# BOUNDING ANALYTICAL ASSESSMENT OF NUREG 0630 MODELS ON LOCA kW/ft LIMITS

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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 depends on the type of accident, the time at which swelling and rupture occur, and the resulting coolant flow blockage.

Appendix K of 10 CFR 50.46 requires that the cladding swelling and rupture calculations 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.

Each utility with a B&W designed NSS was requested to provide supplemental ECCS calculations assessing the impact of NUREG-0630 models. A study was undertaken to determine the impact of NUREG-0630 implementation on LOCA limits for B&W lowered-loop 177-fuel assembly plants operating at power levels up to 2772 MWt. The FLECSET reflood heat transfer correlation was also used as a compensating model to offset any NUREG-0630 LOCA kW/ft limit penalty.

be sufficient margin to satisfy the 2200F limit required by 10 CFR 50.46. Therefore, no LOCA limit penalty is imposed at the 8- and 10-ft core elevations. For the 6-ft core elevation, however, the peak ruptured node cladding temperature[2] was calculated to be 2090F. There may not be enough clad temperature margin to meet the 2200F requirement of 10 CFR 50.46. Use of FLECSET may not produce a sufficiently low peak clad temperature to compensate the 0.5 kW/ft penalty on the LOCA limit at the 6-ft core elevation. The 4 through 10-ft LOCA limtis, based on NUREG-0630 and the compensating model, FLECSET, are determined by comparisons to the results at the 2-ft core elevation and the case analyses.[2]

The analyses were performed for the beginning-of-life (BOL) conditions at which the average fuel temperature is at its maximum value. At higher burnups, the lower fuel temperature will result in a LOCA kW/ft margin when compared to BOL.

A summary of the key results at the 2-ft core elevation comparing the base case[2,3] with a case utilizing boundary NUREG-0630 models and a second case which included bounding NUREG-0630 models and use of FLECSET, is shown in Table 4-1. The 177-FA lowered-loop plant LOCA limits at each elevation are listed separately in Table 4-2.

## 2. SUMMARY AND CONCLUSION

An ECCS bounding analysis was performed to determine the impact of the NUREG-0630 on B&W 177-fuel assembly (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 calculated 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 models.

The implementation of bounding NUREG-0630 models without the use of compensating models will result in a 0.5 kW/ft penalty on the LOCA limit at the 2-ft elevation. NUREG-0630 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 between the peak calculated temperature and the 2200F limits exists that use of NUREG-0630 models will not impose any penalty at these elevations.

Implementation of bounding NUREG-0630 models with the FLECSET reflood heat transfer correlation as a compensating model resulted in no kW/ft penalty on the LOCA limit at the 2-ft core elevation. An engineering assessment was performed for the 4 through 10-ft LOCA limits. For the 4-ft core elevation, there is no penalty due to the implementation of NUREG-0630 for the following reasons: (1) based on previous LOCA analyses[2], the peak ruptured node cladding temperature was calculated to be 1899F; therefore, sufficient margin exists to meet the 10 CFR 50.46 criteria of 2200F, and (2) the FLECSET compensating model results in a higher allowable kW/ft limit, thus resulting in no impact to the LOCA limit at the 4-ft core elevation. For the 8- and 10-ft core elevations, the peak ruptured node cladding temperature[2] was found to be 1664 and 1560F, respectively. There is considered to

# 3. 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[4] and BAW-10104, Rev. 3[5], except for the modifications due to NUREG-0630 and FLECSET implementation which are explained in the following paragraphs. Figures 4-2 through 4-4 show the NUREG-0630 bounding parameters.

The major impact on the base case LOCA limit analysis[2], was the implementation of the NUREG-0630 data in the ECCS large break evaluation model. 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 4-2, was used. This ramp rate represents a bounding value for rupture data.
2. The NUREG-0630 strain versus temperature data are contained in a fast and a slow ramp rate correlation. The circumferential strain model, Figure 4-3, used in the analysis bounds the composite of the slow and the fast ramp models.
3. The NUREG-0630 coolant flow blockage data, Figure 4-4, 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 temperautre data and maximum rod circumferential strain data to maximize metal-water reaction. All other input remained the same as the base case LOCA limit analysis.[2]

Two analyses were performed at the 2-ft core elevation to determine impact on the peak clad temperature due to both the implementation of NUREG-0630

bounding models and use of the FLECSET heat transfer correlation. Previous analyses[4,5] have demonstrated that the 2-ft core elevation is the most sensitive with respect to clad swelling and rupture phenomena. The first case used the large break LOCA ECCS model, Figure 4-1, from reference 2 with NUREG-0630 bounding data as input to the CRAFT2[6] and THETA1-B[7] models. The second case employed the same CRAFT2 and REFLOD models but replaced the FLECKA correlation[5] with the FLECSET model. A new THETA1-B case was then analyzed at 14.0 kW/ft.

