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April 15, 1982

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

Dear Mr. Miller:

Attached are ten (10) copies of the responses to first and second round questions on BAW-10147P, "FUEL ROD BOWING IN BABCOCK & WILCOX FUEL DESIGNS".

In accordance with 10 CFR Section 2.79, we are requesting that certain portions of the responses be treated as proprietary. An affidavit supporting this request as well as proprietary and non-proprietary versions of the responses are attached.

Should you require further information on this submittal, please call Frank McPhatter or me (Ext. 2401).

Very truly yours,

J. H. Taylor
Manager, Licensing

JHT:CFM:dr

Attachments

cc: R. B. Borsum - B&W Bethesda Office

bcc: C. F. McPhatter

Babcock & Wilcox

AFFIDAVIT OF JAMES H. TAYLOR

A. My name is James H. Taylor. I am Manager of Licensing in the Nuclear Power Generation Division of Babcock & Wilcox, and as such I am authorized to execute this Affidavit.

B. I am familiar with the criteria applied by Babcock & Wilcox to determine whether certain information of Babcock & Wilcox is proprietary and I am familiar with the procedures established within Babcock & Wilcox, particularly the Nuclear Power Generation Division (NPGD), to ensure the proper application of these criteria.

C. In determining whether a Babcock & Wilcox document is to be classified as proprietary information, an initial determination is made by the unit manager who is responsible for originating the document as to whether it falls within the criteria set forth in Paragraph D hereof. If the information falls within any one of these criteria, it is classified as proprietary by the originating unit manager. This initial determination is reviewed by the cognizant section manager. If the document is designated as proprietary, it is reviewed again by Licensing personnel and other management within NPGD as designated by the Manager of Licensing to assure that the regulatory requirements of 10 CFR Section 2.790 are met.

D. The following information is provided to demonstrate that the provisions of 10 CFR Section 2.790 of the Commission's regulations have been considered:

(i) The information has been held in confidence by the Babcock & Wilcox Company. Copies of the document are clearly identified as proprietary. In addition, whenever Babcock & Wilcox transmits the information to a customer, customer's agent, potential customer or regulatory agency, the transmittal requests the recipient to hold the information as proprietary. Also, in order to strictly limit any potential or actual customer's use of proprietary information, the following provision is included in all proposals submitted by Babcock & Wilcox, and an applicable version of the proprietary provision is included in all of Babcock & Wilcox's contracts:

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Notwithstanding the above, Purchaser may provide the NRC or any other regulatory agency with any such proprietary information as the NRC or such other agency may require; provided, however, that Purchaser shall first give Company written notice of such proposed disclosure and Company shall have the right to amend such proprietary information so as to make it non-proprietary. In the event that Company cannot amend such proprietary information, Purchaser shall, prior to disclosing such information, use its best efforts to obtain a commitment from NRC or such other agency to have such information withheld from public inspection.

Company shall be given the right to participate in pursuit of such confidential treatment."

(ii) The following criteria are customarily applied by Babcock & Wilcox in a rational decision process to determine whether the information should be classified as proprietary. Information may be classified as proprietary if one or more of the following criteria are met.

a. Information reveals cost or price information, commercial strategies, production capabilities, or budget levels of Babcock & Wilcox, its customers or suppliers.

b. The information reveals data or material concerning Babcock & Wilcox research or development plans or programs of present or potential competitive advantage to Babcock & Wilcox.

c. The use of the information by a competitor would decrease his expenditures, in time or resources, in designing, producing or marketing a similar product.

d. The information consists of test data or other similar data concerning a process, method or component, the application or which results in a competitive advantage to Babcock & Wilcox.

e. The information reveals special aspects of a process, method, component or the like, the exclusive use of which results in a competitive advantage to Babcock & Wilcox.

f. The information contains ideas for which patent protection may be sought.

The document(s) listed on Exhibit "A", which is attached hereto and made a part hereof, has been evaluated in accordance with normal Babcock & Wilcox procedures with respect to classification and has been found to contain information which falls within one or more of the criteria enumerated above. Exhibit "B", which is attached hereto and made a part hereof, specifically identifies the criteria applicable to the document(s) listed in Exhibit "A".

(iii) The document(s) listed in Exhibit "A", which has been made available to the United States Nuclear Regulatory Commission was made available in confidence with a request that the document(s) and the information contained therein be withheld from public disclosure.

(iv) The information is not available in the open literature and to the best of our knowledge is not known by Combustion Engineering, EXXON, General Electric, Westinghouse or other currert or potential domestic or foreign competitors of B&W.

(v) Specific information with regard to whether public disclosure of the information is likely to cause harm to the competitive position of Babcock & Wilcox, taking into account the value of the information to Babcock & Wilcox; the amount of effort or money expended by Babcock & Wilcox developing the information; and the ease or difficulty with which the information could be properly duplicated by others is given in Exhibit "B".

E. I have personally reviewed the document(s) listed on Exhibit "A" and have found that it is considered proprietary by Babcock & Wilcox because it contains information which falls within one or more of the criteria enumerated in Paragraph D, and it is information which is customarily held in confidence and protected as proprietary information by Babcock & Wilcox. This report comprises information utilized by Babcock & Wilcox in its business which afford Babcock & Wilcox an opportunity to obtain a competitive advantage over those who may wish to know or use the information contained in the document(s).

James H. Taylor
JAMES H. TAYLOR

State of Virginia)
) SS. Lynchburg
City of Lynchburg)

James H. Taylor, being duly sworn, on his oath deposes and says that he is the person who subscribed his name to the foregoing statement, and that the matters and facts set forth in the statement are true.

James H. Taylor
JAMES H. TAYLOR

Subscribed and sworn before me
this 16th day of April 1982.

Natalie M Lampman
Notary Public in and for the City
of Lynchburg, State of Virginia

My Commission Expires Aug 18, 1985

Non-Proprietary Responses to First and Second Round Questions on BAW-10147B, "FUEL ROD BOWING IN BABCOCK & WILCOX FUEL DESIGNS", April 1981.

Question 1

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

Response

The available data indicates that rod bow is less in regions where limiting DNBR and power usually occur (upper half of the core). Table 4-3 provides a distribution of the location of worst spans and shows that the worst span is located near the bottom of the assembly (measurement plane 12 in Figure 3-2) in 33% of the spans measured. In addition, in 90% of the spans measured the worst span was located on the bottom half of the fuel assembly.

No credit was taken for this however, as the worst span data only was used as the basis for developing a rod bow correlation.

Question 2

Is there correlation between the direction and magnitude of bow in adjacent grid spans and if so, how is this incorporated in the statistical analysis?

Response

The rod bow correlation was developed based on the bow within the grid span with the largest standard deviation in the rod-to-rod gap measurements. This conservatively brackets the bow in the other spans of the assembly. The DNB analysis considers only the worst span case. Therefore, the axial variation in the water channel gap is not significant and was not incorporated into the rod bow correlation development.

Question 3

In the determination of the effects of rod bowing on local rod power only configurations with a single bowed rod were considered. What error is introduced by assuming that superposition is valid and determining the change in rod power for configurations in which several rods are simultaneously bowed by combining the effects from single rod bowed configurations? It should be noted that this approximation is expected to deteriorate at larger rod displacements.

Response

The reported data does address only configurations with a single bowed rod; however, prior to the selection of superposition theory as a valid analytical approach, the theory was tested with an extensive selection of bowed rod combinations to establish that this approach was satisfactory and conservative. Two extreme tests were calculated. Referring to Figure G-4 of BAW-10147P, one case addressed the situation of 2 B-type rods (rod B and its 180^{o} counterpart relative to Rod A) bowed away from Rod A to contact with Rod C and its 180^{o} counterpart. The power change in rod A was less than two times the equivalent power change in rod A when a single type B rod was bowed to contact with rod C. The second superposition extreme tests was the simultaneous movement of all 24 rods in the 5 x 5 pin array away from rod A and towards rod A by mils; i.e., each rod was moved one mesh interval along a 45^{o} angle relative to the 90^{o} X-Y geometry orientation. The simultaneous rod bow effect upon rod A was approximately less than the power calculated by superposition theory.

Therefore, it is concluded that superposition theory overestimates the absolute value of combined rod bow.

Regarding the deterioration of the superposition approximation with larger rod displacements, the explanation given above, in addition to the results which show power changing linearly for a single bowed rod, supports the B&W position that this analytical approach is valid also for large displacement combination rod bowing.

Question 4

What effect does the rectangular rod representation in the neutronic calculations have on the calculated rod power perturbation.

Response

The accuracy of the incremental power change with rod bow is primarily dependent on modeling lattice parameter changes. Rectangular to cylinderical geometry changes have a negligible, secondary effect.

A measure of the modeling adequacy is provided by the following differences between modeled and physical parameters:

pellet area

pellet diameter

rod to rod surface

A 5 x 5 fuel cell array was considered adequate with a 15 x 15 mesh and discrete representation of the fuel pellets. Equal mesh spacing was required to avoid region area changes when a fuel rod was moved within a fuel cell. The overall results agreed well with a standard, unbowed calculation model used in core design analyses.

Question 5

In the determ nation of a DNBR penalty, only single-rod displacement configuration; are employed. What is the effect of multiple rod placements an gap closures on the DNBR penalty function and how is this effec accounted for?

Response

In the bowed rod test (Appendix E), the effect of gap closure was examined by displacement of a single rod. Since the CHF occurs in the gap between heated rods (see the response to question 60), the primary variable is the amount of closure in the rod-to-rod gap. Thus, for the determination of the DNBR penalty due to rod bow (gap closure), the effect of multiple rod displacements would be the same as the effect of a single rod displacement as long as either of these displacements resulted in the same amount of closure in the rod-to-rod gap.

Question 6

Several conservatisms have been identified in the bowing analysis including (1) selection of the maximum span bowing and (2) neglect of rod power reduction on DNBR, etc. List known conservatisms in the bowing analysis of power peaking and DNBR and give estimates of their magnitudes.

