BOUNDING ANALYTICAL ASSESSMENT OF NUREG 0630 ON LOCA AND OPERATING kW/FT LIMITS

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BABCOCK & WILCOX
Utility Power Generation Division
P. O. Box 1260
Lynchburg, Virginia 24505

Babcock & Wilcox
a McDermott company

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1. INTRODUCTION

During a postulated loss-of-coolant accident (LOCA), when the reactor coolant pressure drops below the fuel rod internal pressure, the fuel cladding may swell and rupture for particular combinations of strain, fuel rod internal pressure, cladding temperature, and material properties of the cladding.

Reactor thermal and hydrodynamic behavior during a LOCA depend on the type of accident, the time at which swelling and rupture occur, and the resulting coolant flow blockage.

Appendix K requires that the cladding swelling and rupture calculations shall be based on applicable data in such a way that the degree of swelling and incidence of rupture are not underestimated. In order to establish an industry data base, the NRC has sponsored several research programs on cladding behavior during and after a LOCA. NUREG-0630[1] is based on this research. It contains revised models for cladding rupture, strain and blockage during and following a LOCA which differ from present B&W evaluation models. The NRC requires compliance to NUREG-0630.

The implementation of NUREG-0630 models is expected to result in a change in fuel cladding temperatures greater than 20°F. This would require changes to the LOCA evaluation model and could also impact the allowable plant operating technical specification limits.

This study was undertaken to determine the impact of NUREG-0630 implementation on LOCA limits and plant operating technical specification limits for B&W lowered-loop 177-fuel assembly plants operating up to 2772 MWt. This report summarizes the results of this analysis for the Oconee 2 plant with specific impacts estimated for the operating limits for Oconee 2 cycle 7.

2. SUMMARY AND CONCLUSION

2.1. Impact on LOCA Limits

An ECCS bounding analysis was performed to determine the impact of the NUREG-0630 on B&W 177-FA lowered-loop plants operating LOCA limits. The break analyzed was an 8.55 ft^2 double-ended cold leg rupture at the RC pump discharge with a discharge coefficient of $C_D = 1.0$. The LOCA limit was evaluated for the 2 ft core elevation. Previous experience has demonstrated this core elevation to be the most sensitive with respect to clad swelling and rupture phenomena which are affected by the NUREG-0630 requirements.

The implementation of NUREG-0630 will result in a 0.5 kW/ft penalty on the LOCA limit at the 2 ft elevation. As NUREG-0630 requirements mainly affects the LOCA limits of the lower core elevations which are limited by the ruptured node temperatures. The 0.5 kW/ft penalty was also assigned to the LOCA limits at the 4 and 6 ft elevations. The LOCA limits at the 8 and 10 ft elevations are limited by the unruptured node temperature, and enough margin exists that the NUREG-0630 will not impose any penalty at these elevations.

The analysis was performed for the BOL conditions at which the average fuel temperature is at its maximum value. At higher burnups the lower fuel temperature will compensate for the impact of NUREG-0630 and no penalty will be required.

A summary of the LOCA limits are given in Table 2-1. It should again be noted that the impact of NUREG-0630 at 4, 6, 8 and 10 ft elevations are based on comparisons to the results of the 2 ft elevation and are engineering judgements.

2.2. Impact on Operating Limits of Cycle 7 of Oconee 2

The impact of using the NUREG-0630 LOCA kW/ft limits is a 6% wd reduction in the APSR withdrawal limit and a 6% reduction in the negative imbalance limit at full power. These limits were derived such that no reduction in the control rod index limits due to NUREG-0630 were required.

3. IMPACT OF NUREG-0630 ON LOCA LIMITS

3.1. Method of Analysis

The analytical methods used in the study are the same as those described in the B&W ECCS evaluation model topicals, BAW-10103A, Rev. 3[2] and BAW-10104, Rev. 3[3], except for the modifications due to NUREG-0630 implementation which are explained in section 3.2.

3.2. Base Case

B&W has recently completed a reanalysis of the LOCA limits for 177-FA lowered-loop plants using TACO2[4] fuel input. The results of that analysis and the new LOCA limits are currently being prepared for reporting to the NRC.[5] Analyses performed prior to the release of this document have used the "Interim" kW/ft limits shown in Table 4-1 per NRC agreement. The most limiting transient for that analysis was identified as an 8.55 ft^2 double-ended break at the RC pump discharge (DEPD). This break when analyzed at BOL for the 2 ft core elevation resulted in the maximum impact of TACO2 fuel model on LOCA limits. The original LOCA limit of 15.5 kW/ft for the 2 ft elevation, reported in BAW-10103A, Rev. 3, was reduced to 14.0 kW/ft to maintain the maximum clad temperature below 2200°F. However, after a burnup of 1000 MWd/mtU the original 15.5 kW/ft could be restored due to lower average fuel temperature.

The analysis of the 8.55 ft^2 DEPD for the 2 ft elevation at a core power of 2772 MWt was chosen as the base case for the NUREG-0630 impact study. The LOCA limit at the 2 ft elevation is limited by the time of rupture and ruptured node clad temperature due to core flow characteristics during the blowdown. Since the NUREG-0630 impact is mainly on the ruptured node temperature, the selection of the 2 ft elevation as the base case for the analysis is bounding for other core elevations.

The major impact on the base case was the implementation of the NUREG-0630 data in the ECCS codes. The modifications due to NUREG-0630 are:

1. The NUREG-0630 rupture temperature as a function of engineering hoop stress correlation with a heating ramp of 0°C/s, shown in Figure 3-1, was used. This ramp rate represents a bounding value for rupture data.

2. The NUREG-0630 strain versus temperature data is contained in a fast and a slow ramp rate correlation. The circumferential strain model, Figure 3-2, used in the analysis bounds the composite of the slow and the fast ramp models.

3. The NUREG-0630 coolant flow blockage data, Figure 3-3, is derived from burst strain data and, therefore, also bounds the composite of the slow and fast ramp models.

Inputs to the CRAFT2[6] code are stress versus rupture temperature data and blockage based on the reduction in flow area data. Inputs to the THETA1-B[7] code are stress versus rupture temperature data and maximum rod circumferential strain data to maximize metal-water reaction. All other input remained the same as the base case.

3.3. Results and Discussion

The results of this analysis are summarized and compared to the base case in Table 1. The maximum clad temperature was calculated as 1736°F and 1692°F for the ruptured and unruptured nodes, respectively. These results are based on a kW/ft limit of 13.5 at the 2 ft elevation, which represents a reduction from the 14.0 kW/ft in the base case. A LOCA case was examined at a 13.8 kW/ft limit at the 2 ft elevation but cladding temperatures failed to remain below the 2200 F limit when including the impact of NUREG-0630 in the analysis.

Previous analyses have shown that the LOCA limits at the lower core elevations are limited by the time of rupture and the rupture node temperature. Since the NUREG-0630 impacts mainly the rupture node clad temperature, the LOCA limits at the upper core elevations are not expected to be affected more than the LOCA limit at the 2 ft elevation. Therefore, the residual impact at the 2 ft elevation can be assigned to LOCA limits at the other core elevation.

