C-E Power Systems
Combustion Engineering, Inc.
1000 Prospect Hill Road
Windsor, Connecticut 06095

Tel. 203/688-1911
Telex: 99297

POWER SYSTEMS

RECEIVED
FEB 24 1982
US NUCLEAR REGULATORY COMMISSION
DOCUMENT MANAGEMENT BR
TIDC

February 19, 1982
LD-82-021

Mr. James R. Miller, Chief
Standardization and Special Projects Branch
Division of Licensing
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Subject: Revised Responses to Second Round Questions on CENPD-225-P

Reference: A) Letter J. R. Miller to A. E. Scherer, dated November 17, 1981
B) Letter A. E. Scherer to J. R. Miller, dated January 28, 1982, LD-82-007

Dear Mr. Miller:

Attached are revised responses to Request Number 2 for Additional Information on CENPD-225-P, "Fuel and Poison Rod Bowing". These revised responses supply the additional information requested during our telephone discussions with Mr. Powers (NRC) and others of February 10 and 11, 1982 and supercede the responses provided by Reference (A). As requested during that telephone call, copy 000001 has been forwarded directly to Mr. Powers and copy 000002 to Dr. Carew (BNL) by a copy of this letter. One copy each of the non-proprietary version has been sent to each of them also.

The proprietary nature of this material is attested to in the affidavit forwarded by Reference (B).

If you have any questions, please contact me or Mr. J. E. Rogers of my staff at (203)688-1911, Extension 3028.

Two Rids T007 - Responses to Questions (2nd Round) on CENPD-225P
8/1/15

T008 Responses to Questions (2nd Round) on CENPD-225 Non-Prop
51/15

Very truly yours,

COMBUSTION ENGINEERING, INC.

A. E. Scherer
Director
Nuclear Licensing

AES/cw

Attachment: (1) Copy numbers 000001-000015 of proprietary responses
(2) 15 copies of non-proprietary responses

Revised Responses to Second Round Questions on CENPD-225, Fuel and Poison Rod Bowing

February 1982

COMBUSTION ENGINEERING, INC.

LEGAL NOTICE

THIS REPORT WAS PREPARED AS AN ACCOUNT OF WORK SPONSORED BY COMBUSTION ENGINEERING, INC. NEITHER COMBUSTION ENGINEERING NOR ANY PERSON ACTING ON ITS BEHALF:

A. MAKES ANY WARRANTY OR REPRESENTATION, EXPRESS OR IMPLIED INCLUDING THE WARRANTIES OF FITNESS FOR A PARTICULAR PURPOSE OR MERCHANTABILITY, WITH RESPECT TO THE ACCURACY, COMPLETENESS, OR USEFULNESS OF THE INFORMATION CONTAINED IN THIS REPORT, OR THAT THE USE OF ANY INFORMATION, APPARATUS, METHOD, OR PROCESS DISCLOSED IN THIS REPORT MAY NOT INFRINGE PRIVATELY OWNED RIGHTS; OR

B. ASSUMES ANY LIABILITIES WITH RESPECT TO THE USE OF, OR FOR DAMAGES RESULTING FROM THE USE OF, ANY INFORMATION, APPARATUS, METHOD OR PROCESS DISCLOSED IN THIS REPORT.

QUESTION #1

Does the available data indicate that rod bow is greater in regions of limiting DNBR and if so, how is this accounted for in the statistical analysis?

Response

There are no measurements available to determine whether rod bow is greater in regions of limiting DNBR. The limiting DNBR usually occurs on rods around the guide tube. Due to the geometry of the C-E design, it is not possible to measure the fuel rod to guide tube channel closure without disassembling the bundle. However, assembly bow measurements made on irradiated assemblies at poolside show that the curvature of the guide tubes between grids is of the same order of magnitude or less than the fuel rod bow curvature between grids that is necessary to explain measured channel closures. The use of the rod to rod channel closure correlation, is therefore conservative when also applied to the fuel rod to guide tube channel.

QUESTION #4

The channel geometry changes which result in the DNBR penalty may be due to multiple rod displacements as well as single rod displacement configurations. What is the effect of multiple rod displacements and gap closures on the DNBR penalty function and how is this effect accounted for?

and

QUESTION #26

The DNBR penalty resulting from channel closure is determined by summing the penalties for each of the individual gaps. Each gap penalty is determined by summing over the contributions from each possible closure. The closure contribution is given by the product of the probability of occurrence for that closure and the associated closure penalty. Therefore, include in the calculation of the DNBR penalty the contributions arising from all of the individual gaps.

