

TECHNICAL EVALUATION OF THE COMBUSTION ENGINEERING FUEL
AND POISON ROD BOWING TOPICAL REPORT CENPD-225-P
AND SUPPLEMENTS 1, 2-P AND 3-P

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TOPICAL REPORT EVALUATION

REPORT IDENTIFICATION: CENPD-225-P and Supplements 1, 2-P and 3-P [CENPD-225 and Supplements 2 and 3 (Non-Proprietary)]

REPORT TITLE: Fuel & Poison Rod Bowing Evaluation

REPORT DATE: October 1976, February 1977, June 1978, and June 1979 [October 1976, June 1978, and June 1979]

ORIGINATING ORGANIZATION: Combustion Engineering Corporation

1.0 Background

In 1973 Westinghouse reported fuel rod bowing observations in PWRs to the Atomic Energy Commission. This fuel rod bowing was a deviation in straightness of fuel rods believed to be caused by irradiation effects. The major concerns with this phenomenon were the potential effects on bundle power distribution and on the margin of fuel rods to departure from nucleate boiling (DNB).

Combustion Engineering observed both fuel and poison rod bowing in operating CE reactors. In the fall of 1974, the inspection of fuel assemblies from a CE plant showed fuel rod bow but, because the gap closure was less than 50%, it was not considered significant. These data were reported to the NRC on February 13, 1975 (reference 1). Additional data from this plant became available in July, 1975 and were sent to the NRC on December 15, 1975 (reference 2). Fuel rod measurements were later carried out in two additional CE plants. Data obtained from the Palisades Plant was submitted to the NRC by Consumers Power in April of 1976 (reference 3).

In 1975, Westinghouse reported new and more severe bowing information to the NRC (reference 4). The NRC assigned interim generic penalties on DNBR

2.0 Summary of Topical Report and Supplements

The Combustion Engineering topical report and supplements on the fuel and poison rod bowing analyses are summarized in the following.

2.1 Rod Bowing Data

2.1.1 Data Base

By October 1976, CE had carried out about 50,000 measurements and observations of gap closure on three operating CE reactors. During the following years, further measurements were performed on assemblies with burnups averaging up to 28,500 MWd/MTU. Combustion Engineering measurements were supplemented by Consumers Power Co. measurements taken using a Sulo strain gauge probe. Combustion Engineering has measured gap closure by using TV tapes and periscopes. The uncertainty in the latter technique is estimated at $\pm 10\%$ of the nominal gap width. A total of 21 assemblies were examined, 16 with 14x14 rod arrays and 5 with 15x15 rod arrays. The five 15x15 Palisades assemblies were not included in the derivation of the bow model, but according to CE were used to confirm the model.

Combustion Engineering has also examined a total of 120 Type 1 and Type 2 burnable poison rods for bowing. In several instances, large rod bow had been observed using the periscope inspection system. Combustion Engineering states that only Type 3 poison rods are currently being used in operating reactors. Data on Type 3 poison rod bow (given in response to question 20) show that Type 3 poison rod bow is comparable to that of fuel rods.

Type 1 and Type 2 poison rods are not used any longer. As a result of design improvements, Type 3 poison rods are expected to show less bowing than Type 1 and Type 2 rods and the correlations used for fuel rod channel closure are also used for channels adjacent to Type 3 poison rods. If Type 1 and Type 2 poison rods are to be used in a future fuel cycle for which CE provides licensing support, additional justification for the use of the rod bow model for Type 1 and Type 2 poison rods must be considered.

