B&W OWNERS GROUP
Analysis Committee
Core Performance Committee

BOUNDING ANALYTICAL ASSESSMENT OF NUREG 0630 MODELS ON LOCA kW/ft LIMITS WITH USE OF FLECSET

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1. INTRODUCTION

Supplemental ECCS calculations[1] have been performed by B&W on behalf of the B&W Owners Group, based on a generic, bounding assessment of the impact of NUREG-0630 on loss-of-coolant accident (LOCA) kW/ft limits. These calculations were performed for the 2 ft core elevation and the resulting reduction in kW/ft limit applied equally at the 4 and 6 foot core elevations. This analysis, which did not use compensating models to offset lost margin, resulted in a 0.5 kW/ft reduction on the LOCA kW/ft limits due to the use of NUREG-0630 bounding models.

In an effort to reduce or eliminate this 0.5 kW/ft penalty, the B&W Owners Group has established the need to consider the use of compensating models. The FLECHT-SEASET heat transfer correlation is used to generate reflood heat transfer coefficients. This correlation is modeled in the computer program named FLECSET.

The work performed herein is an extension of the bounding analyses assessment previously performed.[1] The use of the FLECHT-SEASET reflood heat transfer correlation as a compensating model results in a higher allowable kW/ft limit thus resulting in regained operating margin in the technical specification operating limits.

2. SUMMARY AND CONCLUSION

An ECCS bounding analysis was performed with a compensating model, FLECSET, to determine the offset of the NUREG-0630 penalty 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 evaluated for the 2-ft core elevation. Previous experience has demonstrated this elevation to be the most sensitive with respect to clad swelling and rupture phenomena.

Implementation of NUREG-0630 with the FLECHT-SEASET reflood heat transfer correlation 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 analysis[7], the peak ruptured node cladding temperature was calculated to be 1899F; therefore, sufficient temperature 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 6-ft core elevation, the peak ruptured node cladding temperature[7] was calculated to be 2090F. Therefore utilization of FLECHT-SEASET at the 6-ft core elevation is not expected to provide sufficient temperature margin to compensate for a 0.5 kW/ft penalty. For the 8- and 10-ft core elevations, the peak ruptured node cladding temperature[7] was found to be 1664 and 1560F, respectively. There is considered to be sufficient temperature 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. The 4 through 10-ft LOCA limits, based on NUREG-0630 and the compensating model, FLECSET, are based on comparisons to the results at the 2-ft core elevation and are engineering judgements.

The analysis was 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 greater LOCA kW/ft margin when compared to BOL.

A summary of the final results at the 2-ft core elevation along with those given in references 1 (with NUREG-0630 plus TACO2) and 7 (with TACO2 fuel model[3] only) are shown in Table 3-1. The 177-FA lowered-loop plant LOCA limits for BOL are listed separately in Table 3-2.

Justification for use of the FLECSET code, utilizing the FLECHT-SEASET heat transfer correlation, for generating reflood heat transfer coefficients is also provided. This justification is based on (1) comparisons of calculated heat transfer coefficients calculated by FLECSET with those calculated by the present LBLOCA Evaluation Model, (2) comparison with experimental data, and (3) sensitivity studies.

Reflood heat transfer coefficients versus time were calculated for the 2-, 4-, 6-, 8- and 10-ft elevations using FLECSET and compared to those calculated by the present LBLOCA Evaluation model BAW-10104, Rev. 3.[5] The FLECSET reflood heat transfer coefficients at the 2-ft core elevation are significantly higher than those calculated by FLECKA[9], during the early stage of the reflood phase. These higher reflood heat transfer coefficients allow the peak cladding temperature to be able to turn over much earlier in the transient. The significance of this is to allow a gain of 0.5 kW/ft to the LOCA limit over that predicted by the original FLECKA[9] evaluation model.

The FLECHT-SEASET heat transfer correlation[2] has been developed based on the concept that the heat transfer coefficient is a function of the distance from the quench front and that the integral of power is used, thus the FLECSET correlation[2] is considered to be a more accurate code than FLECKA[9] and would be applicable to predict reflood heat transfer coefficient to both skewed and cosine power shapes at any given core elevation. The use of FLECSET[2] for calculating reflooding heat transfer coefficients at the 2-ft core elevation is therefore applicable.

Reflood heat transfer coefficients predicted by FLECSET[2] at the 4-, 6-, 8-, and 10-ft are comparable to those generated by the FLECKA[9] (at the 4- and 6-ft core elevations) and by the REFLECHT[10] (at the 8- and 10-ft core elevations) models, and are shown to be in good agreement with those reported in WCAP-9891[2] and WCAP-9699[11].

3. NUREG-0630 LOCA LIMIT ANALYSIS

3.1. Method of Analysis

The analytical methods used in the present 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], and the bounding analysis of the impact of NUREG-0630[1] on LOCA and operating kW/ft limits except for the modifications explained in the following paragraph. Figures 3-1 through 3-3 show the NUREG-0630 bounding parameters as described in detail in reference 1.

A computer code called FLECSET[2,8], which was developed to predict the quench time and heat transfer coefficient for cosine as well as skewed power shapes, was used in this analysis. The present study consisted of running FLECSET at 14.0 kW/ft using input on flooding rates obtained from the recent bounding analysis[1]. THETA 1-B[6] was used 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 2200°F to determine acceptability. This analysis was performed only for the 2-ft core elevation and was consistent with the approach taken for the bounding analyses of NUREG-0630 models.[1]

3.2. Results of Analysis

The results of this analysis are summarized and compared to the base case[7] and NUREG-0630[1] limits analyses Table 3-1. The maximum clad temperature for NUREG-0630 plus FLECSET case was calculated as 1847 and 1809°F for the ruptured and unruptured nodes, respectively, as shown in Figure 3-4. These results were calculated based on a 14.0 kW/ft limit at the 2-ft core elevation.

As indicated in reference 1, there was an impact of 0.5 kW/ft for the 2-, 4-, and 6-ft core elevations due to the implementation of NUREG-0630. However, based on the results obtained on the present study, it is shown that, 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 also previously assigned to the 4- and 6-ft core elevations. These elevations are also kW/ft limited by the ruptured node temperatures. The peak cladding temperatures results at these respective elevations were reviewed with the improved FLECSET heat transfer correlation. For the 4-ft core elevation, there should be no penalty due to the implementation of NUREG-0630 for the following reasons: (1) based on previous analysis[7], the peak ruptured node cladding temperature was calculated to be 1899°F; there should be sufficient temperature margin to meet the 10 CFR 50.46 criteria of 2200°F and (2) the improved FLECSET compensating model is expected to result in a higher allowable kW/ft limit, thus it should allow the LOCA limit at the 4-ft core elevation to remain the same. However, for the 6-ft core elevation, the peak ruptured node cladding temperature[7] was calculated to be 2090°F and there may not be enough temperature margin to meet the 2200°F requirements stated in 10 CFR 50.46. Also, FLECSET may not be able to provide sufficient temperature margin 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[7] was found to be 1664°F and 1560°F, respectively, there should be sufficient temperature margin to satisfy the 2200°F limit required by 10 CFR 50.46. Therefore, there should be no penalty on the LOCA limit at the 8- and 10-ft core elevations as given in BAW-10103A, Rev. 3[4].

A summary of the latest 177-FA lowered loop plant LOCA analyses showing the impacts of TACO2[7], NUREG-0630[1], and the NUREG-0630 with FLECSET are shown in Table 3-2.

Table 3-1. NUREG-0630 With FLECSET Offset LOCA Limit Impact at 2-ft Core Elevation, 8.55-ft[2] DEPD, $C_D = 1.0$

	Base case[7]	NUREG-0630[1]	NUREG-0630 FLECSET
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

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

	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,[7] kW/ft	-1.5	0	0	0	0
NUREG-0630[(a)] impact[1], kW/ft	-0.5	-0.5	-0.5	0	0
NUREG-0630 LOCA Limits	13.5	16.1	17.5	17.0	16.0
FLECSET-offset, kW/ft	+0.5	+0.5	0	0	0
NUREG-0630 + FLECSET[(b)] LOCA limits, kW/ft	14.0	16.6	17.5	17.0	16.0

[(a)]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.

[(b)]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 3-1. B&W Model and ORNL Correlation of Rupture Temperature as a Function of Engineering Hoop Stress and Ramp Rate

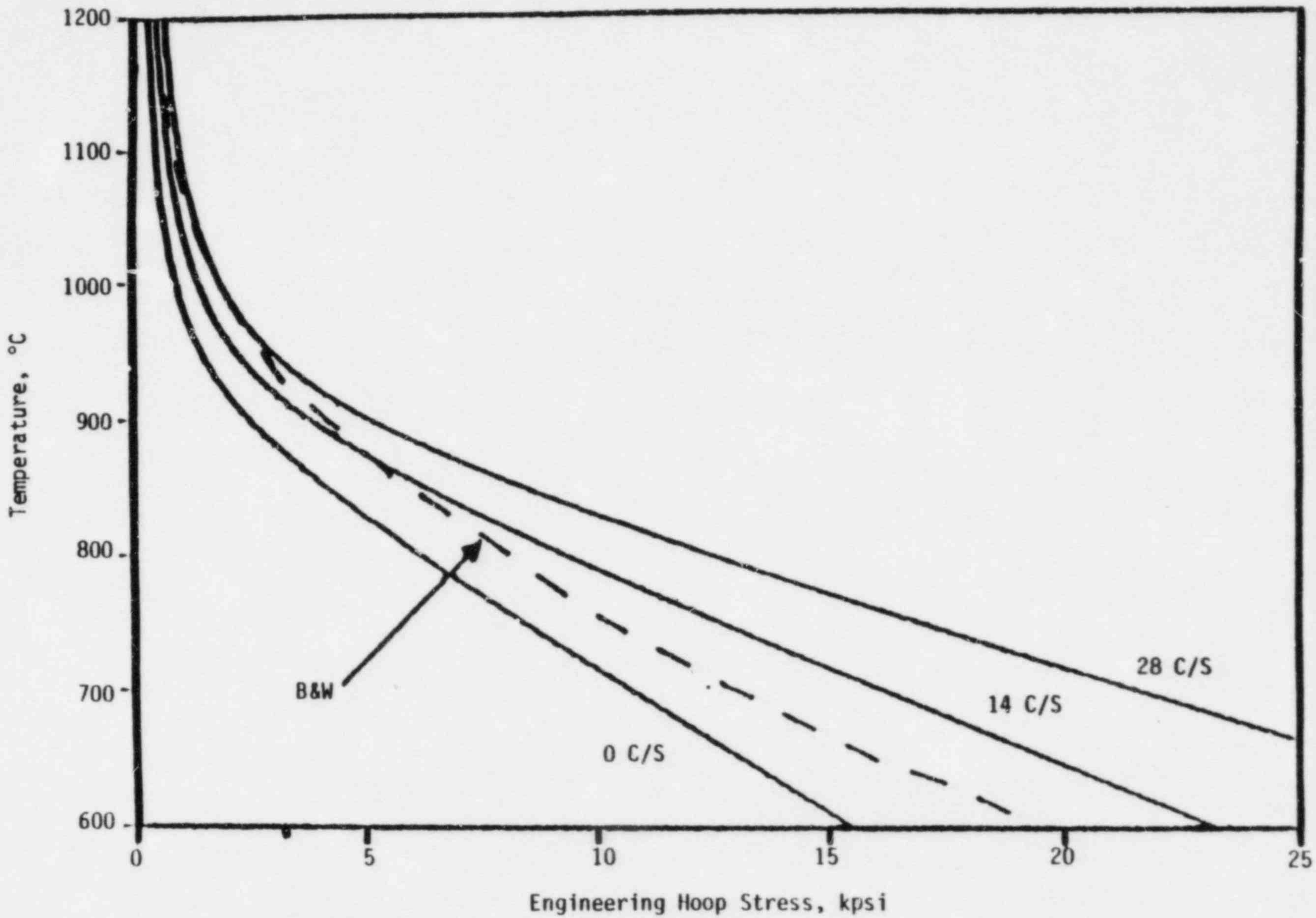


Figure 3-2. B&W THETA Model and Composite NUREG Correlation of Circumferential Burst Strain as a Function of Rupture Temperature

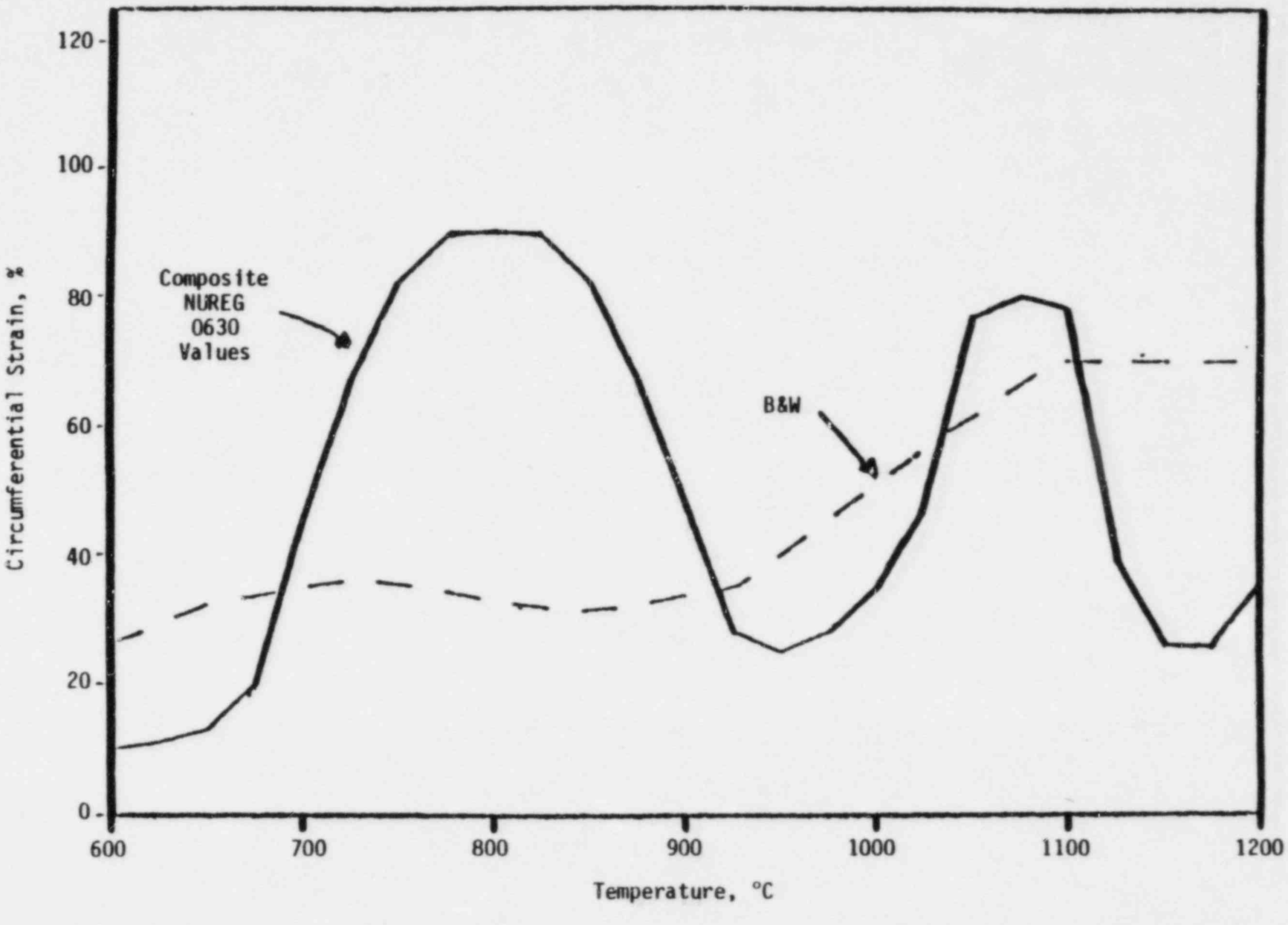


Figure 3-3. B&W Model and Composite NUREG Correlation of Reduction in Assembly Flow Area as a Function of Rupture Temperature

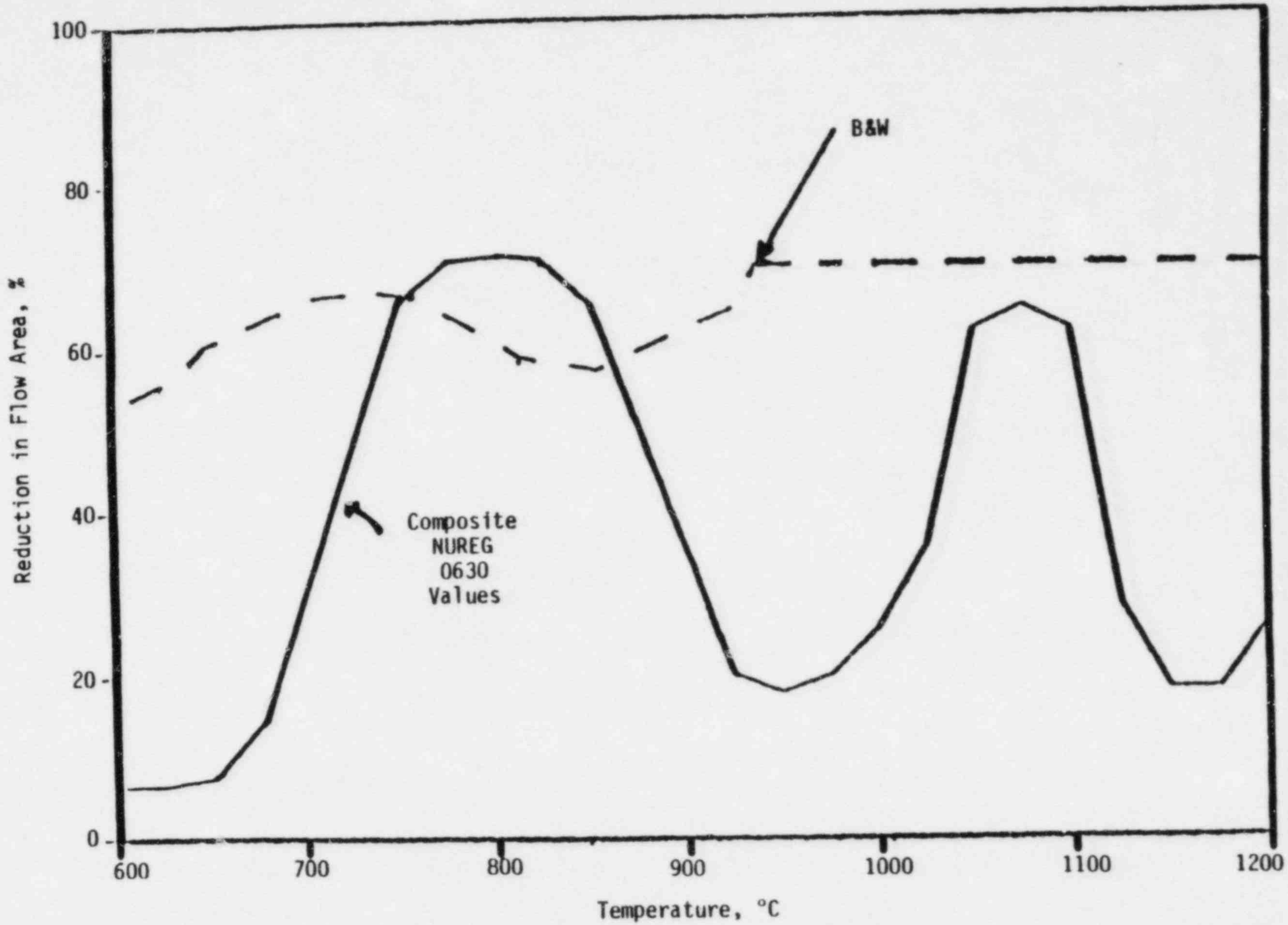
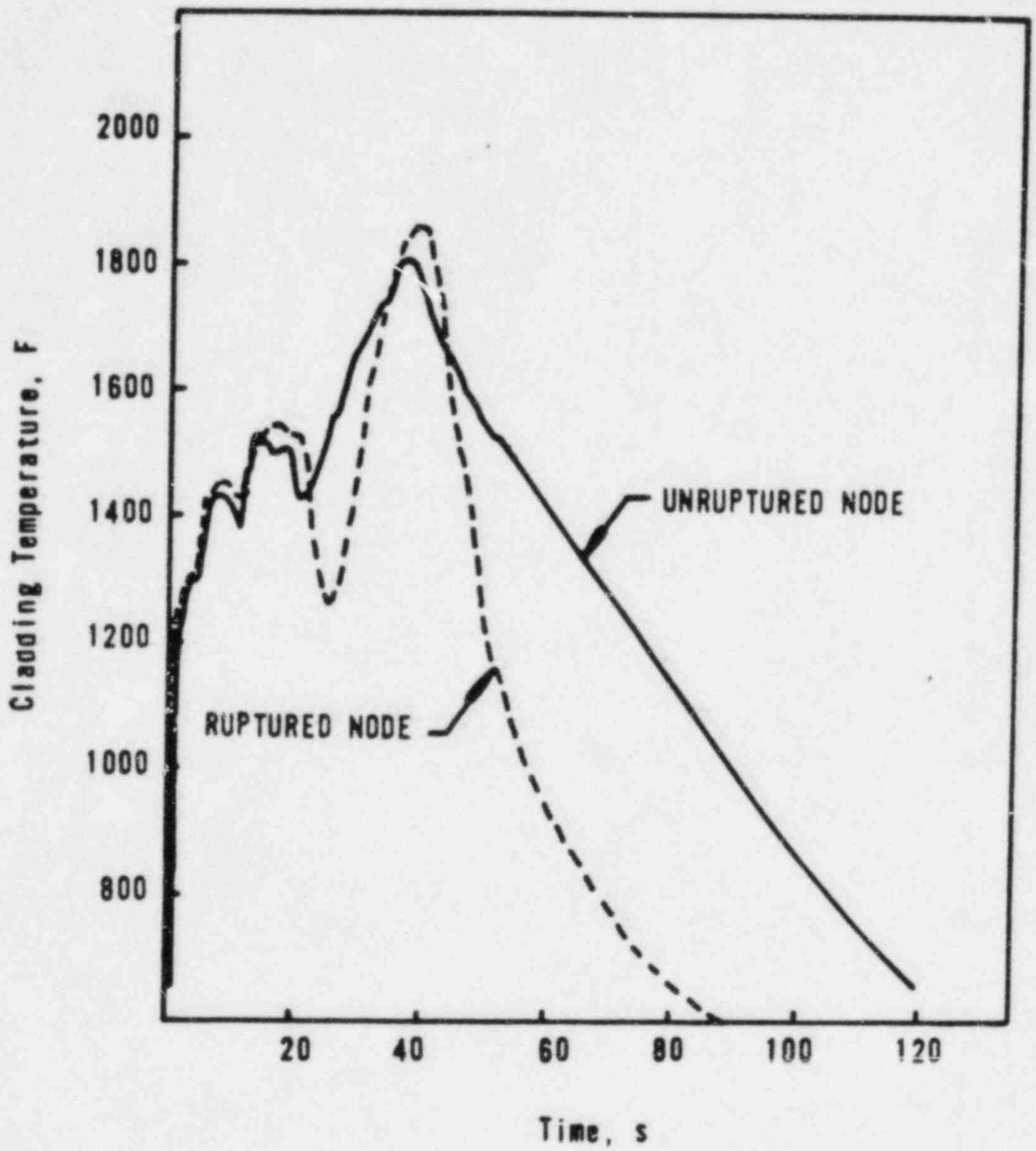


Figure 3-4. Hot Spot Clad Temperature Vs Time With NUREG-0630 and FLECSET — 14.0 kW/ft at 2-ft Core Elevation



4. JUSTIFICATION FOR USE OF FLECHT-SEASET HEAT TRANSFER CORRELATION FOR GENERATING REFLOOD HEAT TRANSFER COEFFICIENTS

4.1. Heat Transfer

The analytical methods used to evaluate reflood heat transfer coefficients are the same as those described in section 4.3.6.5 of B&W ECCS evaluation model topical report BAW-10104, Rev. 3[5] except for the following modifications.

In place of the FLECKA[9] and REFLECHT[10] evaluation models, the FLECSET model is used. FLECSET is the name of the computer code which uses the FLECHT-SEASET correlation for the calculation of reflooding heat transfer coefficients. FLECKA[5] calculates heat transfer coefficients for the 2-, 4-, and 6-ft core elevations based on flooding rates calculated by the REFLOD3 code.[12] REFLECHT[10] is used at the 8- and 10-ft core elevations to generate equivalent flooding rates that are then input to FLECKA[9] to calculate reflood heat transfer coefficients. Unlike the correlation contained in FLECKA[9] and REFLECHT[10], the FLECHT-SEASET heat transfer correlation[2] was developed based on both cosine and skewed power shapes, as shown typically in Figure 4-13. The FLECHT-SEASET correlation[2] is valid for the following ranges of parameters: flooding rate, constant or variable, from 0.4 to 10.0 in./s; system pressure, 15 to 60 psia; inlet subcooling, 16 to 140°F; initial clad temperature, 300 to 2200°F and equivalent peak power, 0.3 to 2.0 kW/ft. The FLECHT-SEASET correlation[2] conserves the integrated power at different core elevations. Figure 5-12 shows how the FLECSET code[2] interfaces with the other ECCS large break LOCA codes.

To justify the use of FLECHT-SEASET correlation[2] as a compensating model, an evaluation has been performed at the 2-, 4-, 6-, 8-, and 10-ft core elevations using the core flooding rates shown in Table 4-3. This analysis has been performed with equivalent key parameters (flooding rates, system pressure, peak rod power, inlet subcooling, initial clad temperature and power

shapes) and has been consistent with the approach taken for the TACO2 LOCA limits analysis.[7]

The results of this analysis are summarized and compared to those given in reference 7 as shown in Figures 4-1 through 4-10.

4.2. Application of FLECSET[2] at 2- and 4-ft Core Elevations -- Bottom Skewed Power Shapes

As indicated in WCAP-9891,[2] the FLECHT-SEASET reflood heat transfer correlation has been based on the experimental data calculated at the core mid-plane and core exit regions. However, the FLECHT-SEASET correlation, as discussed in reference 13, has also been designed on the concept of considering the heat transfer coefficient to be a function of the distance from the quench front for all levels below the PCT elevation, and to be a function of the distance from the PCT elevation for all levels above it. The heat transfer coefficient is primarily a function of the distance from the quench front because the heat transfer required on an unwetted cladding surface starts its development from the quench front. As suggested in WCAP-9183[8], the FLECHT-SEASET correlation[2] could be used to predict the quench front movement of both skewed and cosine power shapes at any elevation by using the ratio of the integral of power. Quench time has been shown to be proportional to the heat input below the quench front.[13] This heat can be reasonably approximated by the integral of power below the quench front. The results reported in reference 8 were found to be in good agreement. Therefore, the FLECHT-SEASET reflood heat transfer correlation[2] is considered applicable for predicting heat transfer coefficients as a function of distance from the quench front to both skewed and cosine power shapes and at any given core level above or below the peak clad temperature elevation.

The reflood heat transfer coefficients versus time calculated by the FLECSET code at the 2-ft core elevation, as shown in Figure 4-2, are significantly higher than those predicted by FLECKA[9], especially for the first 10 seconds following the end of adiabatic heatup. These higher reflood heat transfer coefficients are justified based on the following reasons:

1. They are in good agreement with those provided by the Westinghouse PWR FLECHT-SEASET test data reported in WCAP-9699[11], for compatible key parameters as shown in Table 4-2. The heat transfer coefficients at the 1- and 2-ft core elevations are found to be consistently higher than those at the 4- and 6-ft core elevations, reported in runs 31203, 31302, 34420, and 34524 of WCAP-9699, which have been excerpted and included as Appendix A.

2. As indicated in reference 13 (run 15305) reflood heat transfer coefficients are found to be increasingly higher as distance moves closer toward the quench front, especially within the range of 3-ft above the quench front (i.e., 1- and 2-ft elevations) as shown in Figure 4-14. This rapid rise in the reflood heat transfer coefficient is due to the high proportion of injected water being entrained during the early stage of the reflood phase and carried out of the rod bundle thus improving heat transfer

To determine the effect on the reflood heat transfer coefficients due to the change in ratio of the integral of power, two separate runs have been performed using the 4- and 6-ft 1.7 axial power shapes as shown in Figure 4-13 with the same flooding rates as the 2-ft core elevation. The results show that there is very little difference in the 2-ft reflood heat transfer coefficients using the 2-, 4-, and 6-ft power shapes for the first 10 seconds following the end of adiabatic heatup. However, after 15 seconds following the end of adiabatic heatup, the reflood heat transfer coefficients at the 4- and 6-ft core elevations start to become higher than those at the 2-ft core elevation. This is shown in Figures 4-8 and 4-9. Thus, the effects of power on the reflood heat transfer coefficients during the early stage following the end of adiabatic heatup are considered to be negligible.

Reflood heat transfer coefficients versus time at the 4-ft core elevation predicted by FLECSET[2], as shown in Figure 4-3, are comparable to those calculated by FLECKA[9] given in reference 7. Similar results were also found in all four cases reported in WCAP-9699[11] shown in Table 4-2 and in Appendix A. Thus, it is concluded, based on the similarity of results, that the FLECHT-SEASET reflood heat transfer correlation[2] contained in the FLECSET code is applicable for predicting heat transfer coefficients at the 4-ft core elevation.

4.3. Application at 6-ft Core Elevation Symmetric (Cosine) Power Shapes

The reflood heat transfer coefficients versus time at the 6-ft core elevation calculated by the FLECSET[2] code are reasonably comparable to those predicted by the FLECKA[9] evaluation model, as shown in Figure 4-4. Also, results reported in WCAP-9699[11], (shown in Table 4-2 and Appendix A) and in the benchmark tests (shown in Figures 6-6 and 6-7 of Appendix B) were found to be in good agreement. Therefore, the FLECSET reflood heat transfer correlation[2] is also applicable to predict the reflood heat transfer coefficient at the 6-ft core elevation.

4.4. Application at 8- and 10-ft Core Elevations -- Outlet Skewed Power Shapes

The reflood heat transfer coefficients versus time calculated using FLECSET at the 8- and 10-ft core elevations are reasonably comparable to those predicted by REFLECHT[10] shown in Figures 4-5 and 4-6, respectively. The rapid rise in reflood heat transfer coefficient at both 8- and 10-ft core elevations during the early stage of the reflood phase was also found in WCAP-9891[2], as shown in Figure 4-11. To determine any possible effect on FLECSET heat transfer coefficient predictions due to initial flooding rates, a study has been performed at the 8-ft core elevation, by reducing the initial flooding rates for the first 30 seconds following the end of adiabatic heatup. The calculated FLECSET results, which are shown in Figure 4-7, indicate a substantial drop in heat transfer coefficient during the early period following the end of adiabatic heatup. A similar trend was also found in the test results reported in reference 2. Thus, the reflood heat transfer correlation in FLECSET is suitable for predicting heat transfer coefficients at the 8- and 10-ft core elevations.