Response

Major conservatisms included in the bowing analysis will first be identified and a discussion of each will follow. These conservatisms include:

1.) Selection of worst span bowing

2.) The global tolerance level used in the gap closure prediction model

3.) Analytical modelling for power peaking calculations

4.) Upper tolerance level of DNBR penalty at contact

5.) Gap closure threshold value of 0% DNBR penalty determined from bowed rod CHF test

6.) Linear correlation between δ DNBR and gap closure.

1.) Selection of Worst Span Bowing
As described in BAW-10147P Section 5, the rod bow prediction correlation was based on the worst span gap closure data rather than on the data from all spans. This approach is considered to be conservative since the worst span data is bounding and because the worst span location was usually in the lower half of the assembly, where CHF does not usually occur. Further discussion is provided in the response to question 1.

If all the rod-to-rod data were used as the basis for the prediction data instead of the worst span only, the estimated magnitude of this conservatism is equivalent to a reduction in the DNBR penalty

(Figure 7-1) of approximately DNBR (on the average) and or greater reduction in penalty at a burnup of 40,000 MWd/mtU.

2.) The global tolerance level used in the gap closure prediction model.

A detailed description of the global tolerance factor is provided in Appendix D and additional comments are provided in the response to questions 28 and 29. When compared to the suggested value of 1.5 (reference 1) to be applied to estimated bow to account for bow variations between batches, the global tolerance factor is increasingly conservative with burnup as shown in Figure D-1. The estimated magnitude of this conservatism is equivalent to a reduction in DNBR penalty (Figure 7-1) of approximately DNBR at a burnup of 40,000 MWd/mtU.

3.) Analytical modelling for power peaking calculations.

Calculations of local power changes due to rod bow were based on configurations of single bowed rods by using superposition theory. The response to question 3 supports this method and identifies the magnitude of the conservatism determined for two extreme cases. Beyond this no additional estimates of the magnitude of the conservatism have been determined.

4.) Upper tolerance level of DNBR penalty at contact.

The method used to determine the DNBR contact penalty was provided by the NRC (ref. 7) with no requirements for justifying a confidence limit on the penalty. B&W chose to treat this contact penalty (based on 10 data points) in a conservative fashion as described in section 6 and in the response to question 58 by determining a 95% confidence limit on the penalty. The estimated magnitude of the conservatism, in terms of DNBR penalty vs. burnup, is less than a 1% reduction in DNBR penalty.

5.) Gap closure threshold value of 0% DNBR penalty determined from a bowed rod CHF test.

A bowed rod CHF test was performed at 55% closure, a value that was expected to show no degradation in DNB performance as well as to bound the expected magnitude of gap closure in B&W fuel. The test data presented in Appendix E for the bowed rod test and for an otherwise identical unbowed rod test bundle does not indicate conclusively that a penalty exists at a 55% closure. Additional discussion is provided in the response to question 52. Although the threshold value of gap closure below which no DNBR penalty exists may be higher than 55%, no estimate can be made for the magnitude of this conservatism since test data for gap closures greater than 55% is not available.

6.) Linear correlation between δ DNBR and gap closure.

As pointed out in the response to question 63 the expected DNBR penalty over the applicable range of gap closure is less than predicted DNBR penalty based on a linear correlation over the same range of gap closure. The degree of conservatism resulting from using the linear correlation has not been quantified for BAW-10147P since B&W has not performed rod bow CHF tests at gap closures greater than 55%, the closure value used as the threshold closure below which there is no penalty.

Question 7

In the determination of the effects of rod bowing on local rod powers, the effect of poison rod bowing has been neglected. Describe in detail the effects of poison rod bowing and incorporate this effect into the F_Q^B and DNBR penalties.

Response

The design of B&W fuel assemblies does not incorporate poison rods as an integral part of the fuel assembly lattice. Rather, poison rods are separate components which are contained in guide tubes. This design precludes any significant poison rod bowing and therefore F_Q^B and DNBR penalties are not applicable. The response to Question 21 provides a discussion of control rod and guide tube bowing which indicates no evidence of poison rod (control rod) bowing.

Question 8

During certain transients and accidents, large local flux and thermal gradients and stresses are expected. Can these or other mechanisms give rise to greater bowing and a larger decrease in gap closures than would be determined using the proposed gap closure correlations? If so, how are these bowing increases accounted for?

Response

The rod bow correlation was developed from a very extensive data base that included over 125,000 individual measurements from 26 fuel assemblies. These assemblies were from 2 reactors and were irradiated to fuel assembly average burnups up to 40,000 MWd/MTu which encompasses a wide range of actual operating conditions. Infrequent transient and accidents are not expected to significantly effect the rod bow because the grids are not fixed but are allowed to move axially to limit the build up of axial stesses in the rods. Also, it is unlikely that the flux and thermal gradients which would be in the same direction would be sufficiently different between adjacent rods to cause a significant increase in gap closure.

Question 9

For what fuel designs will the rod bow span length scaling be used to determine the bowing closure reduction?

Response

No span length scaling is required for B&W fuel assembly designs. Both the 15 x 15 and the 17 x 17 Mark-C designs incorporate 6 spacer grids approximately equally spaced along its length resulting in almost identical span lengths. Also, the data base includes measurements from both assembly designs.

Question 10

Have statistical tests been performed to determine if the closure data that has been combined (e.g., for different rod types, spans, plants, exposures, etc.) is poolable and if not, give the basis for pooling this data.

Question 52

Describe in detail how the data was reduced to a "common burn-up".

Response

The water channel measurements from several assemblies was not pooled into a single data point at a common burnup-up. Instead, the statistical analysis treated the span wise distributions for each assembly as individual data points at the assembly average burnup.

Question 11

The rod peaking on certain rods in the neighborhood of guide tubes, water gaps, water holes and instrument tubes, is larger than for an infinite lattice of rods. Describe in detail how this is accounted for in the determination of the power peaking penalty.

Response

The bowing of a fuel rod in the vicinity of a control rod guide tube or instrument guide tube can result in a slightly higher change in magnitude of the power of surrounding rods than if the bowed rod is surrounded by a uniform lattice of fuel rods. Conversely, the change in power of a single rod due to self bow is more negative for rods near guide tubes. The presence of a guide tube reduces by one the number of available rods which can bow and thus have a detrimental peaking effect on the hot rod. Thus, there are two power reduction contributors and one power increase contributor. The bow induced power changes on rods near guide tubes is expected to be bounded by the results of peaking studies based on uniform lattices and requires no additional penalty.

Question 12

Please discuss in detail the effect of the following, on the neutronic calculations of the effects of rod displacement on local power peaking:

(a) spatial mesh size

(b) order of scattering and angular quadrature if a transport calculation was performed

(c) number of choice of energy groups

(d) ability of diffusion theory to track the effects of small geometry changes

(e) effects of spectral changes on the few-group cross sections used

(g) reduced rod array size (e.g., 5 x 5 vs. 15 x 15) and the effect of perturbed image rods introduced by the boundary conditions.

Question 12

(a) Spatial mesh size?

Response

The mesh spacing was selected to facilitate modeling the fuel cell in X-Y geometry.

These constraints resulted in a mesh spacing of
This dimension is small compared to the neutron mean free path in the fuel rod pellet, clad and moderator. This mesh spacing is comparable to that used in conventional lattice studies to calculate neutron flux and reaction rates in fuel and absorber rods.

Question 12

(b) Order of scattering and angular quadrature if a transport calculation was performed.

Response

P_0 scattering order and S_4 quadrature options were used in the DOT code analyses.

The importance of scattering order (P_0, P_1) was evaluated in terms of the change in fast to thermal flux ratio in the pellet region and in the average thermal flux ratio of the pellet to moderator region of the fuel cell. The difference in the fast to the thermal flux ratio in the pellet was for the two scattering options. The difference in the average thermal flux ratio of the fuel to moderator region was percent. An assessment was made of the computer memory requirements for the P_0 and P_1 options in the DOT code.

Question 12

(c) Number and choice of energy groups?

Response

The energy group structure for the DOT code's spatial analysis consists of one fast group and five thermal groups with energy boundaries as follows:

Group	Energy Range
1	
2	
3	
4	
5	

Emphasis was placed on describing the thermal energy spectrum because rod bow neutronic analysis is primarily a study of local moderation changes arising from local redistribution of water between adjacent fuel rods. Multithermal groups are a means to account for neutron energy variations in the thermal energy range. Energy break points were chosen to accommodate resonances in the fuel isotopes. Cross sections for group 1 (>1.855 ev) were calculated with the NULIF code. This is a B&W code that generates a micro-group neutron spectrum and calculates spectrum weighted few group parameters for use in a spatial diffusion code. A B&W data processing code, ANTY, merges the single fast group data with cross section data from an 80 thermal group B&W cross section library (PROLIB) for isotopes of interest. These cross section sets were then input to a second B&W data processing code, TAPMAKE, which created on magnetic tape an 81 group macroscopic cross section set for each material zone of the fuel rod cell for use with the ANISN code. ANISN solves the multigroup transport equation for the space- and energy-dependent flux for an inifinte array of fuel cells with appropriate boundary conditions. The ANISN results are used to obtain flux and volume weight six group cell averaged cross sections for the two dimensional DOT analysis.

Question 12

(d) Ability of diffusion theory to track the effects of small geometry changes?

Response

The principal neutronic problem in rod bow analysis is the treating of moderator asymmetry in the perturbed (bowed rod) fuel cell and the propogation of this perturbation into adjacent and nearby fuel cells as a power change.

The neutronic model used in the analysis was Discrete Ordinate Transport Theory with a P_0 scattering order and S_4 angular quadrature. Test cases were calculated to assess the effect of a few group energy structure, scattering order, and quadrature level upon the relative change in fuel rod power. The differences in perturbed power were sufficiently small to have a negligible effect on the analytical results.

Question 12

(e) Effects of spectral changes on the few-group cross sections used.