As mentioned earlier, the NUREG-0630 impact was 0.5 kW/ft at the 2 ft elevation. The LOCA limits at the 4 and 6 ft elevation can be conservatively reduced by 0.5 kW/ft to reflect the effect of NUREG-0630. The LOCA limits at the 8 and 10 ft elevations are limited by the unruptured node temperature and are not greatly affected by NUREG-0630. Also, the maximum clad temperatures for currently calculated LOCA limits at the 8 and 10 ft elevations are significantly lower than the 2200°F limit which provide additional margin for the effect of NUREG-0630. Therefore, the impact of NUREG-0630 will not require a reduction of LOCA limits at the 8 and 10 ft core elevations. Finally, due to the burnup dependency of the average fuel temperature, the lower fuel temperature at higher burnups will compensate for the impact of NUREG-0630. It has been estimated that the LOCA limits can be restored to their original values after a specified burnup as shown in Table 3-2. A summary of the latest 177-FA lowered-loop plant LOCA analysis showing the impact of TACO2 and NUREG-0630 separately is shown in Table 3-2.

Table 3-1. NUREG-0630 LOCA Limit Impact at 2 ft Core Elevation 8.55 ft^2 DEPD, C_D = 1.0

	Base Case	NUREG-0630
CRAFT run	AD4ICLD	AD4IDWU
REFLOD3 run	AD4IBKD	AD4IVUS
THETA1-B run	AD4ICCA	AD4IEVW
CRAFT, kW/ft	14.5	14.0
THETA1-B LOCA limit	14.0	13.5
Peak temperature, F, unruptured node/time, s	1843/43.5	1692/42.5
Peak temperature, F, ruptured node/time, s	1934/43/5	1736/42.0
Rupture time, s	21.6	22.6
End of blowdown, s	25.2	24.8
End of adiabatic heatup, s	36.0	35.5
Maximum local oxidation, %	2.14	1.52
CRAFT2 blockage, %	58.8	67.65

Table 3-2. 177-FA Lowered-Loop Plant LOCA Limits for BOL

	Core elevation, ft				
	2	4	6	8	10
BAW-10103 limits, kW/ft	15.5	16.6	18.0	17.0	16.0
TACO2 impact, kW/ft	-1.5	0	0	0	0
NUREG-0630 impact, kW/ft	-0.5	-0.5	-0.5	0	0
	13.5	16.1	17.5	17.0	16.0

Note: LOCA limits for 4 and 6 ft elevation can be restored to 16.6 and 18.0 kW/ft, respectively, after a burnup of 1000 MWd/mtU. The 2 ft LOCA limit can be increased to 15.0 kW/ft after a burnup of 1000 MWd/mtU and restored to 15.5 kW/ft after a burnup of 2500 MWd/mtU.

Figure 3-1. B&W Model and ORNL Correlation of Rupture Temperature as a Function of Engineering Hoop Stress and Ramp Rate

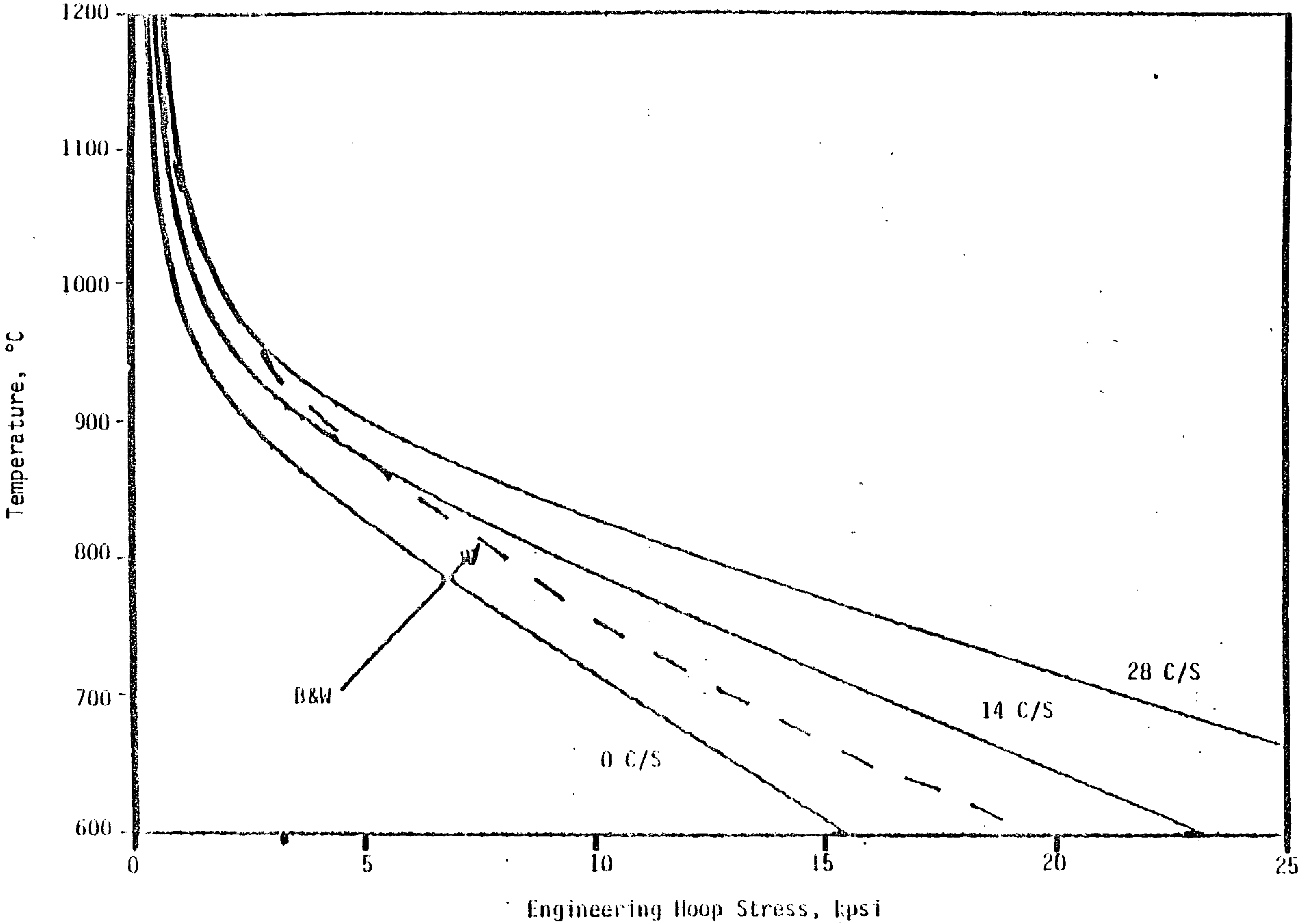


Figure 3-2. B&W THETA Model and Composite NUREG Correlation of Circumferential Burst Strain as a Function of Rupture Temperature