2.2.2 Neutronics

Neutronics calculations were performed with the 2-dimensional integral transport code, NUTEST-2. Fuel pin and absorber pin geometries are represented without homogenization. Eight group cross sections considering linear anisotropic scattering effects were generated by the CEPAC code. Linear anisotropic scattering effects were approximated by the use of transport corrected scattering cross sections. The 14x14 and 16x16 fuel assemblies were represented by 5x5 arrays of the respective fuel rods. Reflective boundary conditions were employed. The effect of nearby water-filled guide tubes was investigated. Fuel burnup was varied from zero to 45,000 MWd/MTU. The poison depletion ranged from zero to 100%. For the fuel rod bowing calculation, the absence of soluble poison in the moderator was assumed. A linear correlation was derived between power changes in the center rod due to the bow of the surrounding rods, and bowing displacement. The sensitivity of the results to boundary conditions and array size was not included in the topical report.

and linear heat generation rate (LHGR) for CE plants until further information from CE indicated that other penalties were more appropriate (reference 5).

In October 1976, CE submitted to the NRC a topical report entitled "Fuel and Poison Rod Bowing" (CENPD-225-P) which summarized CE's experience on fuel and poison rod bowing obtained up to this time.

On June 12, 1978, CE received a formal NRC response regarding this topical report. The NRC concerns were that CE did not adequately treat the (a) effect of batch-to-batch variation on the fuel rod bow magnitude, (b) bowing extrapolation from one fuel design to another with a different span length and/or rod design, and (c) the effect of combining bowing and critical heat flux (CHF) statistics. For the latter issue, NRC proposed a methodology to treat the bowing penalty in a statistically consistent fashion (reference 6).

Combustion Engineering adopted the method and also the NRC suggested bow extrapolation for designs with different span lengths and cladding thickness. In Supplement 2-P to the topical report, CE provided the NRC with additional information on CHF data for a heated rod that was bowed to reduce the rod-to-rod spacing by 54%. Based on additional as-fabricated and post-irradiation measurements of channel widths, the fuel rod bow model was updated. Supplement 3-P to the topical report, dated June 1979, provides additional information CE has obtained since the topical report of 1976 was issued. In some areas, it supplements earlier information, and in other areas it corrects information provided in the original topical report.

2.1.2 Data Analysis

Combustion Engineering does not distinguish between inner and outer row fuel rod bowing. The examination of three irradiated Calvert Cliffs Unit-1 fuel assemblies showed no consistent and statistically significant difference in channel closure between interior and peripheral rods. The ANS statistical test was utilized to assess the assumption of log-normality of poison rod data. No test of the normality of the measured fuel gap closure data was performed.

2.2 Methods and Correlations

2.2.1 Gap Closure

Combustion Engineering derived the following fractional gap closure correlations, FCC_{14} and FCC_{16} , for their 14x14 (18.86 in. span length) and 16x16 (14.81 in. span length) designs:

$$FCC_{14} = 1.2 \times BTB (A_1 + B_1 (BU)^{1/2})/0.140$$

$$FCC_{16} = 1.2 \times BTB \times 1.27 (A_2 + B_2 (BU)^{1/2})/0.124$$

The FCC values are at the 68th percentile or one-standard deviation significance level of channel closure. The A and B coefficients are given in Supplement 3-P. The gap closure depends on the local burnup through the term, $(BU)^{1/2}$. The factor 1.2 corrects for the cold-to-hot variation in closure. The factor BTB is the batch-to-batch variation correction factor. The factor 1.27 is the ratio of L/I (i.e., grid span length/cladding axial moment of inertia) for the 16x16 and 14x14 assemblies. Combustion Engineering assumes that there are equal probabilities for poison rod and fuel rod bow.

2.2.3 DNBR

2.2.3.1 Experimental data

The report describes three types of experiments. One set of experiments measured CHF's for moderately bowed fuel rods in a 21-rod bundle representative of CE's 16x16 fuel assembly. The 21-rod array contained a guide tube. In the various experiments, the fuel rod was bowed laterally or diagonally toward other fuel rods or toward the guide tube. The rod gaps were reduced by as much as 40%.