Response 4 & 26

A telephone communication was held between D. Powers (NRC), J. Carew (BNL), and representatives of C-E on November 13, 1981 to obtain further clarification on the second round of questions on Ref. 2, since these questions are repeated from round one questions. Mr. Carew explained that questions 4 and 26 concern the effect of multiple rod bowing (bowing of the four rods nearest to the limiting rod) on the minimum DNBR as compared to the effect due to single rod bowing. He also explained that the questions requested a description of the method used to account for the effect of multiple rod bowing in thermal margin calculations. The following combined response to these two questions (4 & 26) is based upon this understanding.

There are two effects of fuel rod bowing on minimum DNBR. The first is the interference of the bowed rod(s) with the boundary layer around the limiting rod, the second is the effect of the bowed rod(s) on average coolant conditions in channels surrounding the limiting rod. The limiting rod is the rod which experiences the minimum DNBR. The combined effect of these two factors was investigated by a test conducted at the Columbia University Heat transfer Research Facility for a single rod bowed situation. The results of this test were reported to the NRC in Reference 3. In this test, the heated rod was bowed diagonally into the small side subchannel around the guide tube to reduce the rod-to-rod spacing by approximately 54 percent. With this bowed configuration, the flow area of the small subchannel was reduced significantly. The results from the test showed no reduction in the bundle power to DNB. Two conclusions can be drawn from the test results. First, that the heated rod was not bowed enough to interfere with boundary layer and second that even a significant reduction in the limiting channel flow area had no effect on the margin to DNB.

The rod which is closest to the limiting fuel rod in a multiple bow configuration is most significant with regard to the boundary layer effect of rod bow, since this rod has greatest impact on the boundary layer. Therefore, the single rod bowed tests reported in Reference 3 in which the heated rod has been bowed by the [ ] encompass the multiple rod bowed situations regarding the effect on DNB due to interference with the boundary layer.

The effect on DNB due to the reduction in flow area caused by multiple rod bowing in channels surrounding the limiting rod has been investigated using the "TORC" computer code (Ref. 1).

DNBR subchannel analyses have been performed (with the C-E 16x16 fuel design) for the nominal and the bowed configurations shown in Figure 4-2. The rods are bowed in a cosine shape with the maximum bow occurring at the mid-span between spacer grids 9 and 10 where the minimum DNBR occurs for the nominal case (see Figure 4-3).

Since the effect due to bowing of the distant rods on the limiting rod is small, only the four rods nearest to the limiting rod are considered in the TORC analyses. Although each rod has an equal probability of bowing in any direction, the directions of bow shown in Figure 4-2 are bounding, and therefore, conservative since the channels surrounding the limiting rod experience the maximum reduction in the flow area with these configurations. In addition, in order to maximize the effect of bowing on channel flow areas, the rods have been bowed by amounts which have the same probability of occuring as the maximum observed single rod bow based upon the channel closure measurements (total number of measurements roughly equal to 50,000) made on the C-E 14x14 spent fuel assemblies. Gap closure measurements made on the 16x16 type assemblies (ANO-2 spent fuel assemblies from the first cycle) indicate no worse trend compared to the 14x14 fuel design.

In the single rod bowing case, therefore, the rod has been bowed by an amount which reduces the nominal gap between two rods by [ ] percent (maximum observed channel closure). For the two, three and four rods bowing cases, each rod has been bowed by an amount which reduces the nominal gap betwen each of the two rods by [ ] perent, respectively. This provides a conservative estimate of an equally probable configuration (i.e., with multiple rods bowed, since the direction has been chosen to maximize the impact of bowing).

TORC cases were run for the nominal and bowed configurations shown in Figure 4-2 for the operating conditions provided in Table 4-1 which yielded a minimum CE-1 DNBR close to the design limit of 1.19. The minimum DNBR results obtained from these analyses are presented in Table 4-1 for channels surrounding the limiting rod in the nominal and bowed configurations. As the table shows, the differences between single and multiple bowed rod DNBRs are very small and thus will have an insignificant effect on core thermal margin to DNB.

Based upon the above results, it can be concluded that for the conservative multiple rod bow situations considered here the reduction in DNBR is essentially the same as the reduction associated with single rod bowing. Therefore, the combined effect (interference with the boundary layer and reduction in channel flow areas) due to single rod bowing on minimum DNBR encompasses multiple rod bowed situations, and no additional penalty on DNBR is required to account for multiple rod bowing.