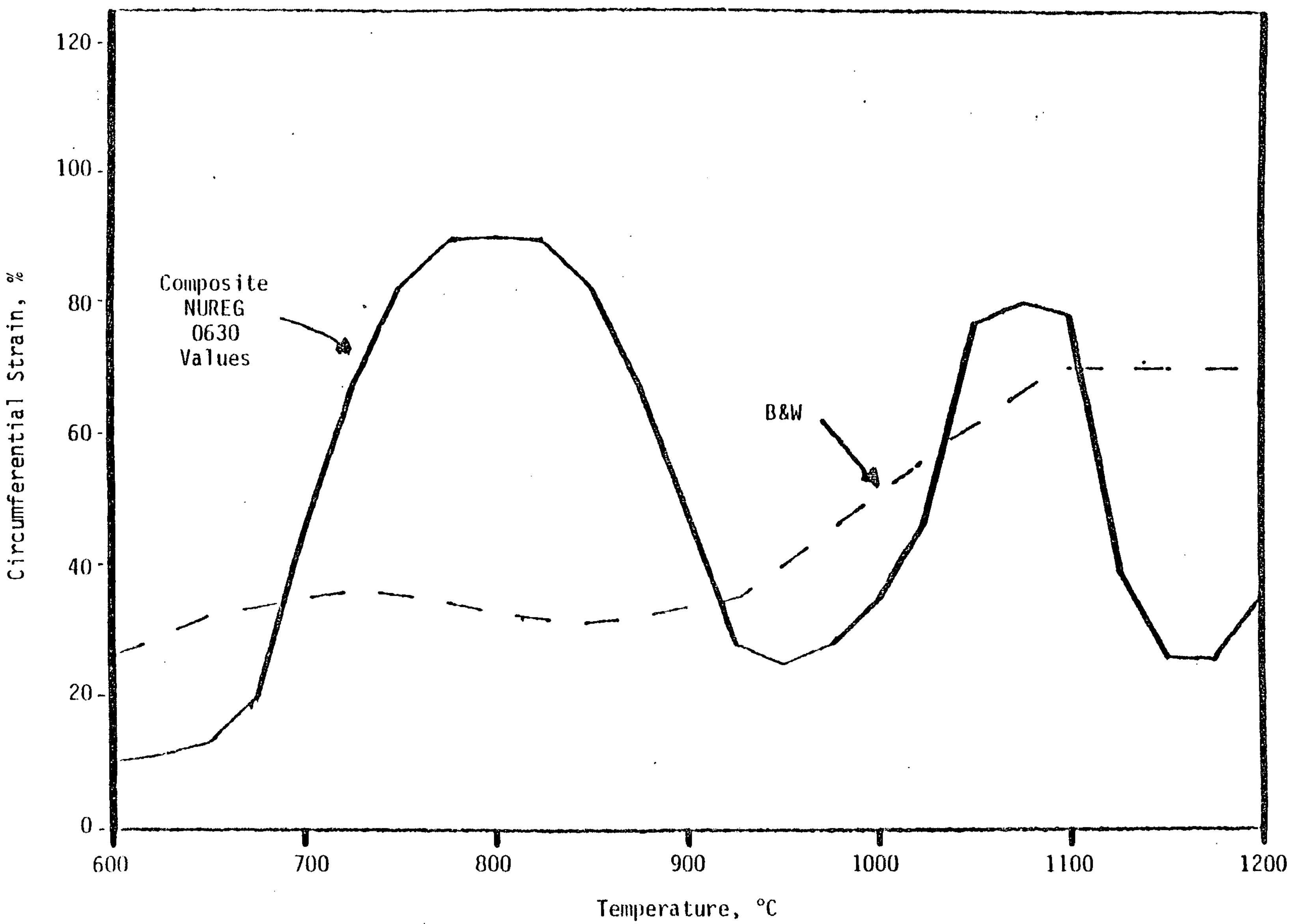


Figure 3-3. B&W Model and Composite NUREG Correlation of Reduction in Assembly Flow Area as a Function of Rupture Temperature

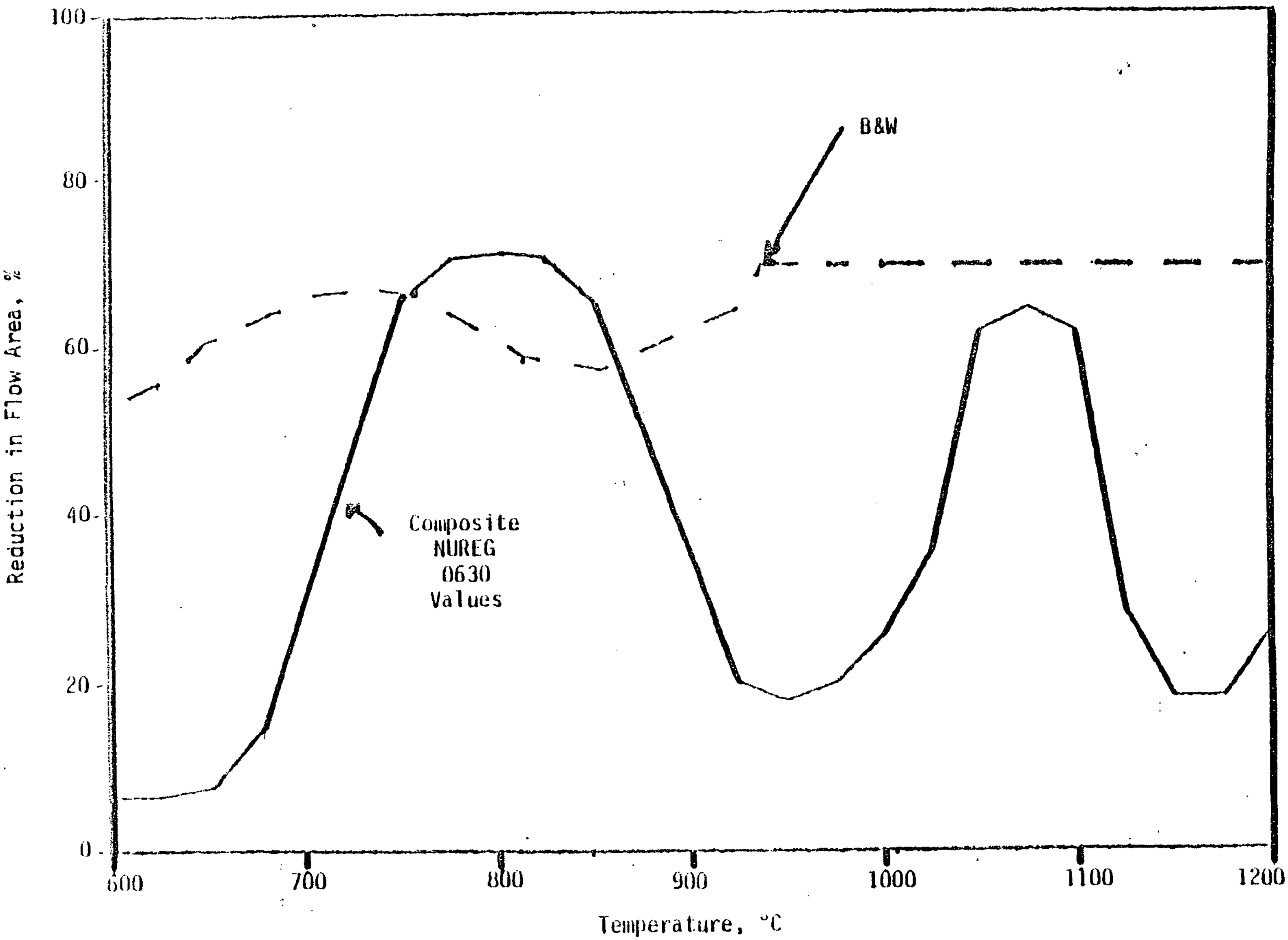
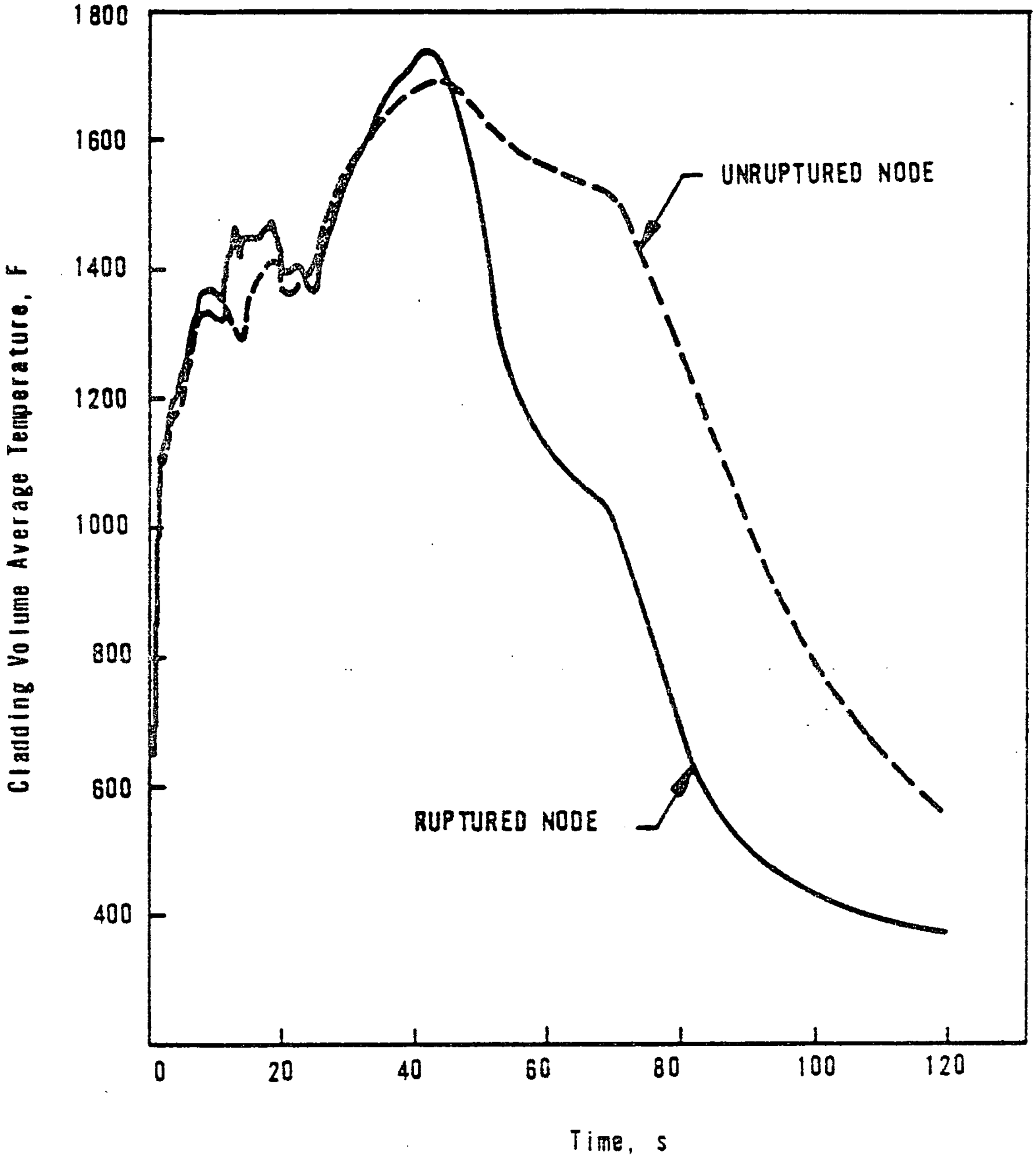


