INTERIM SAFETY EVALUATION REPORT
ON EFFECTS OF FUEL ROD BOWING
ON THERMAL MARGIN CALCULATIONS
FOR LIGHT WATER REACTORS

CONTENTS

1.0 Introduction

Data have recently been presented to the staff which show that previously developed methods for accounting for the effect of fuel rod bowing on departure from nucleate boiling in a pressurized water reactor (PWR) may not contain adequate thermal margin when unheated rods are present (such as instrument tubes). Further experimental verification of these data is in progress. However an interim measure is required pending a final decision on the validity of these new data.

The staff has evaluated the impact of these data on the performance of all operating pressurized water reactors. Models for treating the effects of fuel rod bowing on thermal-hydraulic performance have been derived for all operating PWRs. These models are based on the propensity of the individual fuel designs to bow and on the thermal analysis methods used to predict the coolant conditions for both normal operation and anticipated transients. As a result of these evaluations the staff has concluded that in some cases sufficient thermal margin does not now exist. In these cases, additional thermal margin will be required to assure, with high confidence, that departure from nucleate boiling (DNB) does not occur during anticipated transients. This report discusses how these conclusions were reached and identifies the amount of additional margin required.

The models and the required DNBR reductions which result from these models are meant to be only an interim measure until more data are available. Because the data base is rather sparse, an attempt was made to treat this problem in a conservative way. The required DNBR reductions will be revised as more data become available.

The staff review of the amount and consequences of fuel rod bowing in a boiling water reactor is now underway. At present no conclusions have been reached. When this review reaches a stage where either an interim or final conclusion can be reached, the results of this review will be published in a separate safety evaluation report.

It should be noted that throughout the remainder of this report, all discussion and conclusions apply only to pressurized water reactors.

2.0 DNBR Reduction Due To Rod Bow

2.1 Background

In 1973 Westinghouse Electric presented to the staff the results of experiments in which a 4x4 bundle of electrically heated fuel rods was tested to determine the effect of fuel rod bowing to contact on the thermal margin(DNBR reduction) (Reference 1). The tests were done at conditions representative of PWR coolant conditions. The results of these experiments showed that, for the highest power density at the highest coolant pressure expected in a Westinghouse reactor, the DNBR reduction due to heated rods bowed to contact was approximately 8%.

Fuel bundle coolant mixing and heat transfer computer programs such as COBRA IIIC and THINC-IV were able to predict the results of these experiments. Because the end point could be predicted, i.e., the DNBR reduction at contact, there was confidence that the DNBR reduction due to partial bow, that is, bow to less than contact could also be correctly predicted.

On August 9, 1976 Westinghouse met with the staff to discuss further experiments with the same configuration of fuel bundle (4x4) using electrically heated rods. However, for this set of experiments one of the center 4 fuel rods was replaced by an unheated tube of the same size as a Westinghouse thimble tube. This new test configuration was tested over the same range of power, flow and pressure as the earlier tests. However, with the unheated, larger diameter rod the reduction in DNBR was much larger than in the earlier (1973) tests.

The data consisted of points corresponding to no intentional bowing (that is, a certain amount of bowing due to tolerances cannot be prevented) and to contact. No data were taken at partial clearance reductions between rods.

On August 19, 1976, CE presented results of similar experiments to the staff. These tests were performed using a 21 rod bundle of electrically heated rods and an unheated guide tube. Results were presented for not only the case of full contact, but also the case of partial bowing.

The staff attempted to calculate the Westinghouse results with the COBRA IIIC computer code but could not obtain agreement with the new data. Westinghouse was also unable to obtain agreement between their experimental results and the THINCIV computer code.

Both sets of data (Westinghouse and CE) showed similar effects due to variations in coolant conditions. For both cases, the DNBR reduction became greater as the coolant pressure and the rod power increased.