Case 1

CRAFT2[6] was run at 14.0 kW/ft for the 2-ft core elevation. REFLOD, FLECKA, and THETA1-B[7] were also run at 14.0 kW/ft but did not succeed due to the exceedingly high ruptured node peak cladding temperatures that resulted from the use of the NUREG-0630 models. Both FLECKA and THETA1-B were again run at 13.5 kW/ft and succeeded with a ruptured node peak cladding temperature below the 2200F limit required by NRC criteria 10 CFR 50.46.

Case 2

In an effort to reduce or eliminate the 0.5 kW/ft penalty from the implementation of NUREG-0630, a computer code called FLECSET[8,9], developed to predict the quench time and heat transfer coefficient for cosine and skewed power shapes, was used as a compensating mode. FLECSET was run at 14.0 kW/ft using input on flooding rates obtained from the first bounding analysis case. An analysis using THETA1-B[7] was performed to generate the hot channel response at the 14.0 kW/ft LOCA limit. The peak cladding temperature was compared to the 10 CFR 50.46 limit of 2200F to determine acceptability.

# 4. RESULTS OF ANALYSIS

## 4.1. Impact of NUREG-0630 on LOCA Limits

The results of this anlaysis are summarized and compared to the base case large break LOCA analysis in Table 4-1. The maximum clad temperature was calculated as 1736 and 1692F for the ruptured and unruptured nodes, respectively, as shown in Figure 4-5. 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 2200F limit when including the impact of NUREG-0630 in the analysis.

Previous analyses[4,5] 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 stated above, 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 2200F 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 4-2.

## 4.2. Impacts of NUREG-0630 With FLECSET on LOCA Limits

The results of this analysis are summarized and compared to both the base case[2] and NUREG-0630 case 1 analysis in Table 4-1. The maximum clad temperature for the case using NUREG-0630 and FLECSET was calculated to be 1847 and 1809F for the ruptured and unruptured nodes, respectively, as shown in Figure 4-6. These results were calculated based on a 14.0 kW/ft limit at the 2-ft core elevation.

As stated in section 4.1, there was an impact of 0.5 kW/ft for the 2-, 4-, and 6-ft core elevations due to the implementatin of NUREG-0630. However, based on the results obtained from the analysis using NUREG-0630 with the FLECSET heat transfer correlation, no LOCA impact has been found at the 2-ft core elevation. This is because of the higher heat transfer coefficients generated by the FLECSET compensating model, which in turn resulted in a higher allowable kW/ft limit.

A 0.5 kW/ft NUREG-0630 penalty was assigned in case 1 to the 4- and 6-ft core elevations. These elevations are also kW/ft limited by the ruptured node temperatures. The peak cladding temperature results at these respective elevations were reviewed considering the improved heat transfer predicted by FLECSET. For the 4-ft core elevation, there is no impact on kW/ft limits due to the implemenation of NUREG-0630 and FLECSET for the following reasons: (1) based on the results of reference 2, the peak ruptured node cladding temperature was calculated to be 1899F; therefore, sufficient margin exists to meet the 10 CFR 50.46 criteria of 2200F, and (2) the FLECSET compensating model is expected to a result in a higher allowable kW/ft limit, thus resulting in no impact to the LOCA limit at the 4-ft core elevation. However, for the 6-ft core elevation, the peak ruptured node cladding temperature was calculated to be 2090F. There may not be enough clad temperature margin to meet the 2200F requirement of 10 CFR 50.46. Use of FLECSET may not produce a sufficiently low peak clad temperature to compensate the 0.5 kW/ft penalty on the LOCA limit at the

6-ft core elevation. For the 8- and 10-ft core elevations, the peak ruptured node cladding temperature[2] was found to be 1664 and 1560F, respectively. There is sufficient clad temperature margin to satisfy the 2200F limit required by 10 CFR 50.46. Therefore, there is no penalty on the LOCA limit at the 8- and 10-ft core elevations as given in BAW-10103A, Rev. 3.[4]