Response

The selection of cross section energy grouping and the methodology of collapsing the microgroup cross sections to the few group structure for the fuel cell was based on previous experience, and are described in the answer to question 12 (c). The change in local moderation due to redistribution of water between fuel rods with rod bow was the primary cause of spectral change. The effect of interest is mainly a thermal energy effect. Therefore, the thermal energy range was described by five groups with the energy break points chosen to satisfy key isotopic resonance parameters.

Other studies performed at B&W have indicated that when the thermal energy range is represented by groups, the DOT calculation will account correctly for the interactions due to spectral changes. Above 1.855 ev the mean free path of neutrons is large compared to the lattice pitch, and hence the effects of spectral changes in the epithermal range are insignificant.

Question 12

(g) Reduced rod array size (e.g., 5 x 5 vs. 15 x 15) and the effect of perturbed image rods introduced by the boundary conditions.

Response

Studies were performed to assess the geometric propagation of rod bow induced power perturbations. There is approximately a factor of 4 reduction in the magnitude of the power perturbation two rod pitches from the nominal position of the perturbed rod. See Figures G-4 and G-5 of BAW-10147P. It was concluded that fuel cells more than two rod pitches from the perturbed rod could be modeled as a homogenized fuel zone. The thickness of the homogenized fuel zone was selected to isolate the effect of imaged perturbed rods from the quadrant of interest. The test for isolation was equal mirror image power distribution in the quadrant when the central fuel rod (rod A of Figure G-1 BAW 10147P) was moved in opposite directions. This was achieved.

Question 13

Discuss the effect of rod bowing on clad corrosion.

Response

It has been B&W operating experience that corrosion of the fuel rod cladding is insignificant. Theoretically, a high percent gap closure of the water channel would increase cladding temperatures and associated corrosion. However, for the closures measured in B&W reactors and conservatively predicted by the rod bow correlation, these effects are very small and any resulting corrosion is insignificant.

Question 14

Are all operating plants and fuel designs covered by the submitted topical report analysis? If not, identify those plants and designs that are not covered and indicate why these results are not applicable.

Response

All operating plants and fuel designs are covered by the topical report. The rod bow correlations were developed from data base that included measurements from both the 15 x 15 and 17 x 17 design configurations.

Question 15

The nuclear uncertainty factor, which accounts for the inability of the standard nuclear design codes to calculate the excat rod power, will increase for off-nominal bowed configurations. How is this increase in uncertainty due to bowing accounted for?

Question 32

In the determination of the effect of rod bowing on local power peaking, bowing of only a single rod has been considered. Therefore, either determine the 95/95 tolerance limit on the local rod power when all surrounding rods bow randomly according to the assumed distribution or demonstrate that the selected   penalty is conservative.

Response

The power peaking uncertainty of   presented in Section 7.2 was determined as a result of calculations which considered the effect on a pin surrounded by eight rods bowed in a random manner. The calculations incorporated a Monte Carlo technique which used a normal distribution for the amount of rod displacement and a uniform distribution for the angle of bow, and determined the change in power peaking on the center rod at a 95% confidence level. Values of Δ% power per rod were input to the calculations and which were determined for a 5 x 5 rod array over a range of rod displacements and directions. The calculated values of Δ% power for the bow of various rods plus the effects of self bow of a single rod in a 5 x 5 rod array were performed, and are shown in the figures of Appendix G. The   maximum power peaking change quoted in Section 7.2 demonstrates the change due to the self bowed rod).

In the Monte Carlo technique, the total power change on the center rod was recomputed 100000 times for each selected axial increment to develop a statistical sample. The resulting calculations of power change on the center rod provided the basis that a   peaking uncertainty would bound the calculated power peaking change over the range of burnup (corresponding to predicted gap closure) that would be expected to occur in B&W reacotrs.

Question 15 & 32 Continued

The peaking uncertainty due to rod bow was combined statistically (square root of the sum of squares) with the standard nuclear uncertainty factor of (total peak) and the manufacturing "hot channel" factor of . in the manner detailed in Reference 9. The combined total of is less than the total uncertainty currently used in analyses. When higher burnup cycles (which are anticipated in the future) are considered, along with the predicted gap closure determined as a function of burnup as described in Appendix D, the total peaking uncertainty of remains valid for fuel assembly burnup to MWd/mtU for MKB fuel and MWd/mtU for MKCfuel. It is very unlikely that fuel assemblies with burnup values of these magnitudes will be found limiting when determining core operating limits because of the decreased power producing capability of the fuel (see response to Question 31). However, to ensure that all fuel assemblies and burnups are considered, a burnup dependent rod bow power peaking uncertainty can be determined and combined statistically as described in Reference 9 and will be applied to these fuel assemblies.

Question 16

A. Over what specific range of burn-up is the gap closure correlation and proposed bowing analysis applicable?

B. If there is any increase in uncertainty due to lack of data at high burn-ups, describe quantitatively how this is accounted for.

C. If the gap-closure data is being extrapolated outside the domain of actual measurement data, describe quantitatively how the increase uncertainty is estimated and how it is accounted for in the analysis.

Response

The rod bow equation was developed from a data base with a range of 0. to 40,000 MWd/MTu. The data may be extrapolated to higher burnups using equations 5-1 and 5-4 of BAW-10147P. It should be noted that the global tolerance as well as rod bow is a function of burnup. Increasing burnup increases the ratio of the global tolerance to the predicted value. Additional discussion of the global tolerance is contained in Appendix D of BAW-10147P.

Question 17

Are the calculated power peaking senstivities to rod-bow conservative with respect to all fuel designs? If not, identify the non-conservative designs and explain in detail how this non-conservatism is properly accounted for in the proposed analysis.

Response

The Mark-B and Mark C-fuel assembly designs identified in BAW-10147P have fuel rod peaking characteristics that are conservative when compared to modified ("wet-lattice") Mark-B and C assembly designs that are currently under consideration. In addition, it is anticipated that any future changes in Mark-B and C class assembly designs will be no greater in magnitude than the differences between the Mark-B and C designs. Therefore, results in this report should be applicable to those designs as well.

Question 18

Describe in detail the application of the proposed rod bow analysis to a typical plant, including the input parameters and their basis (either explicitly or by reference) and the equations and figures (appropriately referenced) used to determine both the DNBR and F_Q^B penalties. Indicate what parameters are plant and cycle dependent.

Response

The assessment of a rod bow DNBR penalty to B&W fuel designs is not applicable as concluded in Section 7 and further demonstrated in the response to Question 31. As discussed in the response to Question 31 the net penalty is zero for fuel assembly average burnup values less than 24000 MWd/mtU. Assemblies with burnup values greater than 24000 MWd/mtU do not produce enough power to achieve design limit peaking values and a DNBR penalty due to rod bow has no valid meaning. The philosophy and method of applying a rod bow penalty used previous to BAW-10147P (approved for use as an interim method by the NRC in Reference 5) is presented by example, however, to show how the limiting assembly in the core is determined and to demonstrate typical DNBR margins present relative to design limit values. The following example uses the DNBR penalty model described in Section 6 and Appendix F of BAW-10147P. Numbers shown correspond to Cycle 6 of Oconee Unit 3 and are based on the Reload Licensing Report for that cycle (BAW-1634).

1) for a specific plant and cycle design, the maximum predicted end-of-cycle (EOC) fuel assembly burnup value is determined for each fuel batch (column 2 of Table 18.1).
2) The net fuel rod bow DNBR penalty corresponding to each burnup value determined in 1) is determined from Figure 7-1 or 7-2 of BAW-10147P. These values are each adjusted by subtracting 1%, which corresponds to the DNBR value of the pitch reduction factor used in thermal-hydraulic analyses (column 4 of Table 18.8).
3) The maximum predicted steady-state radial x local peaking factor ($F\Delta h$) is determined for the limiting assembly in each fuel batch, by examination of the fuel cycle design (column 4 of Table 18.1). The maximum value is selected without regard to cycle burnup. This is generally a beginning-of-cycle value.

4) The minimum DNBR corresponding to each of the $F_{\Delta h}$ values determined in 3) is estimated for the design overpower (112% of full power) condition (column 5, of Table 18.1).

5) The rod bow DNBR penalty for each batch is subtracted from the minimum DNBR for that batch (Column 6 of Table 18.1). This provides an indication of which fuel is limiting (batch 8 for the example shown) as well as showing DNBR margin relative to the design case.

6) The rod bow DNBR penalty to be applied in the determination of Reactor Protection System limits is determined by examination of column 4 of Task 18.8. The penalty value selected for application is that corresponding to the fuel batch with the highest predicted $F_{\Delta h}$, or, if a batch with higher burnup (and penalty factor) has an $F_{\Delta h}$ within 5% of the maximum value, the penalty would be based on this batch. For the example shown in Table 18.1 this results in the penalty being based on batch 7, which has an $F_{\Delta h}$ of , rather than batch 8, which has an $F_{\Delta h}$ of .

7) The design DNBR limit value, DNBRL, is adjusted by adding the rod bow DNBR penalty determined in 6). For example, when the B&W-2 (BAW-10000A, May, 1976) CHF correlation is used, with its limit value of 1.30, a rod bow DNBR penalty of 1% would result in a DNBRL = 1.313.

8) DNBR - dependent Reactor Protection System limits are evaluated to insure that the minimum DNBR is greater than or equal to DNBRL.

The peaking uncertainty (F_Q^B penalty) used to verify plant and cycle specific operating limits and applied in this example would be a generic value used for previous cycles. A detailed discussion of the peaking uncertainties is provided in the response to Question 15 and 32.

Table 18.1

Oconee 3 Cycle 6 DNBR Penalty

Fuel Batch	Maximum Assembly Burnup MWd/mtU	Net Fuel Rod Bow Penalty * % DNBR	Maximum Predicted $F_{\Delta H}$	Minimum DNBR @112% Power	DNBR less Rod Bow Penalty
Design Case					
5B					
6					
7					
8					

*Penalty as determined from Figure 7-1 less 1%

Question 19

In the measurements of the DNBR penalty, what effect do the rod holders that maintain the rods in their bowed locations have on the measured DNBR penalty?

