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# CONTROL BLADE EXAMINATION RESULTS AND RESPONSE TO ITEM 4 OF IE BULLETIN 79-26

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# CONTROL BLADE EXAMINATION RESULTS AND RESPONSE TO ITEM 4 OF IE BULLETIN 79-26

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# TABLES

# ILLUSTRATIONS

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# 1. SUMMARY

During the destructive examination of a control blade from an operating Boiling Water Reactor (BWR) performed in a hot cell in 1978-79, it was discovered that there was cracking of the absorber tubes and some loss of boron carbide ($B_4C$) from the tubes. Additional hot cell examinations of absorber tubes from other operating reactors have also shown cracking and $B_4C$ loss. The mechanism has been identified as swelling of the boron carbide under irradiation and subsequent stress corrosion cracking of the tube.

The $B_4C$ loss has been correlated with degree of burnup. The $B_4C$ loss is a slow predictable process which has been modeled and accounted for in control blade lifetime evaluations. Accounting for this mechanism has resulted in a 20% reduction in control blade life (i.e., 34% average Boron-10 depletion). This reduction in life assures no safety impact on plant operation.

References 1 and 2 present the results* of a review of current plant operating parameters. The results of this review clearly show that potential control blade degradation due to this mechanism, for plants which have blades beyond the reduced lifetime, does not affect plant operation. Evaluations also show that there is no significant effect on plant operating parameters and no safety implications attributable to this mechanism.

This report presents recent post-irradiation examination data for the most highly exposed control blade from Plant E . This data provides further substantiation of the conclusions presented previously in References 1 and 2. ]

For the absorber rods from the most highly exposed Plant E control blade , the specific detailed tasks requested in Item 4 of IE Bulletin 79-26 (Reference 3) are presented in the following sections: ]

*References 1 and 2 are identical except Reference 1 contains third party proprietary information.

| Task | Section |
|---|---|
| a. Tube number or identification | 3.1 |
| b. Elevation of each crack in the tubing | 3.3 |
| c. Calculated Boron-10 loss versus elevation for each tube | 4.3 |
| d. Measured Boron-10 loss versus elevation for each tube | 3.4 |
| e. Maximum local depletion for tubes having no cracks | 3.5 |
| f. Maximum local depletion for tubes having no loss of boron | 3.5 |

This report establishes that, when the additional data from the Plant E absorber rods are added to the existing absorber rod data from three operating reactors, the correlations arrived at in References 1 and 2 are directly applicable to the operating reactors in Table 1-1. The correlation derived can be directly applied to the operating reactors in Table 1-1 to predict the behavior of their control blades, since the plant operating parameters and control blade designs are equivalent to the control blades examined.

Therefore, this report satisfies the requirements in Item 4 of IE Bulletin 79-26 (Reference 3) for all the operating reactors listed in Table 1-1.

Table 1-1
OPERATING REACTORS

## 2. INTRODUCTION

This report responds to Item 4 (parts a-f) of IE Bulletin No. 79-26, Revision 1, for the operating reactors in Table 1-1. The response for the operating reactors in Table 1-1 is accomplished by demonstrating the applicability of the destructive (post-irradiation) examinations performed on absorber rods of similar fabrication and operational history from the following operating reactors:

- , Plant D
- , Plant B
- , Plant C
- , Plant E

The results for Plant D , Plant B , and Plant C absorber rod post-irradiation examinations are presented in Reference 1. Results of the most recent absorber rod post-irradiation examination from Plant E's highest exposed control blade are presented in this report.

The computer model for determining boron depletion in each absorber rod in a control blade as a function of elevation is described and the calculated Boron-10 depletion for the Plant E control blade using the depletion model is presented. Correlations are presented between the calculated Boron-10 depletion and the results of the post-irradiation examination of the absorber rods from Plant E .

The report concludes by establishing the applicability of the entire absorber rod post-irradiation examination data base to the control blades in the operating reactors listed in Table 1-1.