As was requested by the NRC and BNL representatives during February 10-11, 1982 telephone communications, two additional bowed configurations (g) and (h) shown in Figure 4-4 have been analyzed using the "TORC" computer code. In these cases we have assumed a maximum gap closure of [ ] between two rods while varying the gap closure of a neighboring rod from 10 to 40%. Another bowed configuration (i) shown in Figure 4-4 has also been analyzed for comparison. In this instance we have simply repeated case (h) omitting the [ ] gap closure between the two rods of interest. The minimum DNBR results obtained from these analyses are presented in Table 4-2 for channels surrounding the limiting rod.

As the table shows, the differences between minimum DNBR results from case (b) and case (g) are very small. Also, the differences in minimum DNBR between cases (i) and (h) are no greater than the differences in minimum DNBR between cases (a) and (b). Thus, the adverse T-H effects associated with the occurrence of extreme fuel rod bow in the presence of another bowed fuel rod (cases (i) and (h)) are no worse than the effects associated with the single rod bow (cases (a) and (b)). The results of these additional analyses further substantiate the conclusion that no additional DNBR penalty is required to account for multiple rod bowing.

REFERENCES

1. TORC Code, A Computer Code for Determining the Thermal Margin of a Reactor Core", CENPD-161-P (Proprietary), CENPD-161 (Non-Proprietary), July, 1975.

2. Fuel & Poison Rod Bowing, CENPD-225-P (Proprietary), October, 1976.

3. Fuel & Poison Rod Bowing, Supplement 2-P (Proprietary) to CENPD-225-P (Proprietary), June, 1978.

TABLE 4-1

Minimum DNBR in Channels Surrounding the Limiting Rod
for Nominal and Several Bowed Configurations

	Minimum DNBR in Channels Surrounding the Limiting Rod					
Channel Number	Nominal Case(a)	Single Rod Bowed Case(b)	Two Rods Bowed Case(c)	Two Rods Bowed Case(d)	Three Rods Bowed Case(e)	Four Rods Bowed Case(f)
21	[					]
22						
30						
31						

OPERATING CONDITIONS

Inlet Temperature = 553.5°F

System Pressure = 2250 psia

Inlet Mass Velocity = 2.34×10^6 lbm/hr-ft^2

TABLE 4-2

Minimum DNBR in Channels Surrounding the
Limiting Rod for Nominal and Several
Additional Bowed Configurations (g, h & i)*

Minimum DNBR in Channels Surrounding the Limiting Rod					
Channel Number	Nominal Case(a)	Single Rod Bowed Case(b)	Two Rods Bowed Case(g)	Two Rods Bowed Case(h)	Single Bowed Case(i)
21					
22					
30					
31					