Figure 3-4. Hot Spot Clad Temperature Vs Time



4. IMPACT OF NUREG-0630 ON NORMAL OPERATING TECHNICAL SPECIFICATION LIMITS

4.1. Introduction

4.1.1. Core Elevation

Control rod position, APSR position, and imbalance alarm limits are established to prevent the LOCA kW/ft criteria from being exceeded during normal operation. Figure 4-1 shows how this is accomplished. The Interim LOCA kW/ft limit is shown as a function of axial height along with typical BOC axial power shapes which include all of the uncertainties normally applied in defining the Technical Specification Limits. The uncertainties and their application are described more fully in section 4 of Topical Report BAW-10122. It should be noted that the radial peaking factors which these shapes inherently include are cycle dependent. The nominal axial power shape represents hot full power steady-state conditions. When something occurs to shift the power toward the bottom of the core (a more negative imbalance) such as APSR withdrawal, control rod insertion, xenon shift, etc., the power shape changes from the nominal. The limits on imbalance and rod position are defined when the shape reaches the LOCA kW/ft criteria as shown in Figure 4-1.

The values of the LOCA kW/ft criteria used in the analysis of the NUREG-0630 impact on operation are given in Table 4-1. The LOCA kW/ft limit at the 2 ft elevation is the most influential in determining the operational impact for two reasons. First, moderator temperature effects on reactivity and control rod insertion from the top of the core cause it to have a greater propensity toward large negative imbalances than toward large positive imbalances. As Figure 4-1 shows, the power is shifted toward the 2 ft elevation and away from the higher elevations at the limiting negative imbalance condition. Secondly, due to the value of the LOCA limit at the 4 ft and higher elevations being significantly higher than the value at the 2 ft elevation, the

distance between the limit and the axial power shape is less for the 2 ft elevation. This generally ensures that the limiting condition will be caused by a power distribution whose peak reaches the LOCA kW/ft limit at or near the 2 ft elevation, while some distance remains between the power shape and the limit for all other, higher elevations.

The effect of a reduction in the LOCA kW/ft criteria is shown in Figure 4-2. The limiting power shape as defined by the NUREG-0630 LOCA criteria is more restricted than that defined by the present Interim LOCA criteria. To further restrict the power shape to meet the tighter LOCA criteria, the allowable control rod position, APSR position, and/or imbalance must be further restricted.

4.1.2. Burnup Dependencies

For a given period in cycle life, the initial conditions for the LOCA are preserved by a set of Technical Specification limits consisting of full length control rod position, Axial Power Shaping Rod position, axial imbalance, and quadrant power tilt limits. B&W presently furnishes a minimum of three different sets of these limits to cover the entire cycle. The applicability of each set is for a specific range of EFPDs. The present interim LOCA limits require the first set to cover from 0 to 50 EFPD. Other sets are provided which cover 50 EFPD to middle-of-cycle and middle to end-of-cycle. As discussed in section 3, NUREG-0630 only impacts the LOCA kW/ft criteria for fuel burnups below 2600 MWd/mtU. As shown in the BOL and EOL comparison in Figure 4-3, burnup generally reduces the power peaking. This decrease in peaking is illustrated in another form in Figure 4-4, which shows the total peak from the nominal depletion versus EFPD. The nominal peak, representing the general trend in present fuel cycles, is highest in the first 100 EFPD. This type of burnup dependent peaking behavior contributes to the fact that the first set of limits is the most restrictive.

Figure 4-5 shows the LOCA kW/ft limit for the 2 ft elevation (including the NUREG-0630 impacts) as a function of core burnup. The limit is most restrictive at the very beginning of the cycle, has increased to the present interim value by 25 EFPD, and has increased to the present Final Acceptance Criteria (FAC) by 70 EFPD. This schedule of limit increase represents the most optimistic, where the limiting nodes burn at a faster rate than the core average.

The most pessimistic schedule would represent a different fuel cycle loading where the limiting nodes burn at a rate that is slower than the core average, perhaps due to rod shadow. Because of this characteristic of the LOCA kW/ft criteria, the limit curves presented in section 4.2 represent the first set of limits which cover from BOL up through 70 to 100 EFPD. These curves can be replaced at 70 to 100 EFPD by a set based on the FAC kW/ft limits (the second set of curves presently in the Tech Specs).