Response

Referring to Figures E-3 and E-2 of Appendix E, intermediate grid E is used to position rod 17 in its bowed position. This intermediate grid is identical to the other intermediate (or minimum turbulence) grids in both the C-9 (unbowed) and C-10 (bowed) tests except for the necessary structure for the positioning of rod 17. The minimum turbulence grids are used in all B&W CHF tests to maintain proper tube spacing in the span between the regular Mark C grids where electrically induced magnetic forces could cause bundle deformation. As opposed to the heavily formed -inch long regular grids, the minimum turbulence grids are specifically designed to produce negligible additional turbulence or flow upset. They are extremely thin, chemically etched wafers laminated to an approximately -inch length. A photograph comparing the intermediate and regular grids is shown in Figure 2-8 of Reference 15, and visibly illustrates the minimum turbulence nature of the intermediate grids. Furthermore, referring to Table E-9, the DNB length (axial position of CHF detection) in the vast majority of data points occurs downstream of the point of maximum bow (usually at the leading edge of the regular Mark C grid #6). This observation is consistent with that of the base comparison test (C-9, table E-8) and, indeed, the observed CHF locations for all of our Mark C tests (Reference 15). These results evidence the lack of effect of the minimum turbulence grids on CHF level.

Question 20

Describe the surveillance procedures and other measures that will be used to confirm and update when necessary the rod bowing data base and analysis.

Response

The rod bow correlation was developed from an extensive data base as described in Appendix B of BAW-10147P. Included in this data base are gap measurements from assemblies representative of the design evolution leading to the current configuration. It is expected that this correlation will be valid in the future for assemblies incorporating minor changes. This position will be reassessed on a case by case basis. If in the course of the design evolution it is desirable to make additional measurements, the data base will be updated and the effect on the rod bow correlation will be evaluated.

Question 21

Provide a discussion of the likelihood and any measurements of control rod bowing.

Response

The control rods are suspended within the assembly's guide tubes where the diametral gap limits the amount of control rod bow relative to the guide tube. The thin walled control rod will conform to the shape of the guide tube. Any significant bow could result in wear of the guide tube. B&W has not experienced any guide tube wear attributed to control rod bow.

The control rods are not subject to many of the postulated causes of fuel rod bow. The rods are free to grow axially which prevents a build-up of axial strains.

No direct measurements of control rod bow have been made but hot cell examinations of an axial power shaping rod showed no significant distortion.

Question 22

In the evaluation of the MDNBR penalty, are the pressure and Q_{AVG} values corresponding to the high pressure and over power trip setpoints used? If these values are not used, justify the values selected.

Response

The Q_{AVG} value used in the evaluation of the DNBR penalty corresponds to the design overpower limit (112% of full power). This value is used to establish a value of DNBR reduction at full contact as described in Section 6. There is no pressure dependent function that is factored into the penalty equation. The B&W bowed rod CHF test data (Appendix E) included the range of allowable plant operating pressure which includes the high pressure trip limit (2400 psia). The conclusion of the test was that no penalty existed for the gap closure tested (55%).

Question 23

In the determination of the fuel rod DNBR penalty, the bowing of the eight surrounding rods and associated gap closures determined the reduction in DNBR margin. The penalty for each gap 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. (In Reference 1 this method was used to determined the penalty arising from the bowing of two rods on opposite sides of the rod of interest). Therefore, update the bowing analysis to include the contribution to the DNBR penalty from all eight surrounding rods.

Response

Variations in gap closure (which would be expected to have corresponding variations in predicted DNBR penalty) were measured within fuel assemblies and this data forms the rod bow correlation data base as described in sections 4 and 5. The gap closures measured for a given fuel assembly were considered to have a burnup equal to the assembly average burnup. The probability distribution of gap closure is included in the burnup dependent gap closure correlation and the DNBR penalty correlation described in section 6 and Appendix F. The response to questions 28 and 29 provide additional information regarding the statistical treatment of the variability in gap closure. The variations in DNBR reduction due to variations in gap closure within a fuel assembly are therefore accounted for in the manner described in BAW-10147P.

Question 24

Discuss the extent to which the gap closure measurements span the actual operating spectrum of rod-to-rod spacings including enrichment, exposure, poison rods, instrument thimbles, guide tubes, fuel design, etc.

Question 40

In deriving the data base, in what way has a distinction been made between different types of assemblies (presence of water holes, burnable poison rods, control rods, etc.)?

Response

The data base used in the development of the rod bow correlations includes more than 125,000 individual gap measurements. It spans a range of design and manufacturing variations that have been incorporated during the evolution and improvement of the Mark-B and Mark-C designs. Also, the data base includes the effects of variations in the irradiation and operation environment during numerous reactor operating cycles.

The statistical analysis used to develop the rod bow correlation is based on the data from the 15 x 15 Mark-B assemblies. This correlation was shown to conservatively envelope the data from the 17 x 17 Mark-C assemblies and, thereby, can be used to predict the rod bow for both designs. No distinction was made between the assemblies within each configuration.

The data base included measurements on 26 assemblies of the Mark-B and Mark-C designs from 8 manufacturing batches with enrichments from 2.15 % U^{235} to 3.2 % U^{235}. These assemblies were used in two reactors during 8 operating plant cycles. They were inserted into core locations that contained orifice rods, burnable poison rods, control or safety rods or were open assemblies. The assemblies were exposed for 1 to 4 plant cycles with burnup to 40,000 MWd/MTu.

Question 25

Provide the most recent gap closure correlation and coefficients for all fuel designs.

Response

The most recent correlation and coefficients for all B&W fuel designs is found in BAW-10147P, Section 5.

Question 26

Large assembly bow of the order of hundreds of mils has recently been measured at several plants.[2,3,4] This bow is of concern because (1) the bow magnitude is at least an order of magnitude larger than the reported rod bow measurements, (2) the resulting rod bow is apparently extremely correlated with all rods in an assembly face bowing together and (3) the bow involves inter-assembly gap closure. All of these aspects are outside the scope of the proposed bowing analysis. Therefore, discuss in detail the effects of assembly bow on fuel rod gap closure and the assumptions and methods used to evaluate rod bowing.

Response

The rod bow correlation documented in the topical roport BAW-10147P addresses the random variation of the water channel gap at midplane between spacer grid elevations. Assembly bow is a measure of the relative lateral movement of the spacer grids (i.e., the mode shape) and is a function of the overall structural characteristics of the assembly.

The geometric configuration of the spacer grid design maintains minimum intra-assembly gaps as well as the inter-assembly gaps. As discussed in Section 4.1 of the topical, there is no significant difference between the bow of the periphery or interior rods. In the case of spacer grid contact between adjacent assemblies, the grid's outer strip which extends beyond the peripheral rod maintains an inter-assembly rod-to-rod gap as large as the rod pitch within an assembly in the grid region. Fuel assembly bow is addressed in thermal hydraulic analysis as an issue separate from rod bow. For purposes of conservative thermal hydraulic design analysis, grids of adjacent fuel assemblies are assumed to bow to touch at an imaginary fuel assembly midplane and the limiting assembly flow area is calculated on this basis. DNBR calculations performed on this basis yield conservative results.

Question 27

Describe in detail the derivation and basis for Equation (D-4) in BAW-10147P.

Response

Equation (D-4) is used to calculate a 95% upper tolerance level on values of bow predicted by equation (D-2) which in turn is based on rod-to-rod gap measurements as described in section 5 of BAW-10147P. The derivation of equation (D-4) is found in reference 12 of BAW-10147P, "Simultaneous Statistical Inferences", R. G. Miller, McGraw-Hill Book Co. (1966).

Question 28

Please provide the details of the determination of the DNBR penalty at full closure, δ_c = (   ), the associated uncertainty, (   ), and also Reference 7 in BAW-10147P.

Question 29

In the determination of the DNBR penalty, the effect of the uncertainty in the penalty due to variability in gap closure (denoted σ_u in Reference 1) has been neglected. Incorporate this variability using a 95/95 upper tolerance limit as outlined in Reference 1, Equation (4.10), or indicate how this effect has been accounted for in the DNBR penalty.

Response

As seen from Figure 6-3, the size of the penalty region is affected by the variability of two factors: 1) the shape of the probability density function and 2) the slope of the boundary line, i.e., the line that forms a boundary for the penalty region.

B&W chose to treat the uncertainty in the penalty due to each effect in a conservative manner.

1) The shape of the density function is due to the variability in gap closure. Variability in the shape of the density function is related in $\sigma(\frac{\Delta C}{C_o})$ as illustrated in Figure 6-3. Thus in estimating $\sigma(\frac{\Delta C}{C_o})$ a very conservative approach was taken by B&W and a global tolerance value established (Eqn. D-4) at a 95% significance level. In all calculations involving penalty, where σ^* was indicated in equation F-10, the value of σ^* was replaced by the global tolerance value of σ 95/95 $(\frac{\Delta C}{C_o})$. This treatment results in a very broad penalty region as Figure 6-3 illustrates. All penalty curves, Figures F-2 and F-3, as well as their simplified versions, Figures 7-1 and 7-2, were derived with the above procedure.

2) The line forming a boundary to the penalty region of Figure 6-3 was also treated conservatively.

B&W had estimates for "K" as described in appendix E but not for δ_c. The NRC provided estimates for $\overline{\delta}_c$, σ_{δ_c} based on 10 experimental points (Ref. 7, see note below). From the available information K and and δ_c were both applied in a conservative manner, as illustrated in Figure 6-2.

However, the solid line should be labelled correctly as the "B&W final penalty region boundary."

In summary, the response to Questions 28 and 29 examined both components that contribute to the uncertainty in the penalty and treat them both conservatively and subsequently arrive at a conservative penalty factor, that is also physically meaningful.