*See Figure 4-4

XX ROD RADIAL POWER FACTOR
XX ROD IDENTIFICATION NUMBER

FIGURE 4-1 SUBCHANNEL MODELLING SCHEME AND ROD RADIAL POWER FACTORS

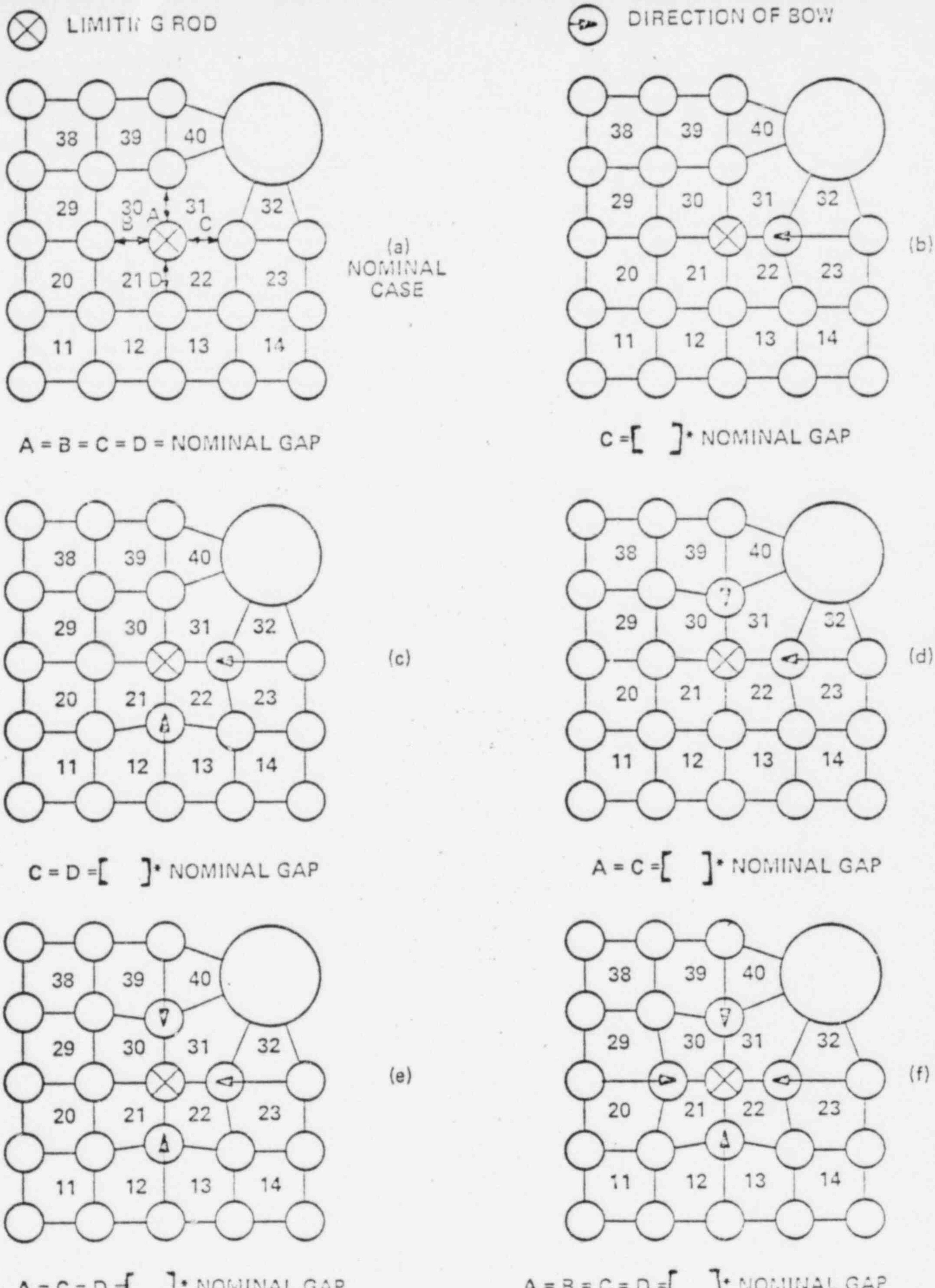


FIGURE 4-2 . BOWED CONFIGURATIONS (b - f) ANALIZED ON "TORC" COMPUTER CODE

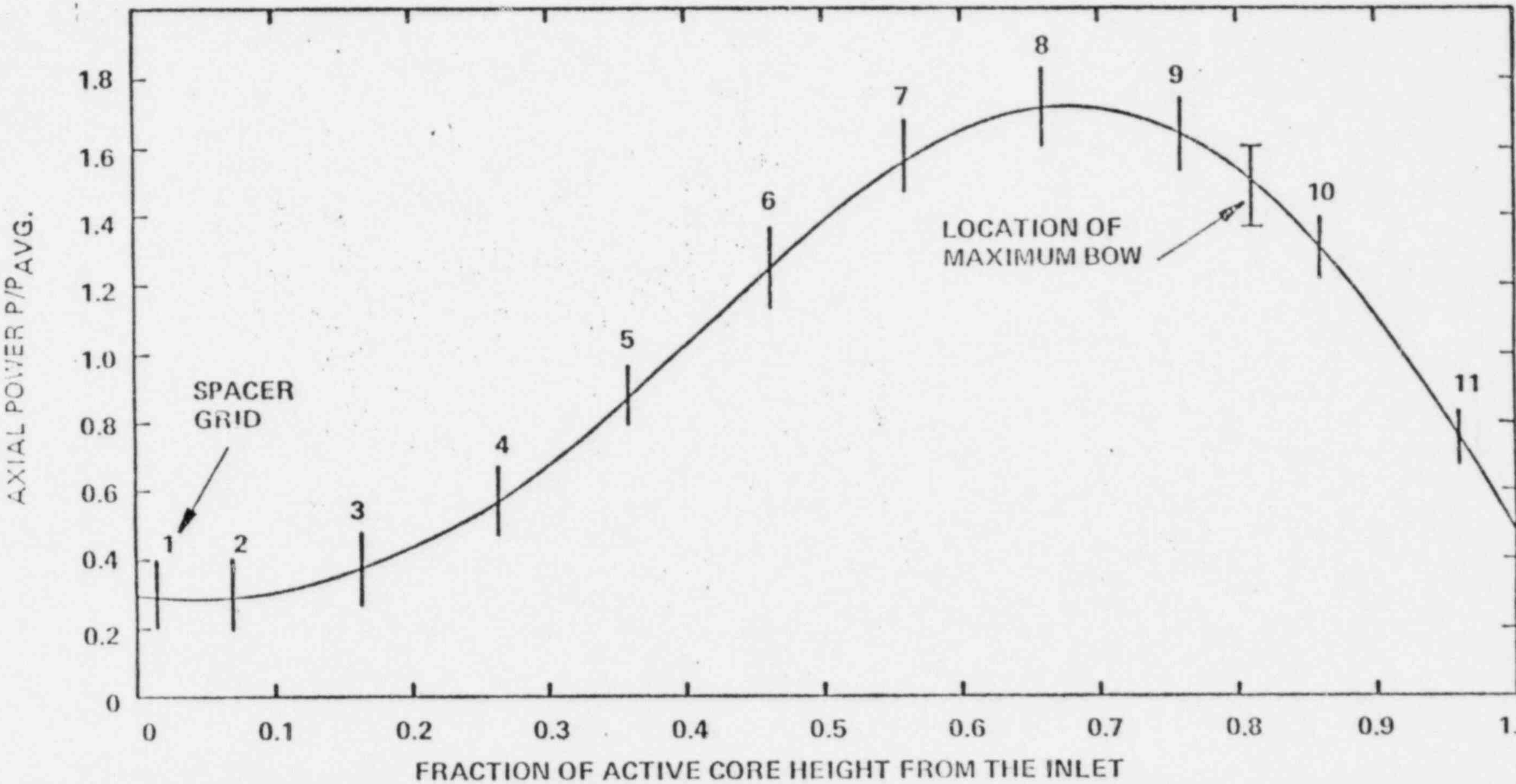