This first set of limits is generally determined at BOL where the LOCA criteria is the most severe. One alternative which will lessen the impact is to use the tightest set from BOL to whenever the kW/ft limits reach 15.0 kW/ft at the 2 ft level, and use 15.0 kW/ft as the basis for the second set of Tech Spec curves. This shortens the time when the greatest restriction is encountered. The limit of 15.0 kW/ft at the 2 ft elevation would restrict the second set of curves only slightly. The third and following sets of windows would then use the present FAC kW/ft limits.

4.2. Impact on Operating Limits of Cycle 7 of Oconee 2

The estimated BOC operating limits for Oconee 2, cycle 7 are shown in Figures 4-6, 4-7, and 4-8 for control rod index, APSR position, and imbalance, respectively. The impact of using the NUREG-0630 LOCA kW/ft limits, indicated by the dashed lines, is a 6% wd reduction in the APSR withdrawal limit and a 6% reduction in the negative imbalance limit at full power. These limits were derived such that no reduction in the control rod index limits due to NUREG-0630 were required.

4.3. Operational Considerations

The general impact of the reduced LOCA kW/ft limits is the reduction in the imbalance limits as discussed above. This is equivalent to a loss in operational flexibility. The most significant reduction is in the imbalance window. Since insertion of the regulating rods forces the core imbalance to become more negative, the alarm limit will be controlled more carefully to maintain axial imbalance within the more restrictive limits.

This will in turn increase feed and bleed requirements. Since NUREG-0630 only impacts very low burnup fuel, this increase will be small because the higher critical boron concentration at BOL, when the fuel is fresh, requires less bleed volume exchange to change reactivity by a given amount. The types of operation affected will include large load reduction transients, runbacks and subsequent power escalation, and power escalation after a reactor trip or extended shutdown.

Table 4-1. LOCA kW/ft Criteria

Core elevation, ft	Interim 0-50 EFPD	Interim FAC[2] 50 EFPD-EOC	NUREG-0630 0-1000 MWd/mtU	NUREG-0630 1000-2600 MWd/mtU
10	16.0	16.0	16.0	16.0
8	17.0	17.0	17.0	17.0
6	17.5	18.0	17.5	18.0
4	16.1	16.6	16.1	16.6
2	14.5	15.5	13.5	15.0