Table 4-1. Summary of LOCA Limits

	Distance from bottom of core, ft				
	2	4	6	8	10
CRAFT/THETA LHR, kW/ft	14.5/14.0	16.6/16.6	18.0/18.0	17.0/17.0	16.0/16.0
CFT actuation time, s	17.6	17.4	17.4	17.4	17.4
Rupture time/blockage, %	21.6/58.8	23.6/61.12	23.2/60.10	25.3/62.34	27.3/64.47
End of blowdown, s	25.2	25.0	24.8	24.6	24.8
End of bypass, s	25.2	25.0	24.8	24.6	24.8
Mass remaining in vessel at end of blowdown, lbm	1604.0	1902.0	1782.0	1616.0	1878.0
End of adiabatic heatup, s	36.0	35.7	35.8	35.3	35.6
Peak unruptured node cladding temperature/time, F/s	1843/43.5	1874/42.5	2030/43.0	1848/143.7	1773/210.9
Peak ruptured node cladding temperature/time, F/s	1934/43.4	1899/42.6	2090/44	1664/39.5	1560/39.5
Local metal-water reaction, %	2.12	1.90	3.92	2.12	1.78
Initial pin pressure, psia	1555	1555	1555	1555	1555

Table 4-2. Heat Transfer Coefficient Versus Time

Time after EOAH, s	h (Btu/h-ft^2-°F)	h(a) (Btu/h-ft^2-°F)	h(a) (Btu/h-ft^2-°F)	h(a) (Btu/h-ft^2-°F)	h(a) (Btu/h-ft^2-°F)
2-ft Core Elevation					
	Reference 4	Reference 7	Reference 7	Reference 7	Reference 7
Peak power	run No. AEKIKQD	run No. 31203	run No. 31302	run No. 34420	run No. 34524
T_{sub}	0.75 kW/ft	0.70 kW/ft	0.69 kW/ft	0.74 kW/ft	1.0 kW/ft
T_{init}	145°F	126°F	126°F	124°F	125°F
pressure	1900°F	1601°F	1597°F	2045°F	1612°F
inlet	40 psia	40 psia	40 psia	39 psia	40 psia
velocity	variable FR	1.51 in./s	3.01 in./s	1.53 in./s	1.57 in./s
0.0	3.6459 (FR=2.758 in./s)	4.0	4.0	3.0	3.0
10.43	21.795 (FR=2.332 in./s)	22.0	40.0	24.0	28.0
19.68	23.8769 (FR=1.743 in./s)	35.0	60.0	40.0	41.0
4-ft Core Elevation					
	Reference 4	Reference 7	Reference 7	Reference 7	Reference 7
Peak power	run No. AEKIDDO	run No. 31203	run No. 31302	run No. 34420	run No. 34524
T_{sub}	0.89 kW/ft	0.70 kW/ft	0.69 kW/ft	0.74 kW/ft	1.0 kW/ft
T_{init}	145°F	126°F	126°F	124°F	125°F
pressure	1800°F	1601°F	1597°F	2045°F	1612°F
inlet	38 psia	40 psia	40 psia	39 psia	40 psia
velocity	variable FR	1.51 in./s	3.01 in./s	1.53 in./s	1.57 in./s
0.0	4.2576 (FR=2.7872 in./s)	2.0	2.0	3.0	2.0
10.47	12.5923 (FR=2.385 in./s)	7.0	18.0	8.0	7.5

Table 4-2. (Cont'd)

Time after EOAH, s	h (Btu/h-ft^2-°F)	h[a] (Btu/h-ft^2-°F)	h[a] (Btu/h-ft^2-°F)	h[a] (Btu/h-ft^2-°F)	h[a] (Btu/h-ft^2-°F)
4-ft Core Elevation (Cont')					
22.08	13.6682 (FR=1.799 in./s)	12.0	22.0	16.0	14.0
41.81	13.9893 (FR=1.479 in./s)	213.0	40.0	20.0	20.0
6-ft Core Elevation					
	Reference 4 run No. AD4IE0A	Reference 7 run No. 31203	Reference 7 run No. 31302	Reference 7 run No. 34420	Reference 7 run No. 34524
Peak power	0.96 kW/ft	0.70 kW/ft	0.69 kW/ft	0.74 kW/ft	1.0 kW/ft
T_{sub}	145°F	126°F	126°F	124°F	125°F
T_{init}	1900°F	1601°F	1597°F	2045°F	1612°F
pressure	43 psia	40 psia	40 psia	39 psia	40 psia
inlet velocity	variable FR	1.51 in./s	3.01 in./s	1.53 in./s	1.57 in./s
0.0	4.3812 (FR=2.809 in./s)	2.0	3.0	2.3	2.0
10.91	11.8943 (FR=2.41 in./s)	8.0	16.0	6.0	5.0
21.36	12.2576 (FR=1.838 in./s)	10.5	20.0	11.0	9.0
40.46	11.2335	10.6	24.0	13.0	12.0

(a) Extrapolated values from test data given in reference 7. FR = flooding rate at time following end of adiabatic heatup (EOAH).

Table 4-3. Flooding Rate Versus Time

Core elevation, ft	Time after end of adiabatic heatup, s	Flooding rate in./s
2	0.0 to 9.29	2.758
	9.3 to 14.29	2.332
	14.3 to 30.29	1.743
	30.3 to 57.29	1.427
	57.3 to end of run	1.35
4	0.0 to 9.072	2.7872
	9.037 to 14.072	2.385
	14.073 to 29.272	1.799
	29.273 to 53.272	1.479
	53.273 to end of run	1.379
6	0.0 to 9.218	2.809
	9.219 to 14.219	2.410
	14.22 to 29.22	1.838
	29.23 to 55.23	1.513
	55.24 to end of run	1.407
8	0.0 to 5.063	2.793
	5.064 to 30.263	2.2141
	30.264 to 65.263	1.539
	65.264 to 89.263	1.4361
	89.264 to 139.263	1.3979
	115.264 to 139.263	1.3604
	139.264 to 165.263	1.3121
	165.264 to 191.263	1.2447
	191.264 to 215.263	1.1746
	215.264 to 241.263	1.100
	241.264 to 267.263	1.0228
	267.264 to end of run	0.9531
10	0.0 to 5.038	2.8993
	5.039 to 20.238	2.8029
	20.239 to 65.238	1.5987
	65.239 to 89.238	1.4727
	89.239 to 115.238	1.4112
	115.239 to 141.238	1.3386
	141.239 to 165.238	1.2547
	165.239 to 191.238	1.1618
	191.239 to 217.238	1.0626
	217.239 to 241.238	0.9728
	241.239 to 267.238	0.8832
	267.239 to 291.528	0.802
	291.529 to end of run	0.802

Figure 4-1. FLECSET Heat Transfer Coefficient Versus Time at 2-ft Core Elevation, 14.0 kW/ft

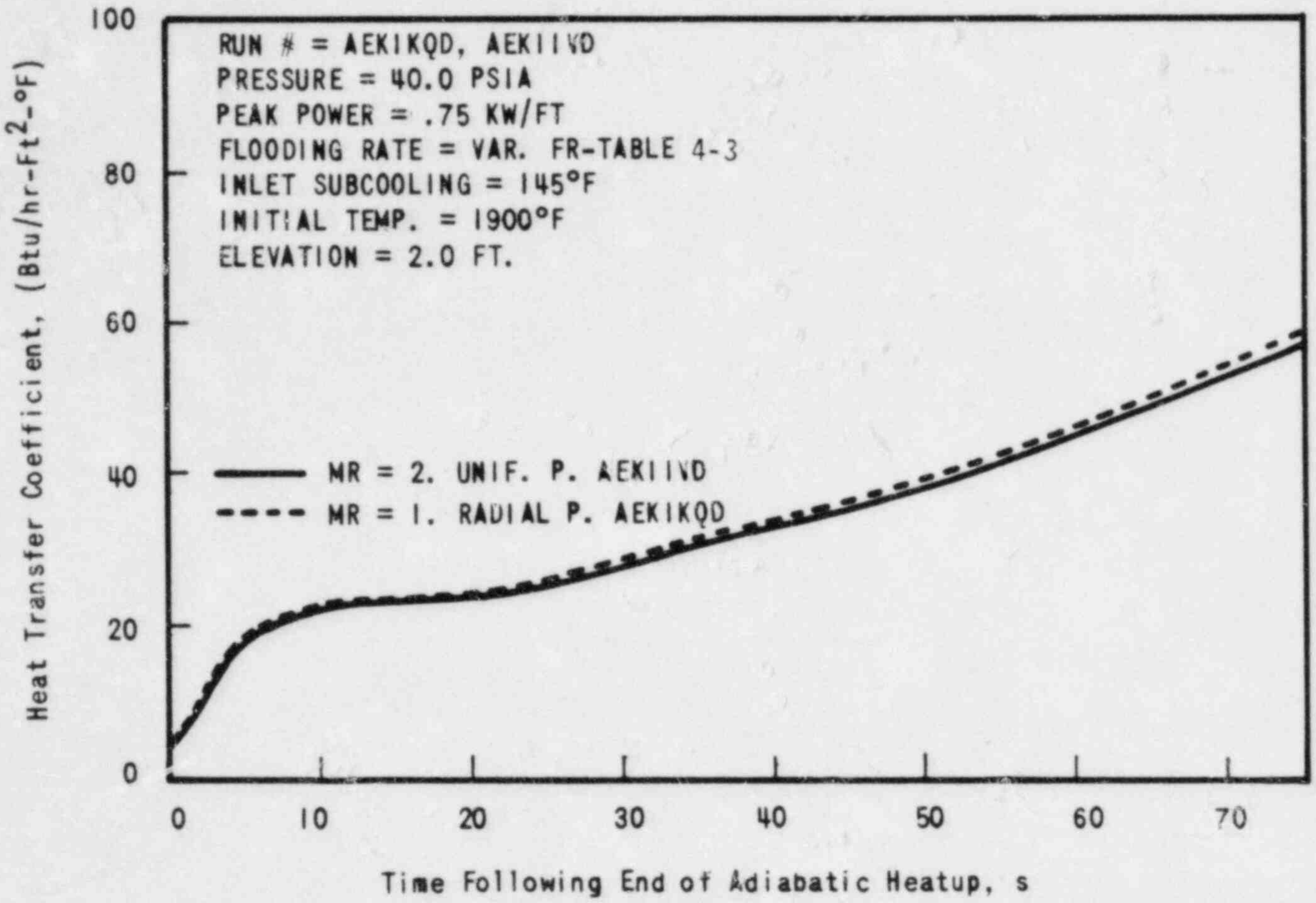


Figure 4-2. Heat Transfer Coefficient Versus Time at 2-ft Core Elevation, 14.0 kW/ft

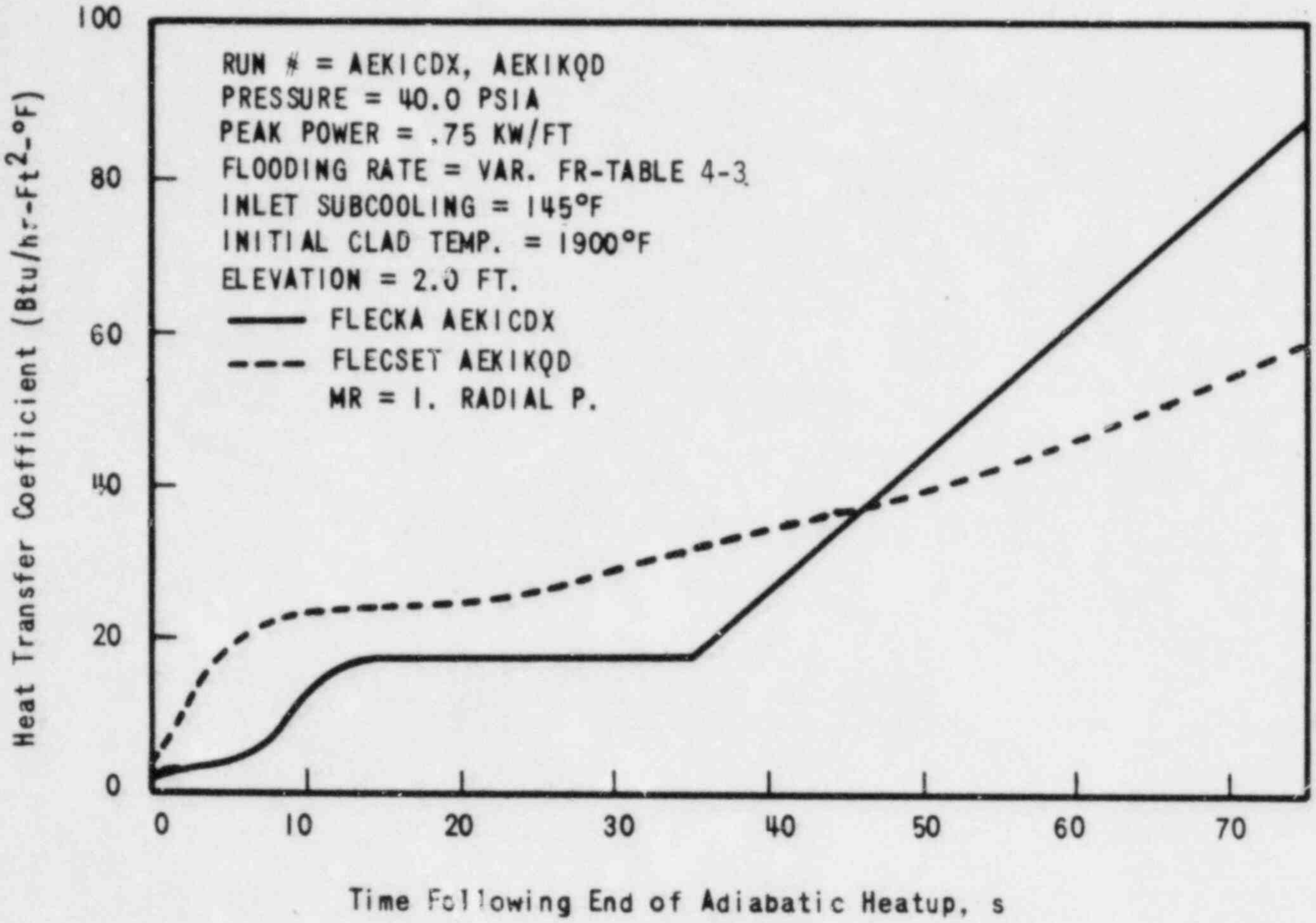


Figure 4-3. Heat Transfer Coefficient Versus Time at
4-ft Core Elevation, 16.6 kW/ft

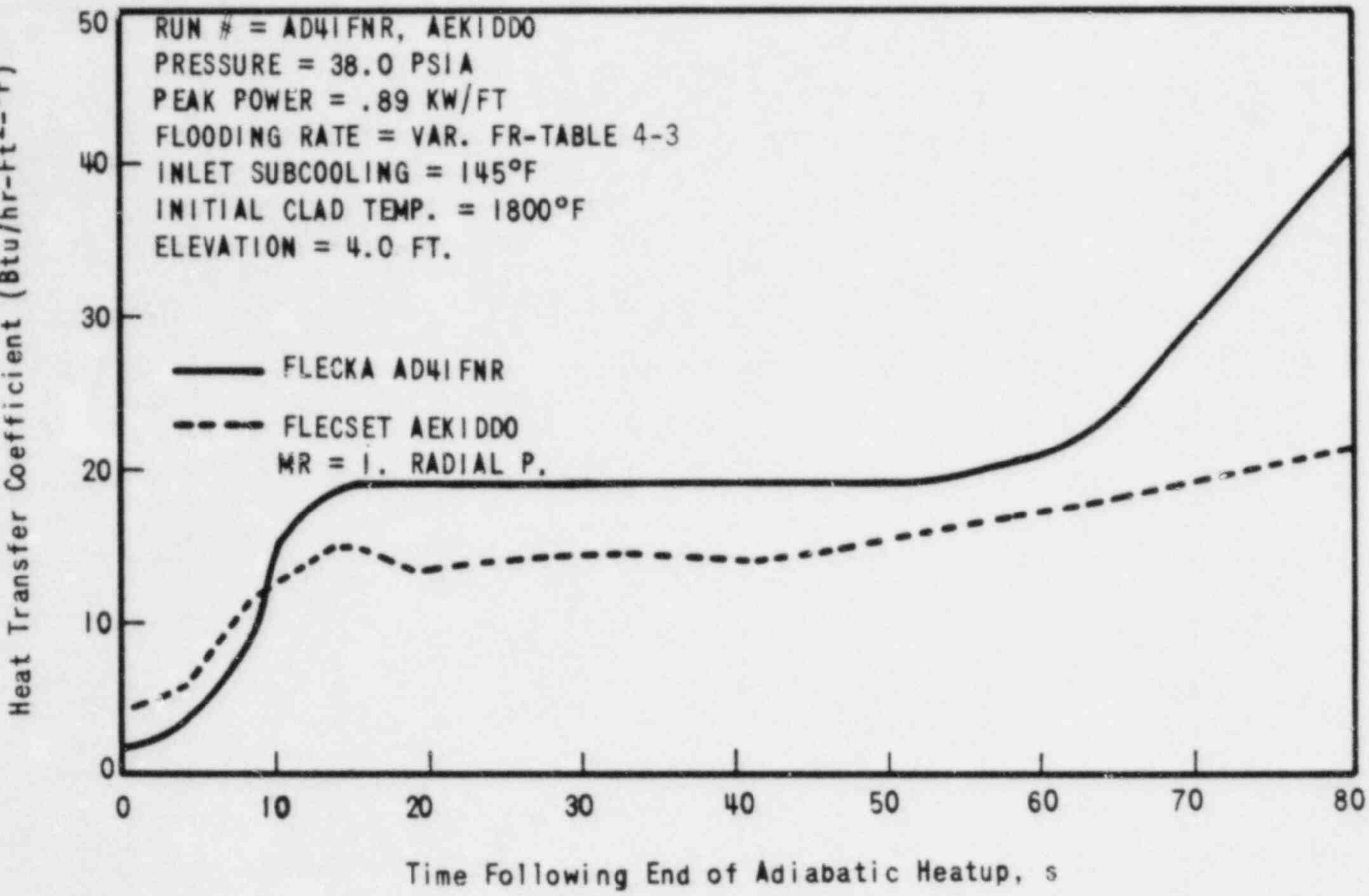


Figure 4-4. Heat Transfer Coefficient Versus Time at 6-ft Core Elevation, 18.0 kW/ft

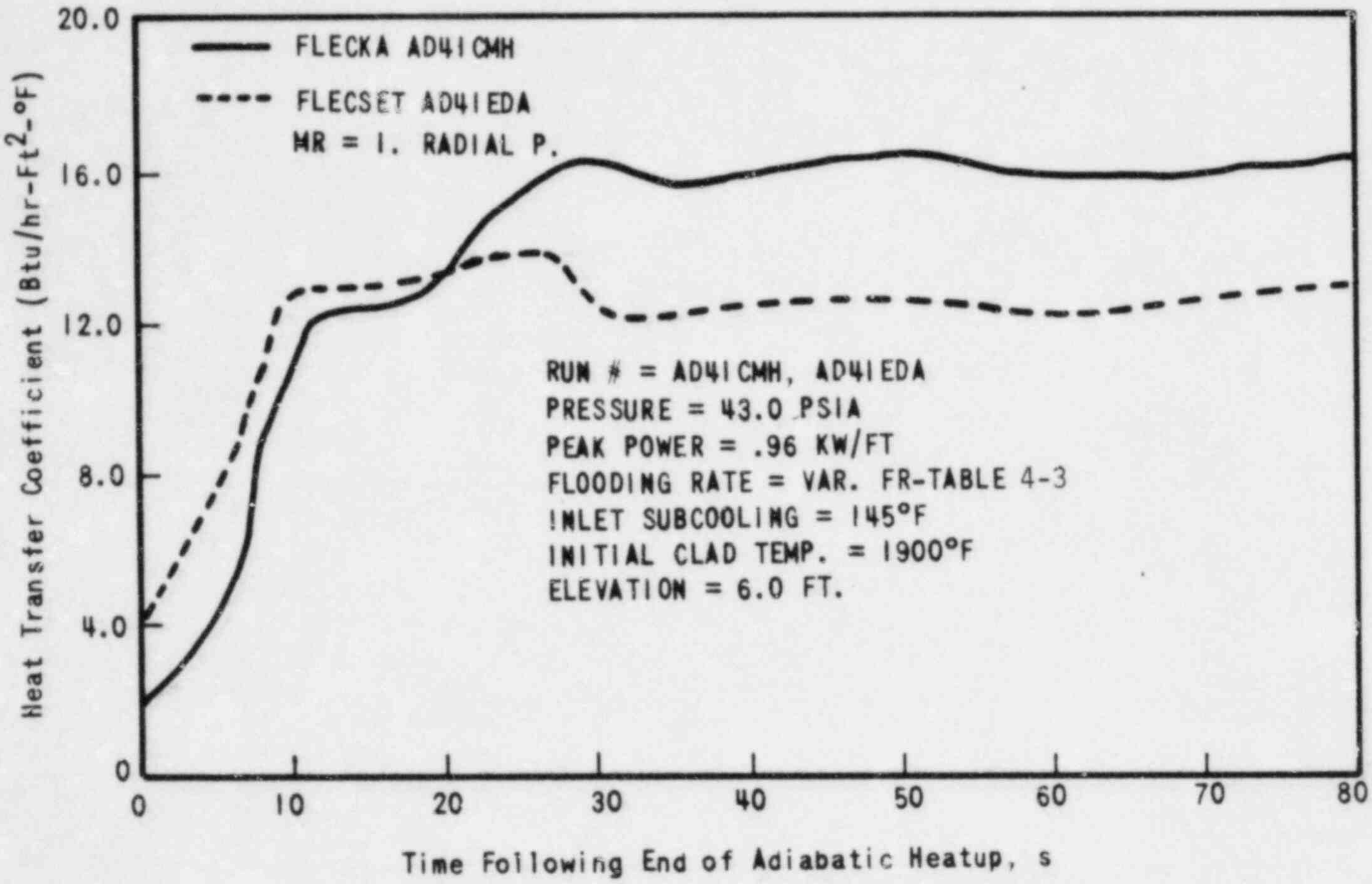


Figure 4-5. Heat Transfer Coefficient Versus Time at 8-ft Core Elevation, 17.0 kW/ft

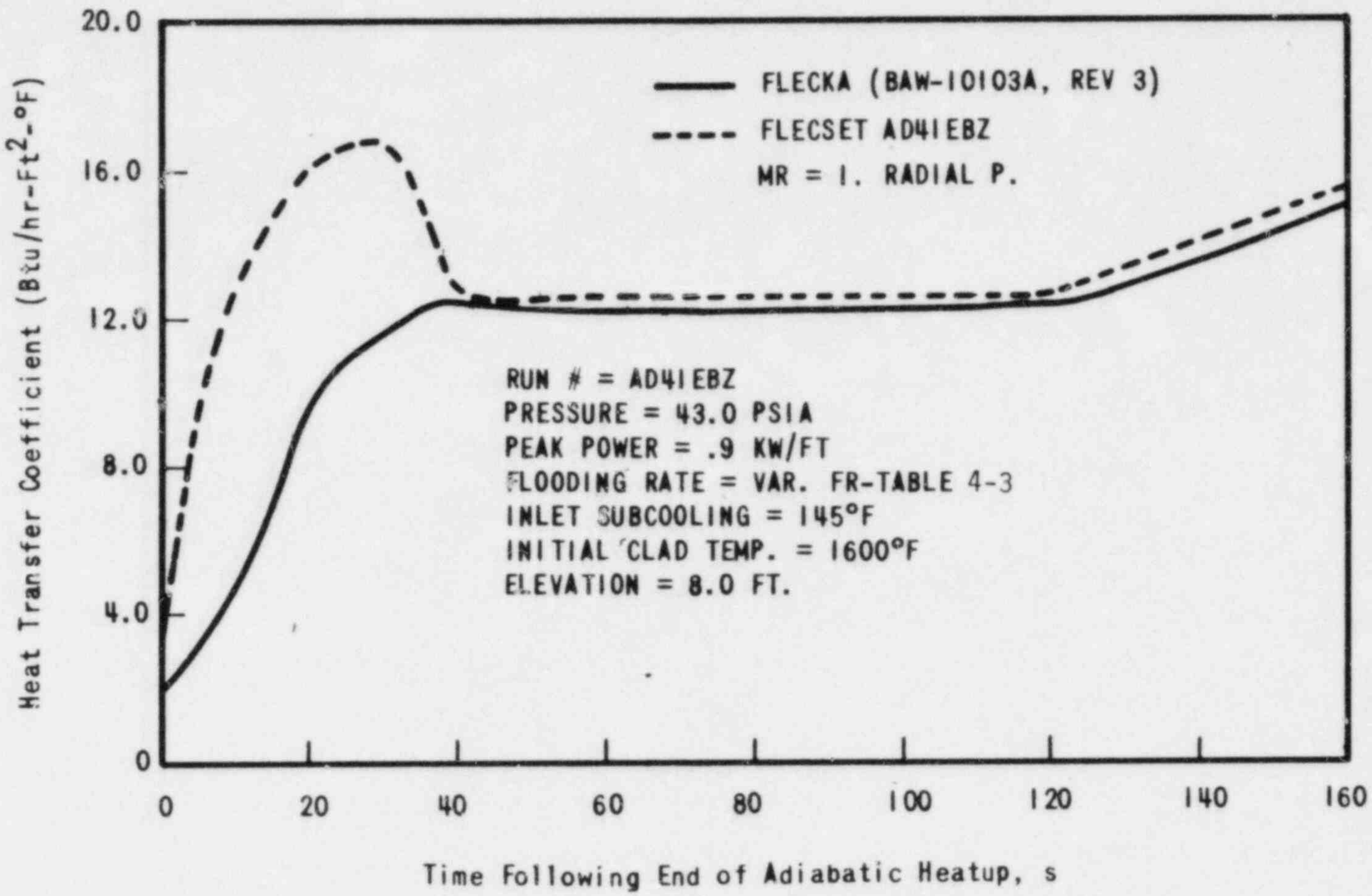


Figure 4-6. Heat Transfer Coefficient Versus Time at 10-ft Core Elevation, 16.0 kW/ft

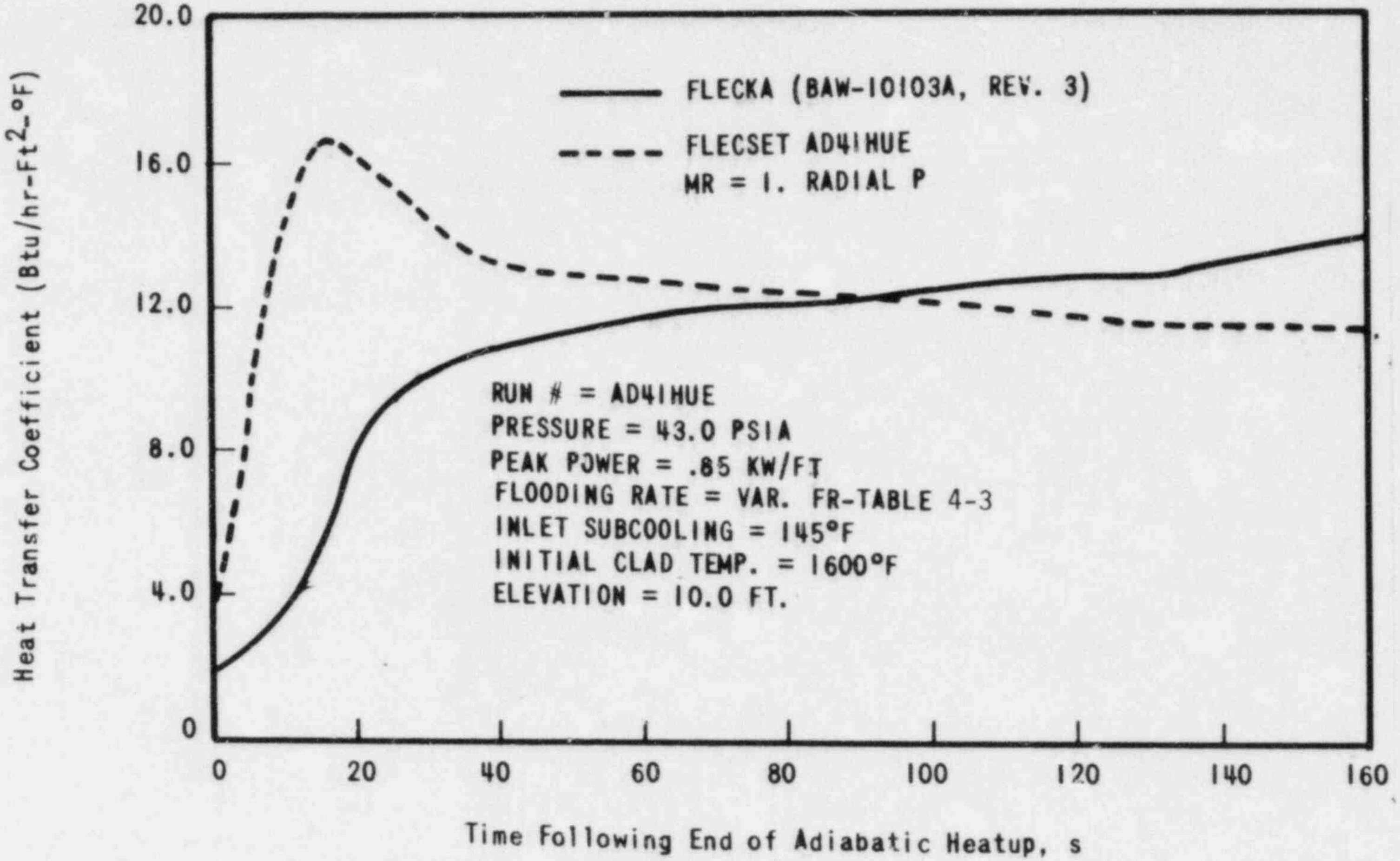


Figure 4-7. Heat Transfer Coefficient Versus Time at 8-ft Core Elevation, 17.0 kW/ft With Reduced Flooding Rate for First 30 Seconds

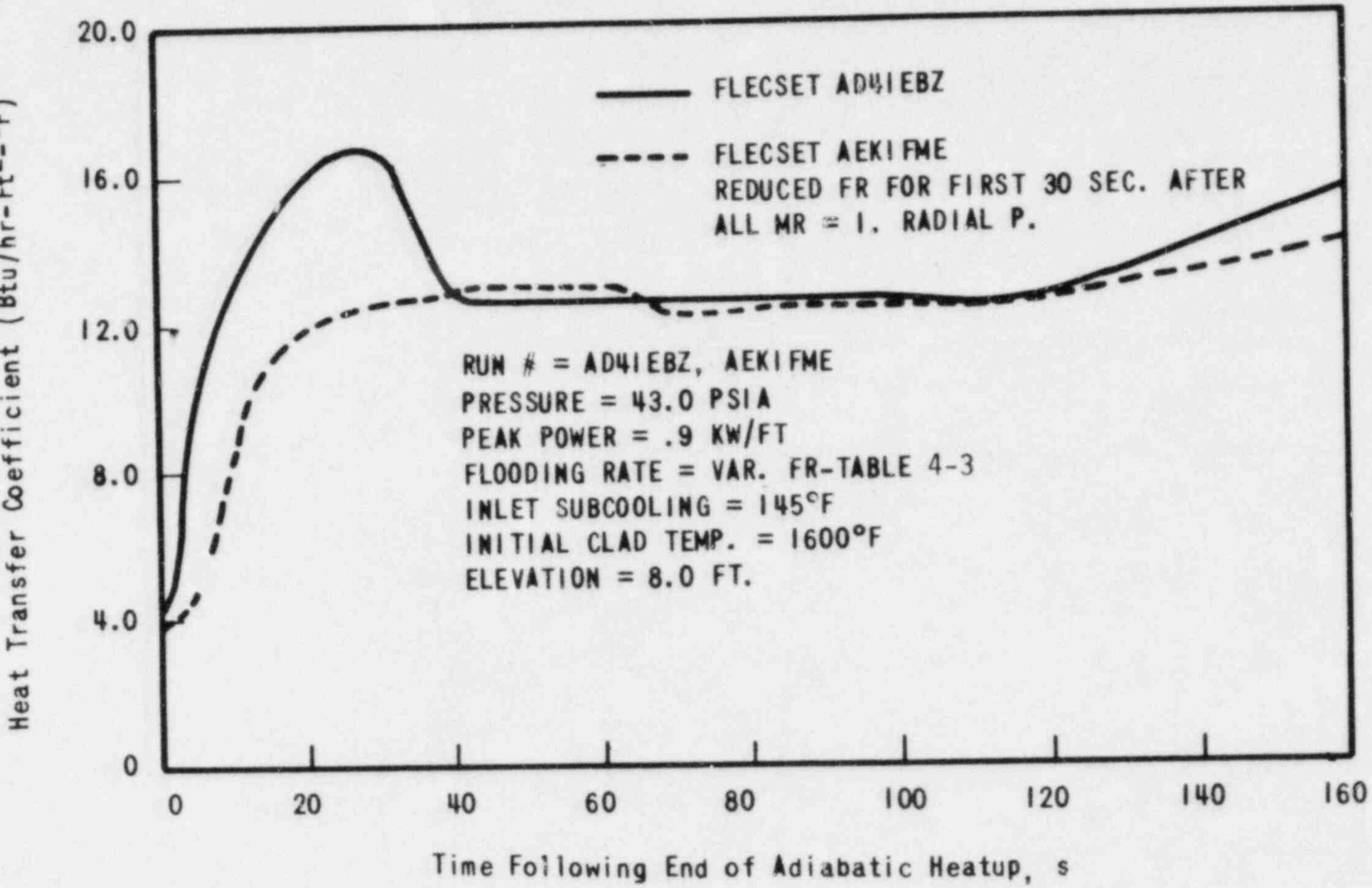


Figure 4-8. Reflood Heat Transfer Coefficients Versus Time at 2-ft Core Elevation for Peak Power Shapes of 2-, 4-, and 6-ft (all peak powers at 14.0 kW/ft)