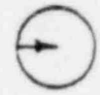
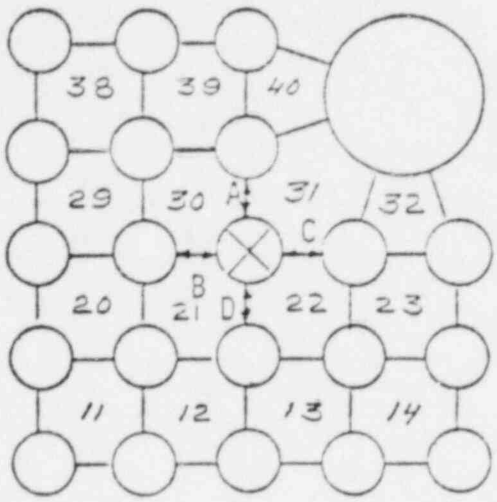


FIGURE 4-3 AXIAL POWER DISTRIBUTION USED IN TORC SUBCHANNEL ANALYSES

LIMITING ROD



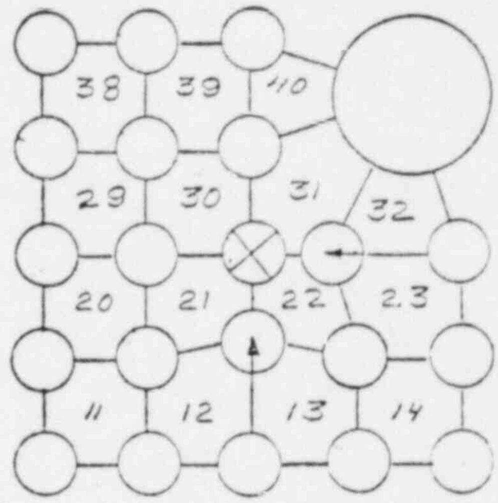
DIRECTION OF BOW



(a)

NOMINAL CASE

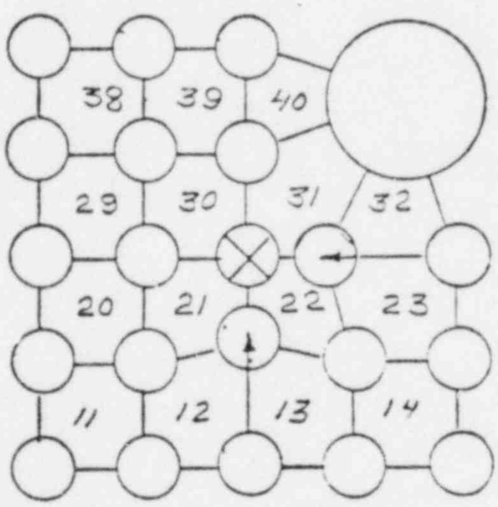
A = B = C = D = NOMINAL GAP



(g)