Because both sets of data showed that plant thermal margins might be less than those intended, the staff derived an interim model to conservatively predict the DNBR reduction. Since the data with unheated rods could not be predicted by existing analytical methods, empirical models were derived. These models give the reduction in DNBR as a function of the clearance reduction between adjacent fuel rods. Two such models were derived, one based on the Westinghouse data and one based on the CE data.

2.2 Model Based on Westinghouse Data

Data were presented by Westinghouse for the DNBR reduction at full contact and with no bow. No data at partial gap closure were presented. Westinghouse proposed, and the staff accepted, a straight line interpolation between these two points as shown in Figure 2.1.

This approach is conservative since one would expect the actual behavior to more nearly follow a curved line as shown in the same figure. The DNBR reduction would increase slowly in magnitude as the fuel rods bowed to contact. As the rods become close enough so that there would be an interaction between the two rods, the DNBR reduction would then increase more rapidly. No physical mechanism has been postulated which would lead to sudden large decreases in the DNBR for small or moderate gap closures. Thus, the straight line approximation is believed to be an overestimate of the expected behavior.

All manufacturers of reactor cores, including Westinghouse, include a factor in their initial core design to account for the reduction in DNBR that may result from pitch reduction from fabrication tolerances and initial rod bow. The amount of this pitch reduction factor varies with the fuel design and the analysis methods which are used. For any particular core this factor is not varied as a function of burnup.

In developing the interim rod bow penalties described in this report, it became apparent that the penalty should be a function of burnup since the magnitude of rod bow is a function of burnup. However, to maintain existing thermal margins early in core life when only a small amount of fuel rod bow is anticipated, the initial pitch reduction factor was included until such time as the rod bow DNBR reduction became greater. This is represented as the straight horizontal line on Figure 2.1.

2.3 Combustion Engineering Model

Combustion Engineering performed experiments to determine the effect of rod bowing on DNBR which included some cases in which the effect of partial bowing as well as bowing to contact was determined. Again, a straight line interpolation is used. However, the point of zero DNBR reduction is not at zero clearance reduction but rather, at an intermediate value of clearance reduction. This is shown schematically in Figure 2.2. The horizontal straight line, representing the initial pitch reduction factor is included as explained previously (Section 2.2).

2.4 Models for Babcock and Wilcox and Exxon

On August 17, 1976 representatives of Babcock and Wilcox met with the staff to discuss this problem. Babcock and Wilcox did not present any data on the effects of rod bowing on DNBR. They had previously presented data to the staff on the amount of bowing to be expected in Babcock and Wilcox 15x15 fuel assemblies. Because Babcock and Wilcox had no data on the effect of rod bow on DNBR, the staff applied the Westinghouse model to calculate the effect of rod bowing on DNBR for Babcock and Wilcox fuel. The amount of fuel rod bowing was calculated using the Babcock and Wilcox 15x15 fuel bundle data.

Representatives of the Exxon Nuclear Corporation discussed the effects of fuel rod bowing in the presence of an unheated rod on DNBR with the staff on August 19, 1976. Exxon has no data pertinent to this problem. Exxon has not performed DNB tests with bowed rods. The first cycle of Exxon fuel has just been removed from H. B. Robinson and the results of measurements on the magnitude of rod bowing have not yet been presented to the staff. The effects of fuel rod bowing for Exxon fuel were evaluated on a plant by plant basis as discussed in Section 4.0.

2.5 Application of the Rod Bow/DNBR Model

Using these empirical models, the staff derived DNBR reductions to be applied to both operating reactors and plants in the Construction Permit and Operating License review stage. The procedure in applying these empirical models is as follows:

Step 1. Predict the clearance reduction due to rod bow as a function of burnup. An expression of the form

$$\frac{\Delta C}{C_o} = a + b\sqrt{BU}$$

is used where

$\frac{\Delta C}{C_o}$ = fractional clearance reduction due to rod bowing

a, b = empirical constants obtained for a given fuel design

BU = burnup (region average or bundle average, depending on the fuel designer).

