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TECHNICAL EVALUATION REPORT

TUE-1 DEPARTURE FROM NUCLEATE BOILING CORRELATION

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ABSTRACT

An evaluation of the departure from nucleate boiling correlation developed by Texas Utilities Electric Company was performed. The correlation is an empirically derived function of the local coolant thermodynamic state and mass flux at which departure from nucleate boiling (DNB) is observed to occur. The correlation is designated as TUE-1 and will be used by TU Electric to support the operational transient analysis for licensing and safety calculations for the Comanche Peak Steam Electric Station (CPSES).

SUMMARY

This report documents the review and evaluation of the TUE-1 departure from nucleate boiling correlation developed by Texas Utility Electric Company. This correlation is developed to evaluate the DNB heat flux for Westinghouse 17x17 fuel assemblies with R type mixing vane grids and Advanced Nuclear Fuel (ANF) 17x17 fuel assemblies. TU Electric reports RXE-88-102-P and RXE-88-102-P, Supplement 1[1,2] documenting the development of the TUE-1 DNB correlation for these fuel designs were submitted to the Office of Nuclear Reactor Regulation of the U.S. Nuclear Regulatory Commission (NRR/NRC) for approval in performing operational transient analysis for licensing and safety analysis at Comanche Peak. The NRR/NRC staff requested assistance from the Idaho National Engineering Laboratory (INEL) in reviewing the TUE-1 correlation.

The review consisted of evaluating the TUE-1 correlation, the data base supporting development of correlation, and the statistical characterization of the correlation. The review was performed using the information provided by TU Electric as documented in RXE-88-102-P and RXE-88-102-P, Supplement 1 and the responses to the requests for additional information submitted by the NRR/NRC to TU Electric regarding the development and use of the correlation.

Based on this review, it is recommended that the TUE-1 correlation be accepted for assessments of departure from nucleate boiling during operational transients at Comanche Peak for the Westinghouse 17x17 fuel assemblies with R type mixing vane grids and the ANF 17x17 fuel assemblies subject to the restrictions presented in Section 3 of this report.

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1.0 INTRODUCTION

The TUE-1 correlation was developed by Texas Utilities Electric Company for assessing the departure from nucleate boiling (DNB) for Westinghouse 17x17 fuel with R-type mixing vane grids and Advanced Nuclear Fuel (ANF) 17x17 fuel assemblies at typical reactor operating conditions at the Comanche Peak Steam Electric Station. Comanche Peak is a two unit Westinghouse 4-loop pressurized water reactor (PWR) utilizing Westinghouse 17x17 fuel with R-type mixing vane grids. TU Electric reports RXE-88-102-P and RXE-88-102-P, Supplement 1[1,2] documenting the TUE-1 correlation were submitted to the Office of Nuclear Reactor Regulation of the U.S. Nuclear Regulatory Commission (NRR/NRC) by TU Electric for review and acceptance for licensing applications as a method to assess the DNB safety limit for operational transient analysis in support of fuel reload at Comanche Peak in a manner that conforms to NRC requirements.

The NRR/NRC is responsible for the evaluation and review of computer codes, analysis methods, and their proposed application. The NRR/NRC requested assistance from the Idaho National Engineering Laboratory (INEL) in reviewing the TUE-1 correlation for predicting DNB. Specifically, the request for assistance included:

1. Evaluation of the correlation.
2. Evaluation of the correlation data base and experimental measurements used to develop the correlation.
3. Evaluation of the statistical characterization of the TUE-1 correlation and uncertainty treatment.

Following the above review, NRR/NRC requested additional information from TU Electric. The INEL reviewed and evaluated the TU Electric responses to NRR/NRC questions regarding the development and use of the correlation. The responses to the requests for additional information are contained in Appendix A to this report.

This technical evaluation report contains the results of the review of the TUE-1 correlation for application to operational transient analysis for fuel reload at Comanche Peak. Section 2 provides a discussion of the correlation, the experimental basis, and statistical development. Section 3 identifies the restrictions to be imposed on the application of the correlation for licensing purposes, while Section 4 summarizes the conclusions from the TUE-1 correlation review.

2.0 TUE-1 CORRELATION

This section presents a brief description of the TUE-1 departure from nucleate boiling correlation discussing the correlation, the experimental basis upon which it was developed, the statistical characterization of the correlation and its intended applications.

2.1 Description of the TUE-1 Correlation

The TUE-1 correlation was developed by TU Electric for application to licensing and safety calculations regarding the assessment of operational transients for Comanche Peak. The TUE-1 correlation was developed specifically for evaluation of Westinghouse 17x17 fuel with R-type mixing vane grids and Advanced Nuclear Fuel (ANF) 17x17 fuel assemblies for typical reactor operating conditions at Comanche Peak.