C = [ ] x NOMINAL GAP

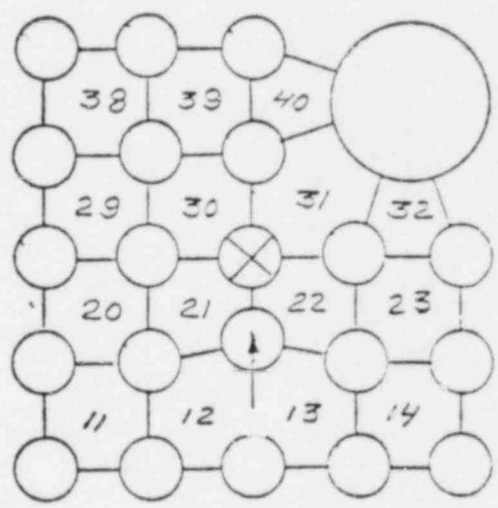
D = 0.90 x NOMINAL GAP



(h)

C = [ ] x NOMINAL GAP

D = 0.60 x NOMINAL GAP



(i)

D = 0.60 NOMINAL GAP

FIGURE 4-4 ADDITIONAL BOWED CONFIGURATIONS (g - i) ANALYZED ON "TORC" COMPUTER CODE

Question 14:

Provide a typical range of design parameters (including variations in enrichment, exposure, poison rods, geometry, etc. covering all NSSS supplied) to which this analysis is applicable and indicate why the calculated sensitivies cover these variations.

Response

Typical ranges of fuel design parameters which can influence the calculated sensitivities* are given below:

a) Assembly geometry: 14x14 or 16x16

b) Enrichment: 1.9 to 4.5 w/o

c) Exposure: 0 to 50,000 MWD/T

d) Poison Rods: Type 3 design, $B_4C\text{-}AL_2O_3$ with loadings of up to 0.0281 and 0.0142 grams/B-10 per inch for 14x14 and 16x16 assemblies, respectively.

---

* Is is assumed that the "calculated sensitivities" referred to in this question are, using the terminology of CENPD-225-P, the linear heat rate augmentation coefficients defined by Eq. 4.2-51. These calculated coefficients are combined with the standard deviation of gap closure to determine the penalty due to fuel rod bow (cf. Eq. 4.2-52). The standard deviation of gap closure is based upon measurements. This quantity is dependent on burnup, assembly type, assembly length, and grid spacing. CENPD-225-P and its supplements describe the methods used to reflect these design variables in the determination of the standard deviation of gap closure.

In order to establish the sensitivity of the coefficients (referred to as linear heat rate augmentation factors in CENPD-225-P) to these important design parameters, parametric analyses were performed. The case list for these parametric analyses is summarized in Tables 4.2-1 and 4.2-2 of CENPD-225-P. The applicability of these parametric analyses to the above range of typical fuel design parameters is discussed below.

1. Geometry

As indicated in the above cited tables, sensitivity coefficients were calculated explicitly for both 14x14 and 16x16 fuel. Coefficients were generated explicitly for each geometry type and are reported in Table 4.2-2. Bowing augmentation factors are thus calculated separately and explicitly for fuel assemblies of the 14x14 and 16x16 designs. With the exception of the Palisades reactor, which employs a 15x15 assembly design, all C-E reactors use either 14x14 or 16x16 fuel. The calculated sensitivites are thus applicable to all C-E reactors with the exception of Palisades. C-E is not presently performing the reload design for the Palisades reactor; if in the future C-E performs the reload design for cores employing 15x15 fuel, sensitivity coefficients would be recalculated for this fuel type to either develop an explicit correlation for 15x15 fuel or to demonstrate that the correlations developed for 14x14 or 16x16 fuel can be conservatively applied.