The variability in gap closure however was not denoted by B&W as σ_u (of Reference 1). The method of that reference is not physically meaningful nor statistically precise (See response to Question 57).

Note: In the Reference 7 telephone conversation of October 30, 1978, R. Lobel (NRC) provided M. R. Stephens (B&W) with data associated with CHF testing of rods bowed to contact, testing which B&W has not conducted. The NRC agreed to provide the data in a previous call on October 26, 1978. The values provided are.

Question 30

Discuss in detail the basis (using either calculations or observations) for concluding that the fretting wear due to rod-to-rod contact is insignificant.

Question 33

How many complete gap closures have actually been observed? Provide details including fuel design, burn-up level, axial position, etc.

Question 41

Has any fretting wear due to rod bowing ever been observed on fuel rods?

Question 42

Has any fretting corrosion due to bowing to contact of two rods and the high clad temperature in the area of rod contact ever been observed?

Question 43

Have any calculations of fretting wear and corrosion been performed.

Response

It has been B&W's operating experience that fuel rod bow greater than 50% gap closure is very unlikely and that complete closure has not been observed at any plant. Only one case of near contact (gap $\approx$ .020 inch) has been observed on a high burnup (40,000 MWd/MTu) Mark-B assembly in the mid core region. This pattern is also evident in the empirical rod bow equation. The predicted 95% tolerance level of rod bow is well below 50% closure at burnup level experienced by the Mark-B and Mark-C fuel assemblies.

To date, no analytical studies have been performed to assess the consequences of rod-to-rod contact, such as fretting wear of the clad. As described above, only one case of near contact of the rods has been observed and no fretting was evident.

Complete gap closure has not been observed and based on the rod bow correlation it is very unlikely it will occur. Therefore, the mechanical consequences of bow, such as clad fretting are not critical design concerns for B&W fuel assemblies.

Question 31

In order to relieve the DNBR rod bowing penalty, it must be demonstrated conclusively that assemblies with sufficient exposure to receive a penalty are never limiting. Therefore, demonstrate that assemblies with exposure greater than 14,000 MWd/mtU are never DNBR or F_Q limiting.

Response

A limiting assembly in a given cycle is the assembly which has the highest predicted peaking during the cycle. This limiting assembly may have a predicted burnup at the end of cycle as high as 24000 MWd/mtU (not 14000 MWd/mtU) or greater. For design purposes the limiting assembly is assumed to have a design radial x local ($F\Delta h$) peaking value which has been established as a maximum peaking criteria. This design peak is used in thermal hydraulic design analyses to establish core operating limits based on DNBR criteria. In Section 7.1 of BAW-10147P, the DNBR penalty associated with both Mark-B and Mark-C fuel designs for burnups below 24,000 MWd/mtU is less than 1% (see Figures 7-1 and 7-2) and this penalty is offset by a 1% DNBR credit in the form of a flow area (pitch) reduction factor. Fuel assemblies with burnups $\geq$ 24000 MWd/mtU have penalties greater than 1% but the penalty is unnecessary since the power production capability relative to other fuel assemblies in the core is diminished by fissile inventory depletion to the point where the design limit peaking values cannot be reached. With respect to the 36 reload cycles that have been designed for the Mark-B 177 fuel assembly plants, all fuel assemblies with a burnup of $\geq$ 24,000 MWd/MTu have had greater than   margin to the design limit peaking values. These cycles include both rodded and feed/bleed operational modes plus the out-in-in and in-out-in fuel shuffle schemes and are therefore representative of what can be expected for future cycles. This decrease in real peaking more than offsets the peaking which corresponds to DNBR reduction associated with the burnup dependent rod bow.

For example, consider a limiting assembly in a MK-B core which has a rod bow penalty applied at a burnup of 40,000 MWd/mtU. Referring to Figure 7-1 (MKB fuel) a rod bow penalty of   is determined. Subtracting the 1% DNBR credit the resulting net penalty is . This DNBR reduction can be offset by a corresponding reduction in peaking of . Since an assembly with a burnup $\geq$ 24000 MWd/mtU was shown in the previous paragraph to have at least a peaking margin (an even greater margin is expected at 40,000 MWd/mtU) the DNBR reduction due to rod bow is easily offset, by a large margin. A similar example for MK-C fuel can be easily constructed and shown to have more than enough peaking margin to offset the rod bow penalty.

Clearly then the application of a DNBR penalty due to rod bow is inappropriate and has no significance for B&W fuel designs.

Question 32

The question and response are found in conjunction with Question 15.

Question 33

The question and response are found in conjunction with Question 30.

Question 34

Why does the worst gap closure occur in the lower spans?

Question 51

It has been observed that the peak bowing is most likely to occur below the core midplane, but it has been observed in all but the top grid span. What significance does B&W attribute to observation?

Response

The largest magnitude of the standard deviation of the water channel gap measurements in most likely to occur below mid-core as shown in table 4.3. It is theorized that bowing of a fuel rod is influenced by the thermal and irradiation histories of the rod as well as its mechanical loading and resulting creepdown. All of these parameters vary axially during the assembly's life depending on a number of factors such as the axial power distribution. The relative importance of the individual parameter has not been determined since the worst span closure can be conservatively used to bracket all of the gaps within the assembly. The fact that the largest rod bow is below mid-core is not considered significant for the B&W analysis technique.

Question 35

Is there a preferred direction for pre-bow in fresh assemblies? If yes, what is the reason for this behavior and how is it accounted for in the analysis?

Question 39

Is there any evidence that bowing is not isotropic?

Response

It has been B&W's experience that as built and operational rod bow is a random isotropic behavior. There is no evidence that a preferred direction for as built rod bow exists.

The analytical techniques used to develop the rod bow correlation are based on water channel gap widths, not on direct measurements of the lateral shift (bow) of the individual rods. Also, the DNBR reduction is a direct function of the water channel or cell dimensions and not the axial mode shape of the rods.

Question 36

Early pictures of rod bowing presented in the Westinghouse report WCAP-8346 showed very severe bowing for the outermost fuel rods. More recently, spacer grids were damaged during refueling at Rancho Seco (March 1980) and Indian Point-2 (January 1981). In the latter case, 272 assemblies were examined and 108 assemblies showed anomalies of some degree. Of these 108 assemblies, 33 assemblies were judged to require some repair and 10 assemblies were judged to have sustained more damage than would be acceptable for reinsertion. Fuel rod bowing seems to be a contributing factor to this grid damage. Has rod bowing typical of these plants been included in the reported data base?

Response

The rod bow correlation was developed from a data base that includes measurements from assemblies which are typical of the type used in the Rancho Seco reactor and which were irradiated at plants very similar to Rancho Seco. There is no evidence that fuel rod bowing was a cause of, or contributed to, the spacer grid damage that was observed at Rancho Seco.

Question 37

How do the correlations depend on the data base selected? For example, how would correlations for the burn-up ranges 0.10 GWd/mtU, 10-20 GWd/mtU, and 20-30 GWd/mtU compare?

Response

The rod bow correlation represents the best estimate of the standard deviation of the water channel measurements as a function of burnup. The correlation was reviewed to assess its sensitivity to the range of the data base used in the derivation.

The data base was subdivided into 4 sequential groups based on burnup. For each grouping, the average of the measured gaps compared favorably with the preidicted gap based on the average burnup. The deviation between the average measured and predicted gaps was not significant compared to the tolerance band of the data.

Question 38

In deriving the gap closure correlation, how has the fact that the number of measurements differs from assembly to assembly been accounted for?

Response

The gap closure correlation was developed from the statistical characteristics of the data distribution of the gap measurement in the worst span of the assembly. In all cases, the large number of data points measured were sufficient to determine the distribution for that span. No adjustment was considered necessary to account for the differences in the number of measurements from assembly to assembly.

Question 39

The question and response are found in conjunction with Question 35.

Question 40

The question and response are found in conjunction with Question 24.

Questions 41, 42, 43

The questions and responses are found in conjunction with Question 30.

Question 44

In carrying out the CHF experiments, the heated rod was bent toward the other rods. In a reactor, this bowing will cause a change in power in the rod. Has this effect been taken into account in these experiments or analysis?

Response

In CHF experiments, the objective is to measure the effects of the controlled (independent) variables on the dependent variable (CHF). In a bowed rod test, one of the controlled variables is the amount of closure. The dependent variable of CHF (ie: rod power to DNB) is then correlated to the independent variables including the closure. Since the allowable rod power is the result, it is implicitly included in the correlation and the associated bow penalty which results from experiment.

Question 45

Is there any justification to support a flow dependence in the DNBR penalty?

Response

In the discussion and analysis of the bowed rod test (Appendix E), the data was examined for both flow and pressure dependence with respect to DNBR penalty. The examination was conducted on both a subchannel (Tables E-3 and E-4) and a bundle average basis (Table E-5). All the paired difference comparisons fell within results of the uncertainty analysis as developed in Section 4.2 of Appendix E except for the extreme high mass velocity comparison of Table E-4. Examination of this comparison indicates that the major part of the deviation is due to the C-9 (unbowed) value as opposed to the C-10 (bowed) value. Based on the paired difference comparisons, the deviations between C-9 and C-10 results were judged to be independent of both pressure and mass velocity.

Furthermore, the entire analysis in Appendix E indicated that any differences in results between C-9 and C-10 were within CHF testing repeatability, and thus there was no DNBR penalty at 55 percent closure. The use of the upper tolerance level bow penalty at 55 percent closure is viewed as a conservative treatment of the data designed to remove any uncertainty on the threshold value of penalty versus closure.

Question 46

What data points were used in BAW-10147P in Figures 4.1-4.3? How was this data selected?

Response

The rod bow correlation was developed from an extensive data base (Appendix B of BAW-10147P) that includes over 125,000 individual measurements of the water channel gaps from 26 fuel assemblies for burnups to 40,000 MWd/mtU. The comparisons presented in Figures 4.1-4.3 were derived from this data base.