Table 4-1. LOCA Limit NUREG-0630 Impact Sensitivity Study at 2-ft Core Elevation, 8.55-ft$^2$ DEPD, $C_D$ = 1.0

| | Base case[2] | Case 1[(a)] | Case 2[(b)] |
|---|---|---|---|
| CRAFT run | AD4ICLD | AD4IDWU | AD4IDWU |
| REFLOD3 run | AD4IBKD | AD4IVUS | AD4IVUS |
| THETA1-B run | AD4ICCA | AD4IEVW | AEKIBUH |
| CRAFT, kW/ft | 14.5 | 14.0 | 14.0 |
| THETA1-B, LOCA limit | 14.0 | 13.5 | 14.0 |
| Peak temperature, °F, unruptured node/time, s | 1843/43.5 | 1692/42.5 | 1809/37.0 |
| Peak temperature, °F, ruptured node/time, s | 1934/43.5 | 1736/42.0 | 1847/37.3 |
| Rupture time, s | 21.6 | 22.6 | 17.9 |
| End of blowdown, s | 25.2 | 24.8 | 24.8 |
| End of adiabatic heatup, s | 36.0 | 35.5 | 35.5 |
| Maximum local oxidation, % | 2.14 | 1.52 | 1.67 |
| CRAFT2 blockage, % | 58.8 | 67.65 | 67.65 |

(a) Case 1 includes the impact of NUREG-0630 bounding models.

(b) Case 2 includes the impact of NUREG-0630 bounding models and the use of FLECSET heat transfer correlation.

Table 4-2. 177-FA Lowered-Loop Plant LOCA Limits

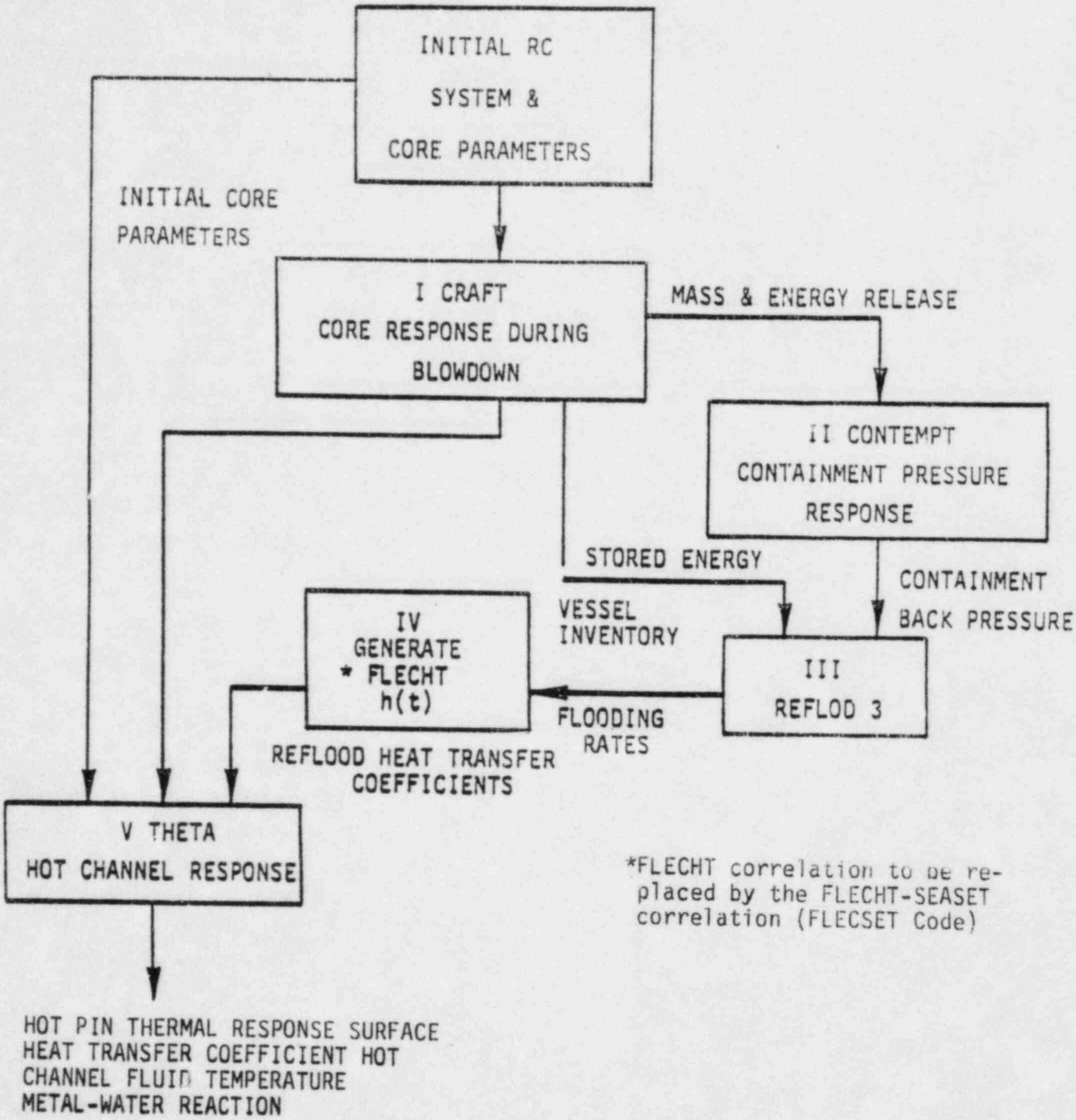
| | Core elevation, ft | | | | |
|---|---|---|---|---|---|
| | 2 | 4 | 6 | 8 | 10 |
| BAW-10103 LOCA limits,[4] kW/ft | 15.5 | 16.6 | 18.0 | 17.0 | 16.0 |
| • TACO2 impact,[2] kW/ft | -1.5 | 0 | 0 | 0 | 0 |
| Base case limits,[(a)] kW/ft | 14.0 | 16.6 | 18.0 | 17.0 | 16.0 |
| • NUREG-0630 impact, kW/ft | -0.5 | -0.5 | -0.5 | 0 | 0 |
| Case 1[(b)] (base case + NUREG-0630), kW/ft | 13.5 | 16.1 | 17.5 | 17.0 | 16.0 |
| • FLECSET-offset, kW/ft | +0.5 | +0.5 | 0 | 0 | 0 |
| Case 2[(c)] (base case + NUREG-0630 + FLECSET), kW/ft | 14.0 | 16.6 | 17.5 | 17.0 | 16.0 |