# 3. PLANT E ABSORBER ROD EXAMINATION

In addition to the post-irradiation examination (results presented in Reference 1), absorber rods from three wings (63 rods total) of the highest exposed control blade at Plant E were examined. The control blade selected was , which was at an average blade depletion of 34%, based on the output of the process computer array that tracks control blade burnup.

Of the high power density BWRs, Plant E was specifically selected because Plant E had the highest depleted control blade available at the time of selection. By adding the Plant E control blade to the data base, the data base provides a complete cross section of data from all domestic BWR types now in operation.

The post-irradiation examination of the 63 absorber rods from the Plant E control blade included visual inspection, eddy current testing, neutron radiography and boron isotopic analysis. The results are presented in the remainder of this section.

## 3.1 ABSORBER ROD NOMENCLATURE

For the purpose of this document the absorber rods in each wing of a control blade are numbered sequentially from 1 to 21, starting at the edge of the wing and working inward toward the center of the control blade. There are four wings per control blade and 21 absorber rods per wing. The wings are numbered from 1 to 4. Therefore, the nomenclature for the edge rod on wing 3 would be (3-1).

## 3.2 VISUAL INSPECTION

Each absorber rod was visually inspected in the hot cell. Nothing unusual was noted during the visual inspection of the absorber rods. Only two cracks

in the tubing material were noted as being visible. These cracks were located in the high burnup regions of edge absorber rods. It was also noted that the absorber rods were very clean (i.e., no evidence of crud buildup).

## 3.3 EDDY CURRENT TESTING

The absorber rods were all nondestructively examined using eddy current method for the purpose of checking for the presence of cracking. The areas where significant crack indications occurred, and their elevation, are given in Table 3-1. In general, the significant crack indications were in the high burnup regions of the absorber rods, as was expected.

On wing 1, a few potentially significant eddy current signals were noted in the low burnup regions. Of these isolated cases, representative absorber rods with the largest signals were sectioned at the elevation of the signal to determine if a crack was present. Cross sections of the absorber tubing were examined metallographically. In all cases examined, no cracks were found.

## 3.4 NEUTRON RADIOGRAPHY

A series of neutron radiographs of the 63 absorber rods was made at the Nuclear Test Reactor at General Electric's Vallecitos Nuclear Center. Table 3-2 shows the amount of boron carbide lost in each absorber rod as measured from the neutrographs. A plot of the average boron carbide loss (Figure 3-1) shows that the boron carbide loss was limited to the three (1, 2 and 3) edge absorber rods in the high burnup region. In determining the distance to which boron carbide was missing, the point selected was the maximum point at which measurable loss of boron carbide was seen. This means that some boron carbide still remained in some of the regions shown as missing boron carbide. This procedure is, therefore, conservative. The boron loss profile is consistent with previous data (References 1 and 2) since the boron loss is in the high burnup region and the loss profile has the same shape as the expected Boron-10 depletion profile.

## 3.5 BORON ISOTOPIC ANALYSIS FOR BURNUP DETERMINATION

Boron carbide specimens were taken from selected absorber rods at various axial locations for boron isotopic analysis to determine the amount of local burnup. The results of the boron isotopic analyses performed are given in Table 3-3. The data are labeled to identify which absorber rods did or did not have boron carbide loss.

## 3.6 SUMMARY

The post-irradiation examination results for the 63 absorber rods from three wings of the Plant E control blade were ]
in agreement with the previous control blade post-irradiation examination results reported in Reference 1.

Some cracking, including throughwall cracking of the absorber rods, was evident. Cracking associated with $B_4C$ loss was located in the high exposure regions of the rods near the edge where neutron exposure was highest.

Neutron radiography showed loss of boron carbide from the absorber rods in some of the areas where cracking occurred. The boron loss profile has the same shape as the expected Boron-10 depletion profile.

The results of the boron isotopic analyses were in good agreement with the conclusion that 50% local Boron-10 depletion is the threshold for boron loss.

