													
			C4		XC		C4						G
	C3		C1		S2		S2		C1		C3		F
		S1				C2				S1			E
	C1			S1		S1				C1			D
C4				XC		C3		XC				C4	C
	S2		S1							S2			B
XC		C2		C3		C4		C3		C2		XC	A
	S2								S1		S2		
C4				XC		C3		XC				C4	
	C1				S1		S1				C1		
		S1				C2				S1			
	C3		C1		S2		S2		C1		C3		
			C4		XC		C4						

Figure 4

Banks C3, C4 and PL

Figure 5

IP2 Representation

<u>Region</u>	<u>Radius (cm)</u>
1	5.65
2	8.85
3	12.13
4	137.80
5	168.54
6	185.00

Figure 6

Figure 7

Figure 8