Step 2. Apply the previously discussed empirical models of DNBR reduction as a function of clearance reduction using the value of $\Delta C/C_o$ calculated from step 1.

Step 3. The staff has permitted the reduction in DNBR calculated in step 2 to be offset by certain available thermal margins. These may be either generic to a given fuel design or plant dependent.

An example of a generic thermal margin which would be used to offset the DNBR reduction due to rod bow is the fact that the DNBR limit of 1.3 is usually greater than the value of DNBR above which 95% of the data lie with a 95% confidence. The difference between 1.3 and this number may be used to offset the DNBR reduction.

An example of a plant specific thermal margin would be core flow greater than the value given in the plant Technical Specifications.

A discussion of the application of this method to Construction Permit and Operating License reviews is given in Section 3.0. A discussion of the application and the results of this method to operating reactors is given in Section 4.0. The application to reactors using Exxon fuel is also discussed in Section 4.0.

3.0 Application to Plants In Construction Permit And Operating License Review Stage

3.1 CP Applications

No interim rod bow DNB penalties should be applied to CP applications. The rod bow data upon which the interim limits have been based should be considered preliminary. There is sufficient time available to review the data and assess a penalty, if any, prior to the OL stage. We will advise each CP applicant of the nature of interim penalties being applied to OL reviews and operating reactors. Since it appears that power derating is not necessary, there is no need to require design commitments at the CP stage; however, since limitations on operating flexibility may be required, we will need commitments from the applicant to (1) fully define the gap closure rate for prototypical bundles, (2) determine by experiments the DNB effect that bounds the gap closure from part (1), and (3) apply any calculated loss of thermal margin from steps (1) and (2) to reactor transient analyses. Such commitments should be part of our CP review effort.

3.2 OL Applications

Plants which are in the operating license review stage should consider a rod bow penalty. This penalty should be as described in Section 2.2 for Westinghouse or Section 2.3 for Combustion Engineering. Babcock and Wilcox plants should use the rod bow vs. burnup curve appropriate to their fuel and the Westinghouse curve of DNBR reduction as a function of rod bow.

All applicants may propose appropriate thermal margins (as discussed in Section 2.4) to help offset the calculated DNBR reduction. DNBR reductions could be greater for plants in the OL review stage than for a similar operating plant because plant specific thermal margins cannot be used to help offset the DNBR reduction resulting from application of the model.

4.0 Application To Operating Reactors

The section divides the operating plants into distinct categories and lists them according to the fuel manufacturer or reactor type. Operating plants which cannot be so categorized (such as plants with fuel supplied by more than one vendor) are placed in a separate category. The plants assigned to each category are listed in the appropriate subsection.

The conclusions reached in this section are in some cases dependent on conditions or analysis which are valid only for the present fuel cycle. Hence, the $F_{\Delta H}$ or DNBR reductions which are given (or the fact that no such reduction is concluded to be required) is valid only for the present operating cycle.

4.1 Westinghouse LOPAR Fuel

The designation LOPAR stands for low parasitic and refers to the fact that the guide tubes in the fuel bundle are made of Zircaloy. Table 4.1 gives a list of the operating plants which fall into this classification.

TABLE 4.1: PLANTS WHICH CURRENTLY USE THE WESTINGHOUSE LOPAR FUEL ASSEMBLY

15x15	17x17
D. C. Cook Cycle 1	Trojan Cycle 1
Zion 1 Cycle 2	Beaver Valley Cycle 1
Zion 2 Cycle 1	
Indian Point 3 Cycle 1	
Turkey Point 3 Cycle 4	
Prairie Island 2 Cycle 2	
Indian Point 3 Cycle 1	

TABLE 4.1 (cont.)

15x15

Turkey Point 4 Cycle 3

Surry 1 Cycle 4

Surry 2 Cycle 3

Kewaunee Cycle 2

Point Beach 1 Cycle 5

Point Beach 2 Cycle 3

Prairie Island 1 Cycle 2

The reduction in DNBR due to fuel rod bowing is assumed to vary linearly with the reduction in clearance between the fuel rods (or fuel rod and thimble rod) according to the model discussed in Section 2.2.