Table 3-1

EDDY CURRENT EXAMINATION RESULTS - PLANT E

Table 3-2
CONTROL BLADE NEUTRON RADIOGRAPHY - PLANT E

Table 3-3

BORON ISOTOPIC ANALYSES – PLANT E

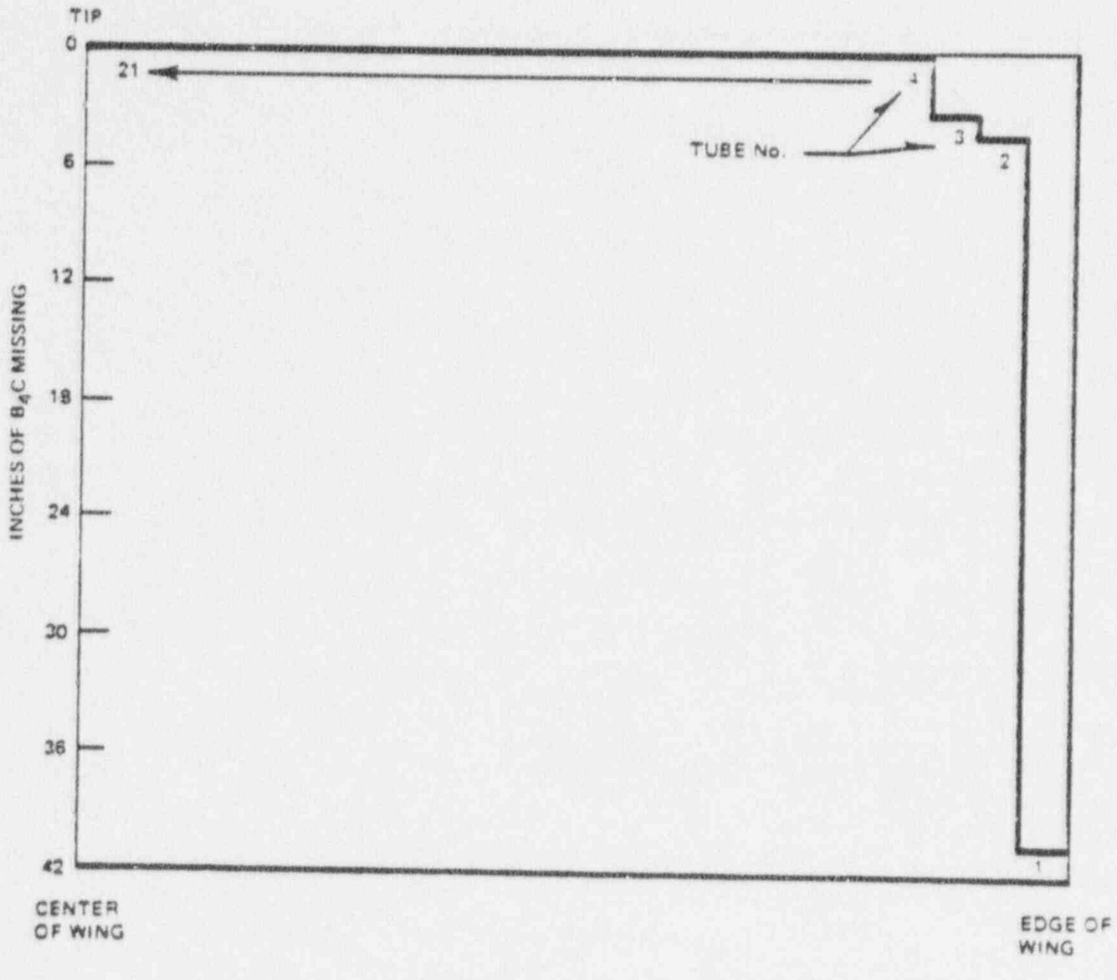


Figure 3-1. Average $B_4C$ Loss - Plant E

# 4. CONTROL BLADE DEPLETION MODEL

The control blade depletion model described in this section was specifically developed for a control blade with the characteristics shown in Figure 4-1. This type of control blade design and lattice arrangement is typical of the design used in all the operating plants listed in Table 1-1 and Plant C . Note that Plant E is included in Table 1-1. ]

The control blade depletion model requires the use of two computer programs. The two-dimensional radial effects on the control blade were simulated using the Monte Carlo program, and the axial core effects were simulated using the 3-D BWR Simulator Code (References 4 and 5). ]