[(a)]The 2-ft LOCA limit can be restored to 15.5 kW/ft after a burnup of 1000 MWd/mtU.

[(b)]LOCA limits for 4- and 6-ft core elevations 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 kW/ft after a burnup of 1000 MWd/mtU and restored to 15.5 kW/ft after a burnup of 2600 MWd/mtU.

[(c)]The 2- and 6-ft LOCA limit can be restored to 15.5 and 18.0 kW/ft[4], respectively, after a burnup of 1000 MWd/mtU.

Figure 4-1. Large Break Analysis Code Interfaces




*FLECHT correlation to be replaced by the FLECHT-SEASET correlation (FLECSET Code)

Figure 4-2. B&W Model and ORNL Correlation of Rupture Temperature as a Function of Engineering Hoop Stress and Ramp Rate

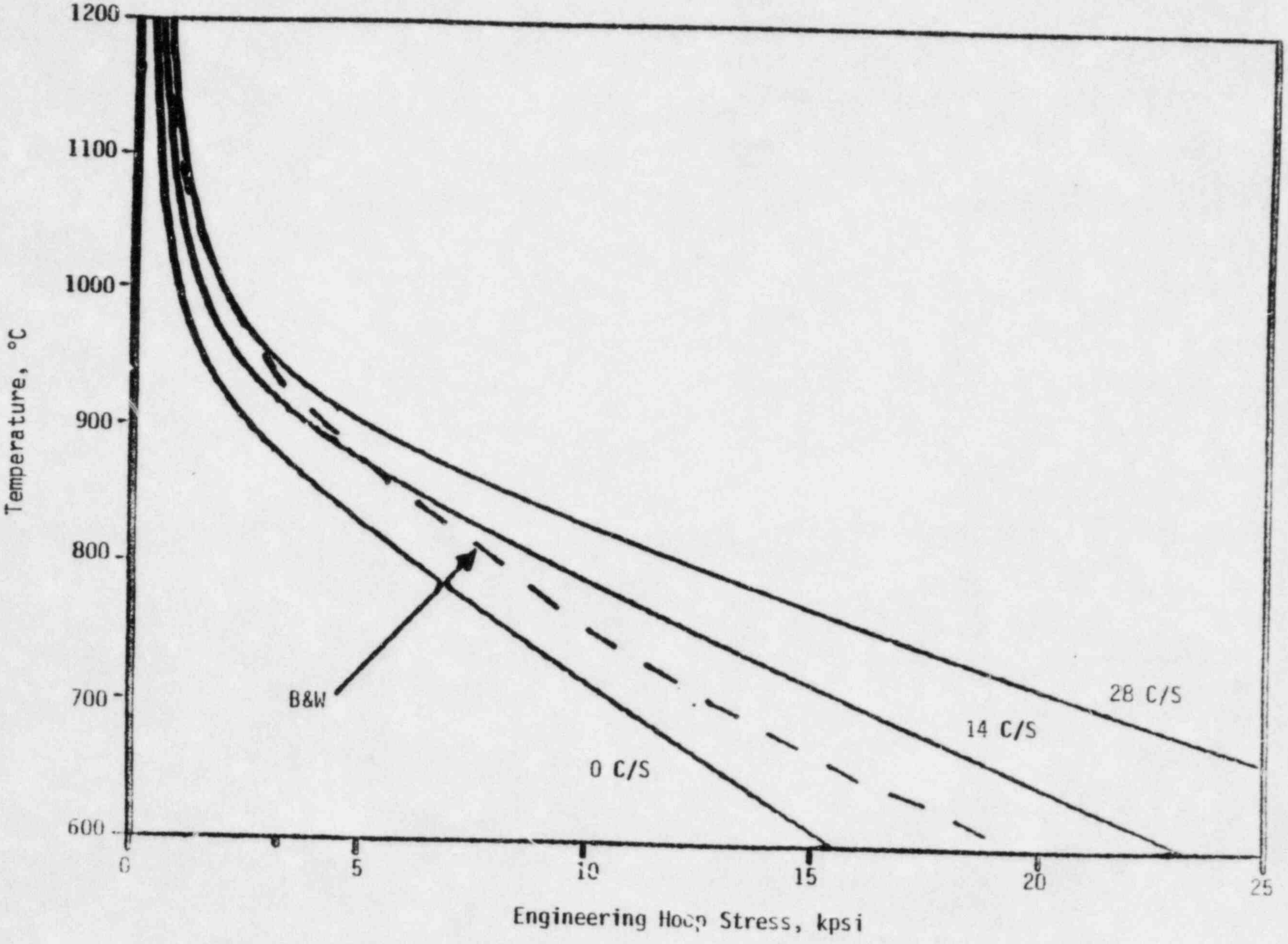


Figure 4-3. B&W THETA Model and Composite NUREG Correlation of Circumferential Burst Strain as a Function of Rupture Temperature