A second set of CHF measurements was carried out for severely bowed fuel rods. Only one rod was bowed at a time. The electrically heated rod bundle of 21 rods was representative of the CE 14x14 fuel assembly. The heater rod was bowed diagonally into contact with two other heater rods. Additional data was obtained with a 20-mils gap between the heated rods. The 21-rod array contained a guide tube, but the rod was not bowed toward the guide tube.

In a third set of CHF measurements, the heated rod was bowed diagonally into a small side subchannel around the guide tube. The rod-to-rod spacing was reduced by 54%. The experiment was conducted with an electrically heated 21-rod bundle, representative of the CE 14x14 fuel assembly geometry.

2.2.3.2 Analysis

For the purpose of making DNB predictions, the subchannel code TORC and the CE-1 correlation with the F-factor were used. The calculation of the DNBR penalty due to rod bow is based on the statistical method proposed by the NRC.

2.3 Summary of Results

2.3.1 Neutronics

Calculations were carried out for bowing in the lateral direction with displacements of $C_0/4$ and $C_0/2$, where C_0 is the nominal distance between adjacent fuel rods, and for bow in the diagonal direction with displacements of $C_0/2\sqrt{2}$ and $C_0/\sqrt{2}$. According to the CE report, the maximum power increase due to bowing of a single fuel rod to full contact is 2.46% for a 14x14 lattice and 1.8% for a 16x16 lattice. Bowing of a single poison rod to full contact yielded a maximum power increase of 5% for the 14x14 lattice and 4% for the 16x16 lattice. Combustion Engineering states that the analysis of power increase versus gap closure was based on the 50% gap closure calculation.

The radial power peaking uncertainty in F_R is expressed as,

$$F_R = 1 + \left[(F_R^N - 1)^2 + (F_R^E - 1)^2 + (F_R^B - 1)^2 \right]^{1/2}.$$

Using the values $F_R^N = 1.06$, $F_R^E = 1.03$ and $F_R^B = 1.018$, for the nuclear power distribution uncertainty, engineering hot channel factor, and rod bow peaking factor, respectively, a value of 1.0695 is obtained for F_R^U . According to the current practice, the limit on F_R was determined in a more conservative fashion by multiplying F_R^N and F_R^E , yielding a F_R^U value of 1.0918 which is substantially greater than the F_R^U value obtained from the statistical combination of uncertainties including the rod bow uncertainty.

A similar equation (Eq. 4.2-63) for F_Q , the total power peaking factor, exists that includes an allowance for poison rod bowing.

In the determination of the fuel rod bow augmentation factor, no allowance for an increase in heat generation rate due to poison rod bowing is made. It is argued that poison rods are bowing away from fuel rods and that the resulting increase in coolant area more than balances the increase in heat generation rate in the fuel.

2.3.2 Mechanical

No fretting wear due to rod bowing and no rod-to-rod contact have been observed in CE fuel.

2.3.3 Thermal-Hydraulics

Penalties for DNBR at the end of cycle 1 (EOC 1) at a burnup of 15,000 MWd/MTU are less than 0.1% for 14x14 fuel and 0.5% for 16x16 fuel. The respective values at 30,000 MWd/MTU (EOC 2) are 0.3% and 1.8%, and at 45,000 MWd/MTU (EOC 3) the values are 0.5% and 4.2%.

Combustion Engineering claims that in the case of 14x14 fuel, the allowance provided in the currently used pitch, bowing and rod diameter enthalpy rise factor of 1.065 is more than sufficient to offset the small DNBR penalties due to bow. A similar statement is made in regard to first cycle 16x16 fuel.

For future plants and reloads CE intends to apply the above cited DNBR penalties. Throughout the cycle being analyzed, CE intends to adjust the minimum DNBR by the penalty at the burnup appropriate to the end of the cycle. Combustion Engineering expects that because of available margins, operational penalties for CE plants will not be required to account for rod bowing.