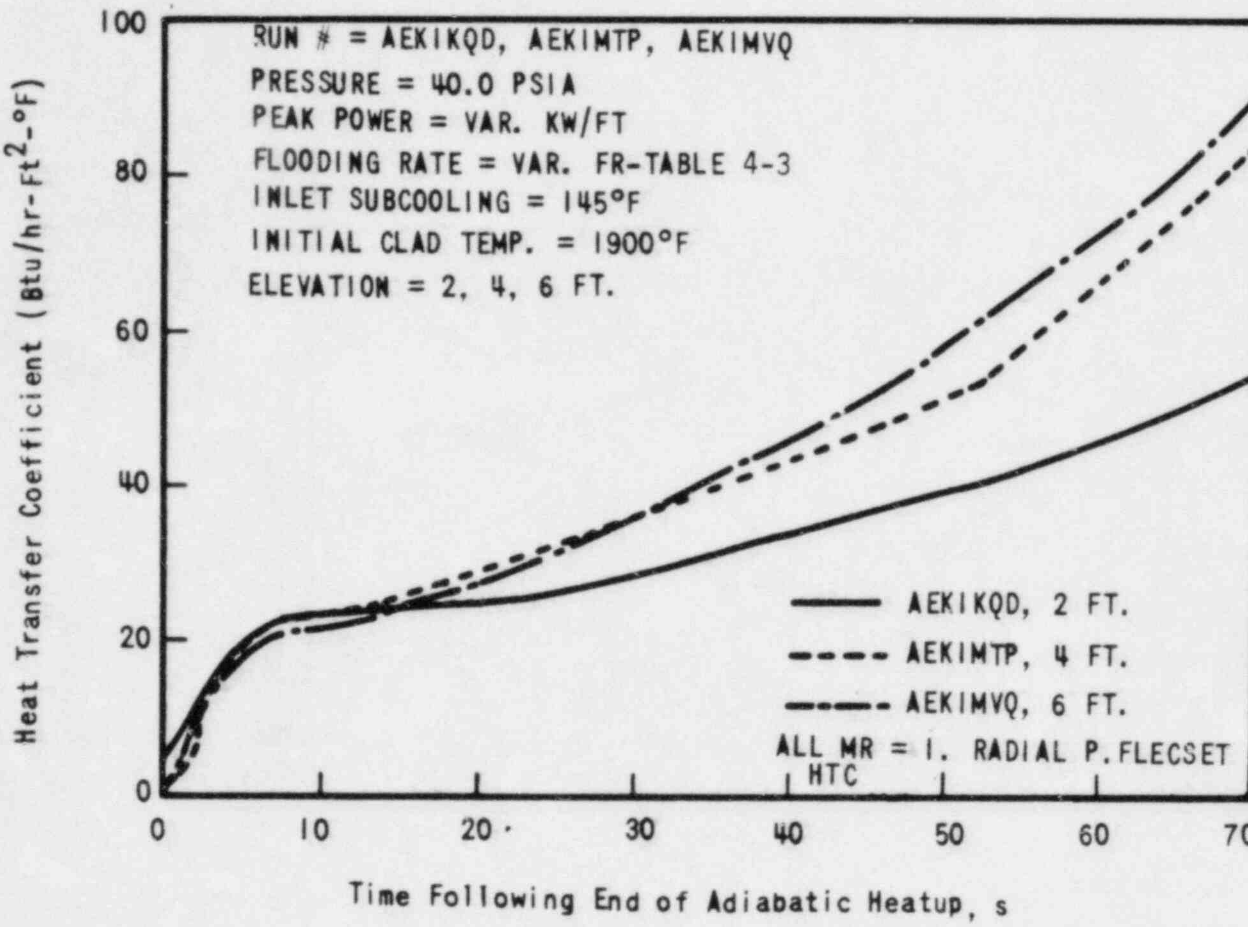


Figure 4-9. Reflood Heat Transfer Coefficient Versus Time at 2-ft Core Elevation for Peak Power Shapes of 2-, 4-, and 6-ft (all peak powers at 14.0 kW/ft)

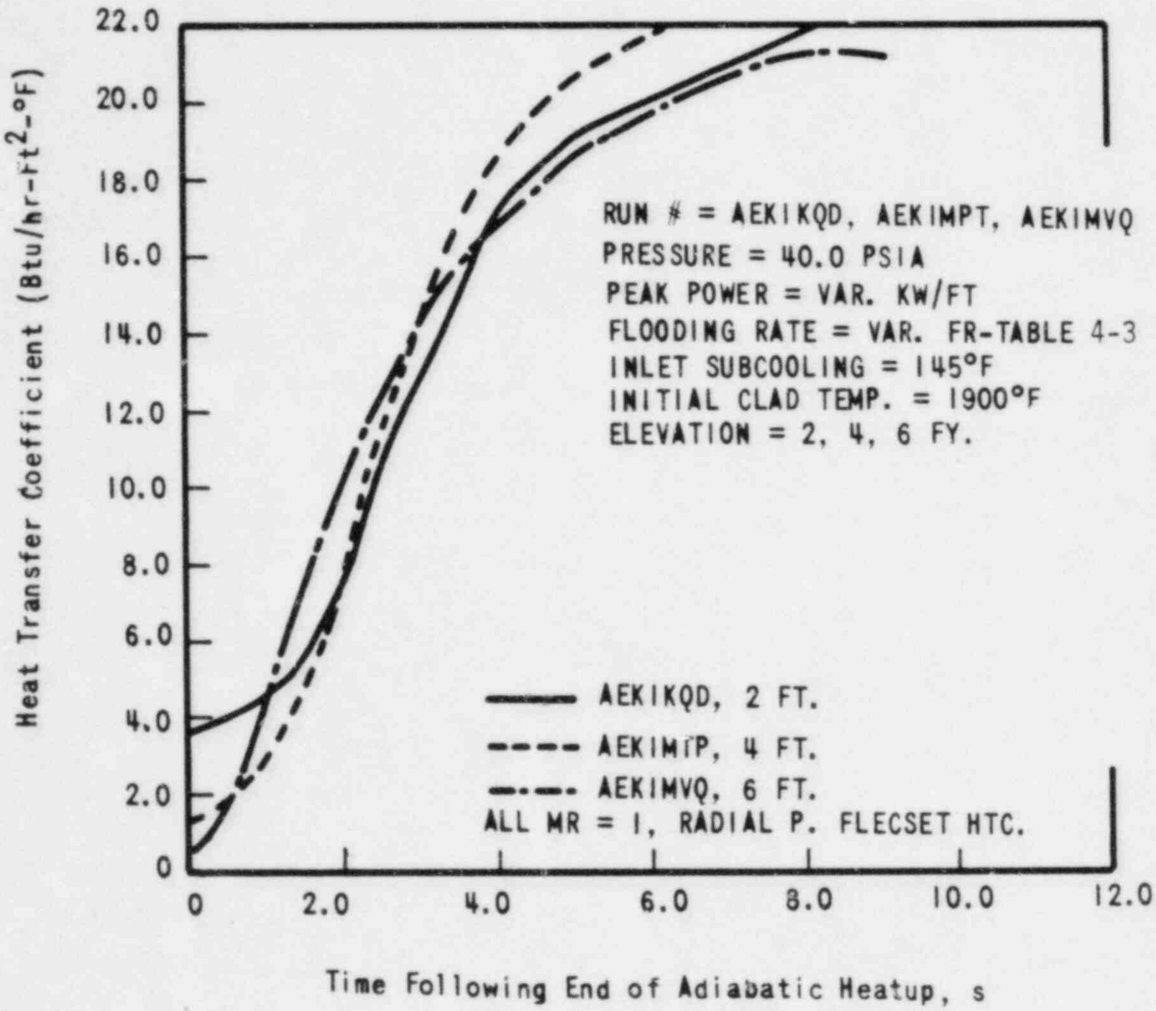


Figure 4-10. Heat Transfer Coefficient Versus Time at 2-, 4-, 6-, 8-, and 10-ft Core Elevations With FLECSET HTC

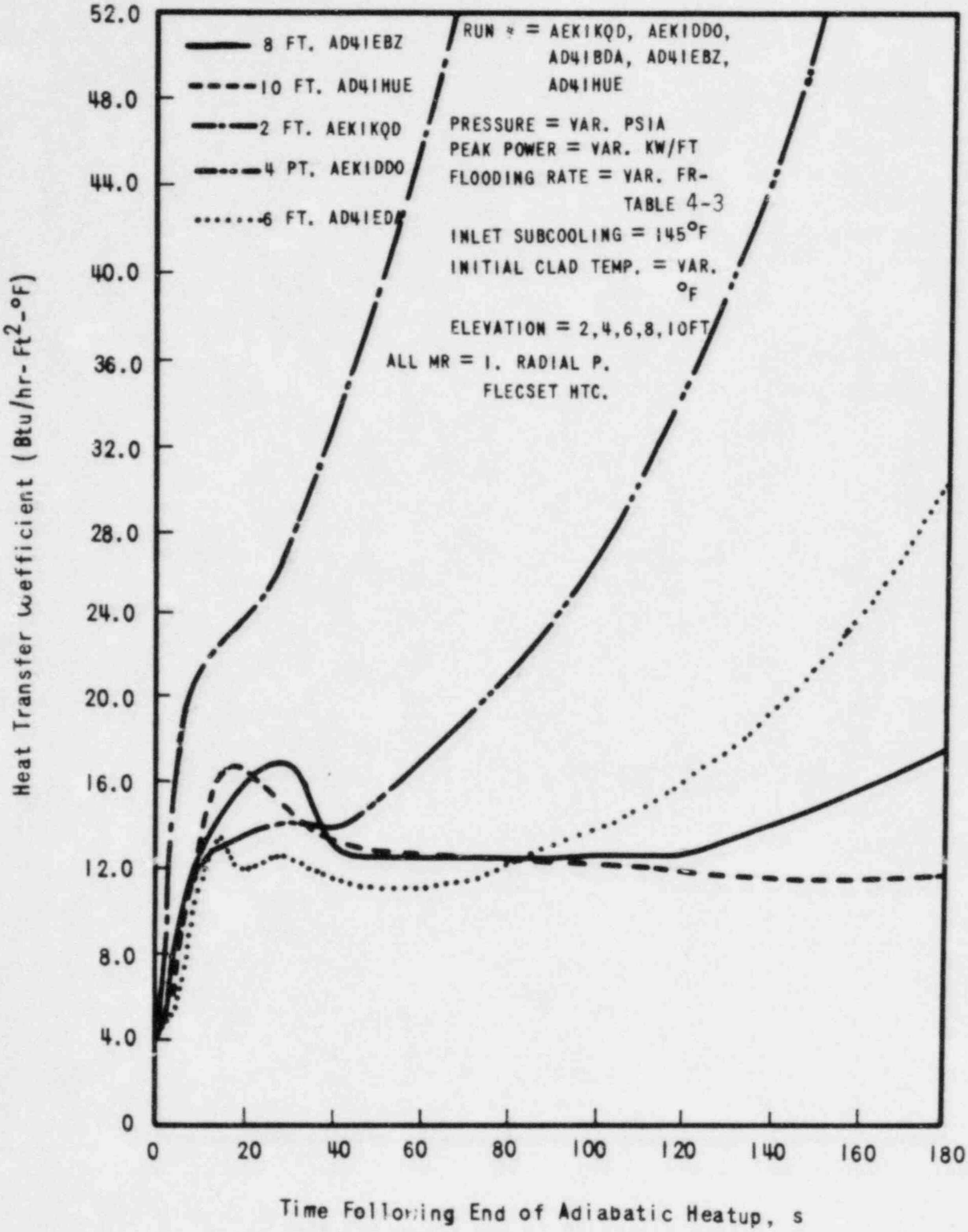


Figure 4-11. Heat Transfer Coefficient Correlation Versus Data, Skewed Power Run 15132

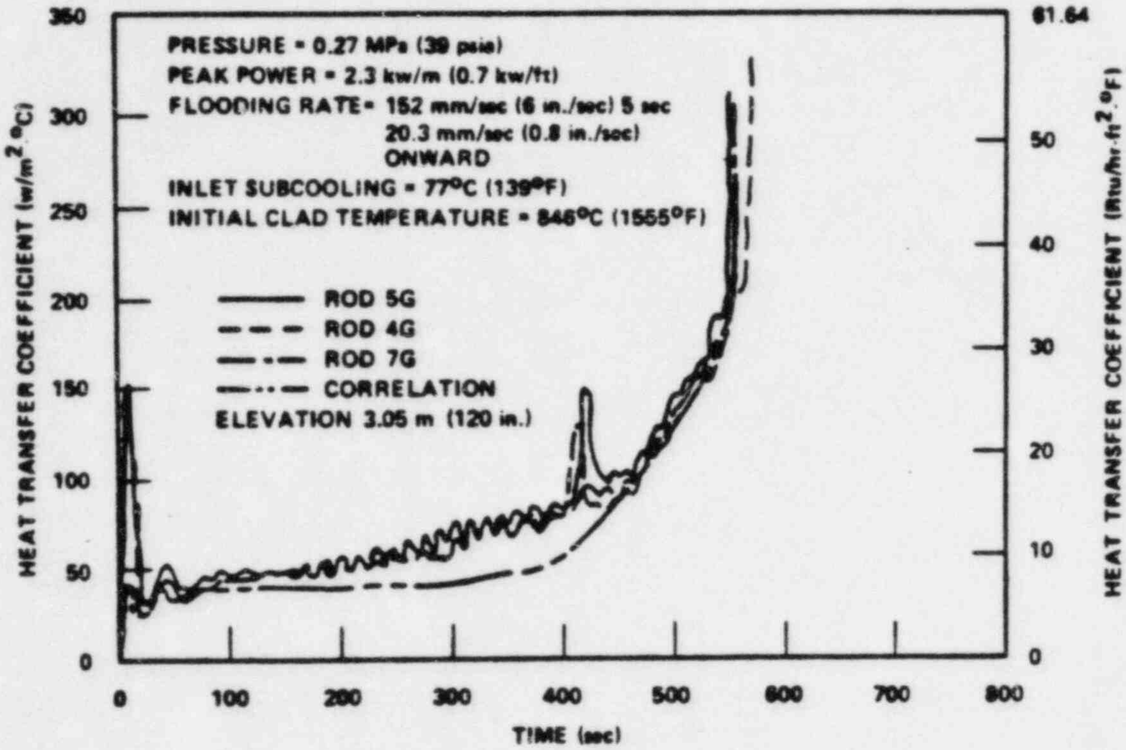


Figure 4-12. Large Break Analyses Code Interfaces

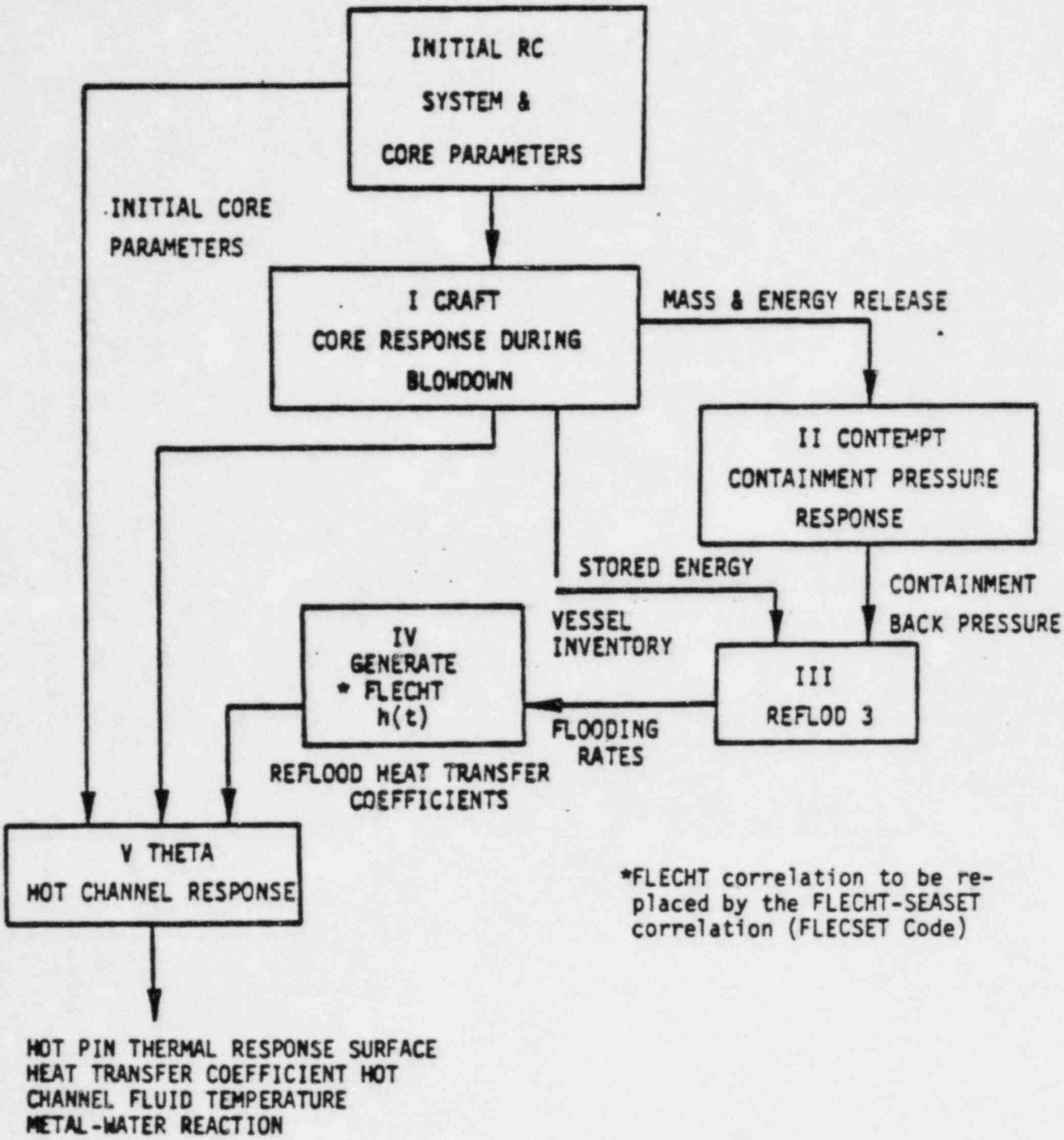


Figure 4-13. LOCA Limits -- Power Shapes

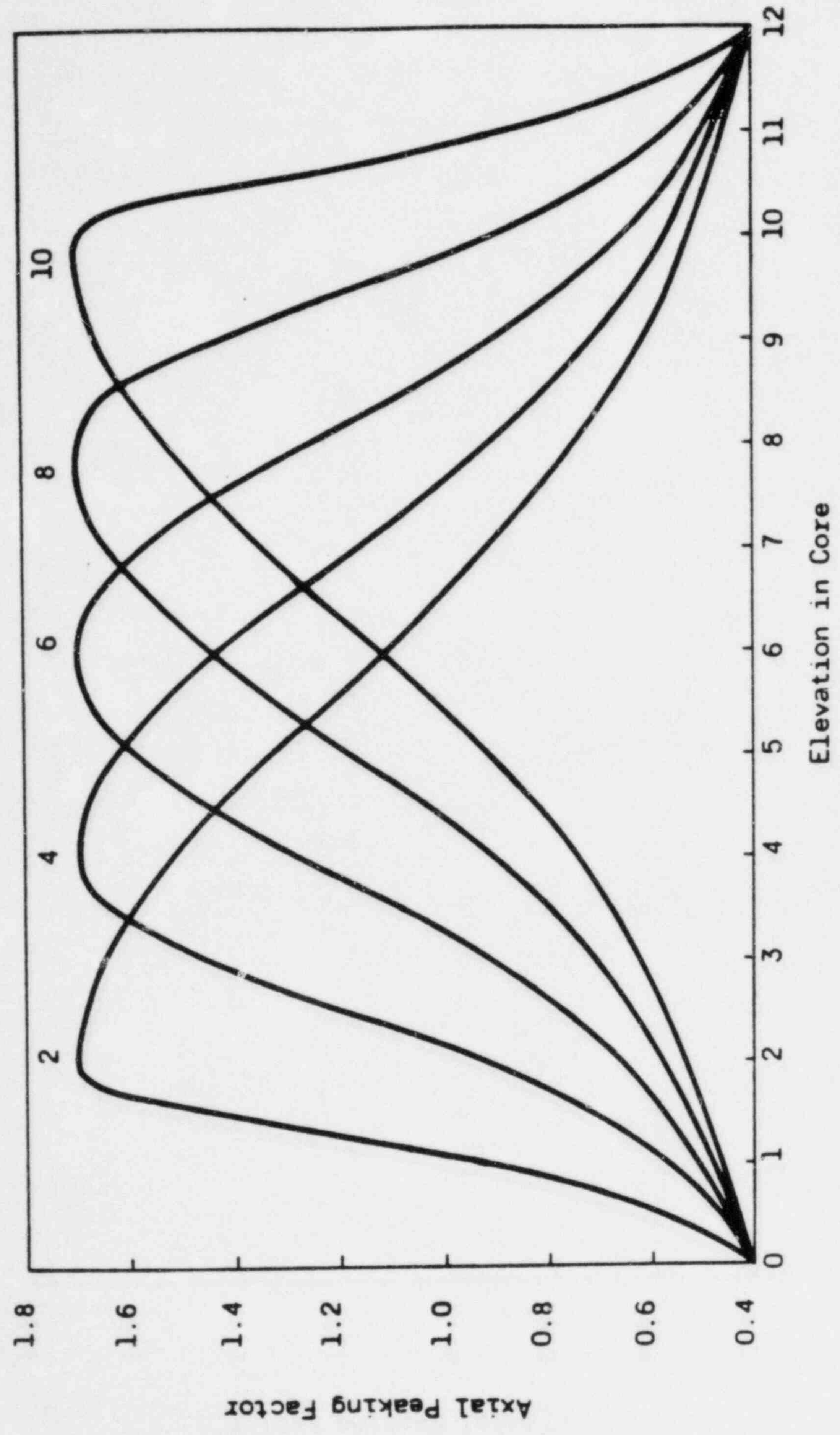
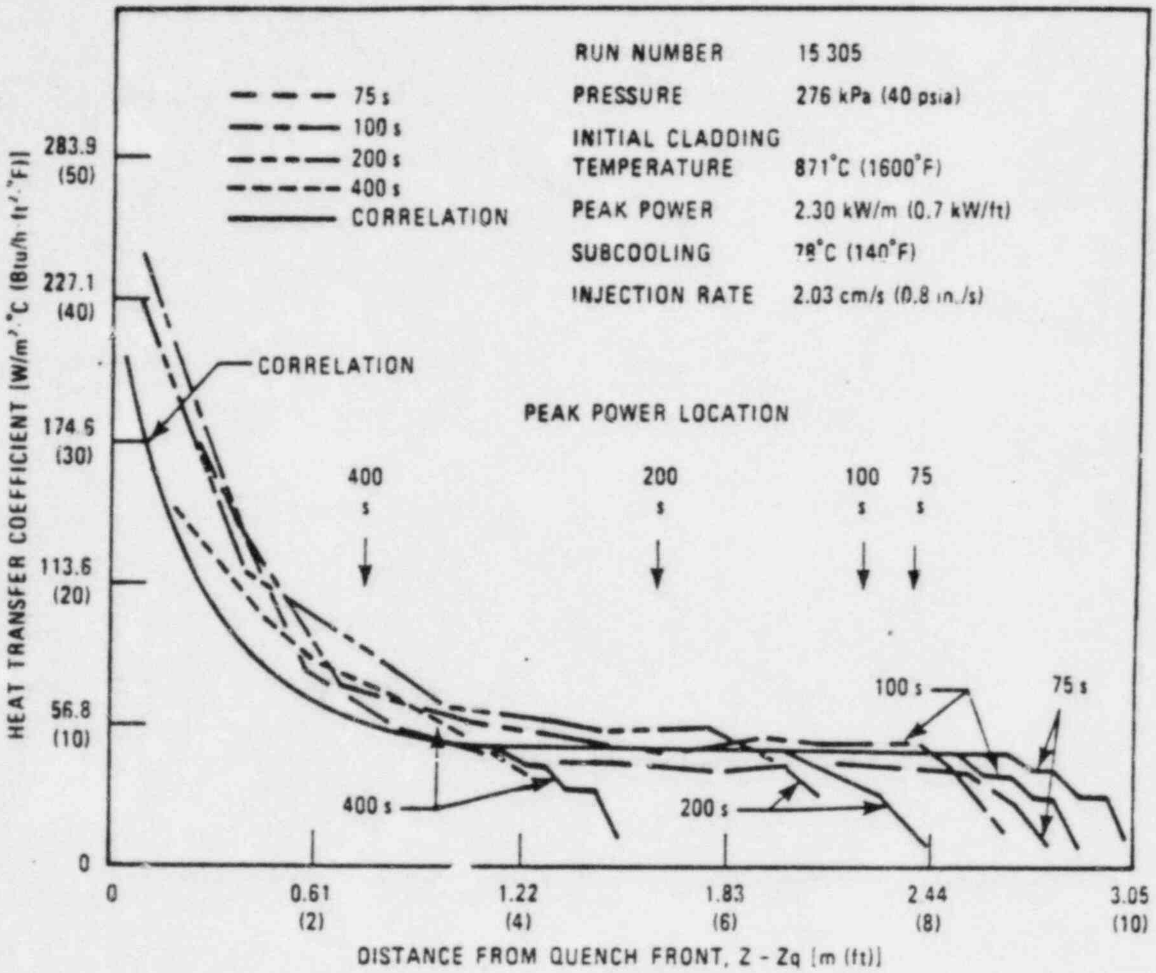


Figure 4-14. Quasi Steady-State Heat Transfer Coefficient Versus Distance From Quench Front for a Skewed Power FLECHT Run 15305

REFLOOD HEAT TRANSFER CORRELATION



5. SENSITIVITY OF PEAK CLAD TEMPERATURE TO REFLOOD HEAT TRANSFER COEFFICIENTS AT THE 2-Ft CORE ELEVATION

A comparison of reflood heat transfer coefficients at the 2-ft core elevation has been performed using FLECKA and FLECSET at the same flooding rate and equivalent peak power of 14.5 kW/ft. Results indicate that the heat transfer coefficients calculated by FLECSET are significantly higher than those predicted by FLECKA for the first 37 seconds following the end of adiabatic heatup, as shown in Figure 5-1. The importance of the higher heat transfer coefficient predicted by FLECSET is shown in Figure 5-2, where the peak cladding temperature predicted by FLECSET[2] is substantially lower and turns around within the first 5 seconds when compared to that calculated with FLECKA heat transfer coefficients. The most critical heat transfer coefficients, as far as the PCT at the 2-ft core elevation is concerned, are those predicted within the first 10 seconds following the end of adiabatic heatup. Thus, the 14.5 kW/ft THETA case, using the heat transfer coefficients generated by FLECSET heat transfer correlation[2], meets the PCT requirements of 2200°F as stated in 10 CFR 50.46. The PCT response of both ruptured and unruptured nodes evaluated at 14.5 kW/ft at the 2-ft core elevation is shown in Figures 5-3 and 5-4, respectively.

Figure 5-1. 2-ft Heat Transfer Coefficients Vs Time Generic LBLOCA Analysis for 177-FA-LL Plants

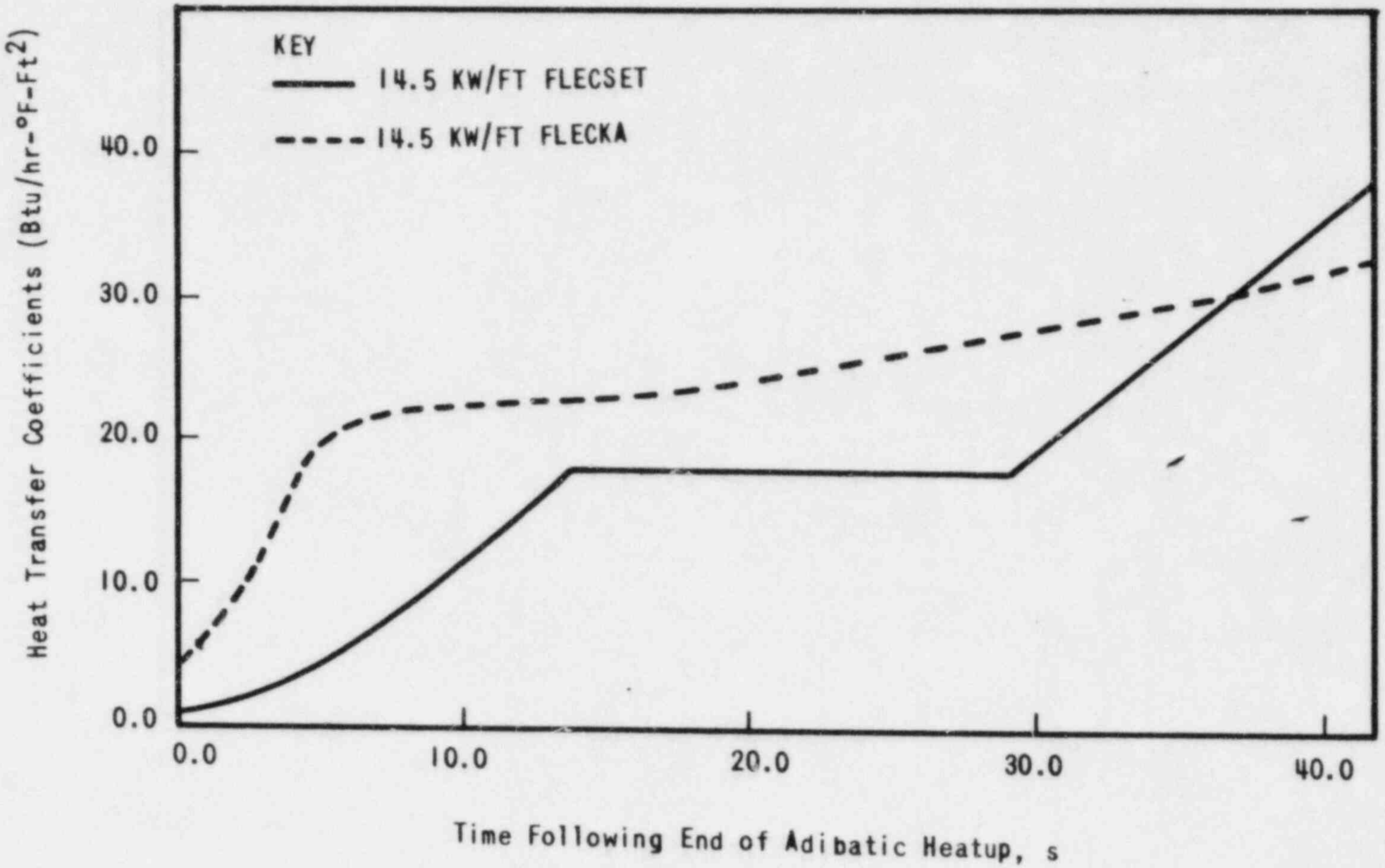


Figure 5-2. Peak Cladding Temperature Versus Time Generic LBLOCA Analysis for 177-FA-LL Plants