The TUE-1 correlation is an empirically derived correlation which has the following form:

$$QDNB = E - F * X$$

Where:

QDNB is the predicted DNB heat flux,

X is the local equilibrium quality,

E and F are functions of parameters such as grid spacing, mass flux, system pressure, etc.

The correlation is based on data derived from experiments on test assemblies to determine the measured heat flux at DNB as a function of fuel geometry and thermal hydraulic conditions. Experimental data based on uniform and non-uniform power distributions were also obtained and the correlation includes factors for both geometry and non-uniform axial power distributions. The VIPRE-01 computer program was used to perform the subchannel analysis[3] to determine the predicted heat flux. Provisions are also included in the VIPRE-01 simulation of the fuel assembly to accommodate turbulent mixing which affects the enthalpy transport between subchannels due to turbulent exchange

and diversion crossflow. Statistical analysis was also performed on the ratio of minimum predicted DNB heat flux to measured DNB heat flux (MDNBR) to check for bias, statistical combinability and to determine the DNBR limit at a 95 percent probability at a 95 percent confidence level.

2.2 Data Base, Predictive Capability and Statistical Capability

The data base used to develop the TUE-1 correlation for Westinghouse 17x17 fuel consists of 934 data points taken from the Columbia University DNB experimental data bank. This data bank includes over 11,000 points from a total of 235 test sections compiled over a 20 year period at the Columbia University Heat Transfer Research Facility and was published in 1982. This data was selected for the TUE-1 data base since it is considered to be representative of Westinghouse fuel with R type mixing vane grid design. The TUE-1 correlation was also evaluated for application to analysis of the ANF 17x17 fuel based on data developed specifically for the fuel design.

Data for Westinghouse fuel is based on test sections with a R type mixing vane grid design and a grid spacing from 20 to 32 inches. These test sections consisted of 4x4 and 5x5 rectangular arrays of rods with heated lengths of 8 and 14 feet. The 4x4 array has a rod outer diameter of 0.422 inch, which is representative of Westinghouse 15x15 fuel. The 5x5 array has a rod outer diameter of 0.374 inch, which is representative of Westinghouse 17x17 fuel. The data base includes both uniform and non-uniform axial heat flux profiles. The non-uniform profiles include cosine or usine(u) top peaked shapes. RXE-88-102-P notes that several test sections contained unheated rods to simulate control rod guide thimble tubes for analysis of the "cold wall" effect.

The 934 data points compiled for development of the TUE-1 correlation for Westinghouse 17x17 fuel excludes 34 points in the original Columbia DNB data. The reasons for excluding these points cited in RXE-88-102-P are: 1) 25 points were based on thermal hydraulic conditions outside the range of application for TUE-1, and 2) nine points were found to be statistical outliers based on an evaluation using Chauvenet's criterion.

The TUE-1 correlation was incorporated into the VIPRE-01 computer program and analyses performed to determine the predicted DNB heat flux for each test point in the data base. The ratios of the predicted DNB heat flux to the measured heat flux or MDNBR was used in a statistical analysis to measure the ability of the TUE-1 correlation, as incorporated into VIPRE-01, to predict the DNB heat flux. The VIPRE-01 analyses utilized the EPRI void model and the Columbia/EPRI two phase multiplier for this analysis.

The overall mean of the distribution from the VIPRE analysis was determined to be 1.0018 with a standard deviation of 0.0884 as presented in RXE-88-102-P. Statistical tests to check that the data is normally distributed and to check statistical combinability were performed. The data were found to be normally distributed based on application of the D' test. Statistical combinability to determine whether the correlation is biased to any particular group of experimental data was tested using Bartlett's test and the general F test in RXE-88-102-P. The data were found to be statistically combinable with the exception of the axial heat flux profile group. RXE-88-102-P states that the correlation prediction is not biased to any particular subgroup of data since the mean of each subgroup is within one percent of the mean of the entire data set. The standard deviation of all of the subgroups of data are within one percent of the 8.84 percent standard deviation of the entire data set.

The 95/95 DNBR limit was determined using Owen's one-sided tolerance limit factor. Based on this calculation, the 95/95 DNBR limit was calculated to be 1.1547 which is rounded to 1.16.

The TUE-1 correlation was evaluated for application to analyses involving ANF 17x17 fuel as described in RXE-88-102-P, Supplement 1 using DNB data developed for ANF fuel. The procedure used is the same as that described above for Westinghouse fuel. The TUE-1 MDNBR limit of 1.16 was determined to also be applicable to ANF fuel. The effect of a mixed core on DNB was not discussed in RXE-88-102-P, Supplement 1. In this case, a mixed core refers to loading both Westinghouse and ANF fuel in the same core. These fuel types could be geometrically different which could affect the DNB predictions. No adjustment for a mixed core is included in the TUE-1 DNBR limit of 1.16.