2. Initial Enrichment

As indicated in Table 4.2-1, calcuations were performed explicitly for enrichments up to 3.6 wt%. At the time CENPD-225-P was written, this enrichment represented an upper bound for C-E reload cores. However, higher enrichments, up to 4.5 wt%, are anticipated in the future for cores employing extended discharge burnup. Enrichment dependence is included in the calculated sensitivites through Equation 4.2-53, which contains a linear functional dependence on initial enrichment. In establishing the augmentation factors, this equation is evaluated at an enrichment equal to or greater than the highest enrichment present in the core since the coefficients increase with enrichment (although the enrichment sensitivity is not large, as shown in Figure 4.2-12). Inspection of the maximum power increase given in Table 4.2-1 for initial enrichments between 3.0 and 3.6 wt% shows that the sensitivity of the maximum power increase to change in enrichment (i.e., change in max power increase/change in enrichment) decreases as initial enrichment is increased. Since the sensitivity of the linear heat rate augmentation factor to enrichment (the "b" coefficient in Equation 4.2-53) decreases for higher enrichments, the use of Equation 4.2-53 for enrichments greater than 3.6 w/o will overestimate the value of the linear heat rate augmentation factor. Therefore, the use of the linear dependency in Equation 4.2-53 is conservative for extrapolations of initial enrichments beyond the 3.6 wt% value employed in establishing the enrichment correlation.

3. Exposure

As indicated in Table 4.2-1 calculations were run explicitly for fuel exposures between 0 and 45,000 MWD/T. Exposure dependence is included in the calculated sensitivities through Equation 4.2-53, which contains a quadratic fit of the sensitivity coefficients to burnup. The sensitivity of these coefficients to fuel burnup is shown in Figure 4.2-11. As this figure illustrates, the coefficients reach a maximum value at a burnup of approximately 20,000 MWD/T, and decrease as fuel burnup is extended further. Since the peak in the augmentation factors occurs at relatively low burnups, Equation 4.2-53 can be used to conservatively extrapolate to burnups beyond the 45,000 MWD/T maximum employed in the explicit calculations. In addition, the peak power density in fuel assemblies having burnups in excess of 25,000 to 30,000 MWD/T rapidly decreases, so that such high burnup fuel assemblies are not the limiting fuel assemblies in the core. Because of their relatively low power density, such high burnup fuel assemblies do not become limiting even when fuel rod bowing is considered.

4. Poison Rod Type

As discussed in CENPD-225-P, calculations were performed for several poison rod designs which were in use at the time the Topical Report was written. All C-E cores now contain poison rods of the type 3 design, and this design will be used in all future reloads. The calculation case list is summarized in Table 4.2-3. Calculations were performed for B_4C in AL_2O_3 shims containing 0.0281 grams/B-10 per inch for the 14x14 lattice and 0.0142 grams/B-10 per inch for the 16x16 lattice. The calculated sensitivites are consequently applicable for 14x14 and 16x16 lattice shims employing B-10 loadings equal to or less than these values. All reloads to date have employed shim loadings equal to or less than these values, and it is anticipated that these loadings will suffice in the future. However, if it becomes necessary to employ shims with higher B-10 loadings, the sensitivities can be recalculated using the methodology described in CENPD-225-P.

Question 29:

Can the assembly peripheral rods become peak power rods as a result of an increase in the inter-assembly gap and rod-rod spacing as a result of assembly bow? If so, how is the variability in the inter-assembly gap due to assembly bow accounted for in the F^b_q penalty?

Response:

CENPD-225-P, "Fuel and Poison Rod Bowing", addresses the phenomena of fuel and poison rod bowing; it was not intended to address the subject of fuel assembly bowing. C-E believes that it would be more appropriate to resolve the rod bow issue and, if necessary, to address the different and distinct phenomena of fuel assembly bow separately. However, since the question has been asked here, a response is provided.

CE has had in place for some time programs to obtain and evaluate experimental data on fuel assembly bow. On the basis of those studies, it is concluded that no increase in F^b_q is required due to assembly bow. The following paragraphs show why that is true.

The effects of fuel assembly bow on peripheral rod power can be seen from the following calculations performed based on our present understanding of this phenomenon. These calculations employed a quarter core model of a CE reactor in which the maximum size gaps were introduced between assemblies located in the [interior] region of the core. This location was selected since available data indicate that the maximum size gaps tend to form at or near the [core center]. The area of the core examined in detail consisted of a checkerboard of lower enrichment A assemblies and higher enrichment B assemblies which characterize the [interior] region of a first cycle core. Similar results are anticipated for reload cores where the [interior] region also contains a mixture of high and low reactivity (higher and lower burnup) fuel. 16 x 16 fuel assemblies were employed in these calculations. Experimental data indicate that this type of fuel assembly is somewhat more prone to fuel assembly bow than the 14 x 14 design, presumably because of the [reduced structural rigidity and greater assembly length]. For reasons of calculational simplicity and conservatism, the fuel assemblies were assumed to be unzoned. In actual application, the 16 x 16 fuel assembly usually contains a zone of lower enrichment fuel rods at the assembly corners which serve to reduce the power in peripheral rods below that indicated in these calculations.