The maximum value of DNBR reduction (at contact), obtained from the experimental data was used to calculate the DNBR reduction vs. bow for the 15x15 LOPAR fuel. This DNBR contact reduction was adjusted for the lower heat flux in the 17x17 LOPAR fuel.

The clearance reduction is conservatively assumed to be given by the following equation for the 15x15 (and 14x14) fuel.

$$\frac{\Delta C}{Co} = a + b\sqrt{Bu}$$

where $\frac{\Delta C}{Co}$ is the % reduction in clearance

Bu is the region average burnup

and a,b are empirical constrants fitted to Westinghouse 15x15 rod bow data

For the 17x17 LOPAR fuel, the clearance reduction was calculated from the equation:

$$\Delta C/Co = \left(\frac{\Delta C}{Co}\right)_{15x15} / \left(\frac{L}{I}\right)_{15x15} \times \left(\frac{I}{L}\right)_{17x17}$$

where L = the distance between grids

I = moment of inertia of fuel rod

On December 2, 1976, Westinghouse informally showed the staff new data pertaining to the magnitude of rod bow as a function of region average burnup in 17x17 fuel assemblies. This data show that the above correction is probably conservative and that the magnitude of fuel rod bowing in 17x17 fuel rods can better be represented by an empirical function. This review is now underway.

The calculated DNBR reduction is partially offset by existing thermal margins in the core design. For the Westinghouse LOPAR fuel design some or all of the following items were used in calculating the thermal margin for the operating plants:

. design pitch reduction

. conservatively chosen TDC used in design*

. Critical heat flux correlation statistics (assumed in thermal analysis safety calculations) are more conservative than required.

. Densification power spike factor included although no longer required

After taking these factors into account, the reductions in $F_{\Delta H}$ shown in Table 4.2 were found necessary. All operating plants listed in Table 4.1 will be required to incorporate these reductions in $F_{\Delta H}$ into their present operating limits.

*TDC (thermal diffusion coefficient) is a measure of the amount of mixing between adjacent subchannels.

TABLE 4.2: $F_{\Delta H}$ REDUCTION FOR WESTINGHOUSE LOPAR FUEL

CYCLE	REDUCTION IN $F_{\Delta H}$ (%)		
	15x15	17x17	ZION 1&2
1st Cycle (0-15 Gwd*/MTU)	0-2 ramp	1-13 ramp	0-6 ramp
2nd Cycle (15-24 Gwd*/MTU)	4	15	8
3rd Cycle (24-33 Gwd*/MTU)	6	15	10

These reductions in $F_{\Delta H}$ may be treated on a region by region basis. If the licensee chooses, credit may be taken for the margin between the actual reactor coolant flow rate and the flow rate used in safety calculations. Credit may also be taken for a difference between the actual core coolant inlet temperature and that assumed in safety analyses. In taking credit for coolant flow or inlet temperature margin, the associated uncertainties in these quantities must be taken into account.

4.2 Westinghouse HIPAR and Stainless Steel Clad Fuel

The designation HIPAR stands for high parasitic and refers to the fact that the guide tubes in the fuel bundle are made of stainless steel. These two fuel types, HIPAR and Stainless Steel clad, are grouped together because the amount of bowing expected (and observed) is significantly less than that in the observed Westinghouse LOPAR fuel. The plants which fall under this classification are listed in Table 4.3.

$$* \frac{Gwd}{MTU} = 1000 \frac{Mwd}{MTU}$$

TABLE 4.3: HIPAR AND STAINLESS STEEL PLANTS

Ginna	Indian Point 2
San Onofre	Connecticut Yankee

The model for the reduction in DNBR due to fuel rod bowing is assumed to be identical to that used for the LOPAR fuel. For reactors in this category, the peak reduction in DNBR (corresponding to 100% closure) was adjusted to correspond to the peak overpower heat flux of that particular reactor.