3.0 Summary of Technical Evaluation

The bowing of fuel rods results in a deviation of fuel rod straightness and a subsequent variation in the fuel rod-to-rod spacing. The major concerns associated with fuel rod bowing are (1) the reduction in fuel rod-to-rod spacing and resulting decrease in margin to DNBR and (2) the increase in fuel rod-to-rod spacing and resulting increase in local power peaking. Also of concern are the potential effects of fuel rod fretting and corrosion which may arise as the fuel rod spacing is reduced to contact.

The CE method for treating these effects is described in the fuel rod bowing topical report, CENPD-225 and Supplements, described in the previous section. This topical report and supplements, the included references, associated NRC/CE correspondence and submittals were the subject of this review. The more important questions that were raised during the course of the review together with the CE responses are to be included as part of the approved version of the topical report. During the review several areas were identified as having high relative importance and/or a substantial degree of uncertainty and to some extent the review was focused on these areas. These included (1) the gap closure data base and its representation, (2) the measurement and determination of the DNBR penalty as a function of rod displacement, (3) the neutronics calculations of the bowing effects on local pin powers, and (4) the statistical method used to determine the 95/95 tolerance limits on DNBR and F_0 . The evaluation of these concerns is described in the following.

3.1 Gap Closure Data Base and Representation

The CE gap closure data base and its representation were reviewed in detail. Areas of special concern included the methods used to measure the rod-to-rod spacings, the extent to which these measurements span the required (CE et al.) fuel designs and expected operating conditions, and the interpretation and correlation of these measurements (vs. exposure, span length, etc.). The CE response to questions raised as a result of these and related concerns (reference 7) has been evaluated and generally found to be satisfactory.

3.2 Measurement and Determination of the DNBR Penalty

The CE measurements and correlation of the DNBR rod bowing penalty vs. gap closure and the use of this penalty function in the determination of a DNBR penalty were reviewed in detail. Areas of special concern included the penalty threshold and contact penalty, and the interpretation of the DNBR measurement data. The CE response to questions raised as a result of these and related concerns (reference 7) has been evaluated and generally found to be satisfactory.

3.3 Neutronics Calculations

The neutronics calculations of the bowing effects on local pin powers were reviewed in detail. Areas of particular concern included the calculational modeling (geometry, cross sections, numerical procedures and

solution, etc.) and accuracy, the extent to which the calculated pin power sensitivities span the required fuel designs and operating conditions, and the correlation of the numerical results. The CE response to questions raised as a result of these and related concerns (reference 7) has been evaluated and generally found to be satisfactory. However, the question of assembly bowing requires some discussion.

ASSEMBLY BOWING - Out-of-pile inspections (references 8, 9 and 10) at several plants have detected large fuel assembly bowing on the order of several hundreds of mils. Such large assembly bowing is an order of magnitude greater than that of fuel rod bowing and can primarily affect both DNB and loss-of-coolant accident (LOCA) margins of peripheral fuel rods.

The DNBR of peripheral rods is significantly higher than that of interior rods of equal power. This is because peripheral rods (a) have no adjacent unheated surfaces (i.e., control element assembly (CEA) guide tubes) to enhance the reduction in departure from nucleate boiling ratio (DNBR) and (b) are subjected to greater cooling. Also, peripheral rods are generally at lower power than central rods and a reduction in assembly gap will reduce the relative peripheral rod powers even further. Consequently, the interior fuel rods, which are essentially unaffected by fuel assembly bowing, will remain DNBR limiting.

The impact of assembly bowing on the LOCA margin arises due to the increased local neutron moderation and concurrent power increase that accompanies the widening of the inter-assembly gap.

In response to question 29, CE has performed neutronic sensitivity calculations in order to investigate the effect of assembly bowing on peripheral rod power. In these calculations, CE employed a time-dependent assembly bow model and assessed the effects out to an inter-assembly gap spacing greater than that experimentally observed in CE designed fuel. It was found for the maximum gap spacing assumed that the location of the most peaked rod (i.e., with respect to the average power density) moved to a peripheral location, but that the power density in the peak peripheral rod was about the same as the power density in the peak interior rod if assembly bowing had not been present.