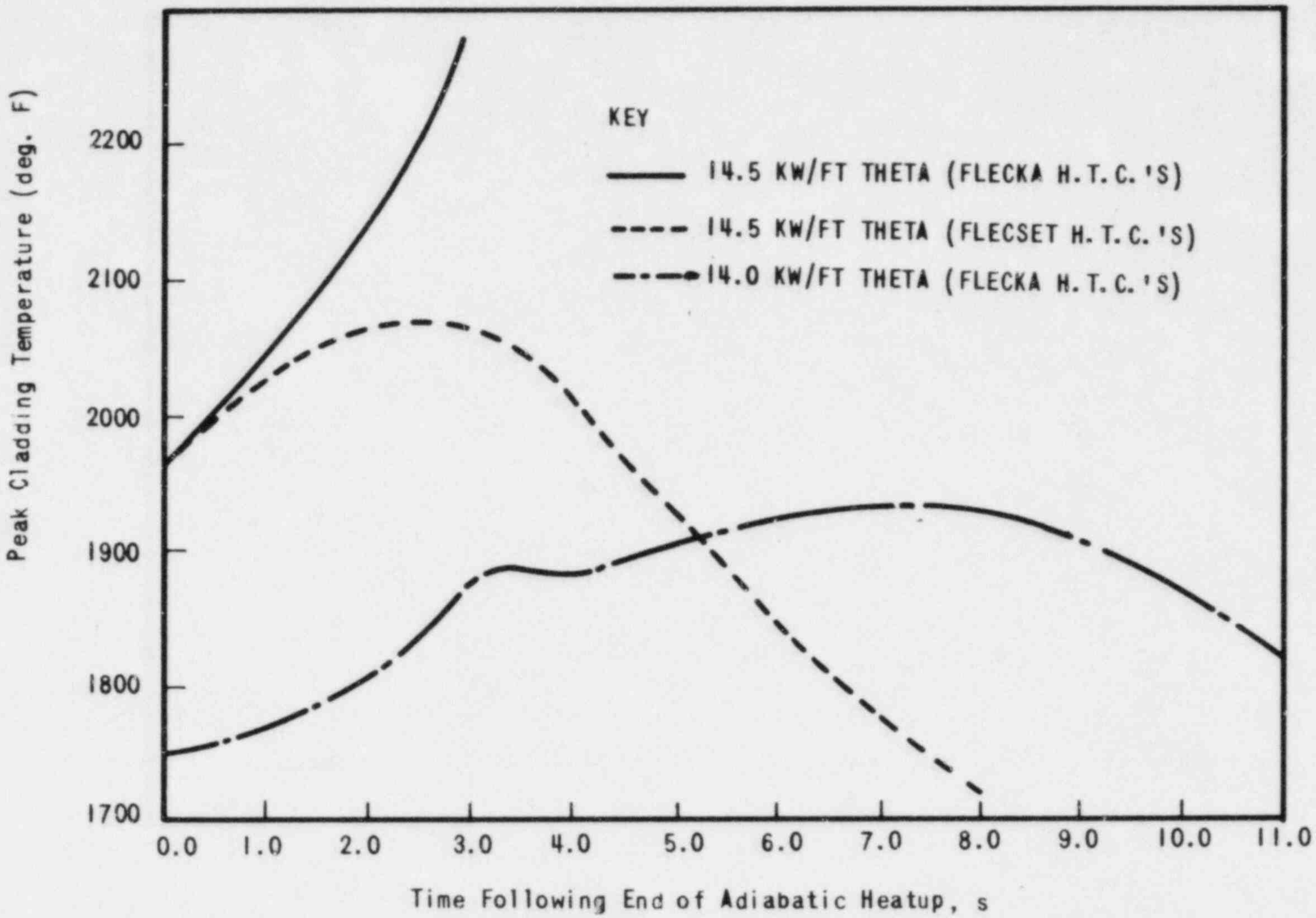
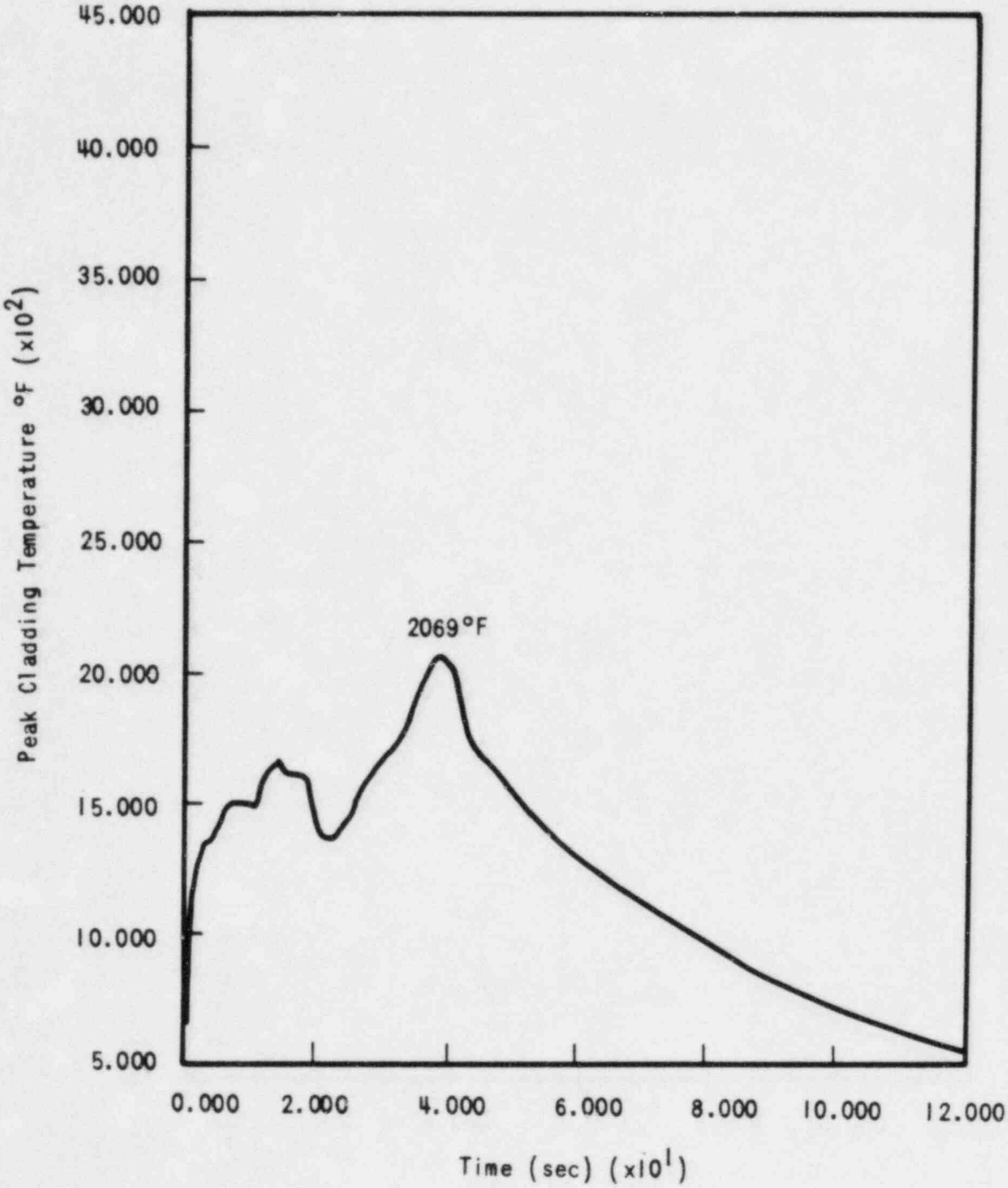
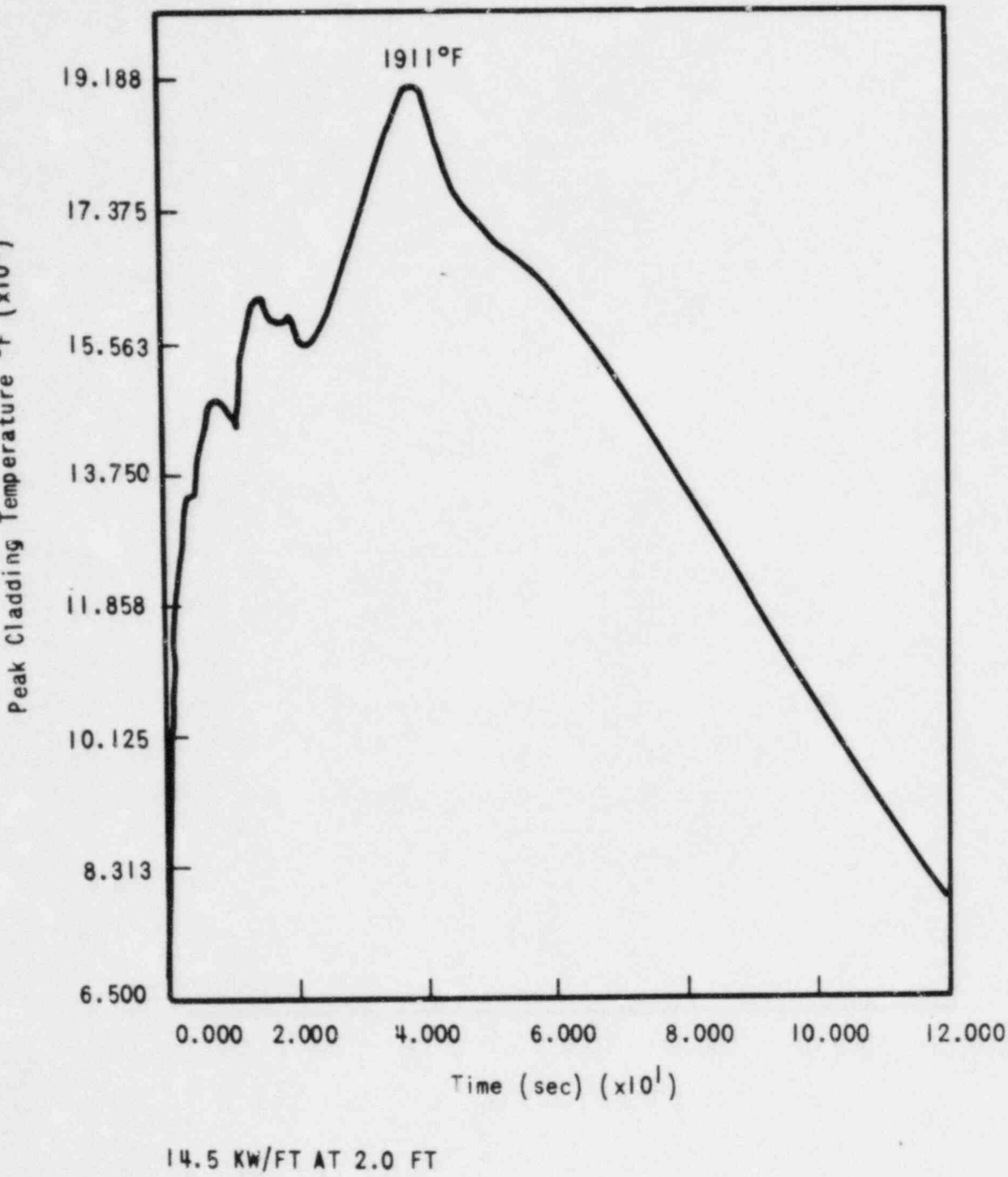


Figure 5-3. Peak Cladding Temperature Versus Time Generic LBLOCA Analysis for 177-FA-LL Plants (ruptured node)



14.5 KW/FT AT 2.0 FT

Figure 5-4. Peak Cladding Temperature Versus Time Generic LBLOCA Analysis for 177-FA-LL Plants (unruptured node)



14.5 KW/FT AT 2.0 FT

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2. N. Lee, S. Wong, H. C. Yeh, and L. E. Hochreiter, "PWR FLECHT SEASET Unblocked Bundle, Forced and Gravity Reflood Task Data Evaluation and Analysis Report, NUREG/CR-2256 (EPRI NI-2013 or WCAP-9891), November 1981.
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6. R. H. Stoudt, et al., THETA1-B - Computer Code for Nuclear Reactor Thermal Analysis, NPGD-TM-405, Rev. L, Babcock & Wilcox, Lynchburg, Virginia, March 1982.
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9. K. C. Heck, et al., "FLECKA, Procedure to Calculate Reflood Heat Transfer Coefficients," NPGD-TM-357, Babcock & Wilcox, March 1976
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11. L. E. Hochreiter, et al., "PWR FLECHT SEASET Unblocked Bundle, Forced and Gravity Reflood Task Data Report," Vol. 2, NUREG/CR-1532 (EPRI-NP-1459 or WCAP-9699), June 1980.

12. B. E. Bingham and K. C. Shieh, REFLOOD - Description of Model for Multinode Core Reflood Analysis," BAW-10093, Babcock & Wilcox, March 1974.

13. H. C. Yeh, et al., "Reflood Heat Transfer Correlation," Nuclear Technology 46, (1979) p. 473.

APPENDIX A

Excerpted From WCAP-9699

This section contains tables and plots used for data comparisons in this report and were originally published in the following report:

FLECHT SEASET Program
NRC/EPRI/Westinghouse Report No. 7
NUREG/CR-1532
EPRI NP-1459
WCAP-9699

PWR FLECHT SEASET
Unblocked Bundle, Forced and
Gravity Reflood Task Data Report

Volume 2, June 1980

Table A-1

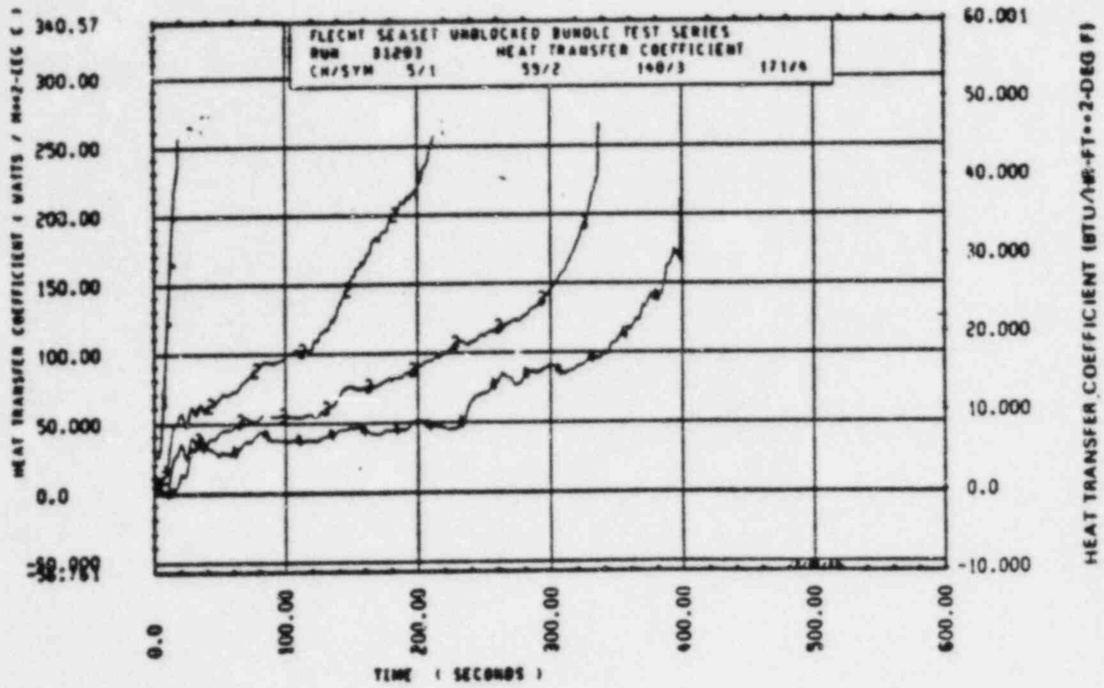
Rod T/C	Elevation, m (in.)	Computer channel
9G	0.305 (12)	2
8N	0.610 (24)	5
9G	0.991 (39)	8
8H	1.22 (48)	13
7J	1.83 (72)	59
8K	1.98 (78)	99
11E	2.29 (90)	124
8K	2.44 (96)	140
11E	2.82 (111)	155
8H	3.05 (120)	163
9G	3.35 (132)	171
8H	3.51 (138)	177

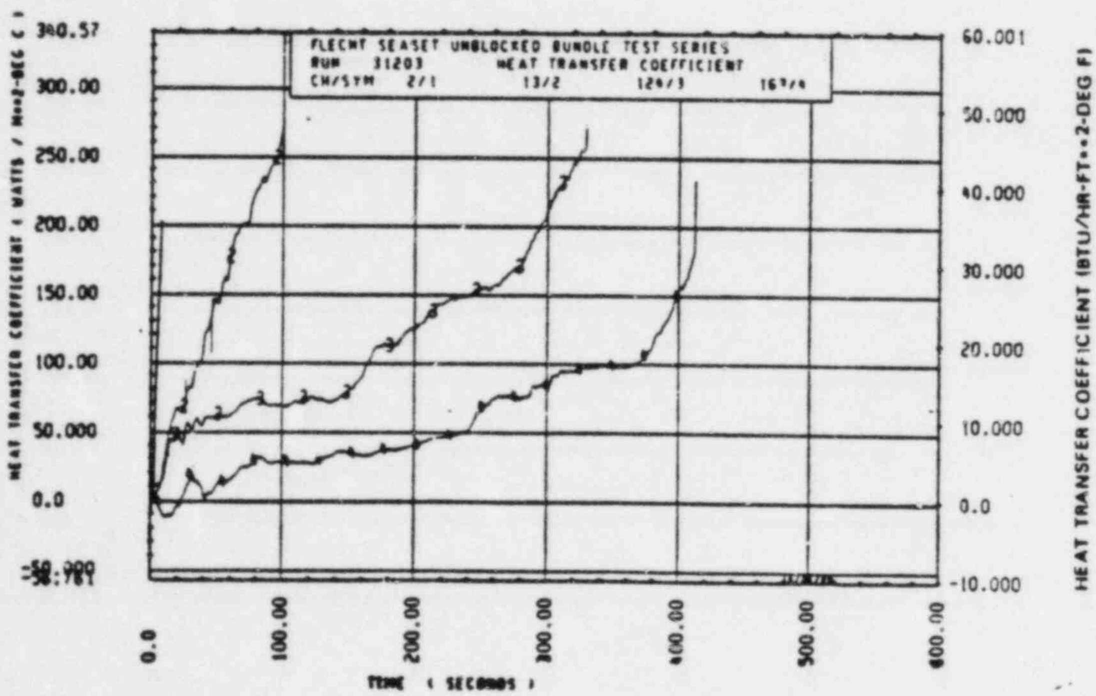
This table provides a legend for interpreting the elevations from the data plots provided in this section.

Table A-2. Run 31203 (3/16/79) Forced Reflood Test

A. Run Conditions

Upper plenum pressure	0.28 MPa (40 psia)
Initial clad temperature at 1.83 m (72 in.) elevation	872°C (1601°F)
Rod peak power	2.3 kW/m (0.70 kW/ft)
Flow rate	38.4 mm/s (1.51 in./s)
Coolant temperature	52°C (126°F)
Bundle radial power profile	Uniform
Disconnected rods	4G, 5G


FLECHT SEASET UNBLOCKED BUNDLE TEST SERIES
RUN 31203 HEAT TRANSFER COEFFICIENT
CH/SYM 5/1 59/2 140/3 171/4
HEAT TRANSFER COEFFICIENT (WATTS / M**2-DEG C)
HEAT TRANSFER COEFFICIENT (BTU/HR-FT**2-DEG F)
TIME (SECONDS)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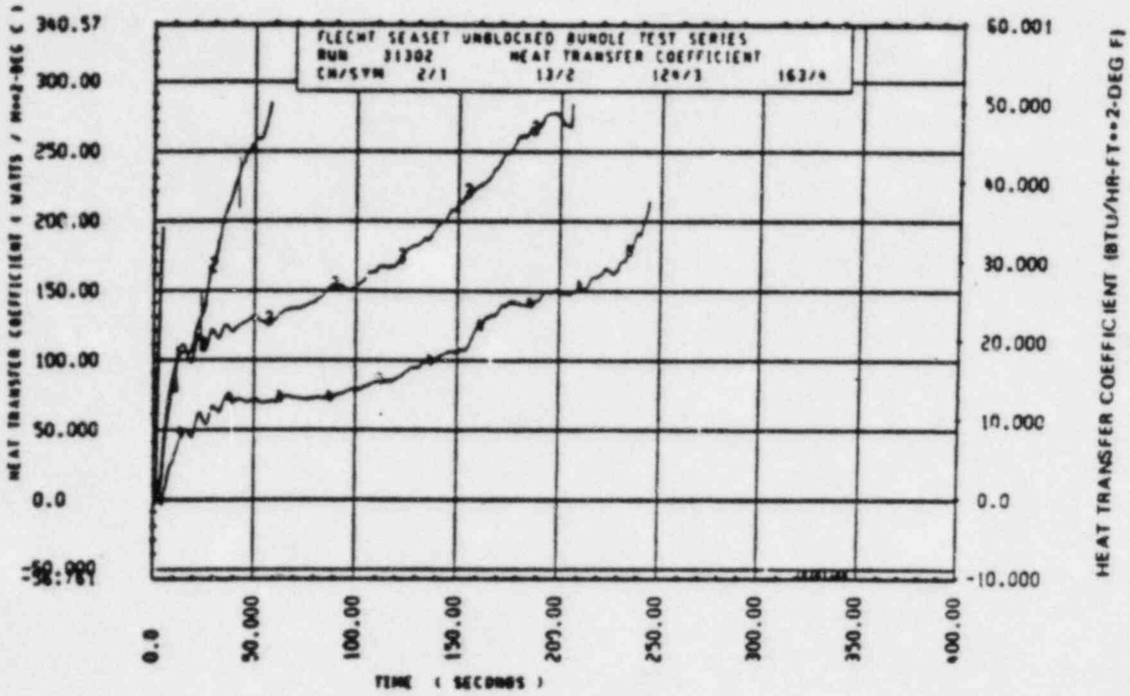
RUN 31203 HEAT TRANSFER COEFFICIENT
HEAT TRANSFER COEFFICIENT (WATTS / M**2-DEG C)
HEAT TRANSFER COEFFICIENT (BTU/HR-FT**2-DEG F)
TIME (SECONDS)

Table A-3. Run 31302 (3/21/79) Forced Reflood Test

A. Run Conditions

Upper plenum pressure	0.28 MPa (40 psia)
Initial clad temperature at 1.83 m (72 in.) elevation	869°C (1597°F)
Rod peak power	2.3 kW/m (0.69 kW/ft)
Flow rate	76.5 mm/s (3.01 in./s)
Coolant temperature	52°C (126°F)
Bundle radial power profile	Uniform
Disconnected rods	4G, 5G, 6J, 11G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RUN 31302 HEAT TRANSFER COEFFICIENT
CH/SYM 2/1 13/2 124/3 163/4
HEAT TRANSFER COEFFICIENT (WATTS / M**2-DEG C)
HEAT TRANSFER COEFFICIENT (BTU/HR-FT**2-DEG F)
TIME (SECONDS)

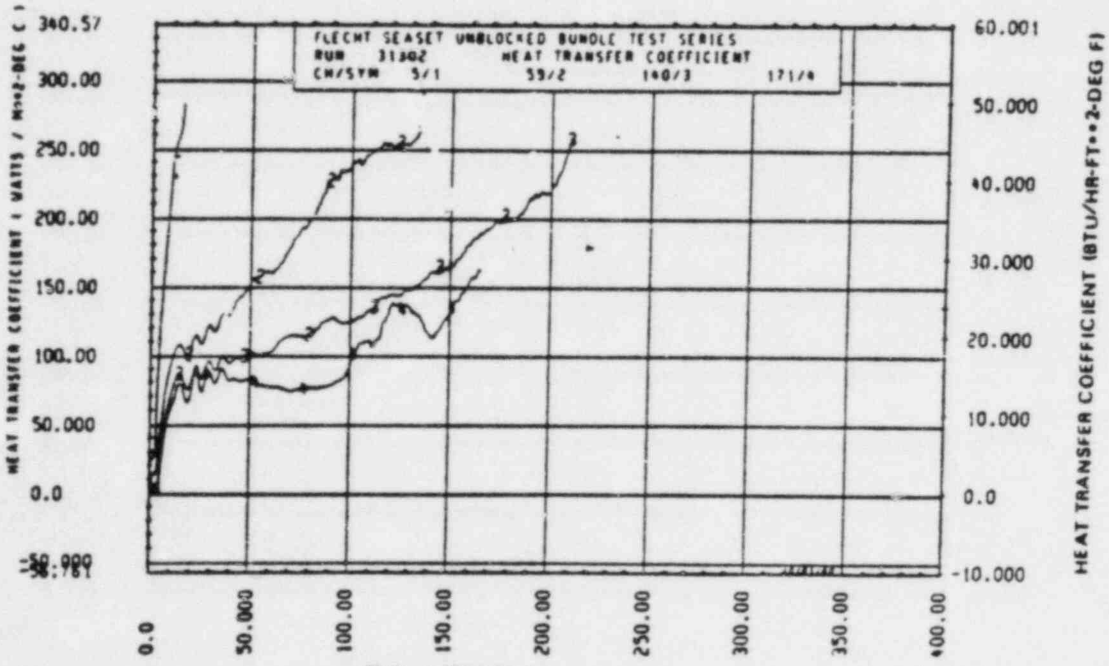
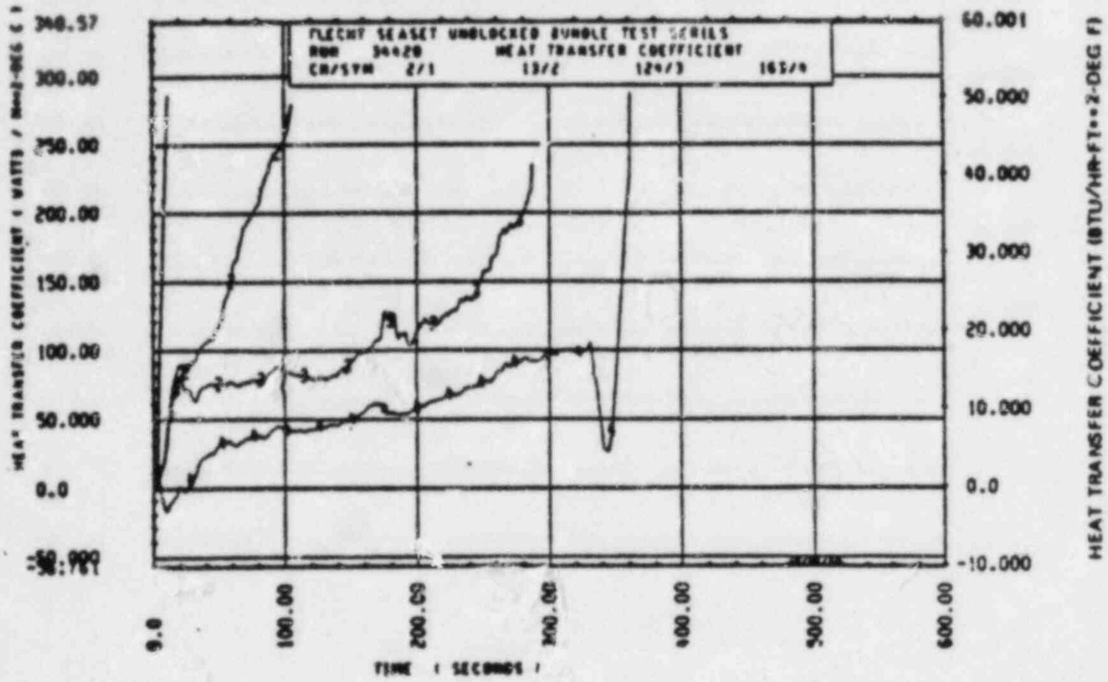

FLECHT SEASET UNBLOCKED BUNDLE TEST SERIES
RUN 31302 HEAT TRANSFER COEFFICIENT
CH/SYM 5/1 55/2 140/3 171/4
HEAT TRANSFER COEFFICIENT (WATTS / M**2-DEG C)
HEAT TRANSFER COEFFICIENT (BTU/HR-FT**2-DEG F)
TIME (SECONDS)

Table A-4. Run 34420 (8/6/79) Forced Reflood Test

A. Run Conditions

Upper plenum pressure	0.27 MPa (39 psia)
Initial clad temperature at 1.83 m (72 in.) elevation	1119°C (2045°F)
Rod peak power	2.4 kW/m (0.74 kW/ft)
Flow rate	38.9 mm/s (1.53 in./s)
Coolant temperature	51°C (124°F)
Bundle radial power profile	Uniform
Disconnected rods	4G, 5G, 11J, 12K, 13JK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RUN 34420 HEAT TRANSFER COEFFICIENT
CH/SYM 2/1 13/2 124/3 165/4
HEAT TRANSFER COEFFICIENT (WATTS / M**2-DEG C)
HEAT TRANSFER COEFFICIENT (BTU/HR-FT**2-DEG F)
TIME (SECONDS)
340.57
300.00
250.00
200.00
150.00
100.00
50.000
0.0
60.001
50.000
40.000
30.000
20.000
10.000
0.0
-10.000
100.00
200.00
300.00
400.00
500.00
600.00

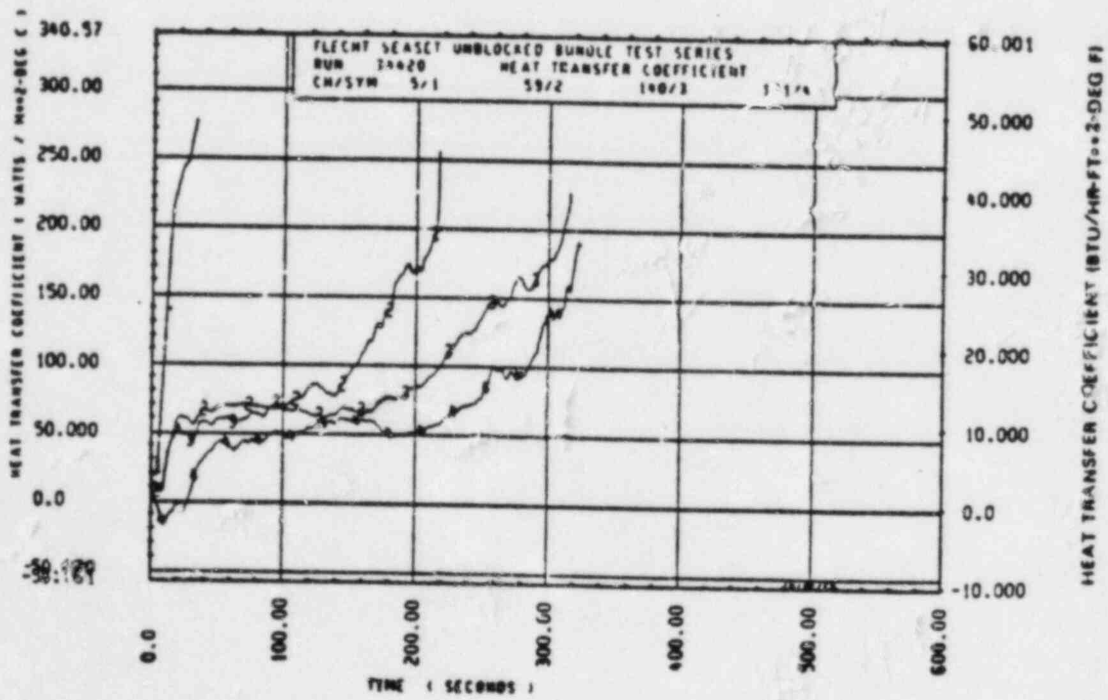
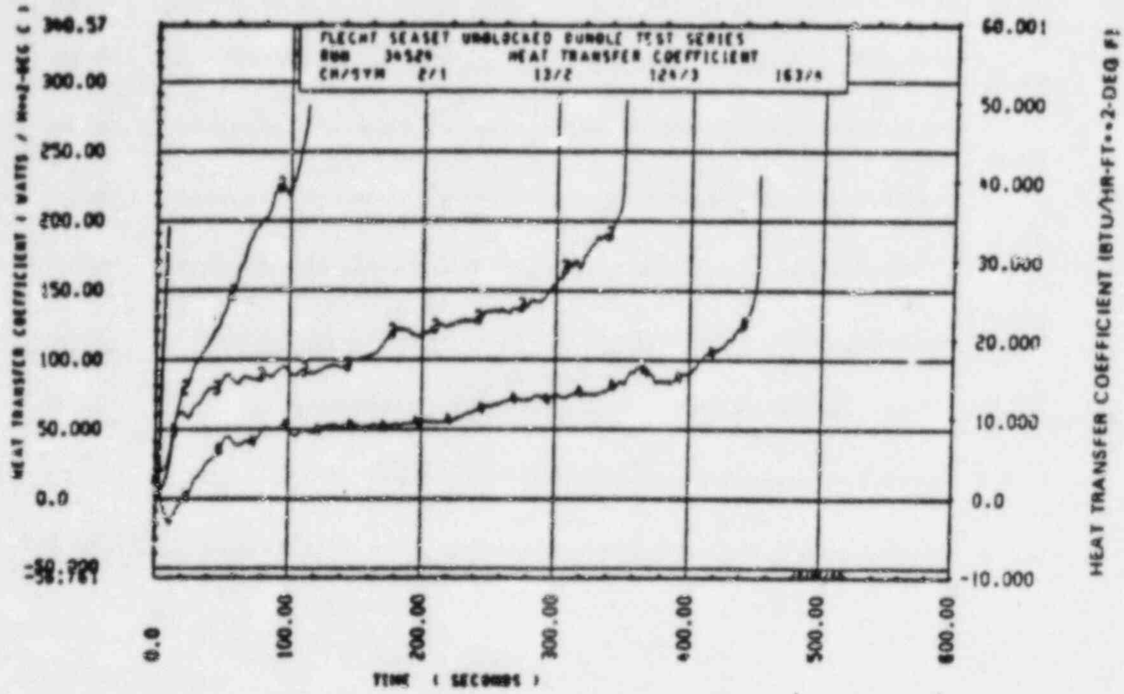

FLECHT SEASET UNBLOCKED BUNDLE TEST SERIES
RUN 34420 HEAT TRANSFER COEFFICIENT
CH/SYM 5/1 59/2 140/3
HEAT TRANSFER COEFFICIENT (WATTS / M**2-DEG C)
HEAT TRANSFER COEFFICIENT (BTU/HR-FT**2-DEG F)
TIME (SECONDS)
340.57
300.00
250.00
200.00
150.00
100.00
50.000
0.0
60.001
50.000
40.000
30.000
20.000
10.000
0.0
-10.000
0.0
100.00
200.00
300.00
400.00
500.00
600.00

Table A-5. Run 34524 (8/7/79) Forced Reflood Test

A. Run Conditions

Upper plenum pressure	0.27 MPa (40 psia)
Initial clad temperature at 1.83 m (72 in.) elevation	878°C (1612°F)
Rod peak power	3.0 kW/m (1.0 kW/ft)
Flow rate	39.9 mm/s (1.57 in./s)
Coolant temperature	52°C (125°F)
Bundle radial power profile	Uniform
Disconnected rods	4G, 5G, 111JK, 121JK, 13JK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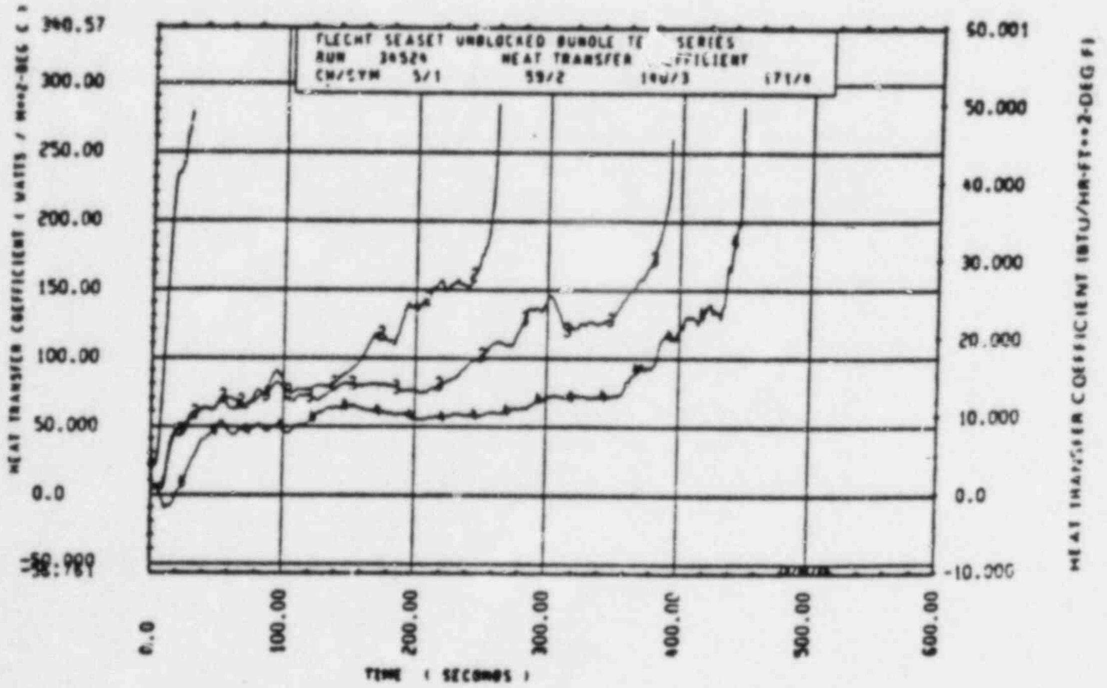
RUN 34524 HEAT TRANSFER COEFFICIENT
CH/SYM 2/1 13/2 124/3 163/4
HEAT TRANSFER COEFFICIENT (WATTS / M**2-DEG C)
HEAT TRANSFER COEFFICIENT (BTU/HR-FT**2-DEG F)
TIME (SECONDS)


FLECHT SEASET UNBLOCKED BUNDLE TEST SERIES
RUN 34524 HEAT TRANSFER COEFFICIENT
CH/SYM 5/1 59/2 140/3 171/4
HEAT TRANSFER COEFFICIENT (WATTS / M**2-DEG C)
HEAT TRANSFER COEFFICIENT (BTU/HR-FT**2-DEG F)
TIME (SECONDS)

APPENDIX B

FLECSET -- A Computer Program to Calculate Heat Transfer Coefficients During Reflooding

CONTENTS

1. INTRODUCTION

The computer program FLECSET calculates the quench time and heat transfer coefficient for cosine as well as skewed power shapes. The calculated heat transfer coefficients can be used to calculate fuel rod surface temperature in computer codes like REFLOD3[2] and UPIFLOD[3] which calculate the primary system behavior during the refill and reflood phases of a postulated loss-of-coolant accident (LOCA). These correlations were developed by Lee, Wong, Yeh and Hochreiter[1] by modifying the correlations of Yeh and Lilly and reformulating them in dimensionless form to provide better agreement with the FLECHT as well as the FLECHT SEASET tests.