## 4.1 MONTE CARLO PROGRAM ]

The Monte Carlo program is a program for solving the linear neutron transport equation as a fixed source or an eigenvalue problem in the three-dimensional space. This program is especially written for the analyses of fuel lattices in the thermal nuclear reactors or experimental criticals. ]

The Monte Carlo program uses cross sections processed from the ENDF/B-IV library files (Reference 6). These cross sections are processed in the 190 group format, and those in resonance energy region may have the form of resonance parameters or Doppler broadened multigroup cross sections. The Haywood thermal scattering kernel is used for the water scattering. Types of reactions considered in the Monte Carlo program are fission, elastic and inelastic scattering and (n,2n); absorption is implicitly treated by reducing the weight applied to the nonabsorption probability in each collision. ] ]

The Monte Carlo program has been qualified for applications in BWR lattice design, fuel rack design and internal core structure neutron fluence estimation. This qualification of the Monte Carlo program rests upon extensive qualification studies based on CSEWG thermal reactor benchmarks, ] ]

B&W $UO_2$ and $PuO_2$ criticals (Reference 7), gamma scan experiment and BWR gadolinium critical experiments, and, in addition, comparison with alternate calculational methods.

## 4.2 DEPLETION MODEL DEVELOPMENT

4.3 PLANT E CONTROL BLADE DEPLETION

The local Boron-10 depletion of each absorber rod in the Plant E control blade as a function of elevation can be determined by utilizing the depletion model results (Section 4.2) and the blade average

axial depletion profile. The depletion model results provide the local Boron-10 depletion of an individual absorber rod at a specified planar average depletion. Therefore, to obtain the local Boron-10 depletion, the average depletion as a function of elevation is required.

## 4.4 CORRELATIONS TO DEPLETION MODEL

The results of the Plant E control blade destructive examination (Section 3) can be compared to the control blade depletion model results (Table 4-3). Boron loss can be estimated by considering all boron at 30%

local Boron-10 depletion or greater to be no longer present. Table 4-4 compares the expected boron carbide loss from the depletion model to the boron carbide loss as determined from the neutron radiography results. Absorber Rod 1 has the largest discrepancy with the analytical model, due to absorber Rod 1 in wing 3 as explained in Table 3-2. The axial depletion profile for absorber Rod 1 is shown in Figure 4-6. The depletion profile for this rod has a definite plateau down to ~60 inches. Therefore, any slight increase increase in peaking for this rod could have a significant effect on the amount of boron loss up to an axial position of about 60 inches. Considering the uncertainties that exist and the fact that there is no precharacterization of these absorber rods, the agreement is very good. Figure 4-7 compares the calculated boron carbide loss to the three-wing average boron loss from the neutron radiography results (Table 3-2).

Table 4-5 compares the Boron-10 depletion as predicted by the depletion model to the results of the boron isotopic analyses. Figure 4-8 shows a graphical representation of the calculated depletion in absorber Rod 12 compared to the isotopic analyses of Rod 12.

The results of the correlation of the absorber rod post-irradiation examination data and the calculated Boron-10 depletion model for the highest exposed Plant E control blade further substantiate the conclusions drawn in References 1 and 2, and extend these conclusions to high power density BWR reactors.

Table 4-1

CUMULATIVE LOCAL DEPLETION (%)

Table 4-2
AXIAL BORON-10 DEPLETION PROFILE - PLANT E

Table 4-3

CALCULATED NODAL BORON-10 DEPLETION (%) — PLANT E

Table 4-4

$B_4C$ LOSS COMPARISON – PLANT E

Table 4-5
LOCAL BORON-10 DEPLETION COMPARISON — PLANT E

Figure 4-1. Model Dimensions

Figure 4-2. Self-Shielding Effect in a Fresh $B_4C$ Tube

Figure 4-3. Absorption Distribution in a Fresh $B_4C$ Tube

Figure 4-4. Absorption Distribution in a Fresh $B_4C$ Tube

Figure 4-5. Control Blade Axial Boron-10 Depletion Profile - Plant E

Figure 4-6. Local Boron-10 Depletion for Absorber Rod 1 - Plant E

Figure 4-7. $B_4C$ Loss from Control Blade - Plant E

Figure 4-8. Local Boron-10 Depletion from Absorber Rod 12 Wing 3 - Plant E

# 5. APPLICABILITY OF ACCUMULATED DATA BASE TO OPERATING PLANTS IN TABLE 1-1

This section establishes the applicability of the results of the absorber rod post-irradiation examinations performed and the correlations that this data base supports to the operating reactors listed in Table 1-1.