The amount of rod bowing for the plants listed in Table 4.3 which use HIPAR and stainless steel fuel, was calculated by means of an adjustment to the 15x15 LOPAR formula. This adjustment took the form of the ratio

$$\frac{\text{amount of bow for assembly type}}{\text{amount of bow for LOPAR fuel}} = \frac{(L/IE)\ \text{assy type}}{(L/IE)\ \text{LOPAR}}$$

where L is the span length between grids

I is the moment of inertia of the fuel rod

E is the modulus of elasticity of the fuel rod cladding

Ginna Cycle 6

The Ginna plant is fueled with 121 fuel assemblies. Two of these are Exxon assemblies, and two are B&W assemblies. The remainder are Westinghouse HIPAR fuel assemblies. The experimental value of DNBR reduction was adjusted for heat flux and pressure from peak experimental to actual plant conditions. Ginna took credit for the thermal margins due to pitch reduction, design vs. analysis values of TDC and fuel densification power spike. These thermal margins offset the calculated DNBR reduction so that no reduction in FΔH is required.

San Onofre Cycle 5

San Onofre is fueled with 157 bundles of 15x15 stainless steel clad fuel. The experimental value of DNBR reduction was adjusted for heat flux and pressure from experimental to actual plant conditions. San Onofre took credit for the thermal margins due to pitch reduction and the fact that a value of 1.75 was used for FΔH in the safety analysis while a value of 1.55 was used in the Technical Specifications. Because of adequate thermal margin, no reduction in FΔH is required for San Onofre.

Indian Point 2 Cycle 2

Indian Point 2 is fueled with HIPAR fuel bundles. The experimental value of DNBR reduction was adjusted for heat flux and pressure to actual plant conditions. Indian Point Unit 2 had thermal margin to offset this DNBR reduction in pitch reduction, design vs. analysis values of TDC, fuel densification power spike and a value of $F\Delta H$ of 1.65 used in the design (vs. 1.55 in the Tech Spec). Therefore, no reduction of $F\Delta H$ is required for Indian Point Unit 2.

Connecticut Yankee Cycle 7

Connecticut Yankee is fueled with 157 stainless steel clad fuel assemblies. The DNBR reduction at contact was assumed to be that used for the Westinghouse LOPAR 15x15 fuel. No adjustment was made for heat flux. The value of pressure was adjusted to the overpressure trip set point value of 2300 psi. Full closure will not occur in stainless steel fuel out to the design burnup.

Connecticut Yankee has sufficient thermal margin in variable overpressure and overpower trip set points to accommodate the calculated DNBR reduction. Therefore no penalty is required.

4.3 Babcock and Wilcox 15x15

The reactors listed in Table 4.4 are fueled with B&W fuel.

TABLE 4.4: REACTOR USING B&W FUEL

Oconee 1 Cycle 3

Oconee 2 Cycle 2

Oconee 3 Cycle 1

Rancho Seco Cycle 1

Three Mile Island 1 Cycle 2

Arkansas 1 Cycle 1

The staff has reviewed the extent of rod bowing which occurs with B&W fuel. Based on this review, the following equation was derived for the clearance reduction between fuel rods due to fuel rod bowing as a function of burnup:

$$\frac{\Delta C}{Co} = a + b\sqrt{Bu}$$

where $\frac{\Delta C}{Co}$ is the fractional amount of closure

Bu is the bundle average burnup

and a,b are empirical constants fitted to B&W data

The reduction in DNBR due to fuel rod bowing is assumed to vary linearly with the reduction in clearance between the fuel rods (or fuel rod and thimble rod) but can never be lower than that due to the pitch reduction factor used in thermal analysis, as explained in Section 2.2.