2. HEAT TRANSFER CORRELATION

The original heat transfer correlation of Yeh and Lilly[5,6] was derived based on the concept that the heat transfer coefficient is primarily a function of the distance from the quench front, and the basis of this concept has been explained in detail. The correlation predicts the quench time and the heat transfer coefficient quite well for the FLECHT cosine power tests and the skewed power tests with the 15x15 assembly rod bundle. However, the correlation is not in dimensionless form; therefore, it is not general enough to be applicable to other rod bundle geometries such as the 17x17 assembly rod bundle of the FLECHT SEASET tests.

Lee et al.[1] reformulated the correlation of Yeh and Lilly in dimensionless form and modified it to provide better agreement with the data of the 15x15 FLECHT cosine power tests and skewed power tests as well as with the data of the 17x17 FLECHT SEASET tests.

This correlation, like its predecessor, consists of two subcorrelations:

— Quench correlation, which predicts the quench front elevation as a function of time

— Heat transfer coefficient correlation, which predicts the heat transfer coefficient as a function of the distance from the quench front, $Z-Z_q$

The heat transfer coefficient can be computed as a function of time by using the quench correlation, which bridges the space variable Z_q and the time variable t. The correlations given in this section are obtained from Reference 1 except that they are corrected for errors as given in Reference 4.

2.1. QUENCH CORRELATION

The original quench correlation has been modified and reformulated by Lee et al.[1] in dimensionless form as follows:[(a)]

$$\frac{t_q V_{in}}{Z_q} = 1 + \frac{\frac{t_{q,peak} V_{in}}{Z_q}\left(Q_r + 0.5\, Q_r e^{-9\, Q_r^2}\right) - 1}{1 + 50^{**}\left(\frac{T_{init\,q} - T_o}{T_o - T_{sat}}\right)} \tag{2-1}$$

where

$$Q_r = \int_0^{Z_q} Q'(Z)\, dZ \bigg/ \int_0^{Z_{peak}} Q'(Z)\, dZ \tag{2-2}$$

$Q'(Z)$ = linear power at elevation Z of one rod [j/sec-m (Btu/sec-ft)]

Z_q = quench elevation [m (ft)]

Z_{peak} = peak power elevation [m (ft)]

t_q = quench time at elevation Z_q (sec)

V_{in} = flooding rate [m/sec (ft/sec)]

T_o = 204°C (400°F)

T_{sat} = saturation temperature [°C (°F)]

a. Whenever confusion is likely to occur, exponentiation is indicated by**.

$$T_{init,q} = (T_{init} - T_{sat}) \frac{Q'(Z_q)}{Q'(Z_{peak})} + T_{sat}, \quad [^oC\ (^oF)]$$

T_{init} = cladding temperature at peak power elevation at beginnng of flood [^oC (^oF)]

and $t_{q,\ peak}$ is the quench time at the peak power elevation which is given by

$$\frac{t_{q,\ peak} V_{in}}{Z_{q\ peak}} = 0.00019 Re\ (\rho_g/\rho_f)^{-0.262} [F_{t1} (F_{t2} + F_{t3} + F_{t4}) + F_{t5}]$$

$$\cdot (F_{t6} - F_{t7}) F_{t8} \qquad (2\text{-}3)$$

where

$$F_{t1} = \exp[-10.09 (C_{pf}\ \Delta T_{sub}/h_{fg})] \Big[6.458(10^{-5})$$

$$Re^{1.938}/(\rho_g/\rho_f)^{0.5078} (G_G\ D_{rod}/Z_{peak})^{1.5}$$

$$-0.7 \{1 - \exp[-0.0000801\ Re/(\rho_g/\rho_f)^{0.262}]\}\Big]$$

$$F_{t2} = 1 + 0.5 \exp[-5.6251 (10^8)(\rho_g/\rho_f)^3]$$

$$F_{t3} = 1.3 \exp[-1.652 (10^{-9}) Re^2/(\rho_g/\rho_f)^{0.524}]$$

$$F_{t4} = 17.3 \exp[-5.6251 (10^8) (\rho_g/\rho_f)^3]$$

$$\exp[-7.293(10^{-9}) Re^2/(\rho_g/\rho_f)^{0.524}]$$

$$F_{t5} = 66203(\rho_g/\rho_f)^{0.2882}/Re^{1.1}$$

$$-2.8 \exp[-0.000122\ Re/(\rho_g/\rho_f)^{0.262}] F_{t2}$$

$$F_{t6} = 1.01552 + 0.01388\ C_T$$

$$F_{t7} = 1.05 \exp(-0.66 - 0.59\, C_T) \{1 + 0.5/[1 + 50^{**} (2 - 8.137 (10^{-5})\, Re/(\rho_g/\rho_f)^{0.262})] \} \quad [FP4]$$

$$F_{P4} = 1.0 + 0.32 / [1.0 + 50.^{**} (5.0 - 2520 \cdot \rho_g/\rho_f)]$$

$$F_{t8} = F_{t81} F_{t82}$$

$$F_{t81} = 0.3 + 0.7 \{1 - \exp[-10.31(10^{-8})\, Re^2/(\rho_g/\rho_f)^{0.524}] \} - 2.9 (10^{-11})\, Re^3 (\rho_g/\rho_f)^{-0.786} \exp[-9.3 (10^{-8})\, Re^2/(\rho_g/\rho_f)^{0.524}] / \{1 + 50^{**} [-15.75 (C_{pf}\, \Delta T_{sub}/h_{fg}) + 1.333] \}$$

$$F_{t82} = 1 - 0.16/[1 + 70^{**}\ 1250 (D_{rod}/Z_{peak}) - 5.45] / [1 + 80^{**} (7.14\, C_Q - 4.93)]$$

$$C_Q = \int_0^{Z_{peak}} Q(Z)\, dZ \Big/ (\rho_f A_f V_{in} h_{fg})$$

$$C_T = (T_{init} - T_{sat}) / (T_{Lei} - T_{sat})$$

ρ_f = water density [kg/m^3 (lbm/ft^3)]

D_{rod} = rod diameters [m (ft)]

A_f = flow area formed by four adjacent rods [m^2 (ft^2)]

h_{fg} = latent heat of evaporation [kcal/kg (Btu/lbm)]

T_{Lei} = Leidenfrost temperature = 260°C (500°F)

ΔT_{sub} = inlet subcooling [°C (°F)]

The rationale and the method of deriving equations (2-1) and (2-3) are as follows. In the early FLECHT correlation,[6] the quench time was predicted only for the peak power elevation, which is 1.83 m (72 in.) for the cosine power shape. In the later version[5,7] and the present version of the FLECHT correlation, since the concept of the heat transfer coefficient h being a function of the distance from the quench front Z-Zq was used, it is necessary to have a correlation which is able to predict the quench time for all elevations. Since the early FLECHT correlation predicts the quench time at the peak power elevation quite well, it is used as a base correlation in the later and the present versions [equation (2-1], which is denoted by $t_{q,\ peak}$; the quench time of the other elevations is predicted by adjusting $t_{q,\ peak}$ with the integral of power Q_r as expressed in equation (2-1).

In the above correlation, the quench time, t_q, is given as a function of the quench elevation, Z_q. In practice, it is necessary to compute the quench elevation as a function of time. This can be accomplished by first computing the quench front velocity, V_q, for a given time t by

$$V_q = \frac{(Z_q + \Delta Z_q) - Z_q}{t_q(Z_q + \Delta Z_q) - t_q(Z_q)} \qquad (2-4)$$

where $t_q\ (Z_q + Z_q)$ and $t_q\ (Z_q)$ are the quench times computed from equation (8-1). The quench front elevation at the time $t + \Delta t$ is then computed by

$$Z_q(t + \Delta t) = Z_q(t) + V_q\ \Delta t \qquad (2-5)$$

This method of computing the quench elevation as function of time is also valid for variable flooding rates. Note that, for the variable flooding rate case, the actual time t is different from t_q.[5,7]

It is noted that the power per flow area is preserved in the above correlation through the parameter C_Q. It is also noted that through the use of dimensionless quench time, $t_q V_{in}/Z_q$, the length effect (originally f- factor[5,7] has been taken care of automatically.

The above quench correlation has been compared with the data of the FLECHT SEASET unblocked test series as well as with the data of the 15x15 FLECHT cosine power test series and skewed power test series by Lee et al.[1] In particular, the overlap runs of these three test series have been compared. The overlap tests are the runs which have the same test conditions and the same total energy (the integral of power plus the stored energy) below the peak power elevations, so that the quench time at the peak power elevation is about the same. All these comparisons show that the quench time at the peak power elevation is about the same in each set of the overlap runs, and that the predicted quench times are in good agreement with the data. They also showed that the present correlation is in better agreement with data than the previous correlations.

2-2. HEAT TRANSFER COEFFICIENT CORRELATION

As in all previous FLECHT reports, the heat transfer coefficient is defined as

$$h = q_{total}/(T_{rod} - T_{sat})$$

where

q_{total} = rod total surface heat flux, which includes radiation and convection

T_{rod} = rod surface (cladding) temperature

T_{sat} = saturation temperature

The present heat transfer coefficient correlation is divided into four parts instead of three parts:[5]

-- Radiative Heat Transfer period

The radiative heat transfer period exists only for the case of low initial cladding temperature. For low initial cladding temperature, there is practically no vapor generation at the beginning of flood because the rods are cold at the lower elevation. Therefore the heat transfer during this period is essentially radiative heat transfer.

-- Early developing period

This period extends from the end of the radiative heat transfer period to the time when the heat transfer reaches a quasi-steady state (figure 2-1). During this developing period, the heat transfer mechanism changes from the radiation-dominated prereflood condition to single-phase steam flow. The mechanism then changes to dispersed flow when the steam velocity becomes great enough to carry droplets up the bundle.

-- Quasi-steady period

During this period the heat transfer is essentially in a quasi-steady state. This means that the heat transfer pattern moves with the quench front; that is, the heat transfer coefficient versus the distance from the quench front is essentially unchanged with time.

-- Heat transfer coefficient above peak cladding temperature elevation

Because the situation above the peak cladding temperature elevation is different from that below the peak cladding temperature elevation, it must be treated separately. Above the peak cladding temperature elevation, the steam temperature may be greater than the cladding surface temperature, and the heat may be transferred from the steam to heater rods. The FLECHT definition of heat transfer coefficient, saturation temperature equal to sink temperature, implies that the heat transfer coefficient is negative. Below the peak cladding temperature elevation, the steam temperature never becomes greater than the cladding surface temperature. Therefore the heat transfer coefficient never becomes negative.

The transition between the radiative heat transfer period and the developing period occurs when Z_q is equal to Z_{ad}, and the transition between the developing period and the quasi-steady period occurs when Z_q is equal to $Z_{ad} + \Delta Z_s$, where Z_{ad} and ΔZ_s are computed from the following formulas.

The expression of the four-part heat transfer coefficient is as follows:

-- Radiative heat transfer period ($Z_q < Z_{ad}$)

$$h \equiv h_1 = C \frac{Q'(Z)}{(\rho C_p A)_{rod}} \left[1 - \exp\left(- \frac{T_{initz} - T_{ro}}{\Delta T_r} \right) \right] \qquad (2-6)$$

where Z_{ad} is computed from the following dimensionless expression:

$$1 = 0.852 \frac{(\rho C_p A)_f \, \Delta T_{sub} V_{in}}{Q'_{max} Z_{ad}} - 0.234 \frac{(\rho C_p A)_{rod} (T_{init} - T_{sat}) V_{in}}{Q'_{max} Z_{ad}} + \frac{Z_o}{Z_{ad}} F_h \qquad (2-7)$$

and

C = $\left[36745 \text{ j}/^{o}C^2/m^2 (0.215 \text{ Btu}/^{o}F^2/ft^2)\right] / 3600.0$

$(\rho C_p A)_{rod}$ = heat capacity of a rod [j/m-°C (Btu/ft-°F)]

T_{initz} = $(T_{init} - T_{sat}) \dfrac{Q'(Z)}{Q'(Z_{peak})} + T_{sat}$ [°C (°F)]

T_{ro} = 371 °C (700°F)

ΔT_r = 224°C (435°F)

$(\rho C_p A)_f$ = heat capacity of water in a channel formed by four adjacent rods [j/m-°C (Btu/ft-°F)]

Z_o = 0.3496 m (1.147 ft)

h = heat transfer coefficient [j/sec-°C-m^2 (Btu/sec-°F-ft^2)

F_h = $1/\left\{1 + 70^{**} \left[1 - 0.0133 (Z_{peak}/D_{rod})\right]\right\}$

It is noted that the radiative heat transfer coefficient h_1 given by equation (2-6) is mainly due to the radiative heat exchange between the rod of interest and its neighboring thimble and rods. Therefore, h_1 depends on the temperature difference between the

rods and the neighboring thimbles. The temperature difference depends on the pre-reflood heatup rate. For example, if the pre-reflood heatup rate is very slow, then the radial temperature will be essentially uniform and the temperature difference practically zero, so that h_1 is also zero. The faster the heatup rate, the larger the temperature difference and hence the larger the h_1. This mechanism has been discussed in great length in WCAP-7931.[3] The heatup rate is proportional to the local power $Q''(Z)$ and is inversely proportional to the heat capacity $(\rho C_p A)_{rod}$ of the rod. This leads to the expression of equation (2-6).

-- Developing period ($Z_{ad} < Z_q < Z_{ad} + \Delta Z_s$)

$$Nu = Nu_1 [1 - \exp(2.5x - 10)] + \{Nu_2 - Nu_1 [1 - \exp(2.5x - 10)]\}$$

$$(1 - e^{-x} - 0.9\, x e^{-x^2}) \qquad (2-8)$$

where $Nu = h D_{rod}/k_g$. When $Z_q = Z_{ad} + \Delta Z_s$, the heat transfer changes from the developing period to the quasi-steady period, where ΔZ_s is computed from

$$\frac{\Delta Z_s}{V_{in} \rho_f C_{p_f} D_e^2/k_f} = 6329 (Re + 4000)^{-1.468} F_h \qquad (2-9)$$

Other parameters are computed as follows:

$$Nu_2 = Nu_3 + 108 \exp[-1.83(10^{-5}) Re/(\rho_g/\rho_f)^{0.262}]$$

$$\exp[-0.0534 (Z - Z_q)/D_e] \qquad (2-10)$$

Nu_1 and Nu_3 are computed by first calculating h_1 and h_3, respectively, then using the definition of the Nusselt number as follows:

h_1 = from equation (8-6)

$Nu_1 = h_1 D_e/k_g$

$$\frac{h_3(T_{eff,Z} - T_{sat}) D_{rod}}{Q'_{eff,Z}} = 1.21 \left\{ 1 - \exp\left[-3.05(10^{-5}) Re(\rho_g/\rho_f)^{-0.262}\right]\right\}$$
$$\left\{0.714 + 0.286 \left[1 - \exp(-3.05(10^{-4})(\rho_g/\rho_f)^{1.524} Re^{-2})\right]\right\} \quad (2\text{-}11)$$

$$Nu_3 = h_3 D_e/k_g$$

The other parameters in the above correlation are

$$\Delta T_{eff} = \Delta T_c \Bigg/ \left\{1 + 60^{**}\left[1.08\left(\frac{T_{init} - T_{sat}}{\Delta T_c}\right) - 1.26\right]\right\}$$

$$\Delta T_c = 427^\circ C\ (800^\circ F)$$

$$T_{eff} = T_{init} + \Delta T_{eff}$$

$$T_{eff,Z} = T_{sat} + (T_{eff} - T_{sat}) \frac{Q'(Z_q)}{Q'(Z_{peak})}$$

$$x = 4(Z_q - Z_{ad})/\Delta Z_s$$

D_e = hydraulic diameter of channel formed by four adjacent rods [m (ft)]

ρ_f = density of water at saturation temperature [kg/m^3 (lbm/ft^3)]

ρ_g = density of steam at saturation temperature [kg/m^3 (lbm/ft^3)]

C_{pf} = specific heat of water at saturation temperature [j/kg-$^\circ$C (Btu/lbm-$^\circ$F)]

k_f = conductivity of water at saturation temperature [j/sec-$^\circ$C-m (Btu/sec-$^\circ$F-ft)]

Q'_{eff} = 2297 w/m = 2297 j/sec-m (0.7 kw/ft)

$Q'_{eff,Z}$ = $Q'_{eff}\, Q'(Z_q)/Q'(Z_{peak})$

k_g = conductivity of steam at saturation temperature [j/sec-^oC-m (Btu/sec-^oF-ft)]

D_{rod} = rod diameter [m (ft)]

Re = $\rho_f V_{in} D_e/\mu_f$

-- Quasi-steady period ($Z_q > Z_{ad} + \Delta Z_s$)

$Nu = Nu_2$

-- Above peak elevation ($Z > Z_{peak}$)

$$Nu = Nu_4 - 44.2\left[1 - \frac{Q'(Z)}{Q'(Z_{peak})}\right]\exp\left[-0.00304\,(Z - Z_{peak})/D_e\right]$$

where $Nu_4 = Nu_1$ for radiative heat transfer period, Nu_4 = equation (2-8) developing period, and $Nu_4 = Nu_2$ for quasi-steady period.

It should be noted that, in the above correlation, all expressions are in dimensionless forms except equation (2-6), which is primarily due to the radiation. Therefore consistent units must be used.

The above correlations are valid over the following range of parameters:

Pressure (P)	103 - 414 kPa (15 - 60 psia)
Inlet subcooling (ΔT_{sub})	9^oC - 78^oC (16^oF - 140^oF)
Initial temperature (T_{init})	149^oC - 1204^oC (300^oF - 2200^oF)
Flooding rate (V_{in})	1.02 - 25.4 cm/sec (0.4 - 10 in./sec)
Equivalent peak power (Q'max, eq)	0.984 - 6.56 kw/m (0.3 - 2 kw/ft)

where the equivalent peak power is the power equivalent to the peak power of the FLECHT cosine power shape when the integrated power is preserved. That is,

$$Q'_{max,\,eq} = \int_0^{Z_{peak}} Q'(Z)dZ \Bigg/ \left(\int_0^{Z_{peak}} \frac{Q'(Z)}{Q'(Z_{peak})} dZ\right)_{FLECHT\ cosine}$$

$$= Q'_{max} \int_0^{Z_{peak}} \frac{Q'(Z)}{Q'(Z_{peak})} dZ \Bigg/ \left(\int_0^{Z_{peak}} \frac{Q'(Z)}{Q'(Z_{peak})} dZ\right) \text{ FLECHT cosine}$$

In terms of dimensionless parameters, the above range of parameters can be written as

$C_Q \left[= \int_0^{Z_{peak}} Q'(Z)dZ \,/\, (\rho_f A_f V_{in} h_{fg})\right]$	0.204 - 1.14
$C_T \left[= (T_{init} - T_{sat}) \,/\, (T_{Lei} - T_{sat})\right]$	0.146 - 6.9
ρ_g / ρ_f	0.000636 - 0.0036
$(C_{pf}\, \Delta T_{SUB} / h_{fg})$	0.0165 - 0.158
$Re\left[= \rho_f V_{in} D_e / \mu_f\right]$	470 - 8620
Z_{peak} / D_{rod}	61 - 284

It is also noted that the dominating term in equation (2-3)of the quench correlation is the first term in the expression for F_{t5}. The next dominating term is the brace containing parameter C_Q in the expression for F_{t1}. The third dominating term is the brace containing ΔT_{SUB} in the expression for F_{t1}. As for the heat transfer coefficient correlation, since the expressions are quite simple, nothing can be said about dominating terms.

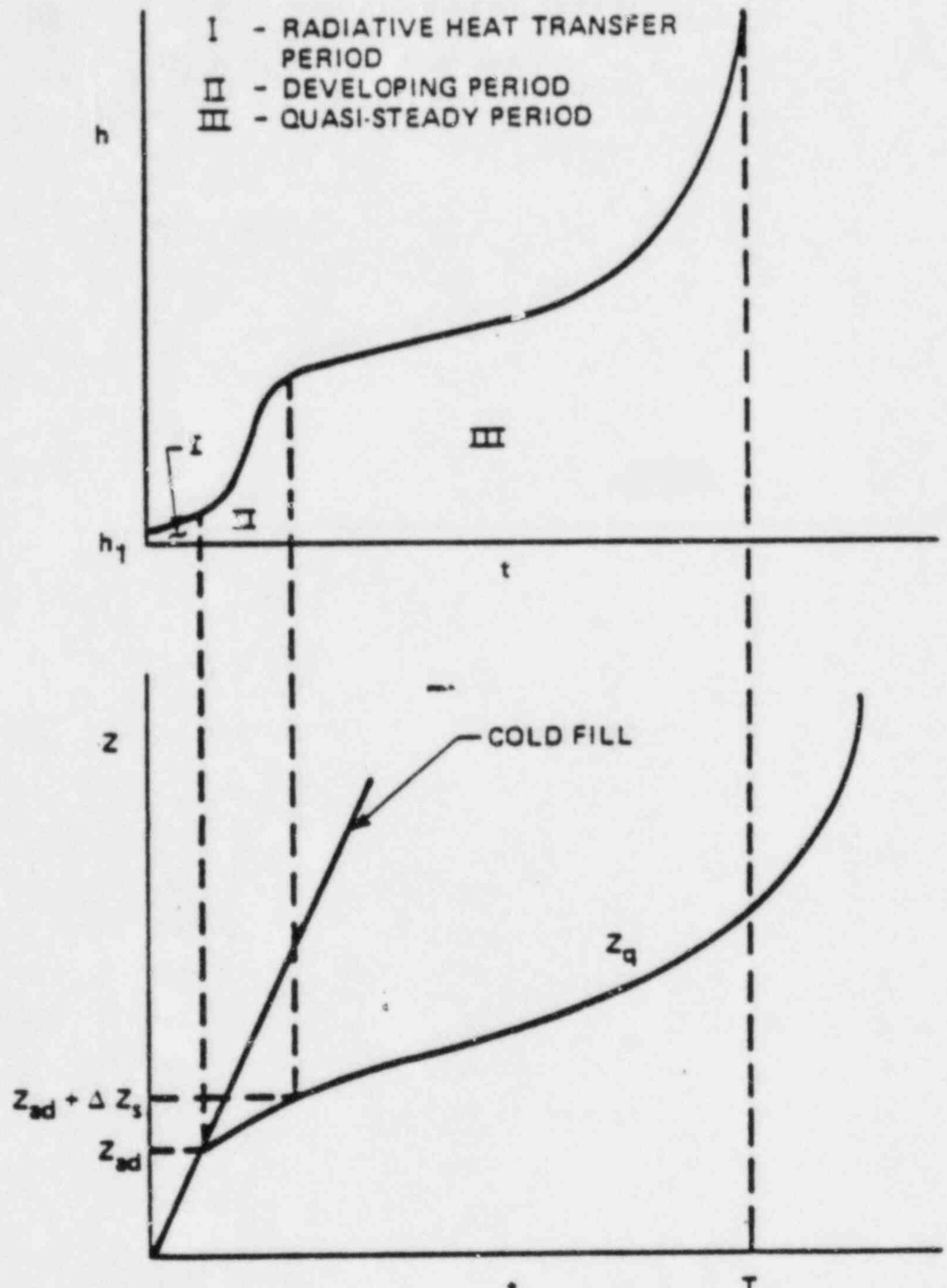


Figure 2-1. Adiabatic, Developing, and Quasi-Steady Periods in Heat Transfer Coefficient Correlation

3. COMPUTER PROGRAM

A computer program FLECSET is written to solve the equations given in Section 2. Major part of the program is taken directly from the computer program given in Reference 1 with minor corrections as given in Reference 4. The program can be run on CDC 7600 computer. The geometry and power informations and the axial location where the heat transfer coefficient is to be calculated are input by the user. The water and steam properties are calculated using STP[9] library. The results printed out are: quench time, heat transfer coefficient, H, quench height, ZQ, the quench front velocity VQ, and the core inlet velocity, VIN. A plot capability is added to the program so that two plots, heat transfer coefficient vs. time and quench height vs. time, will be obtained. The user information and sample output are given in Section 4 and 5, respectively. A copy of the listing of the computer program is given in Section 7.

4. USER INFORMATION

4-1. Input

The input to FLECSET consists of eight cards, the last four of which are multiple cards to input tables. All tables should be input with increasing values for the independent variable (first variable in the card).

Card 1: (Format 4F10.5, I5)

DTSUB = degree of subcooling associated with the water entering the core, °F.

P = system pressure at end of adiabatic heat up (EOAH), psia

TINIT = Initial cladding temperature at EOAH, °F

PWFT = Design peak linear heat power rate for the elevation of a particular power shape. KW/ft.

MR = 1 for FLECHT radial power shape
2 uniform power shape (radial)

Card 2: (Format 5F10.5, F10.8)

Z = Axial position (ft from inlet)

ZDBUG = 0 (if set >0 ft it prints out additional information useful for debug-Q/A purposes)

ZPEAK = Peak Temperature Elevation (ft)

DR = rod diameter (ft)

DE = hydraulic diameter of channel formed by four adjacent rods (ft)

A = flow area formed by four adjacent rods (ft^2)

Card 3: (Format 3F10.8)

POPOX = P/Po factor at the end of adiabatic heat up (Q'_{max} = PWFT x POPOX)

RCPAF = ($\rho C_p A$) for the water (BTU/ft-F)

RCPAR = (ρCpA) for rod (BTU/ft-F)

Card 4: (Format 4I10)

NVIN = number of cards for the inlet velocity table (card 5), maximum 100.

NDECAY = number of cards for normalized power decay (card 6), maximum 100.

NINTPR = number of cards for normalized integral of power (card 7), maximum 100.

NPSHAPE = number of cards for axial power shape factor (card 8), maximum 100.

Card 5: (Format 2F10.5), maximum No. = 100

VINTM(J) = time, seconds

VINTB(J) = flooding rate from reflood, in./sec.

Card 6: (Format 2F10.5), maximum No. = 100

PDCT(J) = time,tj, seconds

$$PDCAY(J) = \frac{\int_0^{t_j} \frac{Q'(Z,t)}{Q'(Z,0)}\, dt}{\int_0^{t_j} \left[\frac{Q'(Z,t)}{Q'(Z,0)}\, dt\right]_{\text{decay curve B (Figure 1)}}}$$

where the normalized FLECHT power decay curve is shown in Figure 1 (Figure I-1, Reference 1). A table of PDCAY for ANS + 20% power decay is given in Table 1 (page I-6, Reference 1).

Card 7: (Format 2F10.5) maximum no. = 100

QAxZQ(J) = axial location Z_j(ft)

$$QAXTB(J) = \int_0^{Z_j} \left[Q'\ Z,0)/Q'_{max}\right] dZ$$

= integral of axial power normalized using the maximum power.

Card 8: (Format 2F10.5), maximum no. = 100

FAXZ(J) = axial elevation Z_j(ft)

FAXTB(J) = $Q'(Zj,0)/Q'_{max}$

= the axial power normalized using the peak power

4.2. Output

Time = time to reach the quench front to certain elevation Zq, seconds (This time is equal to the actual time as long as the quench front propogates from the bottom to top)

H = heat transfer coefficient at a given height Z, BTU/hr-ft^2-F and also in W/m^2-C

ZQ = quench front elevation, ft, and also in m.

VQ = quench front velocity, in/sec.

VIN = inlet flooding rate at the output time, in/sec.

TABLE 4-1

Table of Normalized Power Decay[1]

$$PDCAY = \frac{\int_o^t \frac{Q'(Z,t)dt}{Q'(Z,0)}}{\int_o^t \left[\frac{Q'(Z,t)}{Q'(Z,0)} dt\right]_{\text{FLECHT DECAY CURVE}}}$$

This is the normalized power decay relative to the normalized power decay used in FLECHT experiment. The FLECHT decay curve is shown in Figure 4-1. ANS + 20% power decay is used in FLECHT-SEASET tests. The PDCAY for this ANS + 20% decay are given below.