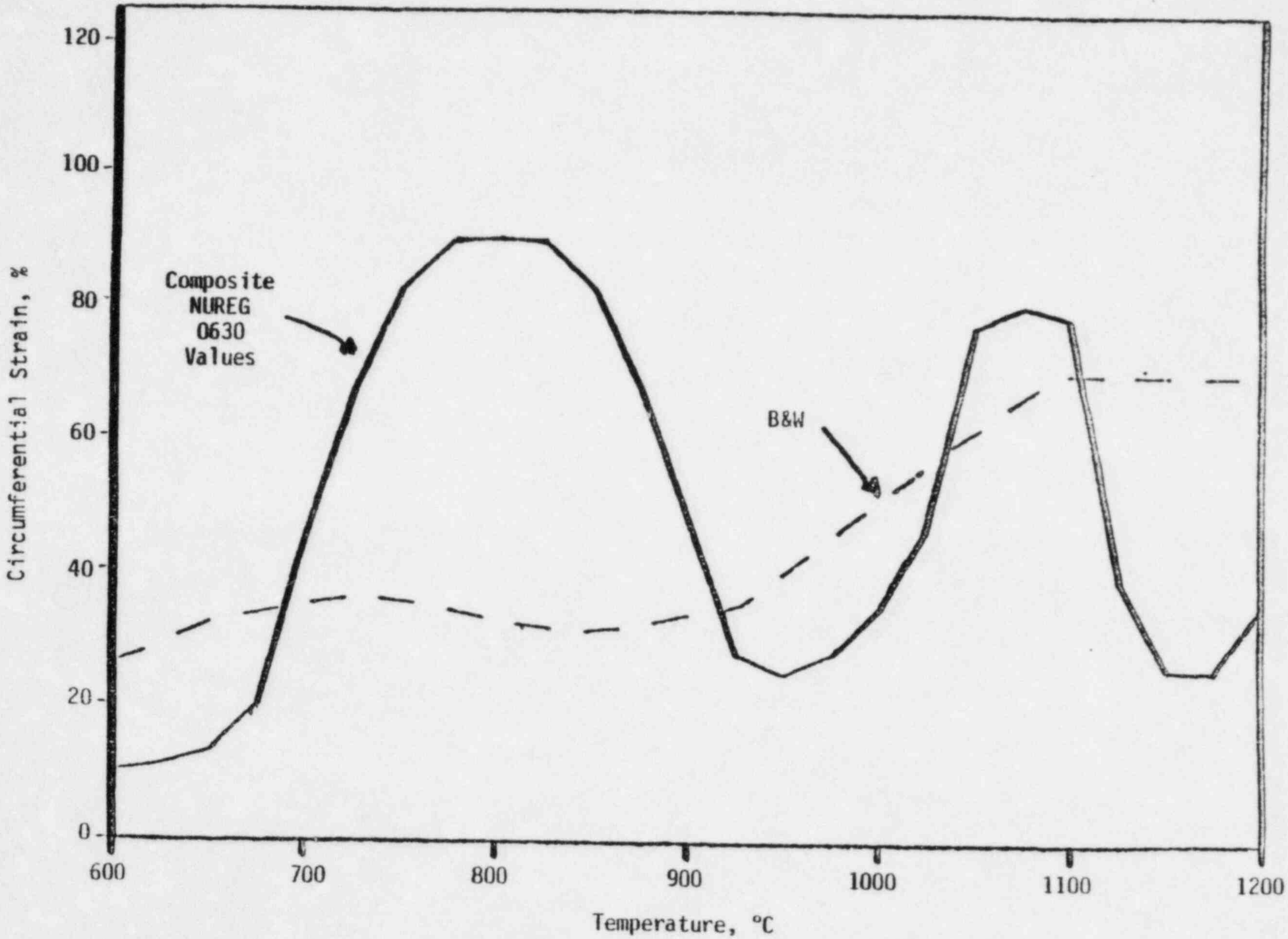


Figure 4-4. B&W Model and Composite NUREG Correlation of Reduction in Assembly Flow Area as a Function of Rupture Temperature