Figure 4-1. Axial Power Shapes Compared
to LOCA Limits

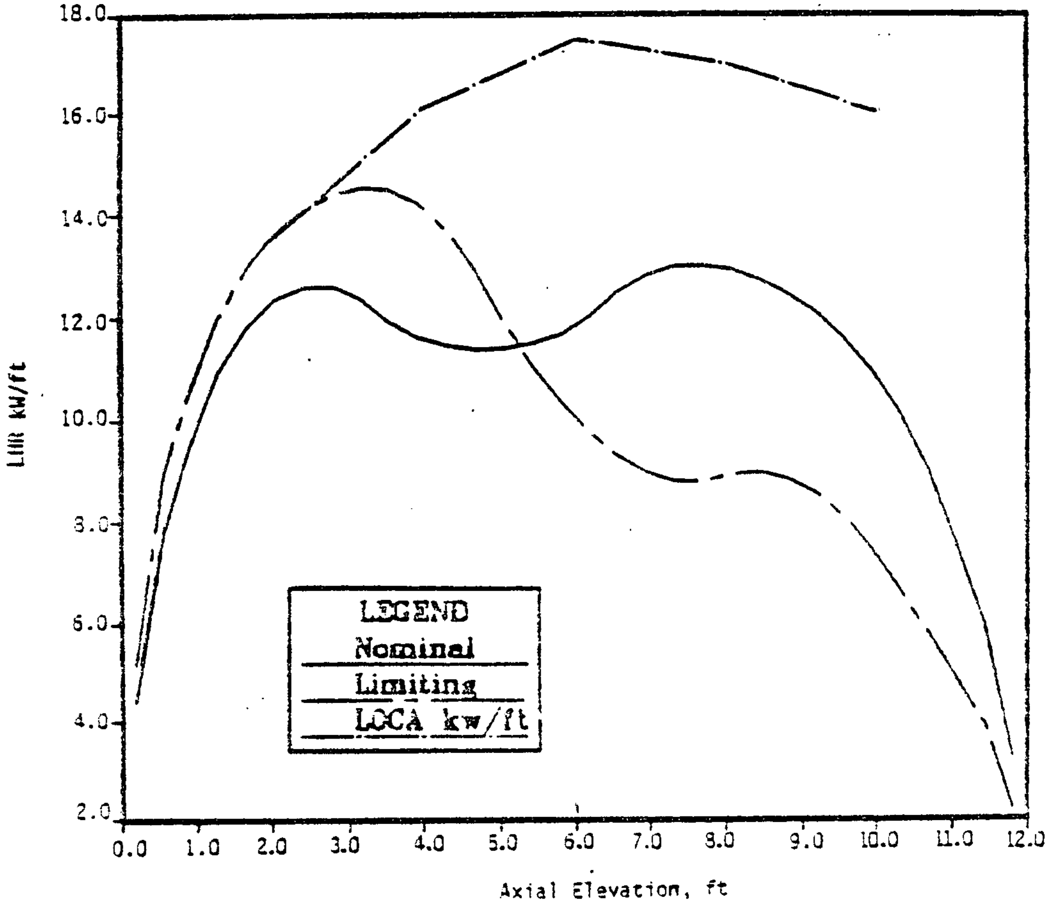


Figure 4-2. LOCA Limit Effect on Permissible Axial Power Shapes

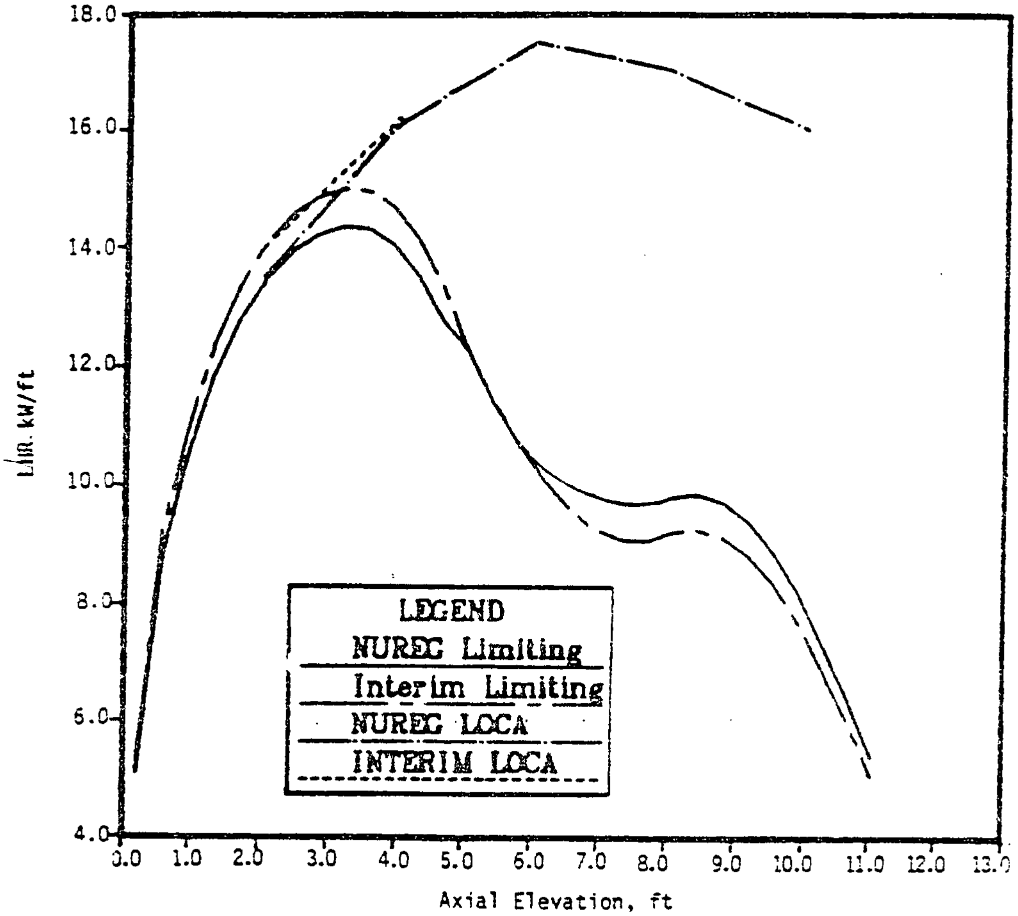


Figure 4-3. BOC and EOC Axial Power Shape Comparison

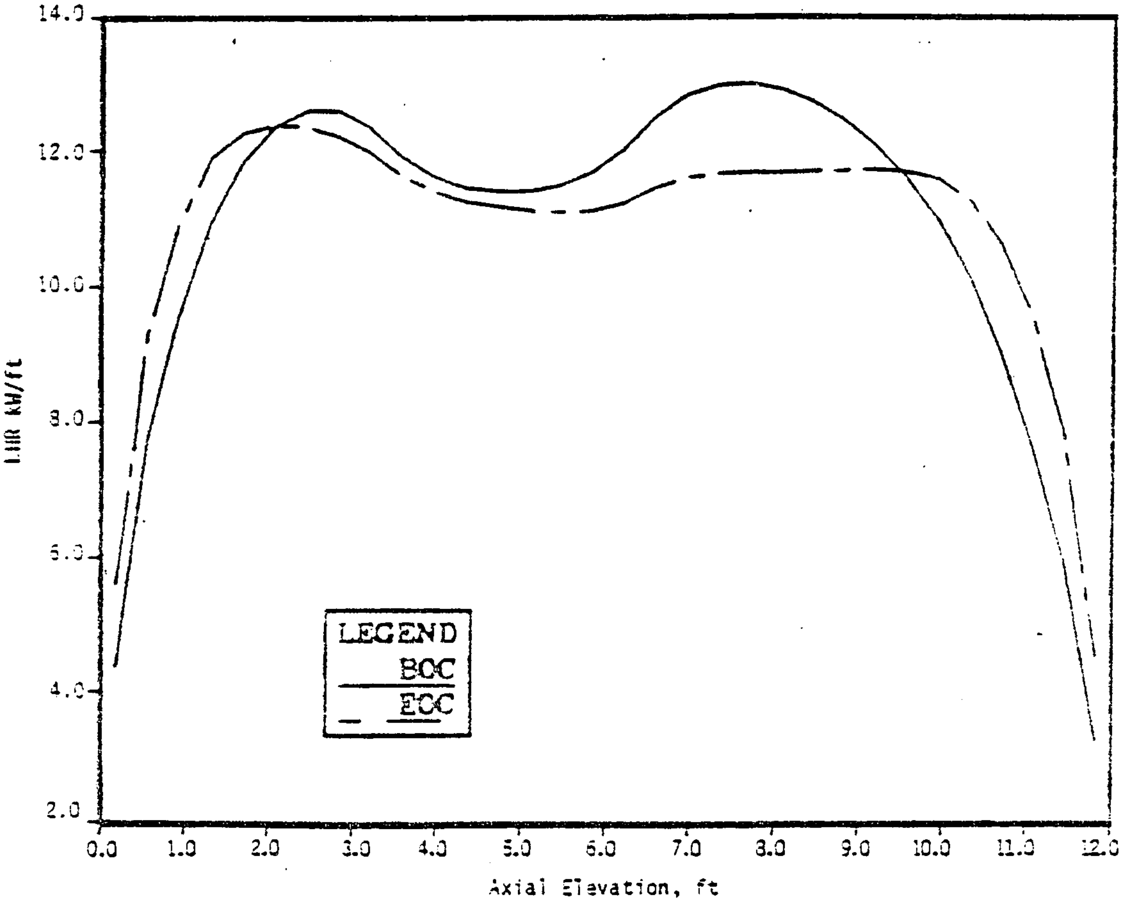