Babcock and Wilcox claimed and the staff approved credit for the following thermal margins:

. Flow Area (Pitch) reduction

. Available Vent Valve credit

. Densification Power Spike removal

. Excess Flow over that used in safety analyses

. Higher than licensed power used for plant safety analyses

Based on this review and the thermal margins presented by B&W to offset the new Westinghouse data, Rancho Seco is the only plant for which a reduction in DNBR is required. Table 5 gives the values for the reduction of DNBR required at this time.

TABLE 5: DNBR REDUCTIONS FOR B&W PLANTS

Burnup	DNBR Reduction
	Rancho Seco
Cycle 1 (0-15 $\frac{Gwd}{MTU}$)	0
Cycle 2 (15-24 $\frac{Gwd}{MTU}$)	1.6%
Cycle 3 (24-33 $\frac{Gwd}{MTU}$)	3%

Plans must be submitted to the staff to establish how these reduction in DNBR will be accommodated.

4.4 Combustion Engineering 14x14

Combustion Engineering has presented data to the staff on the amount of rod bowing as a function of burnup. The staff used this data to derive the following model for CE 14x14 fuel.

$$\frac{\Delta C}{Co} = a + b \sqrt{Bu},$$

$\Delta C/Co$ = fraction of closure for CE fuel

Bu is the bundle average burnup

and a,b are empirical constants fitted to CE data

CE has given credit for thermal margin due to a multiplier of 1.065 on the hot channel enthalpy rise used to account for pitch reduction due to manufacturing tolerances. Table 4.6 presents the required reduction in DNBR using the model described above. after accounting for this thermal margin. Table 4.7 is a list of the reactors to which it applies.

A licensee planning to operate at a burnup greater than 24000 Mwd/MTU should present to the staff an acceptable method of accommodating the thermal margin reduction shown in Table 4.6. This may be done as part of the reload submittal if this burnup will not be obtained during the current cycle.

TABLE 4.6: EFFECT OF ROD BOWING ON DNBR IN REACTORS WITH COMBUSTION ENGINEERING 14x14 FUEL

BURNUP	REDUCTION IN DNBR
Cycle 1 (0-15 $\frac{Gwd}{MTU}$)	0
Cycle 2 (15-24 $\frac{Gwd}{MTU}$)	0
Cycle 3 (24-33 $\frac{Gwd}{MTU}$)	3%

TABLE 4.7: PLANTS FUELED BY CE FUEL TO WHICH VALUES OF TABLE 4.6 APPLY

St. Lucie 1	Cycle 1
Ft. Calhoun	Cycle 3
Millstone 2	Cycle 2
Maine Yankee	Cycle 2
Calvert Cliffs 1	Cycle 1

4.5 Plants Fueled Partially With Exxon Fuel

Palisades, H. B. Robinson, Yankee Rowe and D. C. Cook are partially fueled with Exxon fuel. A discussion of these reactors follows:

Palisades Cycle 2

The Palisades reactor for Cycle 2 is fueled with 136 Exxon fuel assemblies and 68 Combustion Engineering fuel assemblies.

The Combustion Engineering fuel was treated according to the Combustion Engineering model for both extent of rod bow as a function of burnup and DNBR reduction due to clearance reduction.

The Exxon fuel was assumed to bow to the same extent as the Combustion Engineering fuel. This assumption is acceptable since the Exxon fuel has a thicker cladding and other design features which should render the amount of bowing no greater than in the Combustion Engineering fuel.

The DNBR reduction was assumed to be linear with clearance reduction according to the Westinghouse type curve of Figure 2.1. The DNBR reduction at contact was based on the Westinghouse experimental data adjusted for the peak rod average heat flux in Palisades and for the coolant pressure in Palisades. The overpressure trip set point in Palisades is set at 1950 psi. At this pressure the magnitude of the required DNBR reduction is greatly reduced.

The limiting anticipated transient in the Palisades reactor results in a DNBR of 1.36. The thermal margin between this value and the DNBR limit of 1.3 results in adequate thermal margin to offset the rod bow penalty.