Figure 4.1 presents a comparison of the data from the span(s) with the largest magnitude of the rod-to-rod and/or rod-to-guide tube gaps for each Mark-B assembly. The source of data points in the figure are given in Tables 3-1 and 4-1.

Figure 4.2 presents the standard deviations of the rod-to-rod gaps involving only peripheral rods and those involving interior rods for the assembly span with the largest standard deviation for all the rod-to-rod gaps for the Mark B assemblies. The sources of the data points used in the figure is Table 4-2.

Figure 4.3 presents the standard deviation of rod-to-rod gap measurements for all of the Mark-B assemblies within the range of interest of assembly burnup. Different notation is used to distinguish the rods lifted assemblies (NJ008M and NJ008N) and the spiral eccentricity assemblies (NJ00P7 and NJ00PG) compared to the standard configuration assemblies. The source of the data base is Table 3-1.

Question 47

Is there a reason for the trend in BAW-10147P in Figure 4.1 which suggests that the rod-guide tube gaps are larger at low burn-ups but smaller at high burn-ups than the rod-rod gaps?

Response

The design and fabrication of the fuel assembly results in different "as built" bow in the guide tubes than the fuel rods. The magnitude of the irradiation induced bow can be expected to be much lower in the guide tubes compared to the fuel rods. This results in a lower standard deviation for the rod-to-guide tube gaps than the rod-to-rod gaps. The trend is more apparent at the higher burnup levels due to the larger magnitude of the values involved. At low burnups, the data scatter represents a larger percentage of gap magnitudes so that any correlation between the groups is less pronounced.

Question 48

If only 12% of the MK-C spacing distributions passed the normality test, why is it justified to treat all distributions as if they were normal?

Response

On page C-2 it is shown that 38% of the Mark C . t data passed the D' test for Normality. In addition, Figure C-1 shows that when the distribution is very concentrated about the mean, as this data is, it is more conservative to assume the 84th percentile estimate from the normal distribution, than from the actual data points. Thus B&W took the conservative approach of assuming Normality.

Question 49

Is the bow correlation based on interior rod-rod gaps only?

Response

The rod bow correlation was developed from a data base that included all the rod-to-rod measurements (interior and periphery) for that particular assembly configuration.

Question 50

What is the uncertainty in the gap measurement in mils?

Response

The uncertainty in the gap measurements is estimated to be inch for the mean with a maximum increase of inch in the standard deviation of the poolside data. This uncertainty includes the effects of the accuracy tolerance of the probe itself and its electronic signal, fuel rod ovality, probe positioning and the accuracy of recording and reading the data from the strip chart. Also included is the uncertainty in the data correction techniques used to account for fuel rod spreading during probe insertion.

Question 51

The question and response are found in conjunction with Question 34.

Question 52

The question and response are found in conjunction with Question 10.

Question 53

How many batches have been considered in the determination of the 95/95 upper one-sided tolerance limit?

Response

The rod bow correlation was developed from a data base of eight manufacturing batches which included over 125,000 individual measurements.

Question 54

It is stated in BAW-10147P that a review of the data base shows a trend for the rod bow behavior to saturate at high levels of burn-up (>35,000 MWd/mtU) with the magnitude of the standard deviation of gap measurements remaining constant or decreasing. Describe in more detail the results of this review.

Response

The magnitude of the standard deviation of the gap measurements, σ_{gap}, for the assemblies (1D13, 1D42, 1D45, 1D55) that obtained burnups greater than 35,000 MWd/mtU exhibit a tendency to remain constant or decrease. The results of a span-by-span comparison of the third and fourth burnup cycle data from the intermediate spans for these assemblies is shown below:

Direction of Relative Change	Percent of Spans Exhibiting Change
Decrease	
No Change*	
Increase	

* Only changes greater than .0005 inch were considered significant.

Question 55

Does B&W have a basis for the 1.2 cold-to-hot correction factor other than the NRC recommendation?

Response

The 1.2 cold-to-hot correction factor was used based on the NRC recommendations.

Question 56

Why has the B&W gap correlation been changed from a square root to a linear burn-up dependence? Is the high burn-up data increasing faster than E?

Response

The relationship between the B&W low and high burn-up data does not support a square root dependence. As noted in Appendix D, the best fit model was found to be linear (burnup exponent of). The data does indicate that the rod bow behavior tends to saturate at high burnup levels (Ref. Question 54) with the magnitude of bow remaining the same or decreasing in the majority of cases. The correlation equation with its linear burnup dependence will conservatively predict rod bow in the high burnup regions.

Question 57

In the letter, Taylor to Vassallo, dated December 13, 1978, B&W used the NRC (Reference 1) procedure for determining the DNBR penalty. In the latest report, BAW-10147P, a new method is presented. Why was it decided not to use the model which was used two years earlier?

Response

The NRC procedure (Reference 1) was written as a proposed procedure, one to be used as an interim document in lieu of a Topical Report (and not a NUREG or procedures ruling).

Since 1978, B&W has produced a data base as well as performed a thorough review of the reference 1 techniques. It has become apparent that in the techniques of reference 1, sufficient thought was not given to the physical consideration of the problem.

The values of gap closure gc from 0% to 100% or $0 \leq \frac{\Delta c}{c_0} \leq 1.0$, due to the fact that closure is complete at contact. Thus, also the penalty function goes only to contact and is a step function essentially, as defined in eqn. 6-4.

On the other hand, the gap closures assumed to be normally or rather 1/2 normally distributed have arguments between zero and infinity which produce inconsistencies with the above. These two physical and statistical considerations should be reconciled (and were indeed done so in BAW-10147P) by truncating the normal (1/2 normal) distribution and renormalizing the area so that it integrates to unity.

This method results in having more weight assigned to physically feasible gap closures and no weight to physically impossible ones.

By neglecting to truncate the gap closure distribution functions at 100% closure, the NRC procedure becomes physically unrealistic and statistically meaningless because it assigns weight (probability) to physically impossible gap closures between full closure and infinity! B&W does not accept the NRC proposal that $\delta = \frac{\delta_c}{1-K}(X-K)$ is a product of two random variables.

The fact that $X = \frac{\Delta C}{C_0}$ is random is not disputed. However, if "δ_C" is random, then so is "K"! Since they are two points on the same straight line, it seemed more realistic to estimate them and to do so conservatively. Otherwise, the problem statement is unrealistic as well as inconsistent. Finally δ_C, for instance, was considered by the NRC to have a normal distribution, one that has arguments to infinity, yet the penalty at closure is clearly limited by a value of one hundred percent. B&W has carefully considered the above points and concluded that the method presented in BAW-10147P is more realistic.

Question 58

What is the basis for assuming that the distribution of the contact penalty δ_c is normal?

Response

In appendix E, the B&W data was used to estimate a value of K as well as the penalty at 55% closure. These two best estimates would yield best estimate values for the slope of the penalty boundary line (Figures 6-2, 6-3). The B&W data indicated that the normal assumption for the scatter was reasonable.

The contact penalty best estimate value, $\overline{\delta}_c$, as well as σ_{δ_c}, were values at closure supplied by the NRC (ref 7). Due to the proprietary nature of the data, the actual data points were not released. Thus non-parametric bounds were unavailable.

B&W wished to be conservative in estimating the slope in Figures 6-2 and 6-3 and followed this conservative development in Section 6.1.2. It seems reasonable to assume normality of experimental errors for both points on the same curve, when evidence supports the assumption for one point and lack of evidence prevents one from refuting it on the other.

Question 59

In BAW-10147P, is the difference between Figure 7.1 and Figure 7.2 solely attributable to the 12% difference in MK-B and MK-C water channel widths?

Response

As pointed out in Section 5 and Appendix D, the same prediction equation relating gap closure to burnup is used for MK-B and MK-C fuel designs. Although the equation was developed using the MK-B data base it conservatively bounds the MK-C data. The development of the DNBR reduction (penalty) equation includes the probability distribution of gap closure which utilize the mean μ, the value of which is dependent on the fuel design-138 mils for MK-B and 122 mils for MK-C. In this respect then the difference between Figure 7.1 and 7.2 is attributable to the difference in MK-B and MK-C water channel widths.

Question 60

What is the basis for measuring the bowing effect on CHF for rod-guide tube bowing rather than rod-rod or rod-instrument tube bowing? Justify that this is bounding.

Response

In the bowed rod test (C-10) described and analyzed in Appendix F, the bundle is typical of the guide tube geometry. The bowing effect on CHF, however, is investigated in a rod-to-rod configuration (dimension b, figure E-2). The basis for this configuration is that CHF has been found to occur in the gap between heated rods and not in the gap between one heated and one unheated rod. This observation is based on both heat marks found during post-test inspection, and on the relative frequency of corner versus adjacent hot rod CHF occurrence on unbowed tests of the guide tube geometry (reference 15). Furthermore, the difference in CHF level has been found to be a function of only the resultant local conditions of quality and mass velocity for guide tube versus unit type geometry, and not a specific geometry term such as the hydraulic diameter (also reference 15). Therefore, any observed CHF penalty due to rod bow would be expected to be the same for unit, guide tube, or instrument tube geometry as long as the closure is relative to heated rod gaps. The degree of CHF degradation for closure in a heated to non-heated rod gap would be expected to be somewhat less than for the tested heated rod to heated rod gap.

Question 61

In calculating the effects of rod bowing on power peaking in BAW-10147P what is the effect of bowing rod-A diagonally towards rod-D? How is this effect accounted for?

Response

The effect of bowing rod-A diagonally towards rod-D is shown in Figure G-6 and Figure G-11 of BAW-10147P by curves labeled 45^{o} for Mark B and Mark C geometry, respectively.

Question 62

Is there an explanation why there is no CHF penalty up to 55% closure?