Figure 4-4. Steady State Power Peak Vs EFPD

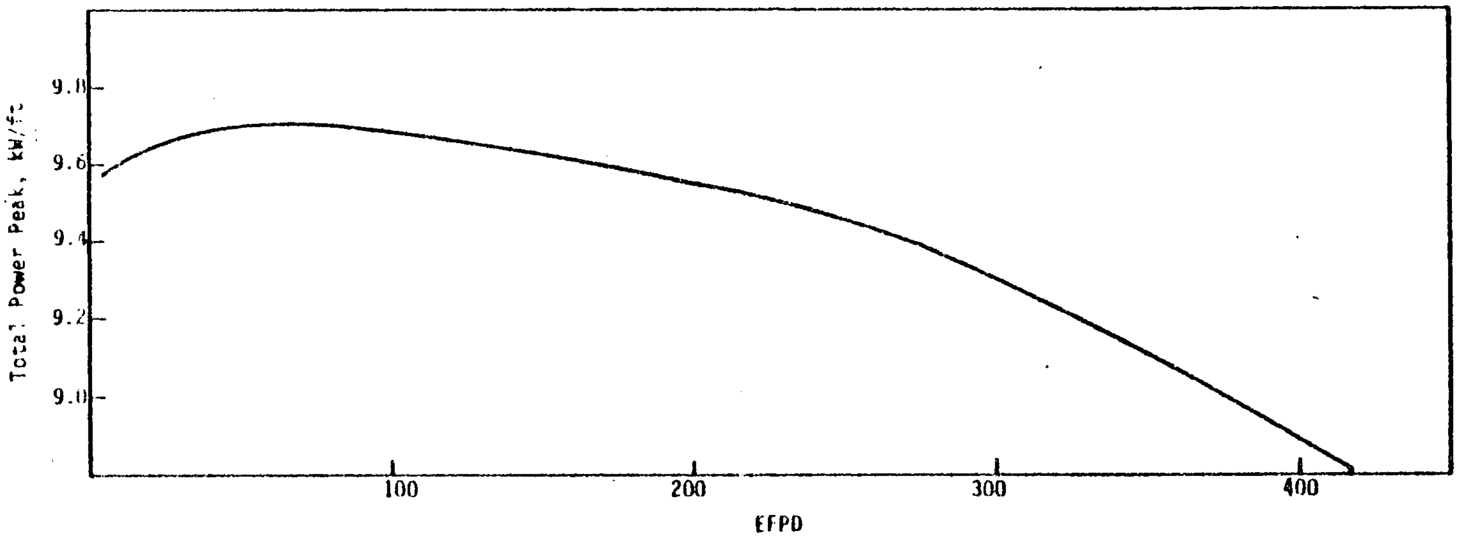


Figure 4-5. Burnup Dependent LOCA kW/ft Limit at 2 ft Elevation

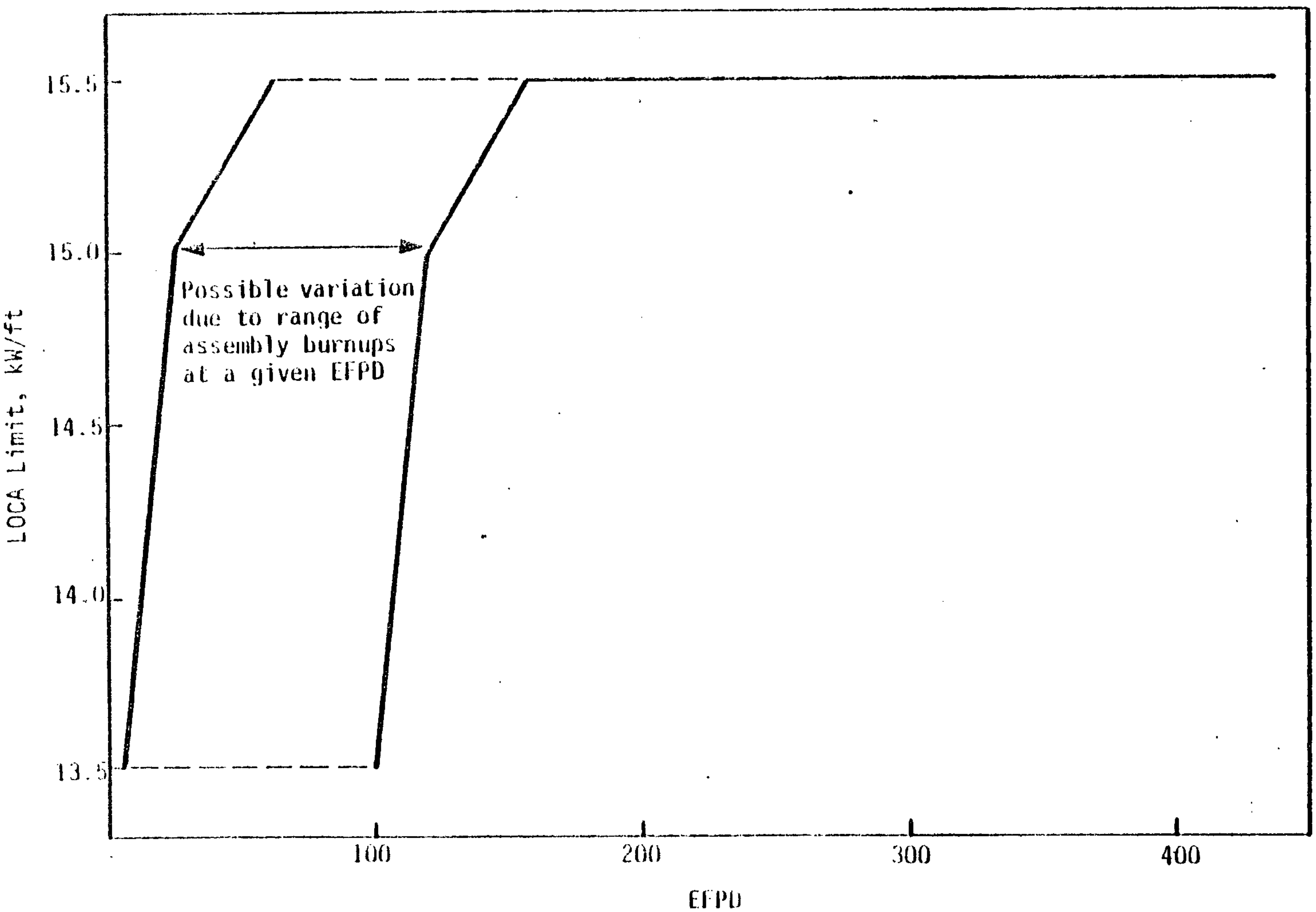


Figure 4-6. Four Pump Operating Limits, Oconee 2
Cycle 7 BOL