The CE results have been extrapolated out to an extreme gap of 800 mils (about 4 times the normal spacing) and the new power density in the peaked peripheral rod is only 5% greater than that found in the CE topical report analysis, which does not account for assembly bowing.

Nevertheless, we agree with CE that there are several conservatisms that are of sufficient magnitude to individually, or certainly collectively, offset the detrimental effect of assembly bowing when the inter-assembly gap increases at a rate less than that assumed in the CE analysis or the 95/95 gap increase is not significantly greater than ~50 mils. The conservatisms are:

- a) See applicable conservatisms listed in the CE response to question 5.
- b) The CE sensitivity analysis conservatively assumed that the fuel assemblies were unzoned; however, actual assemblies are zoned and have a lower enrichment in the corner regions.

- c) Assembly bow measurements have been made out-of-pile under relatively unrestrained conditions. In pile, there are physical constraints imposed on the assembly by the upper and lower core plates as well as neighboring assemblies or the core shroud. These restraints are presently unquantified, though are probably very significant.
- d) In the calculation of the F_Q rod bowing penalty, the worst span bow and a 95/95 closure is used (together with a 95/95 one-sided upper tolerance factor on the F_Q penalty) hence providing additional available conservatism.

If the inter-assembly gap increases at a rate greater than CE assumed and also the 95/95 inter-assembly gap increase exceeds 50 mils the effect of the assembly bow on F_Q may be offset by available power margin between the peripheral rods and the assembly peak rod. Based on neutronic sensitivity calculations, a gap increase of ~ 10 mils may be offset by a 1% margin between the assembly peak rod power and the peripheral assembly rod powers. If sufficient margin between the peripheral and peak rod powers is not available to offset the expected inter-assembly gap increase, a detailed evaluation of the effects of assembly bow on local power peaking should be performed (including, e.g., the effects of burnup, burnable poison rods, water holes, margin to design limit peaking, core loading and the distribution of gap increases considering mechanical tolerances).

3.4 F_Q and DNBR Statistical Methodology

The CE statistical methodology for determining the F_Q and DNBR 95/95 tolerance limits and rod bowing penalties has been reviewed in detail. Of particular concern are the methods for integrating over the individual rod bowing displacements, the determination of the mean and variance of bowing penalties, and the method for accounting for multiple rod displacements. The CE response to questions raised as a result of these and associated concerns (reference 7) has been evaluated and generally found to be satisfactory. However, the statistical method for determining the DNBR penalty requires some discussion.

DNBR STATISTICAL METHODOLOGY - The statistical method used by CE in determining the DNBR penalty is considered incomplete in that it does not properly account for the bowing of all eight rods surrounding the hot rod in the core. In fact, the proposed method is one-dimensional, considering the closure of only the two colinear gaps on the left and right of the hot rod and neglecting the closure of the remaining six gaps. Four of the remaining gaps are associated with "diagonal" neighbor rods which are ~ 2.5 times farther away than the closer neighbors. Consequently, the probability of the gap to one of these diagonal neighbors being smaller than the minimum gap to the closer neighbors is negligible, and the effect of bowing of the four diagonal neighbors may be neglected. The increase in the DNBR penalty due to the inclusion of the remaining two closer gaps has been determined and results in an increase in DNBR penalty by a factor of ~ 2.