Response

CHF is dependent on and correlated as a function of the local thermal-hydraulic conditions of pressure, quality, and mass velocity, and the radial and axial heat input distributions. The mass velocity is a characteristic local value, while the local quality is basically an integrated average value based on the mass velocity, geometry, and heat input up to that position. The sensitivity of CHF to changes in quality is roughly an order of magnitude greater than that to changes in mass velocity. Since the presence of a bowed rod would tend to degrade the local mass velocity with no increase in quality, it is reasonable to expect a threshold value of gap closure below which no degradation in CHF would be observed. As discussed in response to Question 45, the bowed rod CHF data for 55% closure was actually within the range of uncertainty of the other (unbowed) CHF data. This would indicate that the threshold value is at least 55% closure and is most likely somewhat higher.

Question 63

What is the conservatism introduced by using a linear correlation between δ DNBR and gap closure?

Response

A linear correlation relating δ DNBR and gap closure was used between the value of gap closure below which there is no DNBR reduction, and 100% closure (contact), the point at which maximum DNBR reduction occurs.

The actual expected behavior of δ DNBR over the range of zero DNBR reduction to the maximum reduction is that δ DNBR will initially increase gradually from the gap closure of 0 DNBR reduction and increase more rapidly as gap closure approaches contact, as illustrated in Figure 6-1 (and in Reference 1, Figure 4.2). The degree of conservatism resulting from using the linear correlation has not been quantified for BAW-10147P since B&W has not performed rod bow CHF tests at gap closures greater than 55%, the threshold closure below which there is no penalty.

Question 64

What is the basis for the heat flux allocation in Figures E-1 and E-2 in BAW-10147P? Why is there a flatter heat flux distribution in the case of rod bow? Does this bias the rod bow results?

Response

In our 5x5 array CHF tests, the inner 8 rod heat fluxes are peaked higher (usually 10%) than those of the outer 16 rods. This is to insure that primary CHF occurrence is associated with the inner subchannels which are typical of in-reactor geometry.

The design relative heat flux distribution for both the unbowed and bowed rod tests were identical. The as-built rod electrical resistances (which determine the heat flux distribution) varied slightly between the two sets of rods, and resulted in the values shown in figures E-1 and E-2. In the CHF analysis, the actual heat fluxes based on the measured distributions are used. Thus, no bias is included in the results.

Question 65

As a bowed rod burns with a perturbed power, the resultant late-in-life power distribution will be further perturbed due to changes in isotopics. What effect does this perturbation have on the local F_Q^B penalty?

Response

This additional effect on the power is negligible, being less than 0.02%. The change in isotopic composition resulting from a fuel rod being depleted in a bowed position was assessed with calculational checks of the analytical procedure.

The analysis was performed with a fuel pellet composition that simulated end of cycle conditions. End of cycle conditions were chosen because the rod bow increases with in-reactor operating history. The maximum difference in the perturbed power in any fuel rod due to a mil bow of rod A along the 90° axis (Figure G-4), with fuel having MWD/T exposure, was less than power. The same difference was calculated for fuel having MWD/T.

Since the actual isotopic composition was quite different between these several pellet material models, it was concluded that the non-uniform fuel cell burnup is accurately accounted for in the design analysis and no perturbation is required for the non-uniform burnup of a bowed rod.

Question 5

2nd Round:

One cannot conclude from the fact that the CHF occurs in the gap between heated rods that the effect of the location of the remaining rods is not important. Therefore, determine quantitively the effects of multiple rod displacements on the bowing penalty δ_B. If necessary, incorporate these effects in the $F_Q{}^B$ and DNBR operating limits.

2nd Round Answer:

The following discussion provides an assessment of the effect of multiple rod displacements on the bowing penalty, δ_B, of a particular gap of interest.

Two effects are predominant in the determination of CHF level. The first, the integral effect, is basically the thermodynamic quality of the coolant at the axial location of interest. This in turn is just the integrated effect of mass velocity and heat input up to that point. The integral effect represents the progressive deterioration of the capacity of the coolant to accept heat input. Secondly there is the localized effect. This can be viewed as the contribution (or detraction) of the mass velocity at any given axial location to the capacity of the coolant to accept localized heat input. CHF testing has established that of these two effects, the integral effect is much greater than the local effect.

Extensive testing has established that CHF occurs in the gap between heated rods. In testing a bowed rod configuration, the bundle is constructed such that a specified minimum clearance occurs between heated rods where coolant heat capacity becomes critical. CHF is then detected at (or downstream) of this minimum clearance axial location in the heated rod gap. Thus, rod bow clearly has a localized mass velocity effect on CHF level. Up to and including this axial region, the effects on the integral (quality) effect due to rod bow is negligible.

While it is true that the heated rod gaps close to the heated gap of interest could affect the localized mass velocity in that gap, the change (if any) would be a secondary (probably order of magnitude lower) effect on this localized mass velocity. Coupled with the fact that localized mass velocity exhibits only a secondary effect in itself, the compounding additional secondary effect of rod gap variability in the region of the heated gap of interest would be negligible.

Moreover, when considering variable rod gaps close to the gap of interest, any reasonable distribution would result in some gaps larger and some smaller than nominal. This would imply, then, less or more (respectively) flow in the critical gap. Thus the effect would be further reduced.

On the basis of the above reasoning, it is concluded that the penalty due to gap closure can be determined by exclusive consideration of the reduction of the heated rod gap of interest.

Question 7

2nd Round:

What magnitude of poison rod bowing will the guide thimbles permit and what is the effect of this bowing? Consider both the bowing of poison rods and the bowing of fuel rods in the presence of poison rods.

2nd Round Answer:

The poison rods are separate components which are inserted into the guide tubes (thimbles) of the fuel assembly matrix. The guide tubes limit the poison rod bow.

The maximum poison rod bow within the guide tube (thimble) annulus is 34 mils for MK-B and 30 mils for MK-C. This is one half of the diametral clearance between the poison rod and guide thimble.

An assessment of effect of poison rod bowing on local power peaking considers the types of poison rods used in B&W core designs. There are three types of poison rods used in the B&W core design: full length control rods, part length control rods and burnable poison rods.

The effect of control rod (full length or part length) bow and adjacent fuel rod bow upon power in nearby fuel pins is not a concern, because a fuel assembly containing a control rod assembly of either type does not simultaneously have the maximum power producing fuel pin in a B&W core design.

The third type of poison rod, burnable poison rod, is accounted for in the standard nuclear reliability factor (NRF) that is applied to the B&W nominal design core peak pin power. This is because burnable poison rod bow is equivalent to the nominal design radial position uncertainty of the poison rod in the guide thimble. The radial position uncertainty along the axial length of the guide thimble is due to causes such as rod straightness. The standard nuclear reliability factor was established by comparison of calculated to measured peak pin power from a large data base that includes both operating plant and critical experiment data for core designs using burnable poison rods.

Fuel rod bow adjacent to a burnable poison rod is expected to induce a smaller fuel rod power change for the peak rod power than occurs for a uniform lattice configuration for several reasons. The water fraction is slightly less in the immediate area of the bowed rod due to the presence of the guide thimble and poison rod. The peak power producing fuel rod is generally located in a fuel assembly lattice region having higher than average water fraction. Secondly the burnable poison rod is a neutron absorber throughout the fuel cycle with some residual poison remaining at the end of the cycle. This effect adds assurance that the peak power producing fuel rod will not be adjacent to a poison rod. Finally there are less fuel rod contributors in the lattice position statistical population in the vicinity of guide thimbles than was used in the uniform fuel lattice analyses that established the total fuel rod bow induced power change of BAW-10147P.

Question 15

2nd Round:

In the Monte Carlo simulation of rod bowing only the 8 nearest neighbor rods were allowed to bow. What is the effect of bowing of second nearest neighbor rods on the central rod power?

2nd Round Answer:

The calculations which considered the variation in local power peaking with random bowing of surrounding assemblies included the effect of bowing the eight nearest rods plus the next nearest group of sixteen rods. As described in the response to Question 15 (first round) and in Appendix G of BAW-10147P, the Monte Carlo technique used to determine the sensitivity of local power peaking with random rod bow considered a 5 x 5 rod array. With this model the change in power peaking in the center rod was determined as result of bowing each of the surrounding rods in the 5 x 5 array.

Question 16

2nd Round:

What specific burnup is this analysis and gap closure applicable to?

2nd Round Answer:

The rod bow analysis presented in BAW-10147P is expected to be valid for any range of fuel assembly burnup expected to occur in current or future core operation. The maximum burnup for current fuel assembly designs for which this analysis applies is MWd/mtU, and is based on mechanical design considerations. Modifications to existing fuel assembly designs and to fuel cycle designs may allow fuel assembly burnup of MWd/mtU or greater and the current rod bow analysis presented in BAW-10147P is expected to remain applicable.

The rod bowing data presented in BAW-10147P, which included fuel assembly burnups to 40000 MWd/mtU, indicates that the rod bow behavior tends to saturate out at burnup levels greater than 35000 MWd/mtU. The response to Q-54 of the first round questions provides a data summary showing this trend. The prediction of gap closure for burnups greater than 35000 MWd/mtU is conservative because of the linear burnup dependence of the correlation, eq. 5-1 of BAW-10147P. In addition, the global tolerance applied to the correlation, as determined by eq. 5-4 and described in detail in Appendix D of BAW-10147P, increases with burnup, thus providing additional conservatism to the analysis for burnup levels greater than 35000 MWd/mtU.

Question 17

2nd Round:

Provide a typical range of fuel design parameters (including variations in enrichment, poison rods, rod pitch, burnup, water holes, guide thimbles etc. covering all NSSS's supplied) to which this analysis is applicable.

2nd Round Answer:

The data base used in the development of the rod bow correlation encompasses a wide spectrum of fuel design parameters. It includes more than 125,000 individual gap measurements on a range of fuel assembly designs, manufacturing variations, operational and irradiation histories.