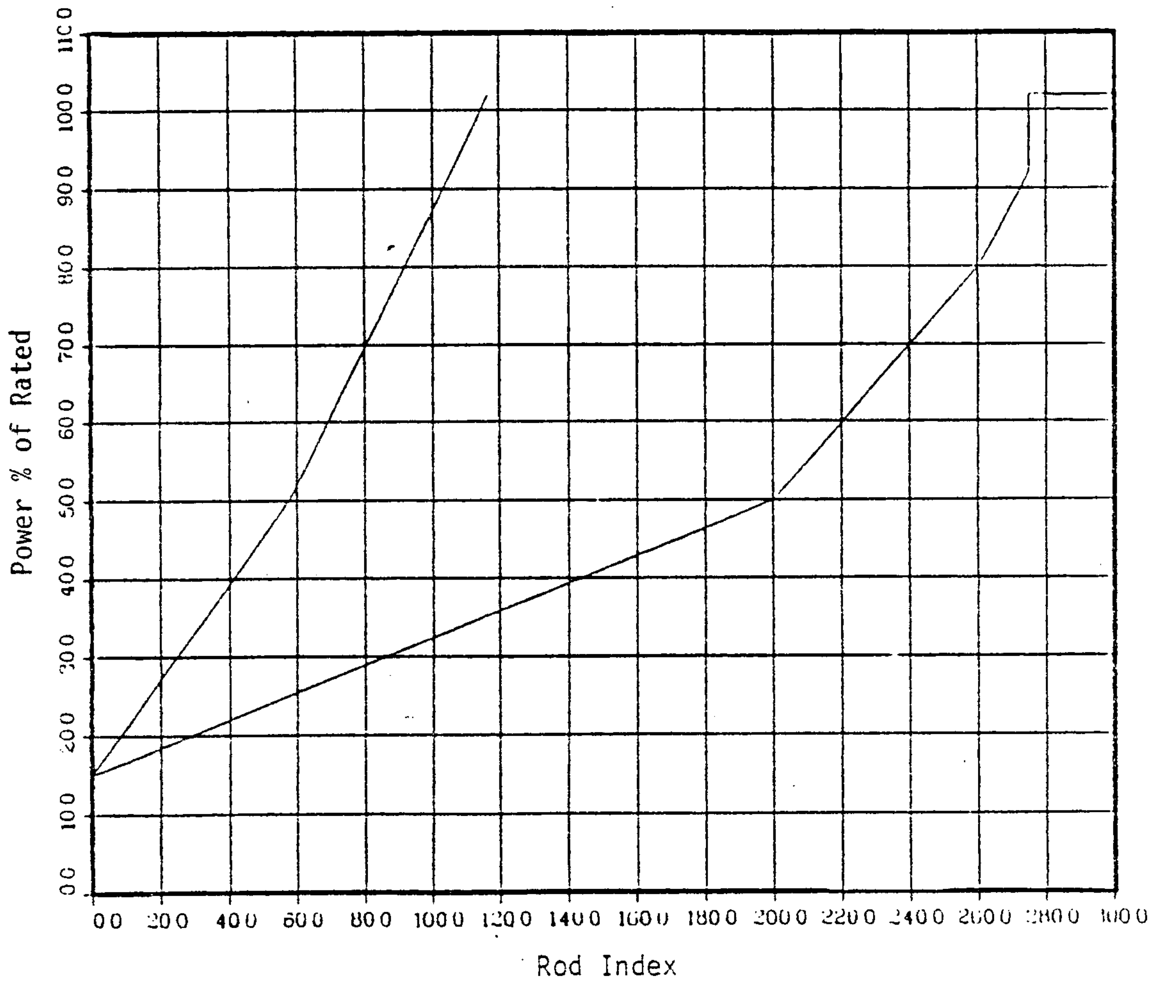


Figure 4-7. APSR Position Limits, Oconee 2
Cycle 7 BOL

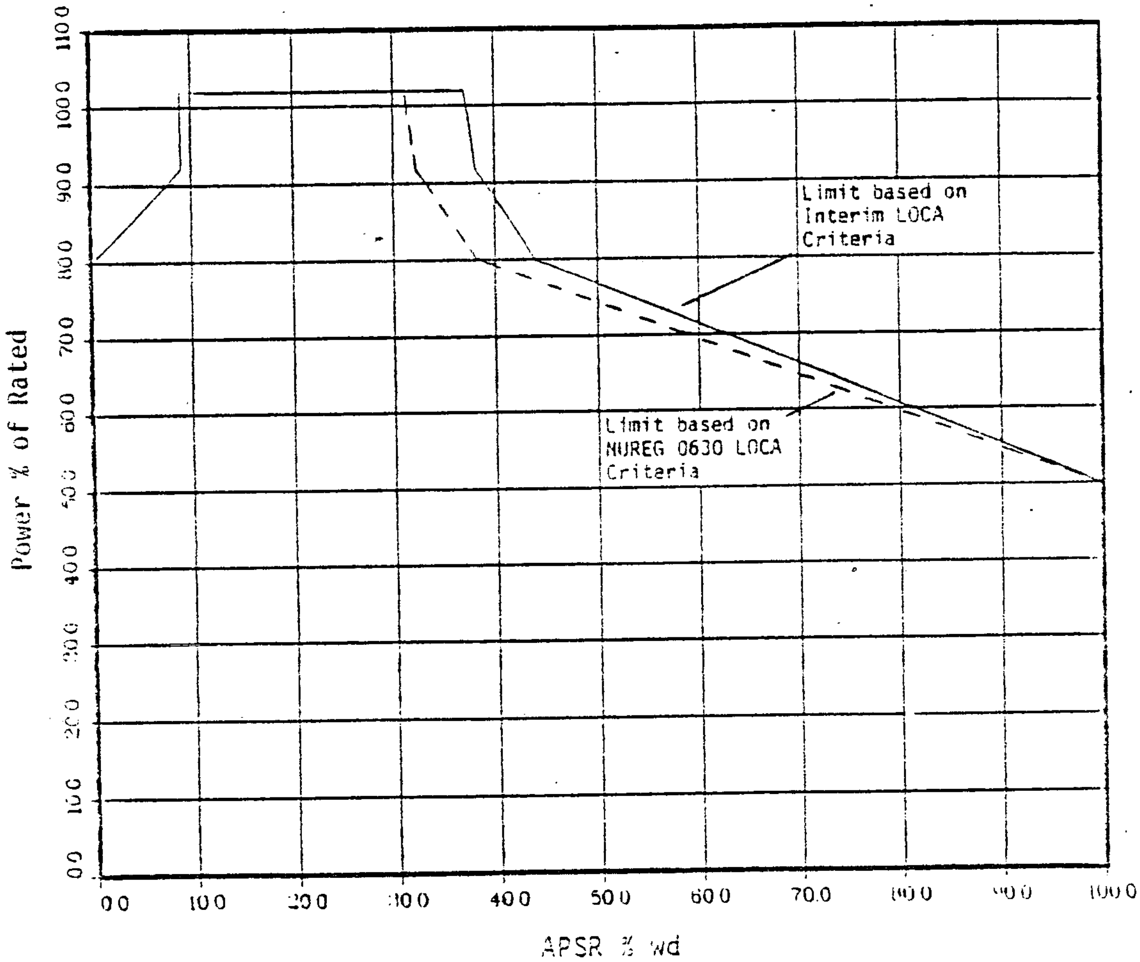
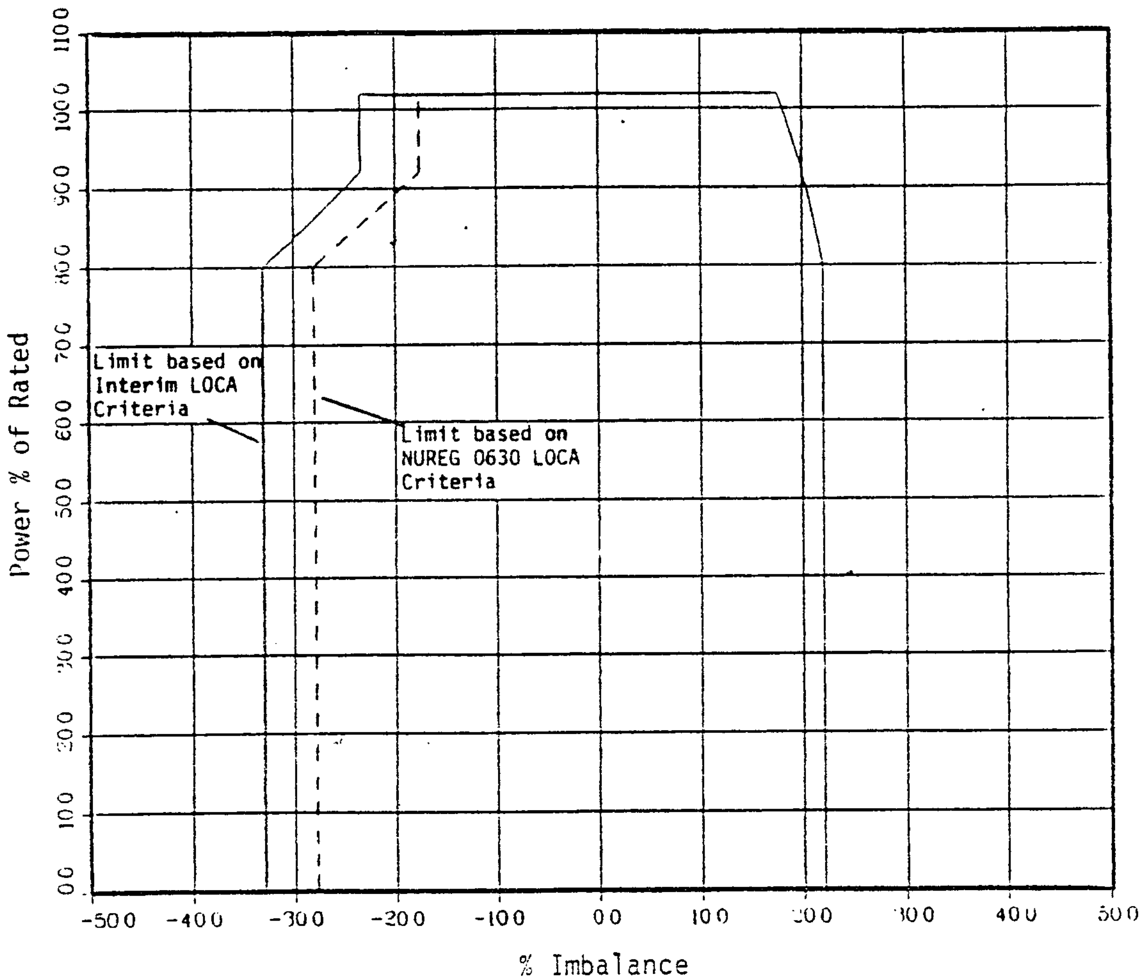


Figure 4-8. Imbalance Limits, Oconee 2 Cycle 7 BOL



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