While this is a significant deficiency in the CE rod bowing DNBR statistical methodology, we agree with CE that there are several conservatisms in their treatment that provide sufficient margin to offset this deficiency. That these conservatisms are sufficient to offset this deficiency has been demonstrated quantitatively by performing DNBR-penalty sensitivity calculations. The conservatisms include the following:

- a) The worst span bow for each assembly is used to obtain the gap closure correlations. In many cases the worst span is in the lower regions of the assembly, where minimum DNBR is not likely to occur.
- b) The use of best estimate closure correlations rather than 95/95 correlations will reduce the DNBR penalty substantially. It should be noted that CE also uses a 95/95 one-sided upper tolerance factor explicitly in the calculation of the DNBR penalty to protect from DNBR.
- c) The DNBR penalty will increase with burnup because of the associated reduction in gap spacing. Conversely, nuclear peaking tends to decrease with burnup. Combustion Engineering has conservatively not accounted for this fuel depletion effect.
- d) The DNBR experiments, which employed a displaced rod and which were designed to assess the effect of bowing of one specific rod, had generalized bowing (though small) throughout on all of the other simulated fuel rods. The bowing was attributable to two factors; (a) the simulated fuel rods were not manufactured perfectly straight and (b) when power was applied to the ferromagnetic cartridge inserts,

magnetic forces between rods were induced thus creating widespread bowing of small magnitudes. Hence, the DNB experiments and the respective analyses of the DNBR penalties are not strictly applicable to only situations involving one large bow. Rather, these penalties are more applicable to actual and more probable inpile situations and associated analyses involving a large bow in a field of several lesser bows. Consequently, this aspect, though unquantifiable, will partially compensate for the use of a 2 rather than an 8 bowed-rod DNBR penalty calculation in the methodology.

- e) Cladding creepdown increases the nominal rod-to-rod spacing. This phenomenon was not modeled in the CE analysis.
- f) There is modeling conservatism in the treatment of reduction in DNBR as a function of gap closure. As shown in Figure 1, the proposed CE licensing curve (depicted by the solid line) bounds the expected behavior (represented by the dashed curve).
- g) The CE augmentation factor of F_r (radial peaking factor) was assumed to be equal to the augmentation factor for F_Q . Actually, the augmentation factor of F_r should be the statistical average of the heat generation augmentation factors of the 4 fuel rods which comprise the coolant channel and thus must be less than the augmentation factor for any one fuel rod.

- h) All CE calculations were performed assuming zero boron concentration in the coolant and thus, maximized the rod bow augmentation factors on F_r and F_Q .
- i) The use of a gap closure distribution which allows negative rod-rod spacings (i.e., use of a normal distribution which is not truncated at contact) and a penalty function which contributes a DNBR penalty for these non-physical situations, provides additional conservatism in the DNBR penalty calculation.

Other responses requiring some note or comment are the following. In response to question 18, CE indicates that the 1.5 batch/batch gap closure multiplier is also to be used in determining the F_Q^B penalty as well as in determining the DNBR penalty. In response 25, CE states that Type 1 and Type 2 poison rods are to be excluded from this methodology and that CE will provide additional justification if these type poison rods are to be used in future cycles. Corrections to figures G-3 and G-4 of Supplement 3-P are provided in response 36. Conservative assumptions are made at several points in the development and application of the proposed methodology; and in response 5, CE identifies the major sources of conservatism and provides estimates of the potential margin associated with each. While we have not performed an independent determination of these estimates we have concluded that these effects do provide a substantial margin of conservatism in the CE methodology and are more than adequate to compensate for other small non-conservatisms.

4.0 Technical Position

The CE data base and calculational procedures proposed for the analysis of the effects of fuel rod bowing have been reviewed in detail. Consideration has been given to the basis and accuracy of the individual elements of the proposed methodology as well as the overall conservatism and adequacy of the resulting F_Q and DNBR penalties. Based on this review, we conclude that the proposed methodology provides an acceptable means for analyzing the effects of fuel rod bowing and determining the F_Q and DNBR rod bowing penalties.

This evaluation is limited to the fuel designs, exposures and conditions stated in the report and supporting documentation and is based, in part, on the CE gap closure representation and the specific assumptions made in formulating this methodology. We recommend CE continue fuel surveillance to ensure confidence in these assumptions and bases.

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Figure 1

DNBR PENALTY DEPENDENCE ON ROD BOW