## 5.1 DATA BASE

The data base supporting the analytical correlations derived to redefine control blade life consists of the following:

| Plant | Quantity of Blades | Quantity of Absorber Rods |
|---|---|---|
| Plant C | 1 | 13 |
| Plant B | 1 | 45 |
| Plant D | 1 | 31 |
| Plant E | 1 | 63 |
| Total | 4 | 152 |

Although four control blades have been examined from four operating plants, this represents a substantial cross section of existing variables. From the four control blades, 152 absorber rods were examined. Each absorber rod provides an exposure history indicative of the performance of control blades at various exposures throughout the core. The exposure of each absorber rod varies axially and yields information on exposure dependency. Each absorber rod within a wing exhibits a different absorber history because exposure varies radially as well as axially. The absorber rods examined also represent distinct periods in the manufacturing cycle of the absorber rods which provides process variability. Although the process variability cannot be quantified, it does exist by virtue of displacement in time. The date and place of fabrication of the control blades are:

The absorber rods examined have built-in variabilities such as method of fabrication, density of $B_4C$, tubing supplier, tolerance variations and design changes made over the period of time involved. Therefore, the present data base does encompass a significantly large time period.

## 5.2 RESPONSE TO ITEM 4 OF IE BULLETIN 79-26

The absorber rods examined are from four different BWR reactor designs with three different control blade designs. The control blades in Plant C and Plant E are identical to the control blades used in all the plants in Table 1-1.

One of the unknowns in the cracking of the absorber tubes and the subsequent loss of boron carbide is defining the mechanism that physically transports the boron carbide out of the absorber rods. Although there are a number of potential transport mechanisms, the actual mechanism has not been determined.

The correlation which was derived and presented in References 1 and 2 established that the loss of boron carbide is a function of local Boron-10 burnup, regardless of the actual transport mechanism. Considering all data gathered since References 1 and 2 were published, this correlation is still valid for control blades exposed up to their original design life. The additional data gathered include Plant E results, which extend this direct correlation with local Boron-10 burnup to high flow and high power density BWR plants.

By examining the plant operating parameters in Table 5-1 of Plant B Plant C , Plant D , and Plant E , which are the plants whose control blades make up the data base, it can be seen that there is significant variability in the plant parameters. Listed in Table 5-1 are the plant operating parameters which could potentially cause variability in the loss rate of boron carbide. All control blades destructively examined from these four plants had consistently predictable boron loss. Therefore, it can be inferred that no single plant operating parameter had a predominant or deleterious effect. If the operating plants in Table 1-1 have operating parameters that are within the range of the operating parameters of the four plants in Table 5-1, then they would not expect to experience any additional loss beyond the amount that would be predicted by the correlation to boron-10 burnup (References 1 and 2). Table 5-2 provides the minimum and maximum values from Table 5-1, and compares these values to the plant operating parameters for the operating reactors in Table 1-1. All of the operating parameters of the operating plants in Table 1-1 are acceptably in the range of maximum and minimum values established by the plants in Table 5-1. There is no reason to believe that the correlations presented in References 1 and 2 will be altered in any way for the plants in Table 1-1.

The control blades in the operating plants listed in Table 1-1 and the four control blades destructively examined are all fabricated by the same vendors. Two of the four control blades destructively examined are identical to those in the operating plants listed in Table 1-1. Their operating parameters are similar to the plants whose control blades were destructively examined. Therefore, the examinations performed will satisfy Item 4 of IE Bulletin 79-26 for the operating plants in Table 1-1 and the onset of boron carbide loss at 50% local depletion is unaffected by plant operating parameters.