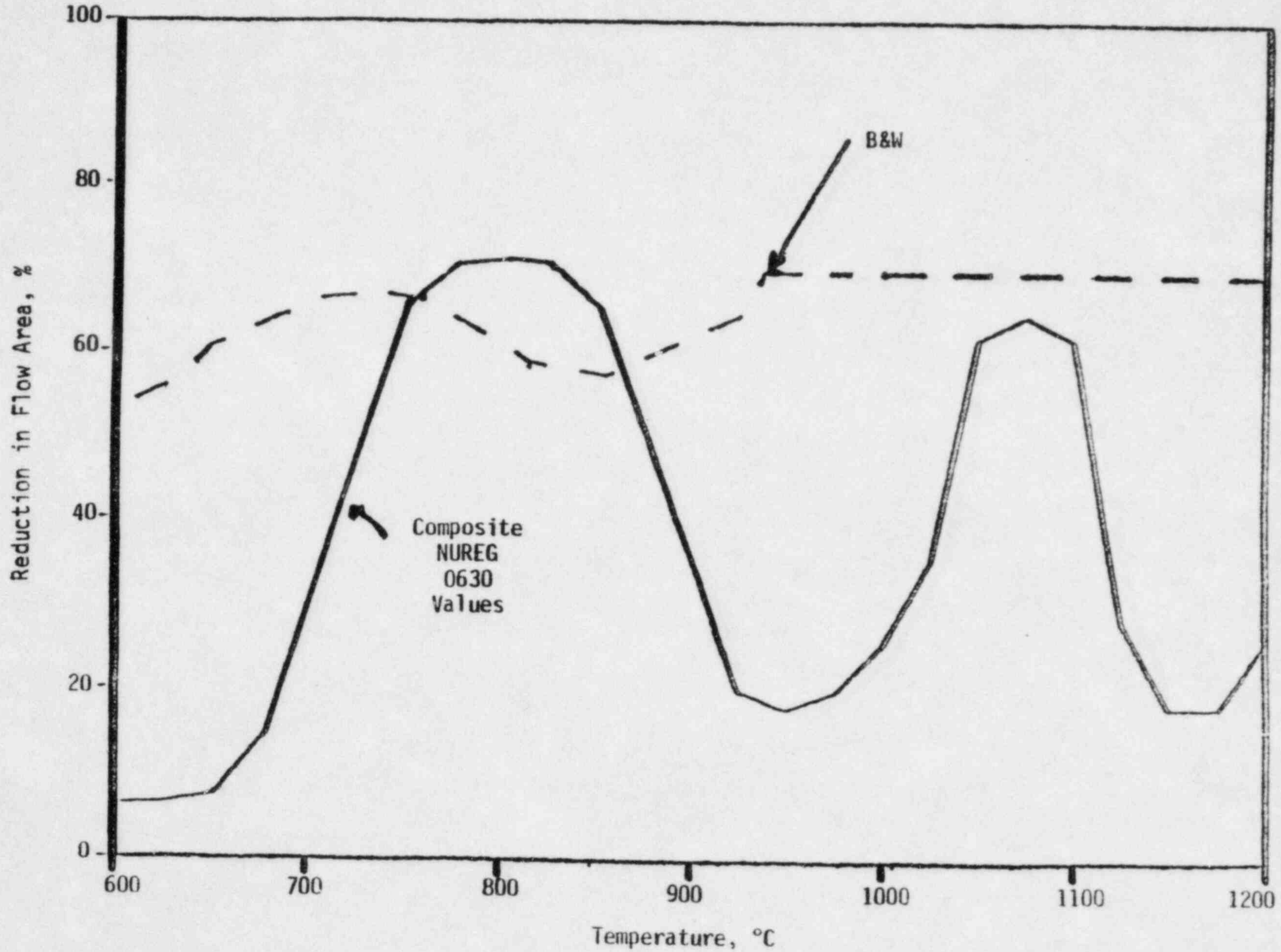


Figure 4-5. Hot Spot Clad Temperature Vs Time With NUREG-0630 – 13.5 kW/ft at 2-ft Core Elevation