[ ]

In order to assess the effect of fuel assembly bowing on peripheral rod power, assumptions were made as to the magnitude and time dependence of the inter-assembly gap. It has been assumed that bowing occurs [ ] and results in a maximum gap size of approximately [ ] inches. This gap size was selected as a conservative estimate based upon available fuel assembly bow measurements in C-E cores. The time dependent behavior of the gaps was estimated based on a [ ]. Although this estimate indicates that the maximum gap size is not reached until [ ], additional calculations were performed to establish the effect of a more rapid rate of gap formation. In these latter calculations, it was assumed that this maximum gap size was reached at a burnup of [ ], and remained constant at this value thereafter.

Figure 1 shows the normalized peak to average power density (F_p) in the high power assembly as a function of burnup for the expected rate of gap formation (ratio of F_p with gaps to the maximum value of F_p in absence of assembly bowing). Similar information is provided in Figure 2 for the accelerated gap rate. Also shown in these figures is the ratio of peak peripheral rod to peak internal rod power as a function of burnup. As the figures illustrate, the peak can move to a peripheral rod location if the inter-assembly gap is sufficiently large. However, these figures also indicate that the peak-to-average power never exceeds the maximum value for the unbowed case.* Although the peak power can shift to rods at the assembly periphery if the inter-assembly gap is sufficiently large, for a constant assembly average power, the power density in the peripheral rods remains below the power density that would be present in interior rods if assembly bow did not occur. Changes in average assembly power density can result from assembly bow. This can occur due to a global power roll into the [ ] of the core where larger gaps are concentrated. The average power of the limiting assembly can either increase or decrease depending upon location in the core. Although such shifts in average assembly power could result in increases in limiting assembly average power, such power shifts would be sensed by the in-core instrumentation system and would appear in the results of INCA, CECOR or similar in-core analysis codes.

---

*For the conservative accelerated gap assumption [ ] This is not considered significant.

The results presented above show that a peripheral rod could be the peak power rod if the inter-assembly gap is sufficiently large. No additional allowance in the F^b_q penalty is necessary to account for this, however, since peripheral rods are expected to be less limiting for all cases of interest for both DNB and LOCA margins. CE DNB margin calculations assume the highest power rods are interior rods, adjacent to a CEA guide tube. The peripheral rods will be less limiting for DNB because no DNBR reduction for unheated adjacent surfaces (i.e., CEA guide tube) is required and because the wider inter-assembly gap will provide superior cooling capability. Therefore the DNBR of peripheral fuel rods will be significantly higher than for interior rods of equal power. For LOCA, peripheral rods will have enhanced cooling with the wider inter-assembly gap and the improved radiation heat transfer to cooler rods of the adjacent assembly. The larger channel flow area due to the wider inter-assembly gap will provide, during the critical late reflood portion of the LOCA transient, a larger steam flow and lower steam temperature, thereby providing enhanced convective cooling for peripheral rods relative to interior rods. Radiation heat transfer from a hot peripheral rod to neighboring rods will be higher than for the case when the high power rod is in the assembly interior. The existence of the relatively low power (and hence cooler) rods in the adjacent assembly will provide more favorable radiation heat transfer. The enhanced heat transfer (convection and radiation) for peripheral hot rods will result in lower clad temperatures and thus more margin to the LOCA limit. The extra DNB and LOCA margins identified in the foregoing are available to accommodate potential increases in uncertainty for using the in-core instrumentation system to determine the core power distribution in the presence of assembly bowing.

In summary, the information presented above leads to the conclusion that no additional allowance is necessary in the F^b_q penalty. That conclusion is strengthened by the observation that the results are not strongly affected by the rate of gap development and by the conservatism introduced by the neglect of assembly enrichment zoning which is typically employed in 16 x 16 fuel and which reduces the power of the peripheral rods.

FIGURE 1

PEAK PIN POWER RATIOS FOR GAP AND NOMINAL CASES IN HIGH POWER ASSEMBLY

FIGURE 2

PEAK PIN POWER RATIOS FOR GAP AND NOMINAL CASES
IN HIGH POWER ASSEMBLY