In the INEL evaluation of the TUE-1 correlation, a random numerical check was performed to confirm that the conditions presented in Appendix A of RXE-88-102-P satisfy the TUE-1 correlation for uniform axial heat flux. The INEL evaluation confirmed the TU Electric analysis. In addition, a parametric analysis of the TUE-1 correlation was performed to determine how well the correlation extrapolates outside of its intended data range. It was found that significant errors can result if the TUE-1 correlation is applied outside of its data range.

The response to the request for additional information regarding the statistical basis of the correlation, the use of the term boiling length, and extrapolation of the TUE-1 correlation outside of its data range was provided by TU Electric and is presented in Appendix A. The responses were found to be acceptable, although it is required that checks be included in the VIPRE code to print a warning message in the code output if the correlation is inadvertently used outside its range of validity. TU Electric notes that DNB will be assumed to occur if any of the calculated conditions are outside the range of the TUE-1 correlation.

3.0 RESTRICTIONS

Based on results of the review of the TU Electric TUE-1 DNB correlation, the following restrictions are identified:

3.1 The TUE-1 DNB correlation shall be restricted to evaluations of the Westinghouse 17x17 fuel with R-grid mixing vane fuel or ANF 17x17 fuel for the range of fuel design parameters given in Table 1.

3.2 Should any of the conditions fall outside the ranges identified in restriction 3.1 above, then DNB shall be assumed to occur.

3.3 The use of the TUE-1 DNB correlation shall be limited to assessments with the VIPRE-01 computer code as described in RXE-88-102-P. Application is restricted to VIPRE-01 since other codes may not predict the same local hydraulic conditions as that calculated by VIPRE-01, which was used to develop the correlation and predict the test data.

3.4 The VIPRE-01 computer program shall be modified to clearly identify in the output from the code that the geometric or thermal hydraulic conditions have fallen outside of the range of application for the TUE-1 correlation.

3.5 The TUE-1 DNB correlation is to be used only for evaluation of steady state overpower and Chapter 15 transients, excluding LOCA, at the Comanche Peak Steam Electric Plant.

The review contained herein pertains only to an assessment of the development of the TUE-1 DNB correlation only. While the VIPRE-01 subchannel code was used to perform analyses of the test data and is documented in TU Electric report RXE-89-002, this review does not represent the technical review necessary to determine the acceptability of the use of the VIPRE-01 code for specific reload licensing applications. As such, the technical review contained herein pertains only to the TUE-1 correlation itself. The use of the VIPRE-01 code with modifications to address the prediction of the Columbia University test data was found to be acceptable only for its use in developing the TUE-1 correlation.

Table 1
Range of Application for the TUE-1 Correlation

Pressure:	1485 to 2435	psia
Local Mass Flux:	0.93 to 3.53	$Mlbm/hr\text{-}ft^2$
Local Quality:	-0.15 to 0.30	
Local Heat Flux:	0.14 to 1.15	$MBTU/hr\text{-}ft^2$
Inlet Subcooling:	30 to 350	BTU/lbm
Mixing Vane Grid Spacing:	20 to 32	inches
Heated Length:	96 to 168	inches
Wetted Hydraulic Diameter:	0.37 to 0.51	inches
Heated Hydraulic Diameter:	0.46 to 0.58	inches

Note:

Range of application data taken from page 2-5 of RXE-88-102-P.

4.0 CONCLUSIONS

The TUE-1 correlation was submitted for approval for use by TU Electric i. evaluating DNB for Westinghouse 17x17 fuel with R grid mixing vane fuel and ANF 17x17 fuel for the Comanche Peak Steam Electric Station. The review and evaluation of the data base, development of the TUE-1 DNB correlation, and statistical characterization has demonstrated that the correlation is acceptable for steady state overpower conditions and reload applications to Chapter 15 transient analyses, excluding LOCA. It is noted that the DNBR limit of 1.16 does not include any adjustment for when a mixed core is analyzed. It is therefore recommended that the TUE-1 correlation be accepted for use by TU Electric for operational transient assessment at the Comanche Peak Steam Electric Plant, subject to the restrictions identified in this Technical Evaluation Report.