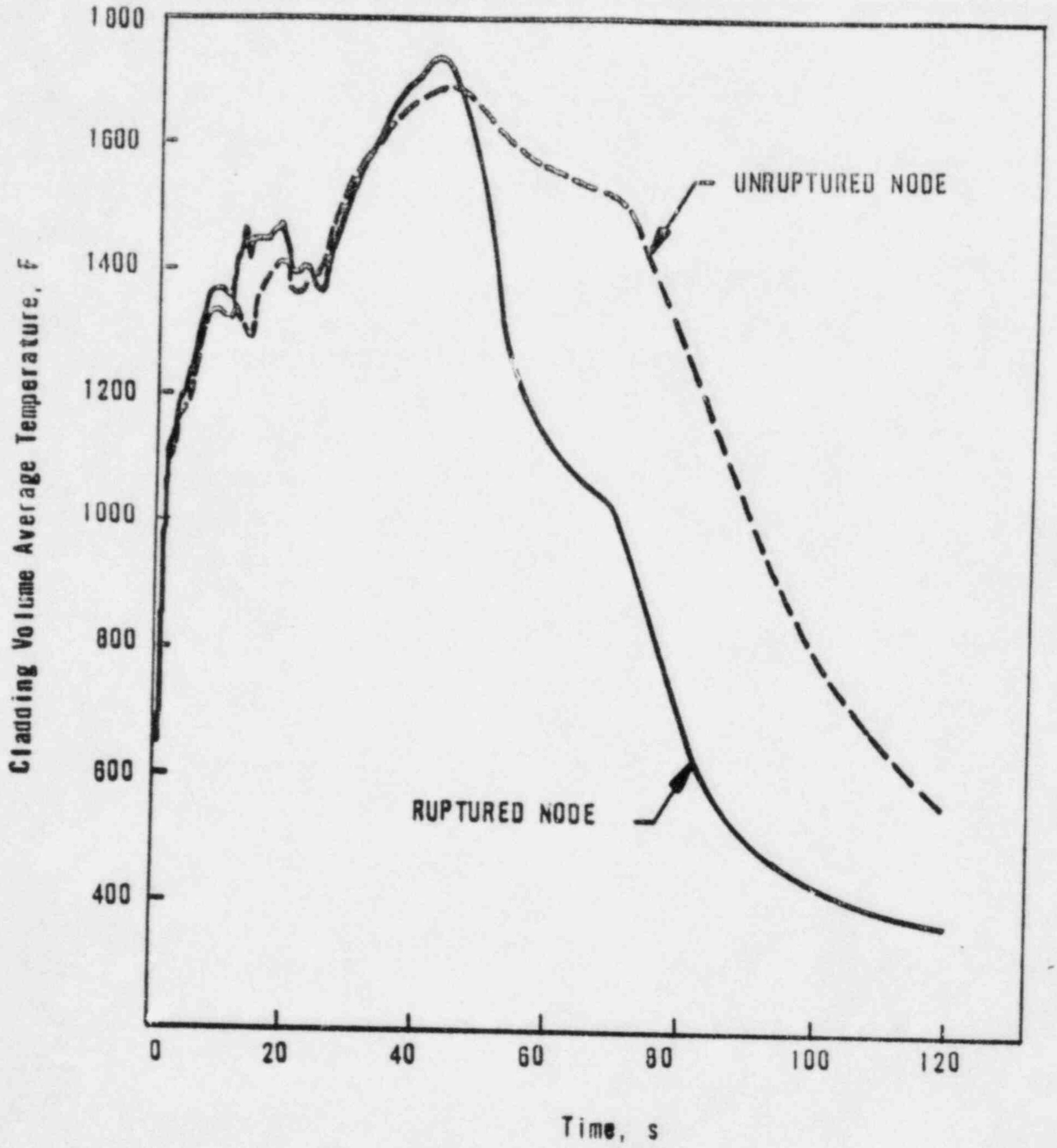
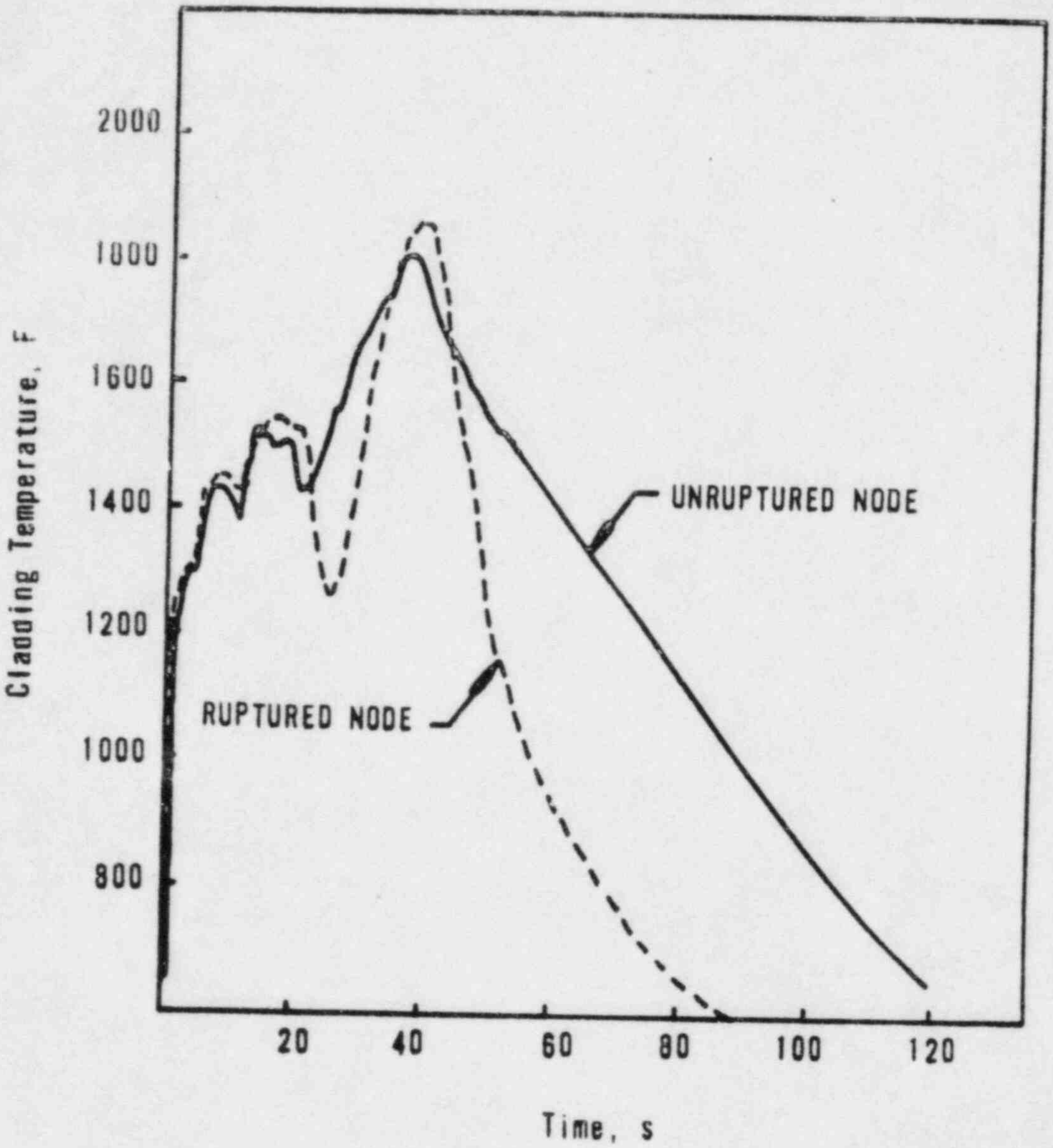


Figure 4-6. Hot Spot Clad Temperature Vs Time With NUREG-0630 and FLECSET — 14.0 kW/ft at 2-ft Core Elevation



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