The data base includes measurements on 26 assemblies of the 15 x 15 Mark-B (.568" pitch) and 17 x 17 Mark-C (.502" pitch) configurations. The assemblies represent 8 manufacturing batches with enrichments from 2.15% U^{235} to 3.2% U^{235}. They were used in two reactors during 8 operating plant cycles for individual exposures of 1 to 4 cycles wnitn burn-up to 40,000 MWd/mtU. The assemblies were inserted into core locations that contained orifice rods, burnable posion rods, safety or control rods or were open guide tube assemblies.

The rod bow analysis presented in BAW-10147P is considered valid for the current fuel assembly designs from which the data base for the analysis was obtained plus future designs which may have design parameters (such as pin pitch, enrichment, etc.) which differ from those described in the previous paragraph. As discussed in the response to the first round Question 20 the need to acquire additional gap closure measurements and to update the analysis for minor fuel assembly design changes will be reassessed on a case by case basis.

Question 18

2nd Round:

Update the description of the application of this analysis to include any changes resulting from this review.

2nd Round Answer:

B&W has concluded that no changes to the methods of rod bow evaluation presented in BAW-10147P are justified from this review. Additional information provided in the responses to the second round review support our conclusion. In particular the data presented in the 2nd round response to Question 31 illustrates the level of pin peaking margin which exists as burnup increases, relative to the design limit peaking value.

Because of the magnitude of peaking margin available, which is much more than necessary to offset the DNBR penalty determined in Figure 7-1 or 7-2, it would seem conclusive that the application of a DNBR penalty due to rod bow is inappropriate and has no significance for B&W fuel designs.

The ultimate consideration of the analysis is the effect of rod bow on core design and operating limits based on DNBR. The first round responses to questions 18 and 31 and the second round response to question 31 discuss the philosophy and methods of applying a rod bow penalty and quantifies the degree of pin power peaking margin that is present with increasing fuel assembly burnup. This peaking margin is more than sufficient to offset DNBR penalty values predicted in BAW-10147P, or by predictions made prior to the current analyses such as by the interim method of Reference 5. In view of the above considerations an update to the analysis to include a contribution to the DNBR penalty from the eight surrounding gap closures is not considered to be appropriate.

Question 23

1st Round:

In the determination of the fuel rod DNBR penalty, the bowing of the eight surrounding rods and associated gap closures determined the reduction in DNBR margin. "The penalty for each gap 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. (In Reference 1 this method was used to determine the penalty arising from the bowing of two rods on opposite sides of the rod of interest)." Therefore, update the bowing anlaysis to include the contribution to the DNBR penalty from all eight surrounding rods.

2nd Round:

The determination of the DNBR penalty using equation (F-3) does not properly account for the gap closures of all eight surrounding rods. Therefore, update the analysis to include the contribution to the DNBR penalty from all eight surrounding gap closures.

2nd Round Answer:

The methods of analysis presented in BAW-10147P have resulted in a treatment of the subject of rod bow in a manner which can be used to conservatively assess the impact of rod bow on core design and operating limits based on DNBR criteria. The treatment of rod bow in BAW-10147P is, we feel, consistent with the objectives suggested in Reference 1 of BAW-10147P.

In consideration of the probability distribution of gap closure, and the associated DNBR penalty, referring to the underlined portion of the 1st round question please note the following equation F-3.

The above integral (instead of sum) is analogous to the underlined statement in the 1st round question. Also the equation F-1 utilizes the same principle presented in Reference 1 Appendix 2.

Question 26

2nd Round:

Determine the effects of assembly bow on local rod powers and incorporate these effects in the F_Q^B penalty.

2nd Round Answer:

Thermal hydraulic design analyses incorporate a conservative bundle (pin by pin) peaking distribution which was established from nuclear analysis that considered the influence of water gap variation between fuel assemblies when determining rod powers. This peaking distribution represents the worst case associated with the range of assembly bow considered feasible, which included maximum, minimum, and nominal spacing between adjacent fuel assemblies. This conservative peaking distribution is used in limiting assembly DNBR analyses along with the conservative method of modeling subchannels between adjacent assemblies to account for assembly bow as described in the response to Q-26, (first round). Thermal hydraulic DNBR analyses performed with the conservative peaking and modeling assumptions therefore properly account for the effects of fuel assembly bow.

Question 27

1st Round:

Describe in detail the derivation and basis for Equation (D-4) in BAW-10147P.

1st Round Answer:

Equation (D-4) is to calculate a 95% upper tolerance level on values of bow predicted by equation (D-2) which in turn is based on rod-to-rod gap measurements as described in Section 5 of BAW-10147P. The derivation of equation (D-4) is found in Reference 12 of BAW-10147P, "Simultaneous Statistical Inferences," R. G. Miller, McGraw-Hill Book Co. (1966).

2nd Round:

Define the symbols and discuss the basis and applicability of equation (D-4) to the calculation of the bow tolerance.

2nd Round Answer:

Equation D.4 is defined as:

Bow Tolerance (at 95/95) =

This term is obtained from the least squares regression program that was used to evaluate coefficients of the prediction equation. The standard error is a measure of the deviation between predicted and measured values (of bow in this case).

(A)

$C_{Bu} = \sqrt{X_0'(X'X)^{-1}X_0}$, the model correction factor is also obtained directly from the regression program. This factor is statistically necessary in order to account for the greater uncertainty in the model predictions, the further one goes from the mean of the independent variable (BU in this case). It may be seen in Figure 5-1 what a "fanning out" effect this term has on the tolerance curve. (X_0 = vector of input for evaluation of regression function and $(X'X)$ is the matrix from which regression coefficients are estimated.)

ρ = degrees of freedom used for estimating the regression coefficients

$n-\rho$ = degrees of freedom available for error

$F_{\rho, n-\rho}^{.95}$ = the 95% value of the F- Statistic with ρ and $n-\rho$ degrees of freedom.

Up to this set of terms the form of D-4 is very much like any other regression function confidence interval on the mean prediction. By using the "F" rather than the "t" statistic the entire regression surface is covered, hence the adjective "global".

(B)

$Z_{.95}$ = the 95% value of the Normal Statistic

$\chi^2_{.05,\, n-\rho}$ = the lower 5% value of the CHI-square statistic with $n-\rho$ degrees of freedom

The unknown scale factor of σ(bow) is bounded with 95% confidence, by:

To quote the author of Reference 12 on Page 124: "A quick and easy family of simultaneous tolerance intervals can be patched together with the aide of the Bonferroni inequality."

The result is equation D-4.

Miller refers to the above technique as being most useful in cases where the total number of predictions one may make in the future are unknown or may be subject to change.

Question 29

1st Round:

In the determination of the DNBR penalty, the effect of the uncertainty in the penalty due to variability in gap closure (denoted σ_u in Reference 1) has been neglected. Incorporate this variability using a 95/95 upper tolerance limit as outlined in Reference 1, Equation (4.19), or indicate how this effect has been accounted for in the DNBR penalty.

2nd Round:

The NRC guidance requires that the variability in gap closure (denoted σ_u in Reference 1) be accounted for explicitly in the calculation of the DNBR penalty. It also requires that a 95/95 upper tolerance limit be used to describe the expected distribution of gap closures. Therefore, incorporate this variability as outlined in Reference 1 (of BAW-10147P), Equation (4.19), or indicate how this effect has been accounted for in the DNBR penalty.

2nd Round Answer:

From Reference 1 of BAW-10147P, equation 4-19 is:

$$\left(\frac{M}{P}\right)_b^{95 \times 95} = \left(\frac{\overline{M}}{P}\right) - \overline{\delta} - k_b^{95 \times 95}\sigma_b \quad (4.19) \qquad \text{or}$$

$$= \left(\frac{\overline{M}}{P}\right)_{nb} - \left(\overline{\delta} + K_b^{95 \times 95}\sigma_b\right)$$

The method chosen by B&W to incorporate the variability of gap closure into the DNBR penalty is such that the term

$$\left(\overline{\delta} + K_b^{95 \times 95}\sigma_b\right)$$

cannot be expressed explicitly as in the Reference 1 method, equation 4.19 above. It is accounted for never-the-less, inherently, in the calculation of values from Equation F-3 of BAW-10147P.

An explanation follows. One way of rewriting equation D-4 of the report is:

However, it must be stressed, once more, that in D-4 the term calculates a global simultaneous tolerance and is therefore much more conservative than a simple "$(K^{95/95}\sigma)$" type value.

Next: Step 1

The expression of D-4 above is then used in F-3 by substituting, appropriately, into the term as follows:

Step 2

Instead of implementing a simple $\overline{\delta}$, the upper tolerance $(\overline{\delta} + K^{95}\ \sigma(\delta))$ is used in F-3 above. The upper bound is represented by the equation F-1 and illustrated in Figure 6-2 of BAW-10147P.

Question 31

2nd Round:

What reload assumptions have been made in establishing the margin in power peaking of assemblies with burnups in excess of ( ) MWd/mtU? In support of this margin, provide the limiting assembly local peaking as a function of burnup.

2nd Round Answer:

An evaluation of nine typical B&W reload cycles has quantified the level of rod power peaking margin that exists as burnup increases. The cycles selected cover a wide range of reload parameters as indicated below:

# Cycles	Cycle Length	BPRAs Used	Mode of Operation
2	Annual	No	Feed/Bleed
1	Annual	No	Rodded
2	18 Month	Yes	Rodded
2	18 Month	Yes	Feed/Bleed
2	15 Month	Yes	Feed/Bleed

For each of the above cycles pin burnup and peaking data was compiled for the once and twice burned fuel assemblies. The conservative assumption was made that within a given assembly the highest burnup pin was also the pin with the highest power.

The resulting pin burnup and pin peaking data * are shown in Figure 1. These data show greater than a margin in peaking for burnups above 24000 MWd/mtU as identified in the 1st round response to Question 31.

* Fuel pin relative power densities (RPDs) are shown in terms of margin to the design limit.

Figure 1

PEAKING MARGIN TO DESIGN LIMIT vs FUEL ROD BURNUP