Table 5-1

PLANT OPERATING PARAMETERS

Table 5-2

OPERATING REACTOR PLANT PARAMETERS

| Operating Parameters | From Table 5-1 Min | From Table 5-1 Max | Operating Reactors* 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lattice | - | - | ← | | | | | | | | | | "D" | | | | | | | | | → |
| CB Stroke (in.) | 68 | 144 | ← | | | | | | | | | | 144 | | | | | | | | | → |
| CB Notch Length (in.) | 2.96 | 6 | ← | | | | | | | | | | 6 | | | | | | | | | → |
| CB Pitch (in.) | 10 | 12 | ← | | | | | | | | | | 12 | | | | | | | | | → |
| CB Span (in.) | 7.84 | 11.5 | ← | | | | | | | | | | 9.75 | | | | | | | | | → |
| CB Tubes/Wing | 15 | 21 | ← | | | | | | | | | | 21 | | | | | | | | | → |
| Power Density (kW/l) | 33.6 | 51 | 50.7 | 50.7 | 50.7 | 50.51 | 50.21 | 50.61 | 36.6 | 36.6 | 50.96 | 51.21 | 51.2 | 49.16 | 35.05 | 50.74 | 50.05 | 38.81 | 36.18 | 36.15 | 50.96 | 48.91 |
| Average Heat Flux (W/cm²) | 33.8 | 51.6 | 51.4 | 51.4 | 45 | 45.5 | 51.8 | 51.8 | 37.3 | 37.1 | 51.6 | 51.8 | 51.8 | 51.8 | 35.1 | 51.6 | 51.5 | 39.5 | 37.0 | 37.0 | 51.6 | 49.6 |
| Linear Heat Generation Rate (kW/ft) | [illegible]<br>13.4 (8x8) | 18.4 (7x7) | 18.5 (7x7)<br>13.4 (8x8) | 18.5 (7x7)<br>13.4 (8x8) | 13.4 | 13.4 | 18.5 (7x7)<br>13.4 (8x8) | 18.5 (7x7)<br>13.4 (8x8) | 17.5 (7x7)<br>13.4 (8x8) | 17.5 (7x7)<br>13.4 (8x8) | 18.5 (7x7)<br>13.4 (8x8) | 18.5 (7x7)<br>13.4 (8x8) | 18.5 (7x7)<br>13.4 (8x8) | 13.4 | 17.5 (7x7)<br>13.4 (8x8) | 18.5 (7x7)<br>13.4 (8x8) | 18.5 (7x7)<br>13.4 (8x8) | 17.5 (7x7)<br>13.4 (8x8) | 17.5 (7x7)<br>13.4 (8x8) | 17.5 (7x7)<br>13.4 (8x8) | 18.5 (7x7)<br>13.4 (8x8) | 18.5 (7x7)<br>13.4 (8x8) |
| Core Average Voids | 0.25 | [illegible] | 0.503 | 0.504 | 0.504 | 0.422 | 0.422 | 0.40 | 0.455 | 0.458 | 0.426 | 0.422 | 0.505 | 0.422 | 0.373 | 0.399 | 0.402 | 0.371 | 0.356 | [illegible] | 0.505 | 0.512 |
| Dome Pressure (psia) | 1000 | 1150 | 1005 | 1005 | 1005 | 1005 | 1005 | 1005 | 1000 | 1000 | 1005 | 1005 | 1005 | 1005 | 1015 | 1005 | 1005 | 1015 | 1005 | 1005 | 1005 | 1005 |
| Core Flow/Fuel Assembly ($\times 10^6$ lb/hr) | 0.081 | 0.152 | 0.135 | 0.136 | 0.135 | 0.1375 | 0.1375 | 0.146 | 0.135 | 0.115 | 0.111 | 0.1375 | 0.140 | 0.1375 | 0.119 | 0.116 | 0.114 | 0.119 | 0.115 | 0.115 | 0.140 | 0.140 |

*Numbers correspond to plant number in Table 1-1.

## 5. REFERENCES

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*These documents are not publicly available because they contain proprietary information.

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