<u>Yankee Rowe</u> Cycle 12

Yankee Rowe is fueled with 40 Exxon fuel assemblies and 36 Gulf United Nuclear Corporation fuel assemblies. The fuel assemblies consist of 16x16 Zircaloy clad fuel rods.

The reduction in DNBR due to fuel rod bowing was assumed to vary linearly with the reduction in clearance between fuel rods. The peak experimental conditions used in the Westinghouse test were used to fix the penalty at full closure. The calculated reduction in DNBR is still less than that which would produce a DNBR less than 1.3 for the most limiting anticipated transient (two pump out of four pump loss-of-flow). Thus, no penalty is required.

H. B. Robinson Cycle 5

H. B. Robinson is fueled with 105 Westinghouse fuel assemblies and 52 Exxon Nuclear Corporation fuel assemblies. The Westinghouse 15x15 DNBR penalty model was applied to the Westinghouse fuel with a correction for the actual heat flux rather than the peak experimental values. The Exxon fuel was considered to bow to the same extent as the Westinghouse 15x15 fuel so that the Westinghouse bow vs. burnup equation was also applied to the Exxon fuel. This assumption is conservative since the Exxon fuel has a thicker cladding and other design features which should render the amount of bowing no greater than in the Westinghouse fuel.

The DNBR reduction calculated by this method was offset by the fact that the worst anticipated transient for H. B. Robinson results in a DNBR of 1.68.