PDCT(J) (sec)	PDCAY(J) (-)
0.00000	1.00000
20.00000	1.08500
40.00000	1.15300
60.00000	1.19800
80.00000	1.22600
100.00000	1.24400
120.00000	1.25500
140.00000	1.26200
160.00000	1.27000
200.00000	1.28000
280.00000	1.29800
360.00000	1.31100
440.00000	1.31900
520.00000	1.32400
600.00000	1.32700
680.00000	1.32800
2000.00000	1.33000

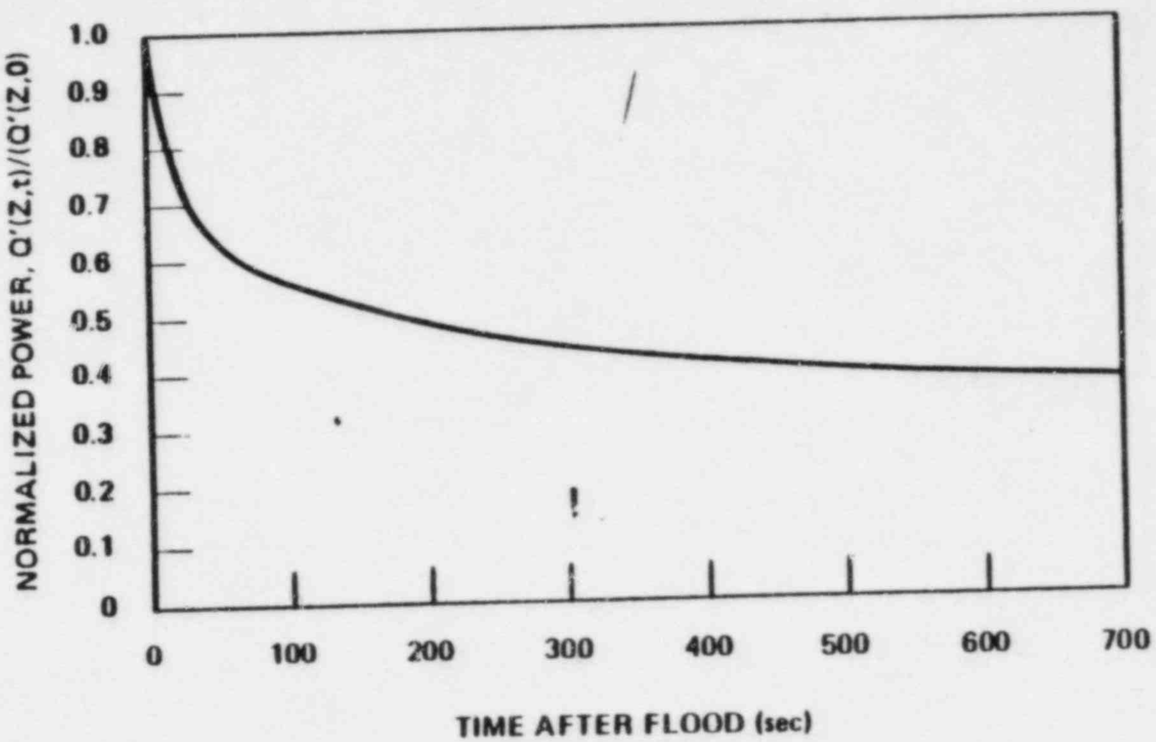


Figure 4-1. FLECHT Power Decay Curve B Normalized With Initial Power

5. Sample Output

A copy of sample print out is given in Section 5.1.5, and the sample plots are given in Figures 5-1 and 5-2.

5.1. Sample Printout

```
  C A R D    I M A G E    L I S T I N G
                                  C O L U M N    N U M B E R
          11111111112222222222333333333344444444445555555555666666
 1234567890123456789012345678901234567890123456789012345678901234

 140.0     40.0          1600.0     17.0        2
 6.0        0.0       6.0        0.03117     0.03863   0.0009455
 0.041776  0.05663       0.0355
          2          17          17          30
    0.0         0.80
  990.0         0.80
    0.0         1.0
   20.0         1.085
   40.0         1.153
   60.0         1.198
   80.0         1.226
  100.0         1.244
  120.0         1.255
  140.0         1.262
  160.0         1.270
  200.0         1.288
  280.0         1.298
  360.0         1.311
  440.0         1.319
  520.0         1.324
  600.0         1.327
  680.0         1.328
 2000.0         1.330
      0.0       0.0
      1.83      0.53
      2.34      0.735
      3.0       1.088
      3.58      1.478
      4.17      1.935
      4.83      2.534
      5.42      3.096
      6.0       3.6795
      6.58      4.263
      7.17      4.825
      7.83      5.424
      8.42      5.881
      9.0       6.271
      9.66      6.624
     10.17      6.829
     12.0       7.359
      0.0       0.289
      1.83      0.289
      1.84      0.410
      2.33      0.410
      2.34      0.530
      3.00      0.530
      3.01      0.669
      3.[illegible]      0.669
      3.59      0.783
      4.17      0.783
      4.18      0.898
```

```
           C A R D    I M A G E    L I S T I N G

                                           C O L U M N    N U M B
                   11111111112222222222333333333344444444444
          1234567890123456789012345678901234567890123456789

             4.83          0.898
             4.84          0.964
             5.42          0.964
             5.43          1.00
             6.58          1.00
             6.59          0.964
             7.17          0.964
             7.18          0.898
             7.83          0.898
             7.84          0.783
             8.42          0.783
             8.43          0.669
             9.0           0.669
             9.01          0.530
             9.67          0.530
             9.68          0.410
            10.17          0.410
            10.18          0.289
            12.0           0.289

*** E N D    O F    I N P U T    L I S T I N G *


 DTSUB(F)      P(PSIA)        TINIT(F)       PWFT(KW/FT              NR
.140000E+03   .400000E+02   .160000E+04   .170000E+02                 2

 Z(FT)           ZDBUG(FT)    ZPEAK(FT)      DR(FT)         DE(FT)         A(FT2)
.600000E+01             0   .600000E+01   .311700E-01   .386300E-01   .945300E-03

 PDPDX(-)       RCPAF          RCPAR
.417760E-01   .566300E-01   .385000E-01

      NVIN          NDECAY          NINTPR          NPSHPE
         2              17              17              30

 TABLE OF TIME VS VIN

       TIME            VIN(IN/S)

        0.00000        .80000
      990.00000        .80000
```

TABLE OF NORMALIZED POWER DECAY

TIME	PDCAY
0.00000	1.00000
20.00000	1.08500
40.00000	1.15300
60.00000	1.19800
80.00000	1.22600
100.00000	1.24400
120.00000	1.25500
140.00000	1.25200
160.00000	1.27000
200.00000	1.28000
280.00000	1.29800
360.00000	1.31100
440.00000	1.31900
520.00000	1.32400
600.00000	1.32700
680.00000	1.32800
2000.00000	1.33000

NORMALIZED INTEGRAL OF POWER

HEIGHT(FT)	QAXTBS
0.00000	0.00000
1.83000	.53000
2.34000	.73500
3.00000	1.08800
3.58000	1.47800
4.17000	1.93500
4.83000	2.53400
5.42000	3.09600
6.00000	3.67950
6.58000	4.26300
7.17000	4.82500
7.83000	5.42400
8.42000	5.88100
9.00000	6.27100
9.66000	6.62400
10.17000	6.82900
12.00000	7.35900

TABLE OF AXIAL POWER SHAPE FACTOR

FAXZ(FT)	FAXTB
0.00000	.28900
1.83000	.28900
1.84000	.41000
2.33000	.41000
2.34000	.53000
3.00000	.53000
3.01000	.66900
3.58000	.66900
3.59000	.78300
4.17000	.78300
4.18000	.89800
4.83000	.89800
4.84000	.96400
5.42000	.96400
5.43000	1.00000
6.58000	1.00000
6.59000	.96400
7.17000	.96400
7.18000	.89800
7.83000	.89800
7.84000	.78300
8.42000	.78300
8.43000	.66900
9.00000	.66900
9.01000	.53000
9.67000	.53000
9.68000	.41000
10.17000	.41000
10.18000	.28900
12.00000	.28900

TSAT=267.316391 VOLF= .01714633 VOLG=10.5018222
KG= .00000453 VISC= .0001414 CPF= 1.0190884

HF= 236.2[illegible]30 HG=1170.03627 KF= .0001099

****

THE RESULTS OF THIS TEST CASE Z = 6.00000 FT

****

TIME	H (BTU/HR-FT2-F)	ZQ(FT)	H(SI)	ZQ(M)	VQ(IN/S)	VIN(IN/S)
0.00000	3.2852	.00500	18.6542	.00152	.47185	.80000
2.54529	3.2852	.10000	18.6542	.03048	.47114	.80000
5.09317	3.2852	.20000	18.6542	.06096	.47091	.80000
7.64085	3.2852	.30000	18.6542	.09144	.47122	.80000
10.18553	3.2852	.40000	18.6542	.12192	.47200	.80000
12.72442	3.2852	.50000	18.6542	.15240	.47332	.80000
15.25480	3.2852	.60000	18.6542	.18288	.47515	.80000
17.77400	3.3250	.70000	18.8804	.21336	.47750	.80000
20.27875	3.5447	.80000	20.1275	.24384	.48123	.80000
22.76282	4.2326	.90000	24.0340	.27432	.48484	.80000
25.22709	5.1889	1.00000	29.4642	.30480	.48897	.80000
27.66925	6.0539	1.10000	34.3758	.33528	.49363	.80000
30.08714	6.6472	1.20000	37.7445	.36576	.49881	.80000
32.4787_	6.9933	1.30000	39.7098	.39624	.50452	.80000
34.84213	7.1882	1.40000	40.8167	.42672	.51075	.80000
37.17562	7.3065	1.50000	41.4879	.45720	.51751	.80000
39.47763	7.3855	1.60000	41.9365	.48768	.52479	.80000
41.73768	7.4404	1.70000	42.2483	.51816	.53540	.80000
43.96035	7.4765	1.80000	42.4534	.54864	.54406	.80000
50.90580	7.6367	1.90000	43.3633	.57912	.36489	.80000
54.15314	7.6578	2.00000	43.4828	.60960	.37386	.80000
57.32089	7.6819	2.10000	43.6201	.64008	.38343	.80000
60.40487	7.7097	2.20000	43.7777	.67056	.39974	.80000
63.39341	7.7416	2.30000	43.9587	.70104	.40669	.80000

70.71028	7.7782	2.40000	44.1665	.73152	.29748	.80000
74.66699	7.8202	2.50000	44.4051	.76200	.30866	.80000
78.48094	7.8684	2.60000	44.6790	.79248	.32014	.80000
82.14682	7.9238	2.70000	44.9936	.82296	.33326	.80000
85.68268	7.9875	2.80000	45.3548	.85344	.34495	.80000
89.10236	8.0605	2.90000	45.7696	.88392	.35629	.80000
92.41757	8.1444	3.00000	46.2459	.91440	.36704	.80000
100.71931	8.2407	3.10000	46.7927	.94488	.28906	.80000
104.80906	8.3513	3.20000	47.4207	.97536	.29716	.80000
108.80001	8.4782	3.30000	48.1417	1.00584	.30362	.80000
112.71894	8.6240	3.40000	48.9696	1.03632	.30827	.80000
116.59140	8.7915	3.50000	49.9202	1.06680	.31105	.80000
123.67618	8.9837	3.60000	51.0118	1.09728	.26438	.80000
128.21957	9.2044	3.70000	52.2652	1.12776	.26362	.80000
132.79046	9.4579	3.80000	53.7044	1.15824	.26133	.80000
137.41293	9.7489	3.90000	55.3569	1.18872	.25789	.80000
142.10842	10.0831	4.00000	57.2544	1.21920	.25344	.80000
146.88961	10.4668	4.10000	59.4332	1.24968	.24873	.80000
155.08480	10.9074	4.20000	61.9351	1.28016	.20358	.80000
161.04651	11.4133	4.30000	64.8078	1.31064	.19938	.80000
167.13761	11.9942	4.40000	68.1063	1.34112	.19493	.80000
173.36292	12.6613	4.50000	71.8939	1.37160	.19088	.80000
179.71418	13.4272	4.60000	76.2[illegible]	1.40208	.18727	.80000
186.18036	14.3066	4.70000	81.2367	1.43256	.18413	.80000
192.74887	15.3165	4.80000	86.5708	1.46304	.18146	.80000
201.59639	16.4760	4.90000	93.5549	1.49352	.16908	.80000
208.73508	17.8074	5.00000	101.1151	1.52400	.16727	.80000
215.94350	19.3362	5.10000	109.7960	1.55448	.16580	.80000
223.20881	21.0916	5.20000	119.7639	1.58496	.16464	.80000

230.51980	23.1073	5.30000	131.2094	1.61544	.16372	.80000
237.86696	25.4218	5.40000	144.35[illegible]	1.64592	.16300	.80000
246.78593	28.0794	5.50000	159.4422	1.67640	.15303	.80000
254.63928	31.1310	5.60000	176.7698	1.70688	.15261	.80000
262.51117	34.6349	5.70000	196.6662	1.73736	.15230	.80000
270.39718	38.6583	5.80000	219.5121	1.76784	.15206	.80000
278.29401	43.2782	5.90000	245.7448	1.79832	.15188	.80000
286.18463	48.5829	6.00000	275.8663	1.82880	.15204	.80000
294.08026	54.6740	6.10000	310.4532	1.85928	.15194	.80000
301.98049	61.6681	6.20000	350.1674	1.88976	.15186	.80000
309.88452	69.6990	6.30000	395.7691	1.92024	.15179	.80000
317.79179	78.9205	6.40000	448.1309	1.95072	.15173	.80000
325.70193	89.5098	6.50000	508.2552	1.98120	.15168	.80000
331.85551	101.6672	6.60000	577.2925	2.01168	.16095	.80000
339.31260	115.6277	6.70000	656.5643	2.04216	.16090	.80000
346.77181	131.6579	6.80000	747.5877	2.07264	.16085	.80000
354.23308	150.0644	6.90000	852.1049	2.10312	.16081	.80000
361.68882	171.1997	7.00000	972.1[illegible]61	2.13360	.16117	.80000
369.13520	195.4681	7.10000	1109.9185	2.16408	.16114	.80000
372.65228	223.3341	7.20000	1268.1493	2.19456	.17079	.80000
379.67906	255.3312	7.30000	1449.8370	2.22504	.17076	.80000
386.70693	292.0717	7.40000	1658.4590	2.25552	.17074	.80000
393.73589	334.2587	7.50000	1898.0081	2.28600	.17071	.80000
400.76593	382.6998	7.60000	2173.8691	2.31648	.17068	.80000
407.79705	438.3220	7.70000	2488.9065	2.34696	.17066	.80000
414.82926	502.1980	7.80000	2851.5651	2.37744	.17063	.80000
412.31376	575.5260	7.90000	3267.9860	2.40792	.20411	.80000
417.89331	659.7336	8.00000	3746.1392	2.43840	.20408	.80000
423.77362	756.4247	8.10000	4295.1761	2.46888	.20406	.80000

429.65468	867.4497	8.20000	4925.6048	2.49936	.20403	.80000
435.53651	994.9335	8.30000	5649.4914	2.52984	.20401	.80000
441.41270	1141.3162	8.40000	6480.6903	2.56032	.20435	.80000
434.09987	1309.3994	8.50000	7435.1103	2.59080	.24136	.80000
439.06884	1502.4000	8.60000	8531.0180	2.62128	.24177	.80000
444.03238	1724.0120	8.70000	9789.3884	2.65176	.24175	.80000
448.99626	1978.4768	8.80000	11234.3056	2.68224	.24174	.80000
453.96047	2270.6647	8.90000	12893.4244	2.71272	.24172	.80000
458.92500	2606.1679	9.00000	14798.4989	2.74320	.24171	.80000
440.22186	2991.4077	9.10000	16985.9909	2.77368	.31821	.80000
443.99385	3433.7574	9.20000	19497.7672	2.80416	.31819	.80000
447.76443	3941.6831	9.30000	22381.9013	2.83464	.31818	.80000
451.53600	4524.9061	9.40000	25693.5934	2.86512	.31816	.80000
455.30775	5194.5889	9.50000	29496.2266	2.89560	.31815	.80000
459.27970	5963.5488	9.60000	33862.5806	2.92608	.31813	.80000
433.58370	6846.5030	9.70000	38876.2239	2.95656	.44834	.80000
436.25548	7860.3505	9.80000	44633.1138	2.98704	.44913	.80000
438.92736	9024.4957	9.90000	51243.4329	3.01752	.44911	.80000
441.59934	10361.2194	10.00000	58833.6975	3.04800	.44910	.80000
444.27142	11896.1054	10.10000	67549.1796	3.07848	.44908	.80000
403.64142	13658.5304	10.20000	77556.6866	3.10896	.68177	.80000
405.40159	15682.2257	10.30000	89047.7548	3.13944	.68174	.80000
407.16183	18005.9234	10.40000	102292.3143	3.16992	.68171	.80000
408.92213	20674.0972	10.50000	117392.8989	3.20040	.68169	.80000
410.68250	23737.8139	10.60000	134789.4792	3.23088	.68166	.80000
412.44294	27255.7108	10.70000	154765.0124	3.26136	.68164	.80000
414.20345	31295.1177	10.80000	177701.8149	3.29184	.68161	.80000
415.96403	35933.3457	10.90000	204038.8796	3.32232	.68158	.80000
417.72467	41259.1670	11.00000	234280.2777	3.35280	.68156	.80000

419.48538	47374.5137	11.10000	269004.8064	3.38328	.68153	.80000
421.24616	54396.4289	11.20000	308877.0665	3.41376	.68150	.80000
423.00701	62459.3067	11.30000	354660.1827	3.44424	.68148	.80000
424.76793	71717.4643	11.40000	407230.4087	3.47472	.68145	.80000
426.52891	82348.0958	11.50000	467593.8986	3.50520	.68142	.80000
428.28996	94554.6633	11.60000	536905.9627	3.53568	.68140	.80000
430.05108	108570.7913	11.70000	616493.1815	3.56616	.68137	.80000
431.80925	124664.7376	11.80000	707878.7932	3.59664	.68258	.80000
433.56731	143144.5251	11.90000	812811.8484	3.62712	.68256	.80000
435.32540	164363.8519	12.00000	933300.6854	3.65760	.68255	.80000

ID OF CALCULATION *****

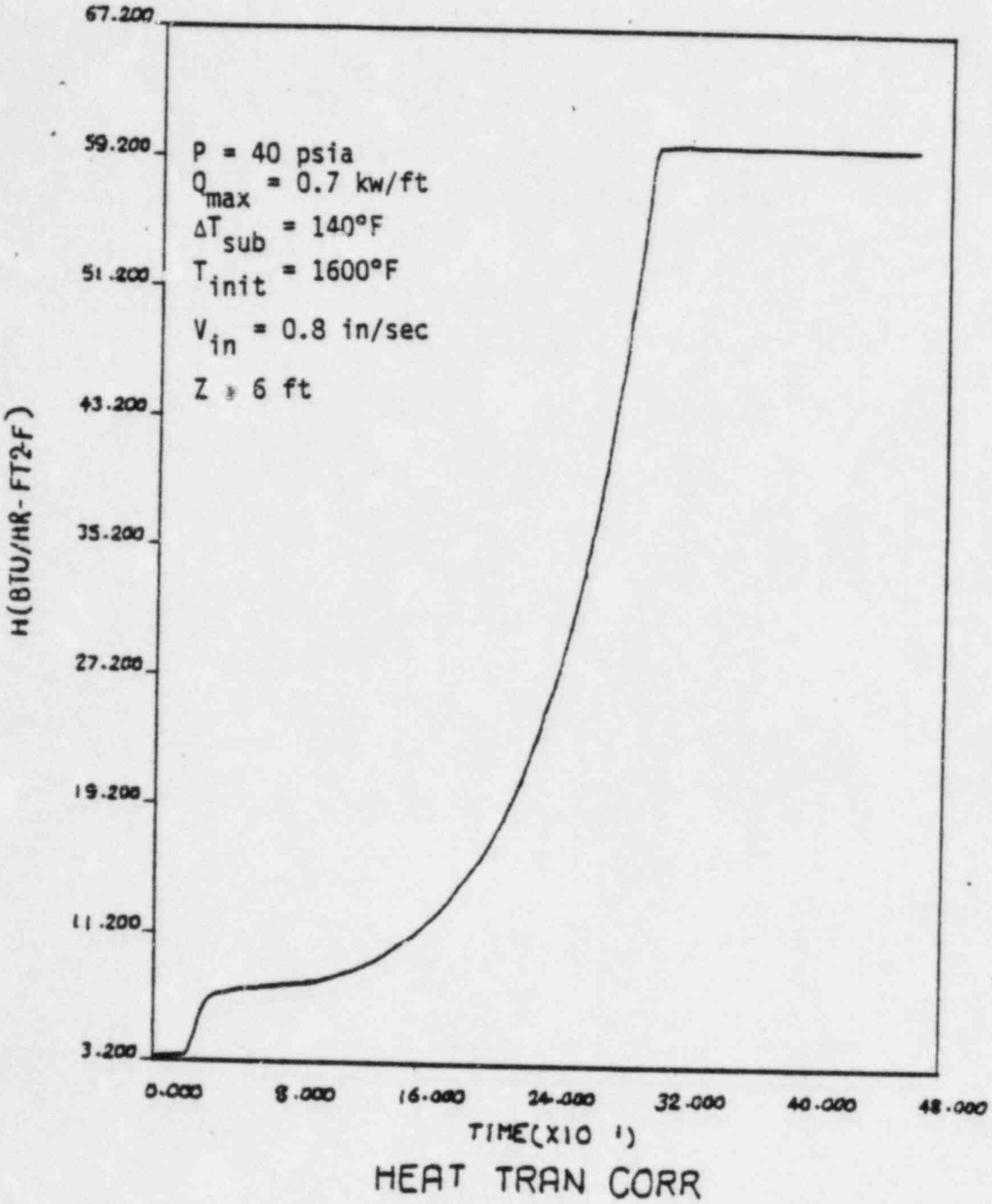


FIGURE 5-1. Heat Transfer Coefficient Vs. Time

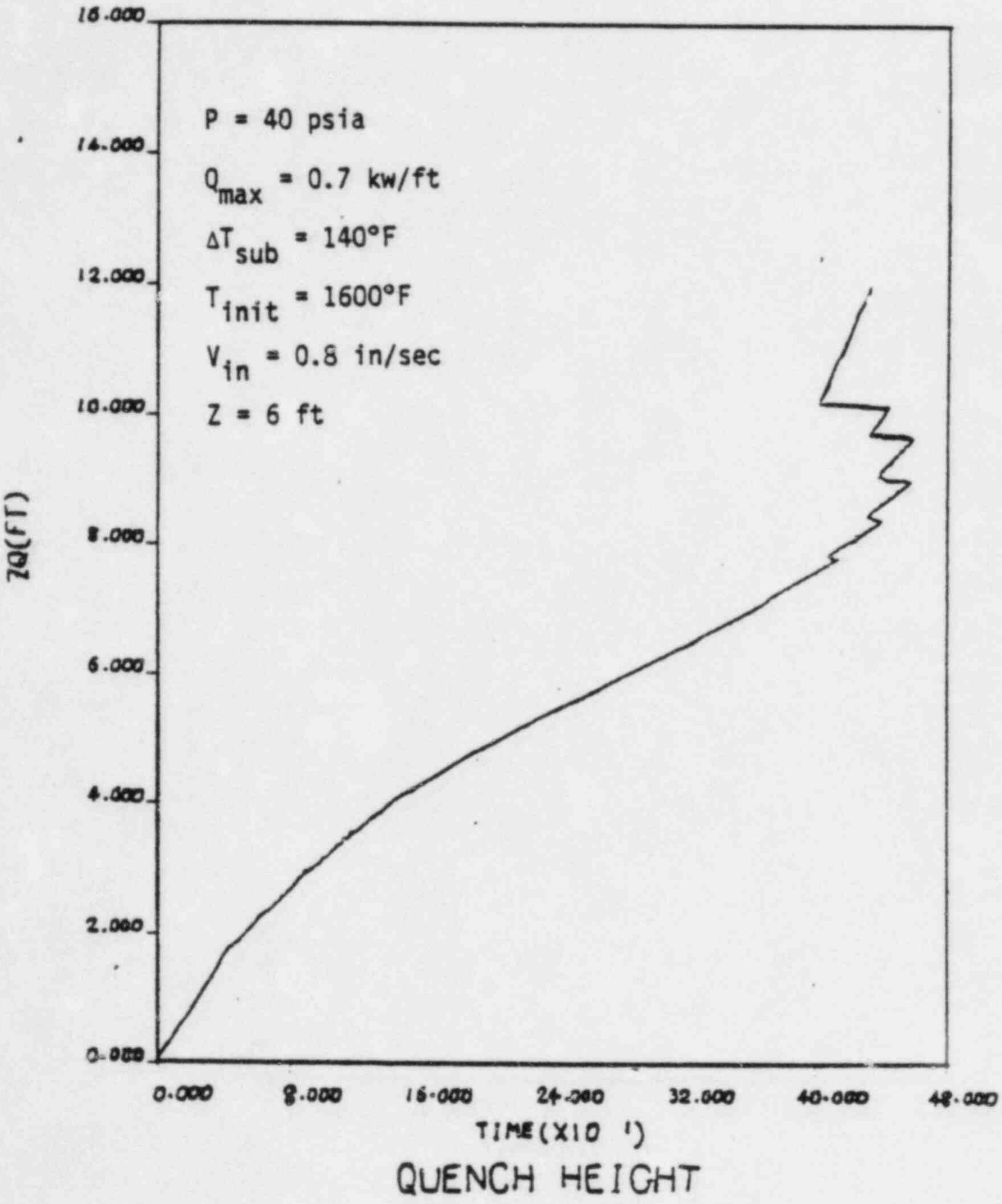


FIGURE 5-2. Quench Height Vs. Quench Time

6. CODE BENCHMARK

The purpose of the FLECSET computer code benchmark is to show that the predicted results agree reasonably well with the experimental results reported in Reference 1. Lee et al.[1] have made an extension comparison study between the correlation (predicted) results and the measured results of FLECHT SEASET experiments. Their predicted results have agreed reasonably well with the measured values. They have also shown that the present correlation gives better comparison with the WCAP-9183 and WCAP-8838 data than the previous correlations given in these reports. Comparison of the present correlation with some of the boiling water reactor (BWR) FLECHT[10] data and Semiscale test data[11] have also been made by them with reasonably good agreement.

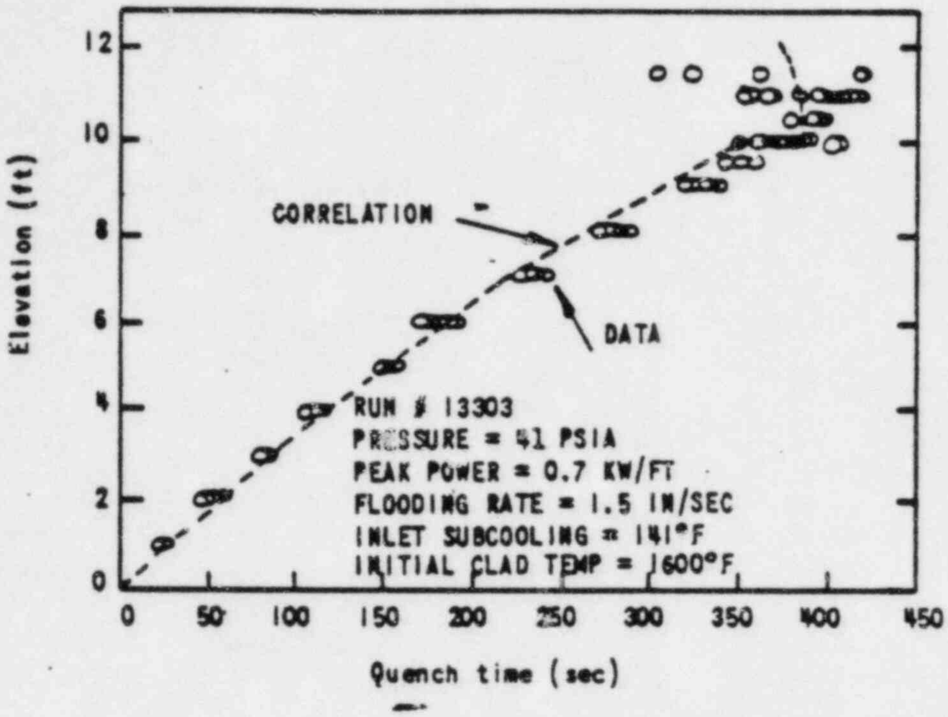
In the present study, nine test cases were selected from Reference 1 covering the wide range of variables used in their experiment. The FLECSET code run ID, the experimental test run ID and the test conditions for these nine test cases are given in Table 6-1. Figures 6-1 through 6-9 show that the predicted heat transfer coefficient and quench elevation vs. quench time agree well with the experimental results.

Two additional test runs were also made using the typical input values, variable flooding rates, and skewed power shapes with peak power values at 8 feet and 10 feet, respectively, from the bottom of the core. The FLECSET code run ID and the initial conditions for these two test cases are also given in Table 6-1. Figures 6-10 and 6-11 give the predicted heat transfer coefficient and quench height versus time for these two test cases.

From these results it can be concluded that FLECSET code can be used, with confidence, to calculate the core heat transfer coefficient values during the reflood phase of a postulated loss of coolant accident (LOCA).

TABLE 6-1. Benchmark Cases Supporting FLECSET Computer Code

S. No.	Run I.D.	Test Case Number	Bundle Type	Power Shape	Peak Power Kw/ft	Flooding Rate in/sec	Initial Clad Temp °F	Inlet Subcooling Temp °F	Pressure psia	Zq-Zpeak ft	Reference	Page #
1.	ADKAEJL	13303	15 x 15	Skewed	0.7	1.5	1600	141	41	10.0	1	H-18
2.	ADKAFAX	15305	15 x 15	Skewed	0.7	0.8	1600	140	40	10.0	1	H-19
3.	ADKAFCC	16110	15 x 15	Skewed	0.7	0.8	1617	132	20	10.0	1	H-20
4.	ADKAFDN	12816	15 x 15	Skewed	0.7	1.5	507	141	40	10.0	1	H-22
5.	ADKAFEQ	16022	15 x 15	Skewed	1.0	1.5	1536	139	40	10.0	1	H-23
6.	ADKADHB	31701	17 x 17	Cosine	0.7	6.0	1600	140	40	6.0	1	H-3
7.	ADKADJA	32013	17 x 17	Cosine	0.7	1.0	1600	140	60	6.0	1	H-7
8.	ADKAAUY	35114	17 x 17	Cosine	0.7	1.0	1600	5	40	6.0	1	H-8
9.	ACAIBYC	32333	17 x 17	Cosine	0.7	Variable Rate	1600	140	40	6.0	1	G-18
10.	ADKAATR		17 x 17	Skewed	0.90831	Variable	1600	145	43	8.0	12	
11.	ADKADZD		17 x 17	Skewed	0.9044	Variable	1600	145	43	10.0	12	



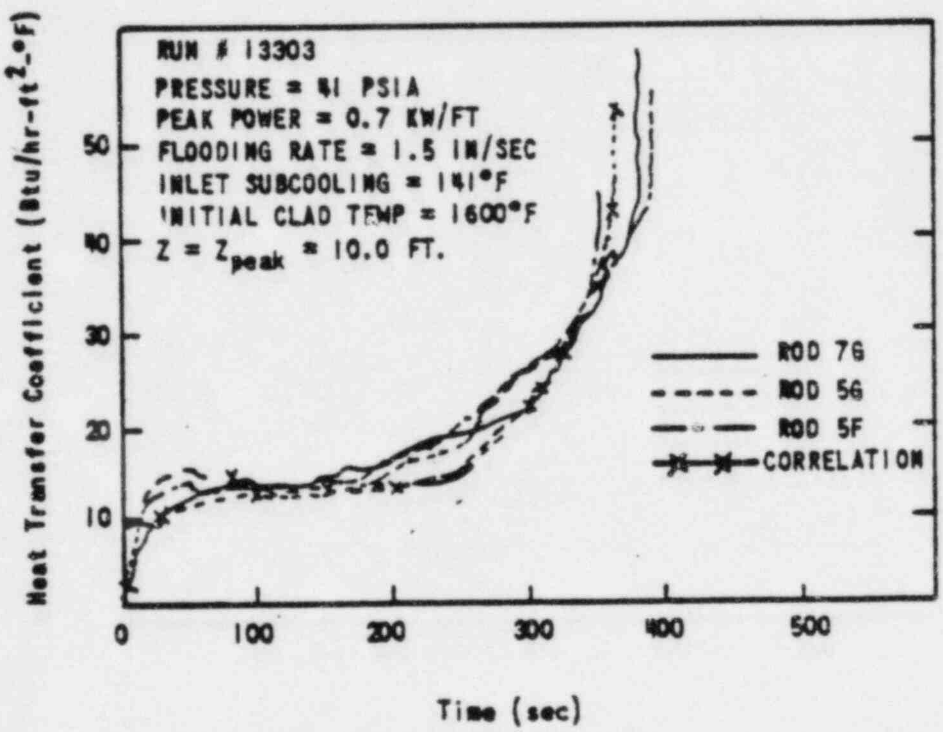


Figure 6-1. Quench Correlation and Heat Transfer Coefficient Versus Data, Skewed Power Run #13303

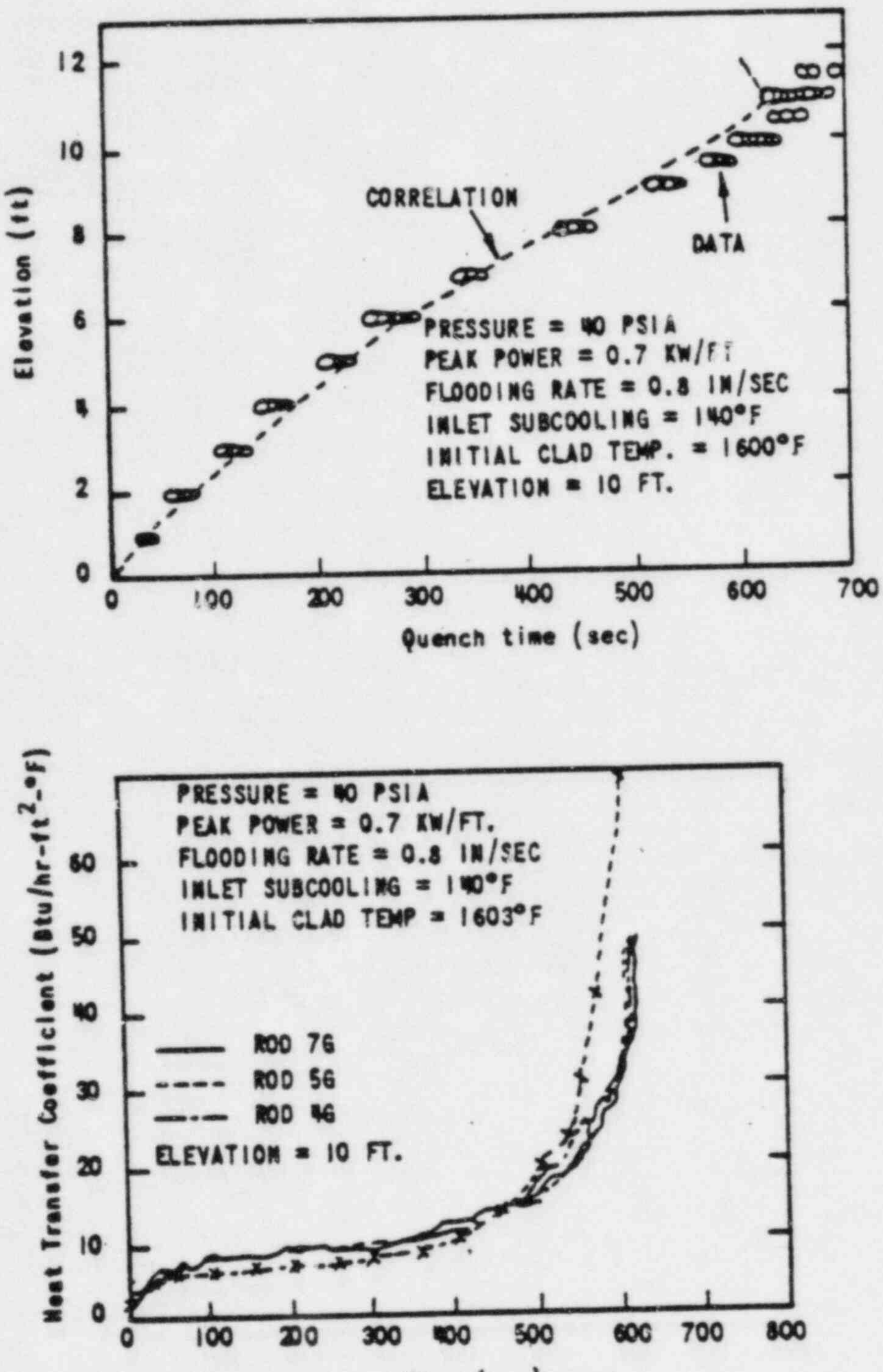
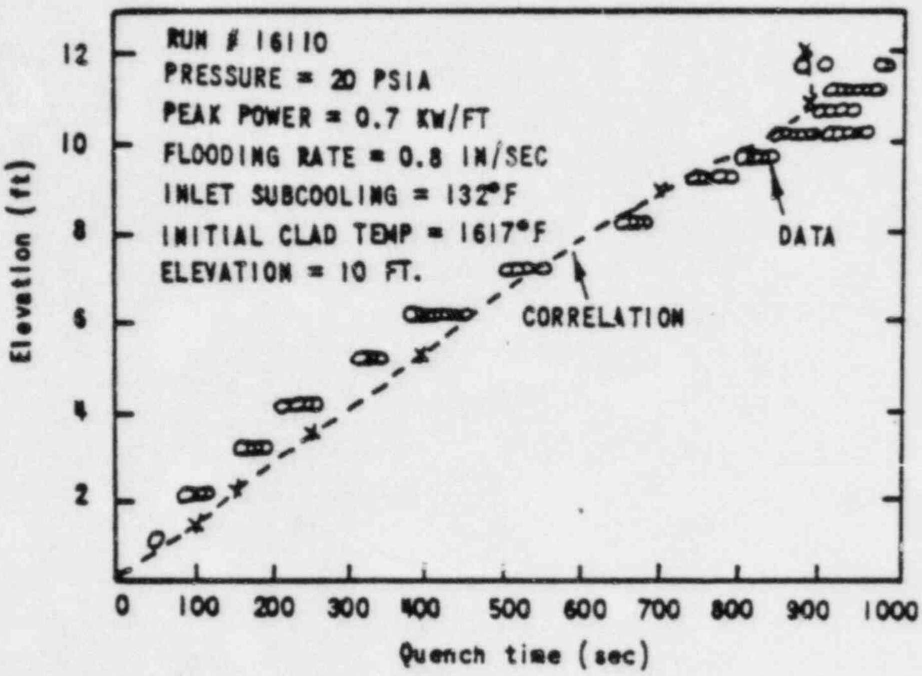


Figure 6-2. Quench Correlation and Heat Transfer Coefficient Versus Data, Skewed Power Run #15305



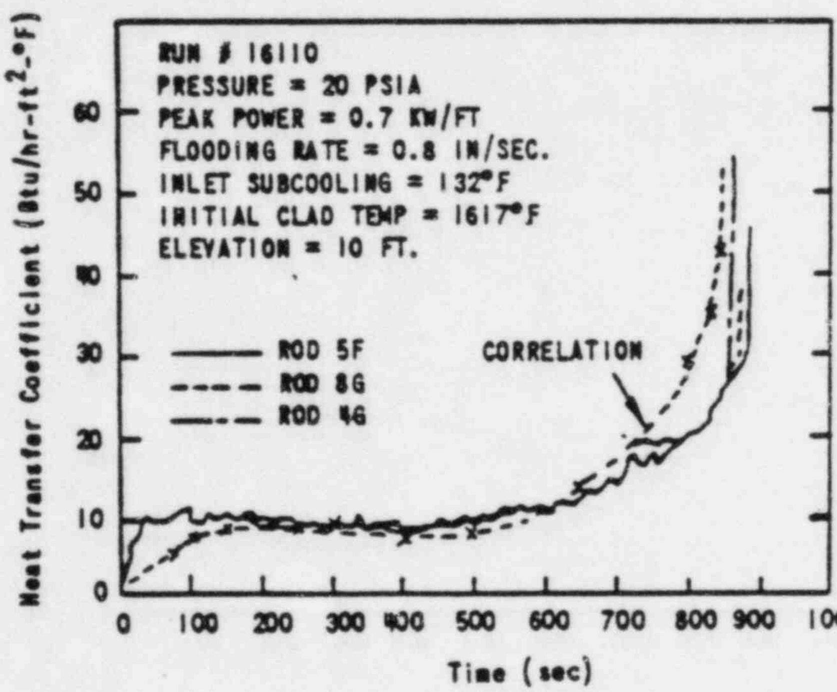
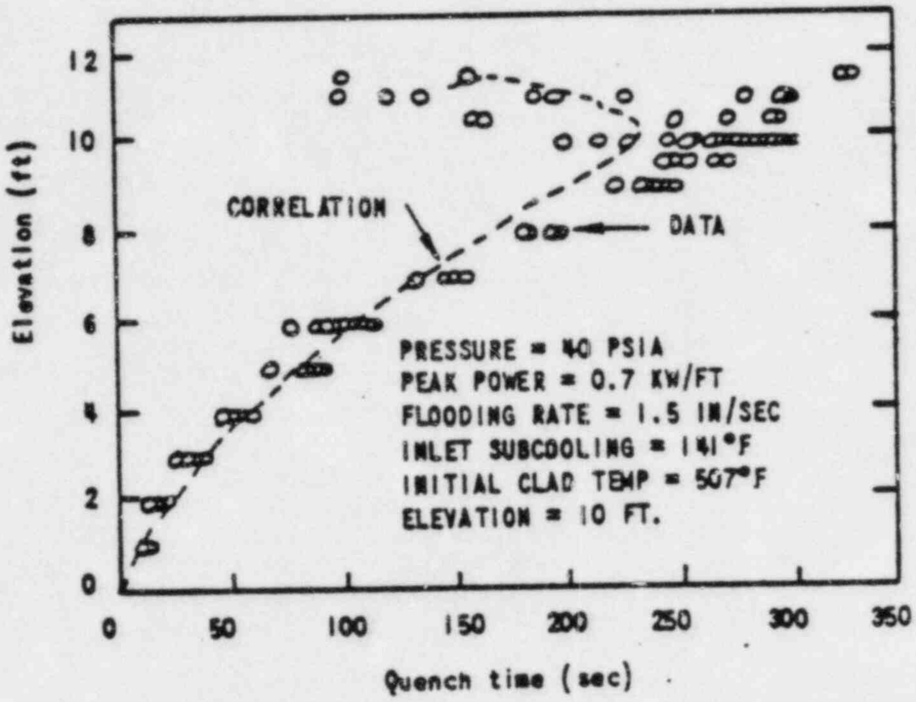


Figure 6-3. Quench Correlation and Heat Transfer Coefficient Versus Data, Skewed Power Run #16110



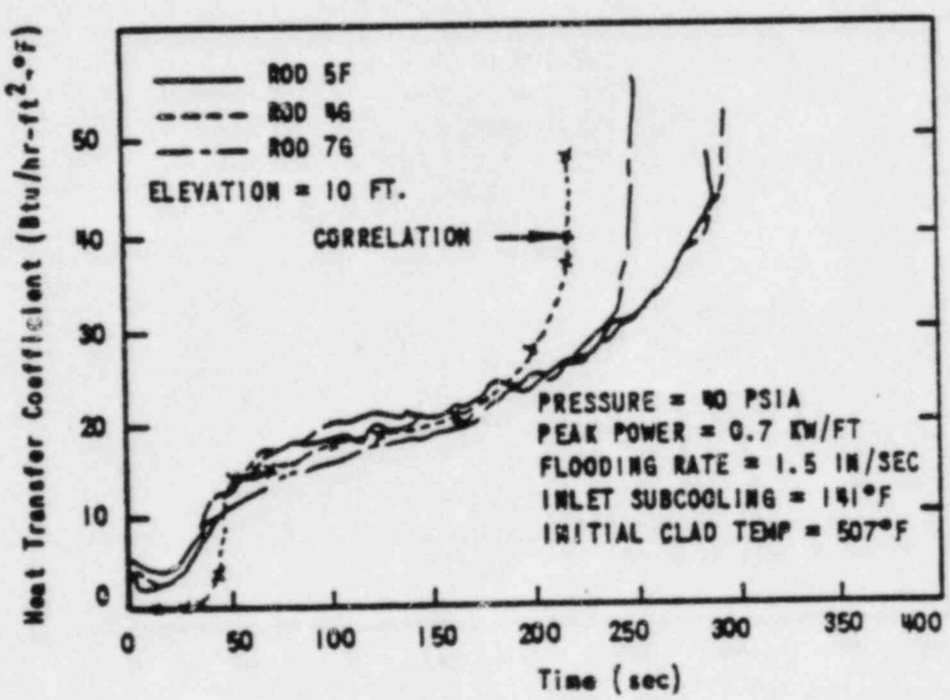
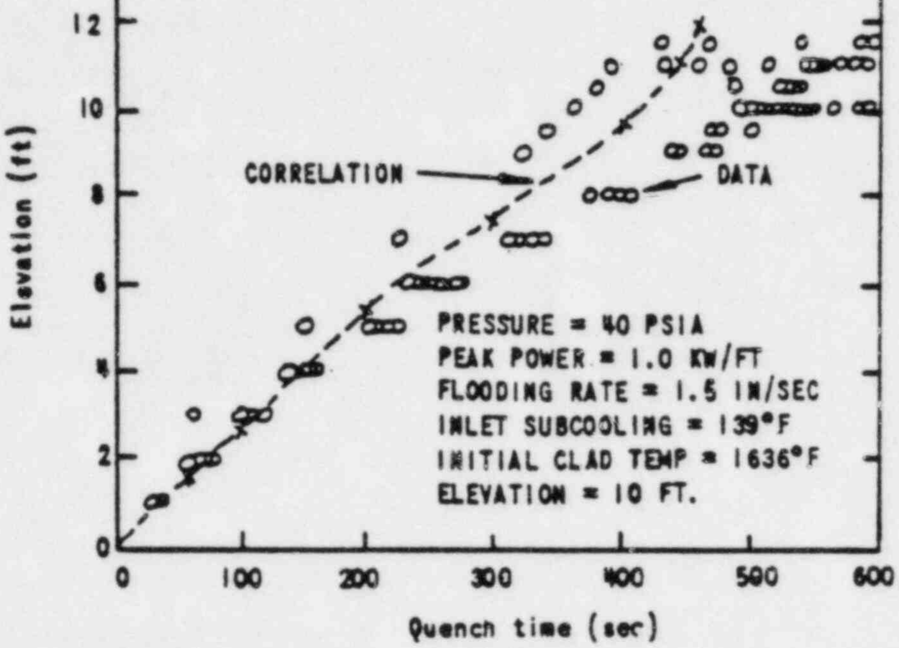


Figure 6-4. Quench Correlation and Heat Transfer Coefficient Versus Data, Skewed Power Run #12816



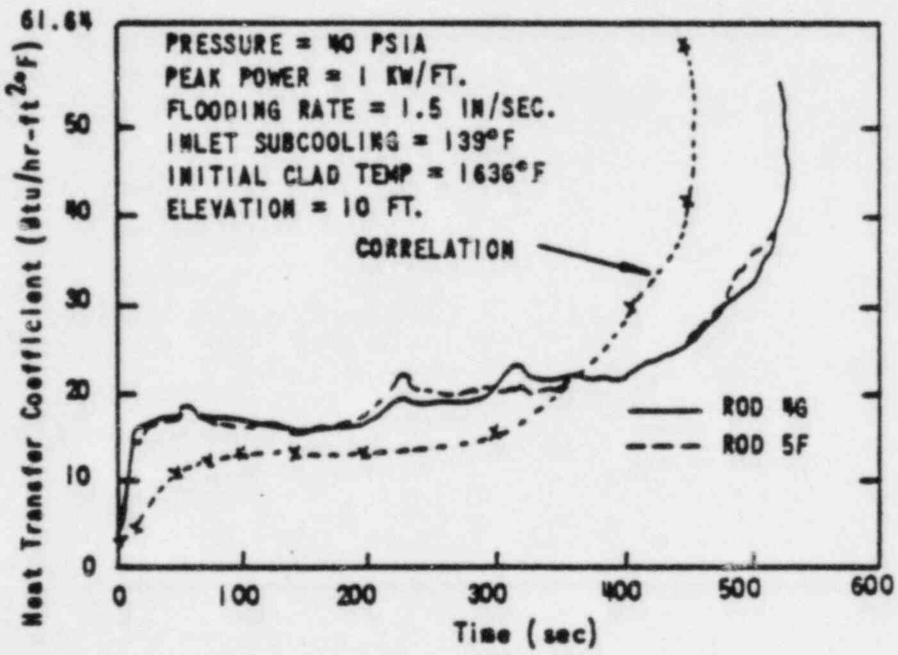
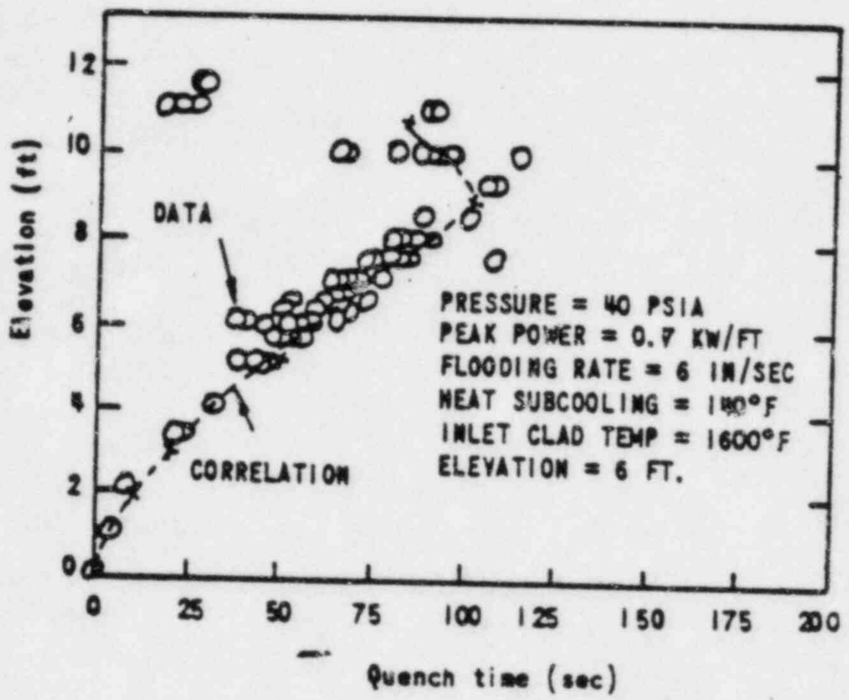


Figure 6-5. Quench Correlation and Heat Transfer Coefficient Versus Data, Skewed Power Run #16022



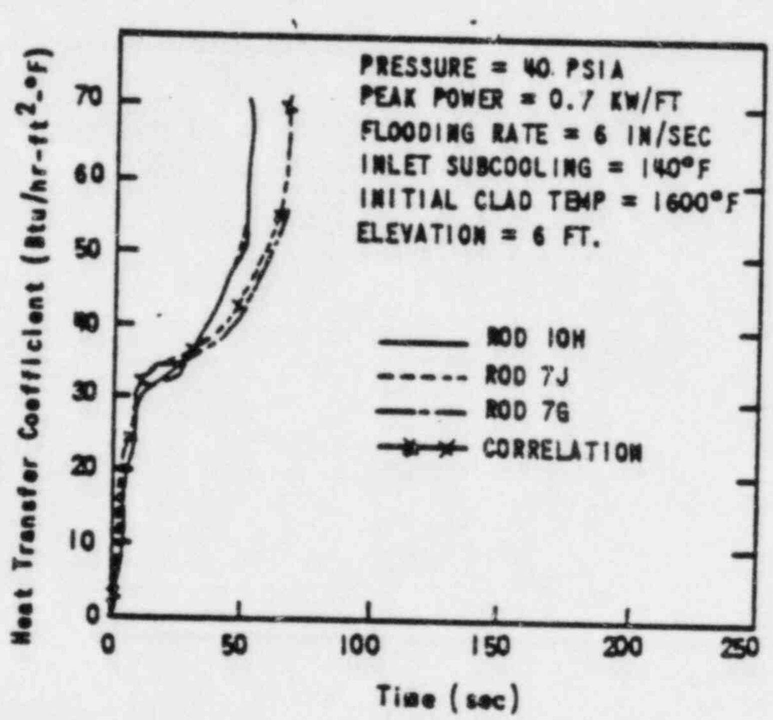
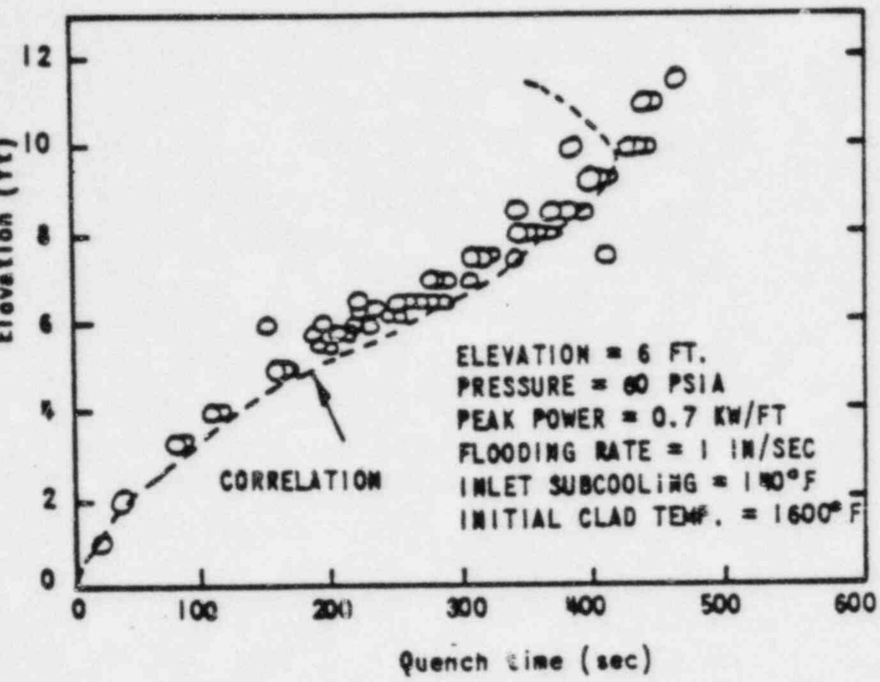


Figure 6-6. Quench Correlation and Heat Transfer Coefficient Versus Data, Cosine Power FLECHT SEASET Run #31701



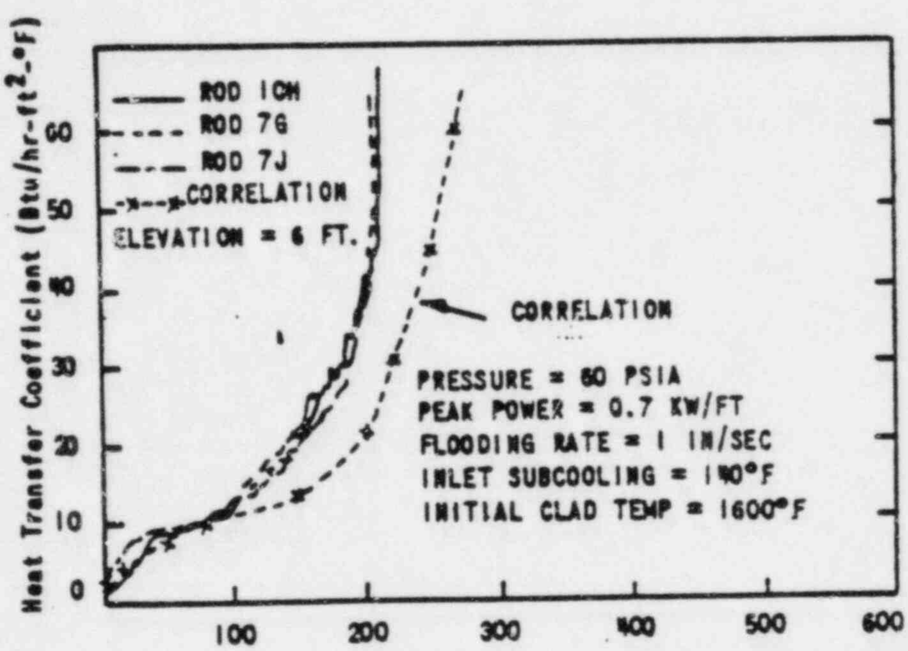


Figure 6-7. Quench Correlation and Heat Transfer Coefficient Versus Data, Cosine Power FLECHT SEASET Run #32013

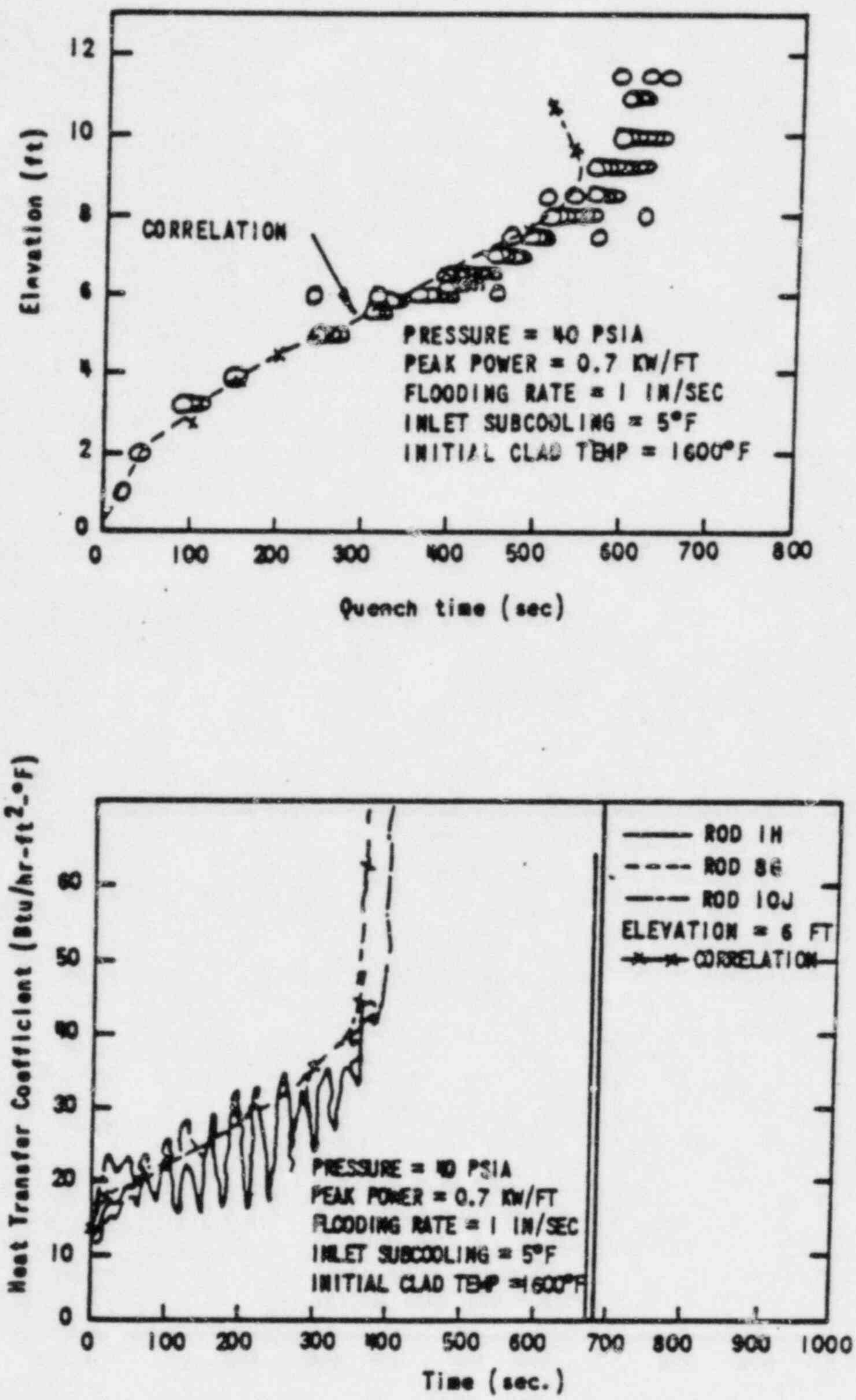
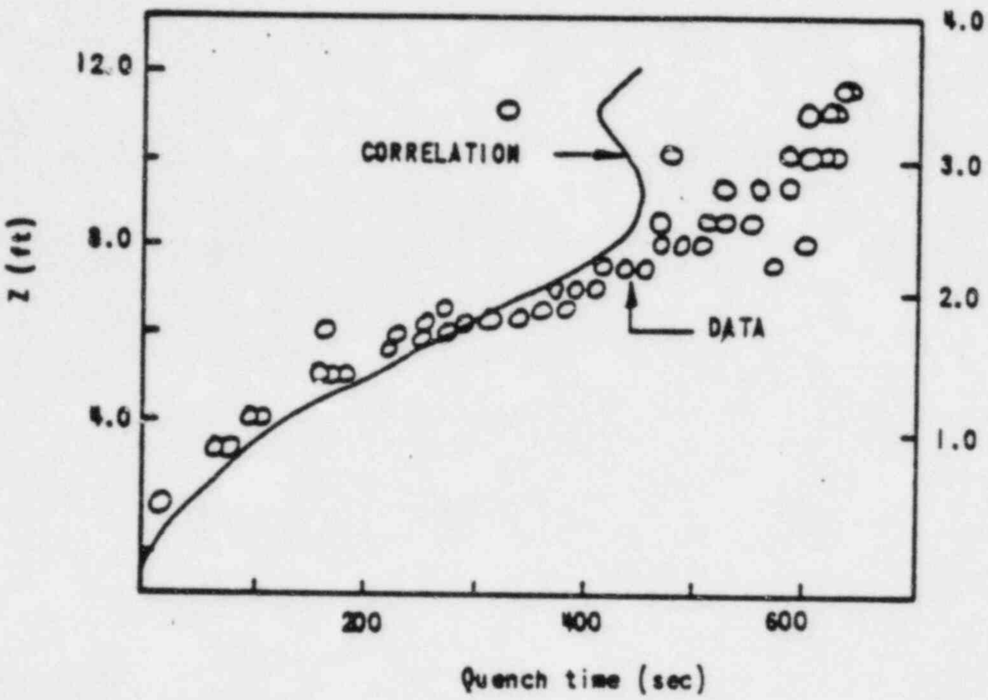


Figure 6-8. Quench Correlation and Heat Transfer Coefficient Versus Data, Cosine Power FLECHT SEASET Run #35114



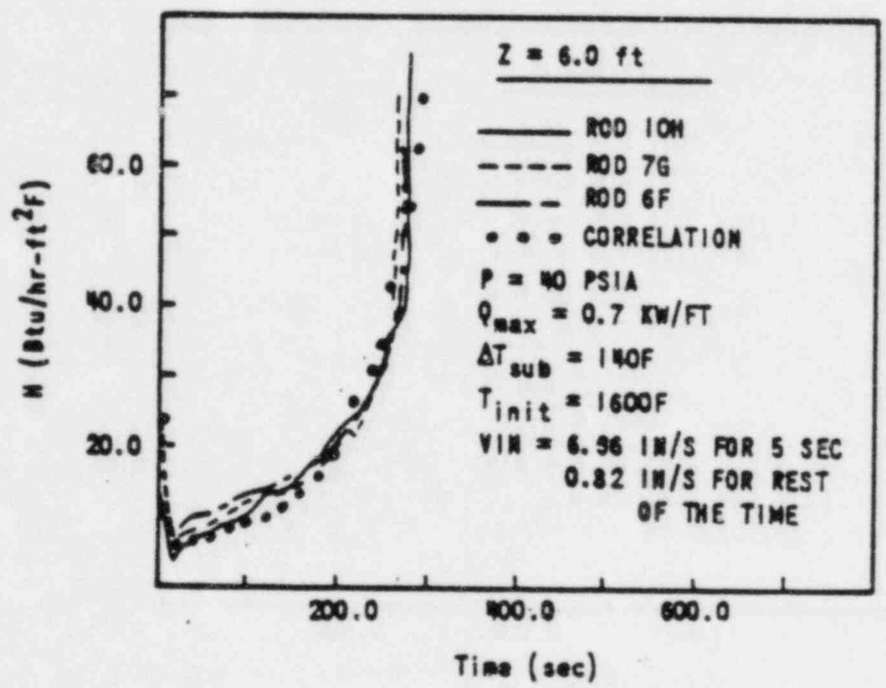


Figure 6-9. Quench Correlation and Heat Transfer Coefficient Versus Data, Cosine Power FLECHT SEASET Run #32333