5.0 References

5.1 Hill, K. W., et. al, "Effect of a Bowed Rod on DNB", Westinghouse Electric Corporation, WCAP 8176.

FIGURE 2.1

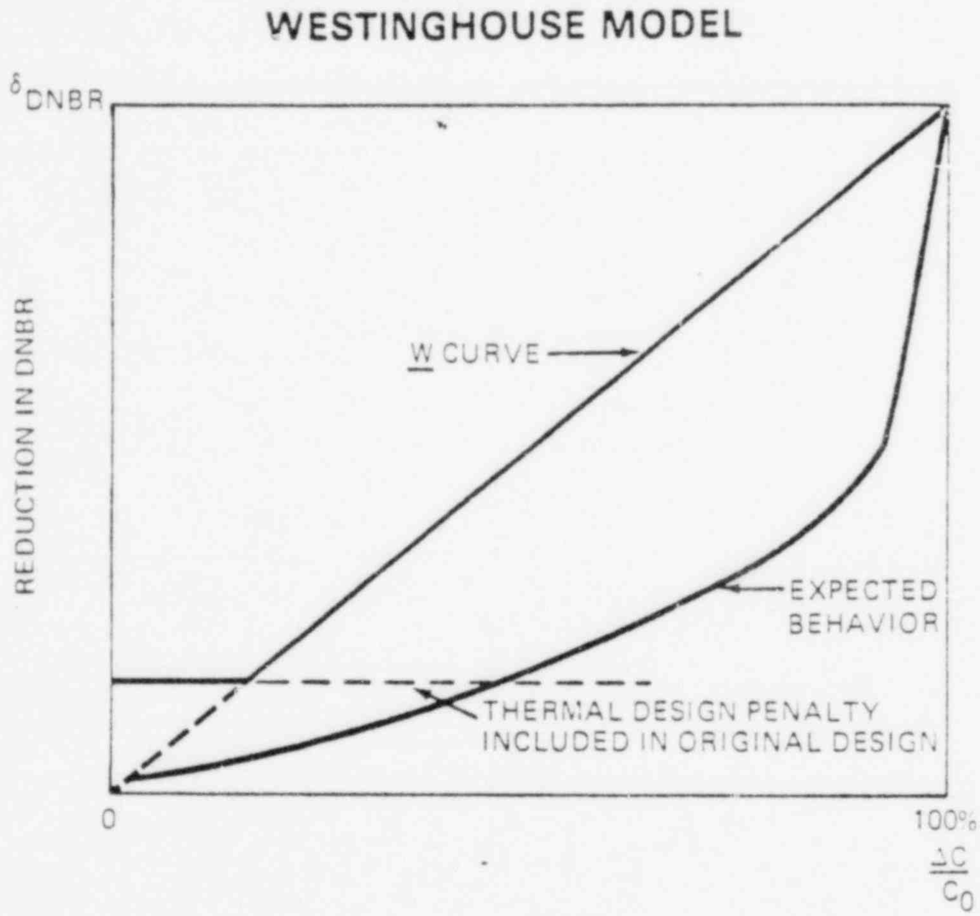
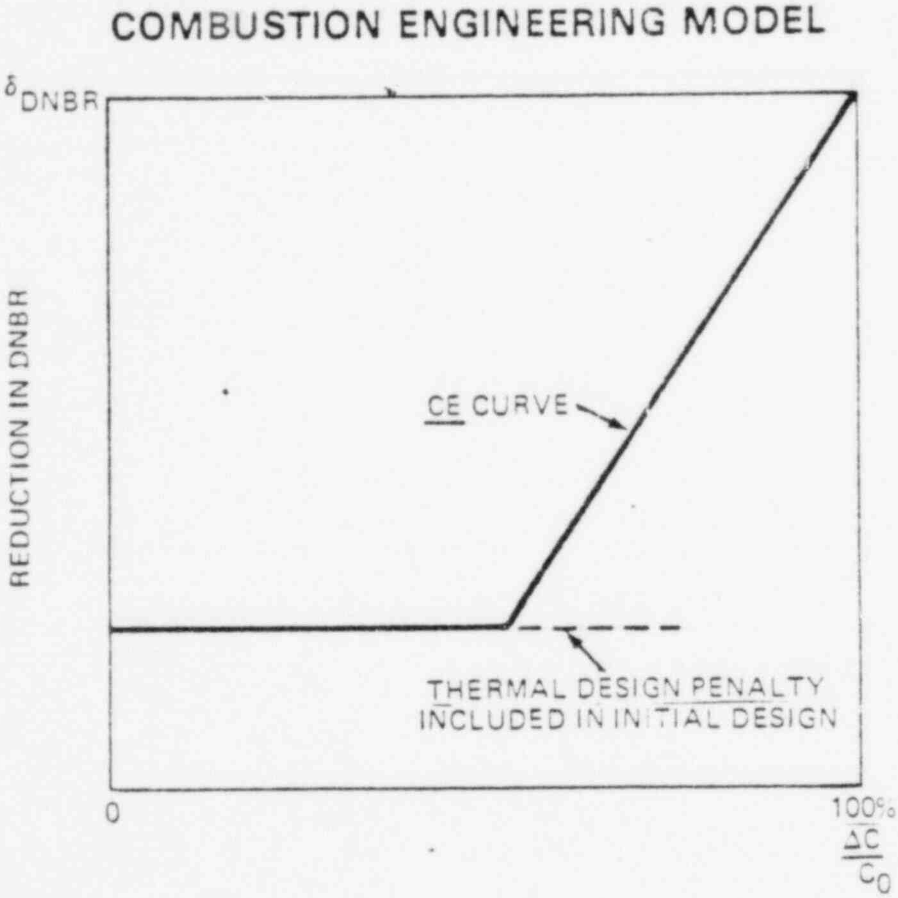

WESTINGHOUSE MODEL
δ_{DNBR}
REDUCTION IN DNBR
W CURVE
EXPECTED
BEHAVIOR
THERMAL DESIGN PENALTY
INCLUDED IN ORIGINAL DESIGN
0
100%
$\frac{\Delta C}{C_0}$

FIGURE 2.2


COMBUSTION ENGINEERING MODEL
δ_{DNBR}
REDUCTION IN DNBR
CE CURVE
THERMAL DESIGN PENALTY
INCLUDED IN INITIAL DESIGN
0
100%
$\frac{\Delta C}{C_0}$