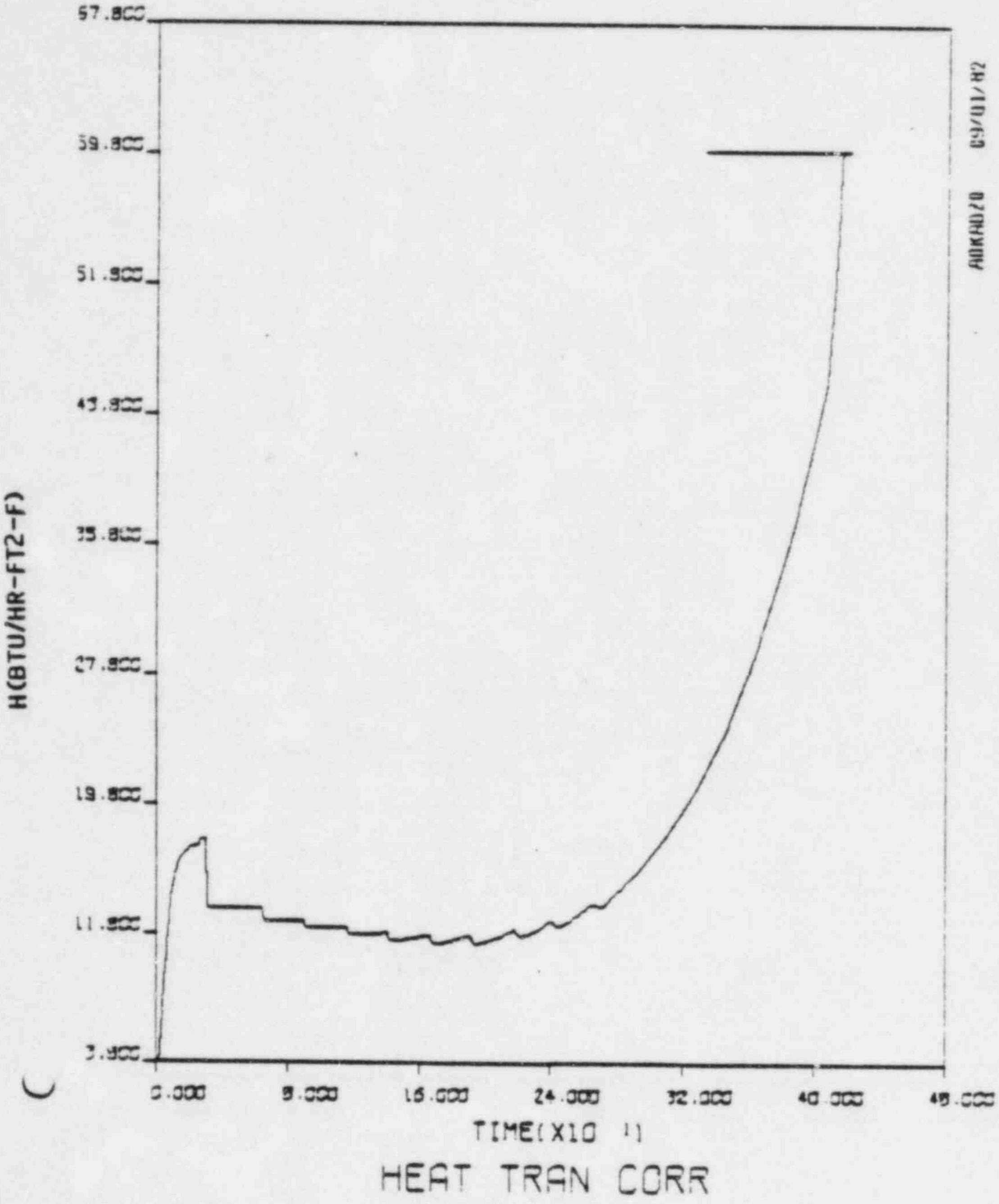


Figure 6-10 a): Predicted Heat Transfer Coefficient for Skewed Power Run ADKAATR

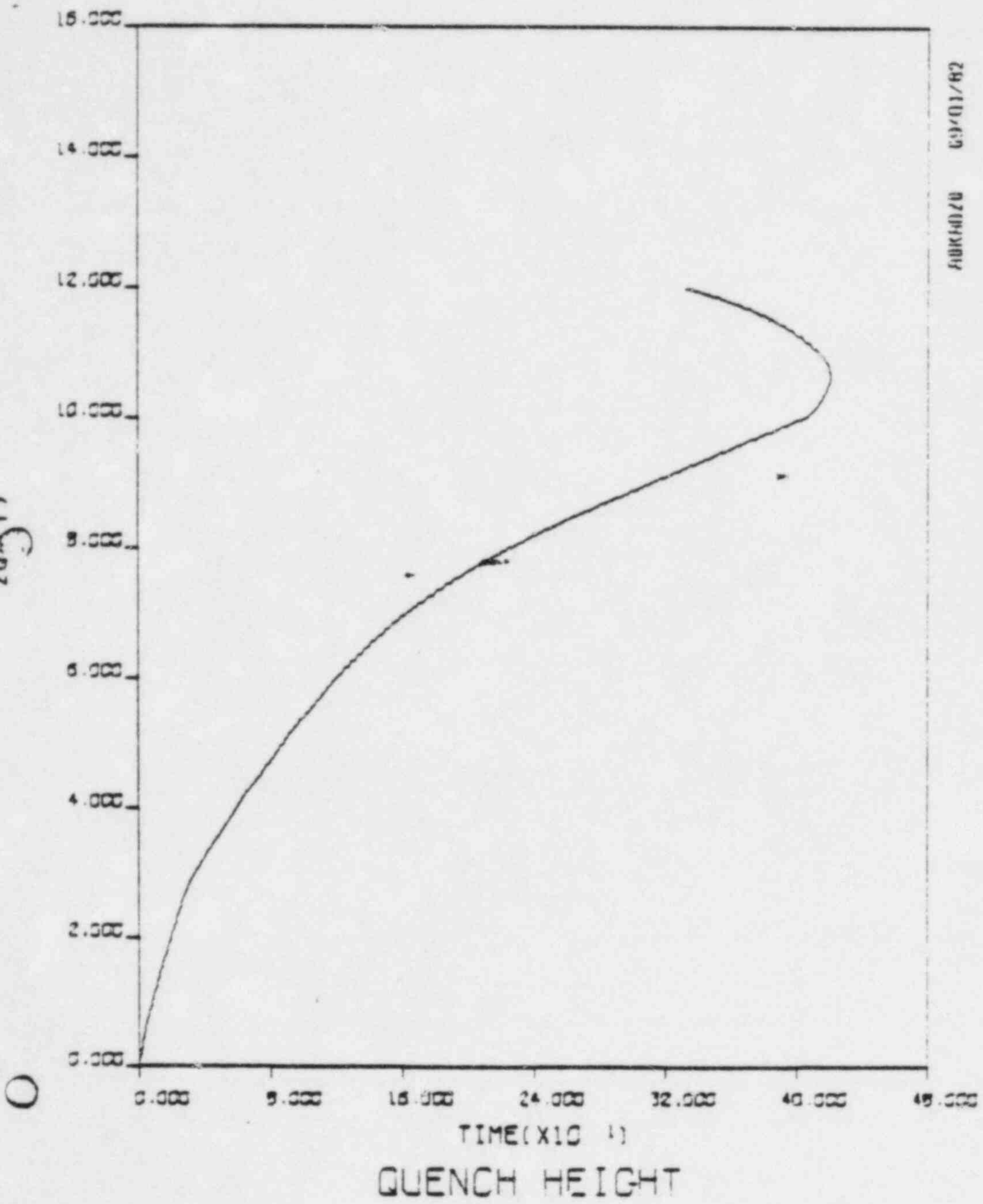


Figure 6-10 b): Predicted Quench Elevation for Skewed Power Run ADKAATR

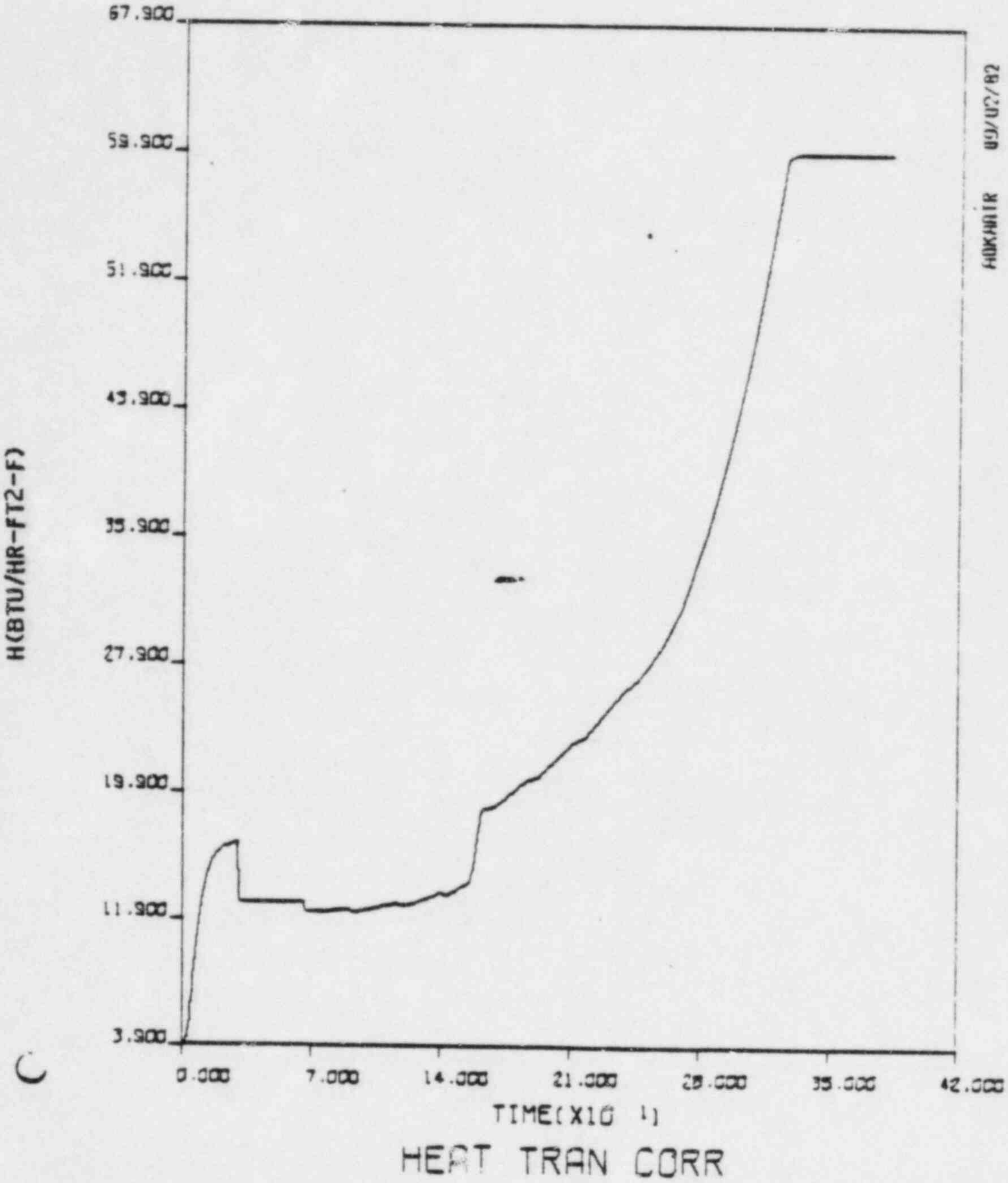


Figure 6-11 a): Predicted Heat Transfer Coefficient for Skewed Power Run ADKADZD

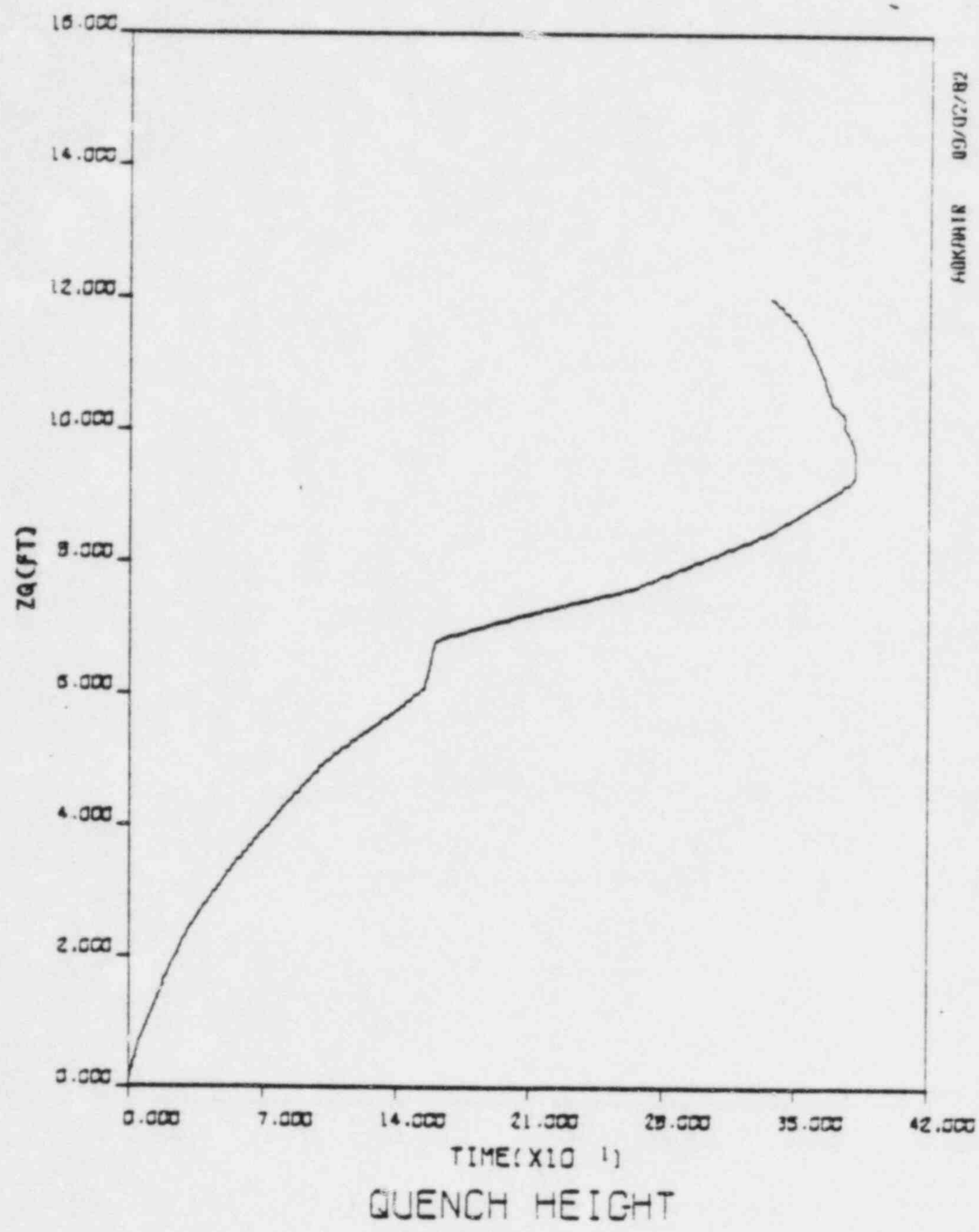


Figure 6-11 b): Predicted Quench Elevation for Skewed Power Run ADKADZD

7. FLECSET Computer Code Listing

```
C  ****************************************************
C
C   REFLOOD HEAT TRANSFER COEFFICIENT CORRELATION
C
C    REF. ----- NUREG/CR-2256   NOVEMBER 1981
C
C  ****************************************************
C
      REAL KF,KG,NU1,NU2,NU3,NU
      DIMENSION QAXZQ(100),QAXTB(100),FAXTB(100),FAXZ(100)
     1          ,PDCAY(100),PDCT(100),VINTM(100),VINTB(100)
      DIMENSION TX(300),HTC(300),ZONCH(300),ARRAY(10)
      COMMON/STP/IUNIT,IFLAG,IPHASE,T,P,V,H,S,U,X,CSUBPI,
     1       XKAPPAI,BETAI,SPEED
C
      CALL INLIST
C
C     SET DEBUG FLAGS
      IDBUG = 0
      IDBFLG = 0
C
C  ****************************************************
C
C   GENERAL INPUT
C
C  ****************************************************
C
      READ (5,1000)DTSUB,F,TINIT,PWFT,MR
      CALL PIKL(8HDTSUB(F),DTSUB,7HP(PSIA),F,8HTINIT(F),TINIT
     1,11HPWFT(KW/FT),PWFT,2HMR,MR)
 1000 FORMAT(4F10.5,I5)
      READ (5,1010) Z,ZDBUG,ZPEAK,DR,DE,A
      CALL PIKL(5HZ(FT),Z,9HZDBUG(FT),ZDBUG,9HZPEAK(FT),ZPEAK
     1,6HDR(FT),DR,6HDE(FT),DE,6HA(FT2),A)
 1010 FORMAT(5F10.5,F10.8)
      READ(5,1015) POPOX,RCPAF,RCPAR
      CALL PIKL(8HPOPOX(-),POPOX,5HRCPAF,RCPAF,5HRCPAR,RCPAR)
 1015 FORMAT (3F10.8)
      READ (5,1020) NVIN,NDECAY,NINTPR,NPSHPE
      CALL PIKL(4HNVIN,NVIN,6HNDECAY,NDECAY,6HNINTPR,NINTPR,
     1        6HNPSHPE,NPSHPE)
 1020 FORMAT(4I10)
C
C  ****************************************************
C
C   TABLE OF TIME VS VIN
C
C  ****************************************************
C
      WRITE(6,1100)
 1100 FORMAT (1H0,2X,* TABLE OF TIME VS VIN */)
      WRITE (6,1105)
 1105 FORMAT (10X,*TIME*,10X,*VIN(IN/S)*/)
      DO 1110 J = 1,NVIN
      READ (5,1300) VINTM(J),VINTB(J)
      WRITE (6,1301) VINTM(J),VINTB(J)
 1110 CONTINUE
C  ****************************************************
C
C          TABLE OF NORMALIZED POWER DECAY
C
C
   ....................................................
```

```
C
      WRITE (6,1200)
 1200 FORMAT (1H0,2X,*TABLE OF NORMALIZED POWER DECAY*/)
      WRITE (6,1210)
 1210 FORMAT (10X,* TIME *,10X,* PDCAY */)
      DO 1220 J = 1,NDECAY
      READ (5,1300) PDCT(J),PDCAY(J)
      WRITE (6,1301) PDCT(J),PDCAY(J)
 1220 CONTINUE
C
C  ***************************************************
C
C   TABLE OF NORMALIZED INTEGRAL OF POWER
C
C  ***************************************************
C
      WRITE (6,1230)
 1230 FORMAT (1H0,2X,* NORMALIZED INTEGRAL OF POWER */)
      WRITE (6,1240)
 1240 FORMAT (10X,*HEIGHT(FT)*,5X,* QAXTBS */)
      DO 1250 J = 1,NINTPR
      READ (5,1300) QAXZQ(J),QAXTB(J)
      WRITE (6,1301) QAXZQ(J),QAXTB(J)
 1250 CONTINUE
C
C  ****************************************************
C
C   TABLE OF AXIAL POWER SHAPE FACTOR
C
C  ****************************************************
C
      WRITE (6,1260)
 1260 FORMAT (1H0,2X,* TABLE OF AXIAL POWER SHAPE FACTOR */)
      WRITE (6,1270)
 1270 FORMAT(10X,* FAXZ(FT) *,5X,* FAXTB */)
      DO 1280 J = 1,NPSHPE
      READ (5,1300) FAXZ(J),FAXTB(J)
      WRITE (6,1301) FAXZ(J),FAXTB(J)
 1280 CONTINUE
C
C  *****************************************************
C
C  INPUT IS COMPLETE
C
C  *****************************************************
 1300 FORMAT(2F10.5)
 1301 FORMAT(10X,2F10.5)
C
C  ****************************************************
C    STEAM PROPERTIES USING STP
C
C  ****************************************************
C
C
C   BRITISH UNIT
      IUNIT = 2
      IFLAG = 1
      PSAVE = P
C   LIQUID SAT PROPERTIES
      IPHASE = -1
      CALL ZZP
      HF = H
      VOLF = V
      TSAT = T
      CPF  = 1.0/CSUBP1
```

```
C     SAT LIQ TH.COND. BTU/S-FT-F
        KF    = TCW(IUNIT,ICHEK,V,T)/3600.0
C     SAT LIQ VISCOSITY LBM/FT-SEC
        VISF = DVW(IUNIT,ICHEK,V,T)*32.0
C     SAT VAPOR PROPERTIES HG,SP,VOL
        IPHASE = 1
        P = PSAVE
        CALL ZZP
        P = PSAVE
        HG = H
        VOLG = V
C     SAT THER. COND BTU/S-FT-F
        KG = TCW(IUNIT,ICHEK,V,T)/3600.0
        WRITE(6,200)TSAT,VOLF,VOLG,HF,HG,KF,KG,VISF,CPF
  200   FORMAT(1H0,2X,*TSAT=*,F10.6,5X,*VOLF=*,F10.8,5X,*VOLG=*,
     1 F10.7,5X,*HF=*,F10.5,5X,*HG=*,F10.5,5X,*KF=*,F10.7/
     2 5X,*KG=*,F10.8,5X,*VISC=*,F10.7,5X,*CPF=*,F10.7)
C
C     PROPERTY CALCULATION IS OVER
C
C  ******************************************************
C
C   CALCULATION BEGINS
C
C  ******************************************************
C
      WRITE (6,2050)
 2050 FORMAT (1H1,9X,20H********************,/)
      WRITE (6,2060)Z
 2060 FORMAT (10X,*THE RESULTS OF THIS TEST CASE*,5X,*Z = *
     1  F10.5,5X,* FT */)
      WRITE (6,2070)
 2070 FORMAT (10X,20H********************,//)
      WRITE (6,2100)
 2100 FORMAT(15X,4HTIME,8X,1HH,8X,6HZQ(FT),8X,5HH(SI),
     1 7X,5HZQ(M),3X,8HVQ(IN/S),4X,9HVIN(IN/S))
      WRITE(6,2101)
 2101 FORMAT(23X,14H(BTU/HR-FT2-F)//)
      CALL INTERP(FAXZ,FAXTB,NPSHPE,Z,FAX)
      QMAX = PWFT*POPOX
      TINITZ = (TINIT-TSAT)*FAX+TSAT
      H1 = 0.215*QMAX*0.9481*FAX/RCPAR*(1.-EXP(-(TINITZ-700.)/435.))
      IF (TINITZ .LT. 700.) H1=0.
      RHOG=1./VOLG
      RHOF=1./VOLF
      RHOGF=RHOG/RHOF
      CT=(TINIT-TSAT)/(500.-TSAT)
      HFG=HG-HF
      H=H1
      HSI=H*5.67826
      DZQ = 0.005
      T=0.
      ZQ=0.
      CALL INTERP(QAXZQ,QAXTB,NINTPR,ZPEAK,QAXZPK)
      CALL INTERP(VINTM,VINTB,NVIN,0..VIN)
      JTYPE=0
      IPLOT = 1
      I = 1
      J=1
15    CONTINUE
C  ******************************************************
C
C  COMPUTE QUENCH FRONT ELEVATION
C
```

```
C  ***************************************************************
C
      IF (ZQ .GE. ZDBUG) IDBUG = 1
      IF (ZDBUG .LE. 0) IDBUG = 0
      IF (IDBFLG .NE. 0) IDBUG =0
      ZQ=ZQ+DZQ
      DO 40 IVQ=1,2
      IF (IVQ .EQ. 1) ZQ=ZQ-.0005
      IF (IVQ .EQ. 2) ZQ=ZQ+.0005
      CALL INTERP (QAXZQ,QAXTB,NINTPR,ZQ,QAX)
      QEQ1 = QMAX
      IF(MR .EQ. 2)QEQ1 = QEQ1*1.1
      QEQ = QEQ1
      CALL INTERP(FAXZ,FAXTB,NPSHPE,ZQ,FAX)
      TINITE=(TINIT-TSAT)*FAX+TSAT
      DTC=800.
      DTE=DTC/(1.+60.**(1.08*(TINIT-TSAT)/DTC-1.26))
      TE=TINIT+DTE
      TEZ=TSAT+(TE-TSAT)*FAX
      QEFFZ=.7*FAX*.9481
      CALL INTERP(VINTM,VINTB,NVIN,T,VIN)
      RE=VIN/12.*RHOF*DE/VISF
      FH=1./(1.+70.**(1.-.0133*(ZPEAK/DR)))
      ZS=6329.*(RE+4000.)**(-1.468)*VIN/12.*RHOF
     1*CPF*DE*DE/KF*FH
      ZAD=0.852*RCPAF*DTSUB*VIN/12./QMAX/.9481-.234*RCPAR
     1*(TINIT-TSAT)*VIN/12./QMAX/.9481+1.147*FH
      IF (ZAD .LE. 0.) ZAD=0.
      FDTSUB=EXP(-10.09*(CPF*DTSUB/HFG))
      FVIN2=1.3*EXP(-1.652E-9*RE*RE/RHOGF**.524)
      FVIN3=EXP(-7.293E-9*RE*RE/RHOGF**.524)
      FVIN4=66203.*RHOGF**.2882/RE**1.1-2.8*EXP(-.000122*
     1RE/RHOGF**.262)
      FVIN5=1.+.5/(1.+50**(2.-.00008137*RE/RHOGF**.262))
      FP1=1.+.5*EXP(-5.6251E+08*RHOGF*RHOGF*RHOGF)
      FP2=17.3*EXP(-5.6251E+08*RHOGF*RHOGF*RHOGF)
      FP3=FP1
      FP4=1.+.32/(1.+50.**(5.-2520.*RHOGF))
      CT=(TINITE-TSAT)/(500.-TSAT)
      FT1=1.01552+.01398*CT
      FT2=1.05*EXP(-.66-.59*CT)
      FVSUB=.3+.7*(1.-EXP(-10.31E-8*RE*RE/RHOGF**.524
     1))-2.9E-11*RE*RE*RE/RHOGF**.786*EXP(-9.3E-8*RE*RE
     2/RHOGF**.524)/(1.+50.**(-15.75*(CPF*DTSUB/HFG)+1.333))
      IF (IDBUG .NE. 1) GO TO 400
       CALL PIKL(1HT,T,2HZQ,ZQ,3HFAX,FAX,2HRE,RE,2HFH,FH,2HZS,ZS,
     1  3HZAD,ZAD,6HFDTSUB,FDTSUB,5HFVIN2,FVIN2,5HFVIN3,FVIN3,
     2  5HFVIN4,FVIN4,5HFVIN5,FVIN5,3HFP1,FP1,3HFP2,FP2,3HFP4,FP4,
     3  2HCT,CT,3HFT1,FT1,3HFT2,FT2,5HFVSUB,FVSUB)
  400 CONTINUE
      DO 20 K = 1,3
                 QDLS=.9481*QAXZPK/RHOF/A/VIN*12./HFG
      CQ=QEQ*QDLS
      FVQ1=-.7*(1.-EXP(-.0000801*RE/RHOGF**.262))
      FVQ2=6.458E-5*RE**1.938/RHOGF**.5078*(CQ*DR/ZPEAK)**1.5
      FVQ=FVQ1+FVQ2
      FQ=1.-.16/(1.+70.**(1250.*(DR/ZPEAK)-5.45))
     1/(1.+80.**(7.14*CQ-4.93))
      TQ=(FDTSUB*FVQ*(FP1+FVIN2+FP2*FVIN3)
     1+FVIN4*FP3)*(FT1-FT2*FVIN5*FP4)*FVSUB*FQ
      TQA = TQ
      TQ=ZPEAK/VIN*.00228*RE*RHOGF**(-.262)*TQ
      TQPEAK = TQ
      FR1=.5
```

```
      FR2=9.
      QR = QAX/QAXZPK
      FQ=QR+FR1*QR*EXP(-FR2*QR*QR)
      TQ=TQ*FQ
      TQ=ZQ/VIN*12.+(TQ-ZQ/VIN*12.)/(1.+50.**
     1(-(TINITE-400.)/(400.-TSAT)))
      CALL INTERP(PDCT,PDCAY,NDECAY,TQ,PDECAY)
      QEQ=QEQ1*PDECAY
      IF (IDBUG .NE. 1) GO TO 450
      CALL PIKL(3HQEQ,QEQ,4HQDLS.QDLS.4HFVQ1.FVQ1.4HFVQ2.FVQ2.3HFVQ.
     1 FVQ.2HFQ.FQ.3HTQA.TQA.6HTQPEAK.TQPEAK.3HQAX.QAX.2HFQ.FQ.
     2 2HTQ.TQ.6HPDECAY.PDECAY.3HQEQ.QEQ)
 450  CONTINUE
 20   CONTINUE
      IF (IVQ .EQ. 1) ZQ1=ZQ
      IF (IVQ .EQ. 1) TQ1=TQ
      IF (IVQ .EQ. 2) ZQ2=ZQ
      IF (IVQ .EQ. 2) TQ2=TQ
40    CONTINUE
      VQ=(ZQ2-ZQ1)/(TQ2-TQ1)
      VQINCH=VQ*12.
C
C  **************************************************
C
C  COMPUTE HEAT TRANSFER COEFFICIENT
C
C  **************************************************
C
      ZQM=ZQ*.3048
      IF(J.EQ.1) WRITE (6,2200)T.H.ZQ.HSI.ZQM.VQINCH.VIN
C     STORE INITIAL VALUES FOR PLOT
      IF(J .NE. 1) GO TO 300
      TX(IPLOT) = T
      HTC(IPLOT) = H
      ZQNCH(IPLOT) = ZQ
 300  CONTINUE
      T=T+DZQ/VQ
      X=4.*(ZQ-ZAD)/ZS
      NU1=H1/3600.*DE/KG
      H3=QEFFZ/(TEZ-TSAT)/DR*1.21*(1.-EXP(-.0000305*RE/RHOGF
     1**.262))
     2*(.714+.286*(1.-EXP(-3.05E-4*RHOGF**1.524/RE/RE)))
      NU3=H3*DE/KG
      NU2=NU3+108.*EXP(-.0000183*RE/RHOGF**.262)*
     1EXP(-.0534*(Z-ZQ)/DE)
      IF (ZQ .LE. ZAD) NU=NU1
      IF (ZQ .LT. (ZS+ZAD) .AND. ZQ .GT. ZAD) NU=NU1*
     1(1.-EXP(2.5*X-10.))+(NU2-NU1*(1.-EXP(2.5*X-10.)))
     2*(1.-EXP(-X)-.9*X*EXP(-X*X))
      IF (ZQ .GE. (ZS+ZAD)) NU=NU2
      IF (Z .LE. ZPEAK) GO TO 27
      CALL INTERP(FAXZ.FAXTB.NPSHPE.Z.FAX)
27    CONTINUE
      IF (Z .GT. ZPEAK) NU=NU-44.2*(1.-FAX)*EXP(-.00304
     1*(Z-ZPEAK)/DE)
      JTYPE=JTYPE+1
      H=NU*KG*3600./DE
      HSI=H*5.67826
      IF(IDBUG .NE. 1) GO TO 500
      CALL PIKL(1HX,X,3HNU1.NU1.2HH3.H3.3HNU3.NU3.3HNU2.NU2.2HNU.NU.
     1  1HH,H)
 500  CONTINUE
      IF(JTYPE.EQ.20)WRITE (6,2200)T,H,ZQ,HSI.ZQM,VQINCH,VIN
2200  FORMAT(12X,F10.5.F12.4.F10.5.F12.4,3F10.5/)
```

```
      IF (JTYPE .EQ. 20) JTYPE=0
      J=J+1
C    STORE INFORMATION FOR PLOT
      IF(I . NE . 10) GO TO 310
      TX(IPLOT) = T
      HTC(IPLOT) = H
      IF(H .GE. 60.0) HTC(IPLOT) = 60.0
      ZONCH(IPLOT) = ZQ
      IPLOT = IPLOT+1
      I = 0
 310  CONTINUE
      I=I+1
      IF(ZQ .GE. 12.) GO TO 30
      IF(IDBUG .EQ. 1) IDBFLG = 1
      GO TO 15
30    CONTINUE
C
C   ************************************************
C
C   PLOT HTC AND ZQ
C
C   ************************************************
C
        IPLOT =IPLOT-1
C     START PLOTTING HTC COEFF AND ZQ
        NFLAG = 0
        CALL QPLOT(TX,HTC,IPLOT,4HTIME,13HH(BTU/HR-FT2),14HHEAT TRAN CORR
     1,4,13,14,APRAY,NFLAG)
        NFLAG = 0
        CALL QPLOT(TX,ZONCH,IPLOT,4HTIME,6HZQ(FT),13HQUENCH HEIGHT,4,6
     1,13,ARRAY,NFLAG)
        NFLAG = -1
        CALL QPLOT(TX,HTC,IPLOT,IX,IY,IG,NIX,NIY,NIG,ARRAY,NFLAG)
        WRITE(6,3000)
 3000 FORMAT(1H0,30H***** END OF CALCULATION *****)
      STOP
      END
      SUBROUTINE INTERP(X,Y,L,X1,Y1,SLOPE)
      DIMENSION X(100),Y(100)
      DO 100 K=1,L
      K1=K
      IF (X(K1)-X1) 100,100,200
100   CONTINUE
200   Y1=Y(K1-1)+((X1-X(K1-1))/(X(K1)-X(K1-1)))
     1*(Y(K1)-Y(K1-1))
      SLOPE=(Y(K1)-Y(K1-1))/(X(K1)-X(K1-1))
      RETURN
      END
```

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