5.0 REFERENCES

1. Huan B. Giap and Yi-Xing Sung, TUE-1 Departure From Nucleate Boiling Correlation, TU Electric Company, RXE-88-102-P, January, 1989

2. Huan B. Giap and David W. Hiltbrand, TUE-1 DNB Correlation, Supplement 1, TU Electric Company, RXE-88-102-P, Sup. 1, December, 1990

3. Yi-Xing Sung and Huan B. Giap, VIPRE-01 Core Thermal Hydraulic Analysis Methods for Comanche Peak Steam Electric Station Licensing Applications, TU Electric Company, RXE-89-002, June, 1989

APPENDIX A

Response to Request for Additional Information on TUE-1 Departure from Nucleate Boiling Correlation

TU ELECTRIC

Log # TXX-91402
File # 10010
915

October 30, 1991

William J. Cahill, Jr.
Group Vice President

U. S. Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, D. C. 20555

SUBJECT: COMANCHE PEAK STEAM ELECTRIC STATION (CPSES)-UNIT 1
DOCKET NO. 50-445
REQUEST FOR ADDITIONAL INFORMATION ON RXE-88-102
"TUE-1 DEPARTURE FROM NUCLEATE BOILING CORRELATION"

REF: Letter from the NRC to Mr. William J. Cahill, Jr. dated October 4, 1991, Requesting Additional Information regarding Topical Report RXE-88-102

Gentlemen:

Attached, please find TU Electric's response to the list of questions provided in the referenced letter.

Should clarification or additional information regarding responses to the referenced letter be required to enable the Staff to complete its review, contact Mr. Jimmy D. Seawright at 214/812-4375.

Sincerely,

William J. Cahill, Jr.

By:
D. R. Woodlan
Docket Licensing Manager

MCP/gj
Attachment

c - Mr. R. D. Martin, Region IV
Resident Inspectors, CPSES (2)
Mr. T. A. Bergman, NRR

Response to NRC Request
for Additional Information
on RXE-88-102-P

1. NRC Request: The number of experimental data points, 934, was tabulated for the effects of array size, axial heat flux distribution, grid pitch, heated length, and guide tubes. This translates to about 187 data points per effect. To complete the review of the TUE DNB correlation and comparisons with other correlations, please tabulate the number of data points corresponding to the various pressure levels and mass fluxes investigated during the testing.

   TU Electric Response: Four discrete pressure levels can be identified within the experimental data base used to develop the TUE-1 DNB Correlation. The ranges of these pressure levels and the respective number of data points within each range are:

Pressure Range	# of Data points within range
1485 - 1565 psia	208
1785 - 1825 psia	176
2045 - 2205 psia	281
2365 - 2435 psia	269

   The mass flux range over which the correlation was developed is not as conveniently discretized as the pressure range. As Figure 5-2 in RXE-88-102-P shows, the local mass flux is relatively continuously distributed over the entire range. However, to facilitate an assessment of the adequacy of the number of data points for a subset of the mass flux range, the following local mass flux levels, along with the number of data points in each level, have been selected:

Mass Flux Range	# of Data points within range
0.90 - 1.60 Mlbm/hr-ft2	172
1.60 - 2.25 Mlbm/hr-ft2	306
2.25 - 2.70 Mlbm/hr-ft2	187
2.70 - 3.53 Mlbm/hr-ft2	269

2. NRC Request: The nomenclature given on page 2-4 identifies Z_o as "the boiling length." In the literature, boiling length refers to the portion of the heated length that is experiencing boiling conditions, while TUE has chosen this parameter to be the distance from the inlet to the heated section to the point where boiling

first occurs. Please clarify that this parameter, which reflects the subcooled length, has been properly used in the development and use of the correlation.

TU Electric Response: The parameter Z_o, in the non-uniform axial heat flux factor, the standard Tong factor, does indeed represent the subcooled length of a channel. The use of the subcooled length as the lower limit in the integral in the Tong factor is consistent with the development of the Tong factor as described in Reference 3 of RXE-88-102-P. It has been correctly applied in both the development and the subsequent use of the TUE-1 DNB correlation.

3. NRC Request: To make the table on page 2-5 [of RXE-88-102] complete, please identify the ranges for the following parameters: 1) fuel rod diameter, 2) thimble guide tube diameter, 3) rod pitch, 4) distance from inlet at which DNB occurred, and 5) enthalpy at the DNB location. Please also supply the inlet temperature for the tests.

TU Electric Response: The ranges for items 1 through 4 requested above are:

Fuel Rod Diameter:	0.374 - 0.422 inches
Thimble Guide Tube Diameter:	0.482 - 0.544 inches
Rod Pitch:	0.496 - 0.555 inches
Distance to DNB:	68 - 168 inches

The range of the distance to DNB over which the correlation is considered applicable is not limited to distances greater than 68 inches even though this represents the lower limit of the experimental data used in the correlation development. As Figure 1 (attached) shows, the behavior of the calculated MDNBR exhibits no trend with changing distances to DNB. This behavior indicates that extrapolation below the 68" value is acceptable.

The range for the enthalpy at the DNB location is not identified. The equivalent fluid property which accounts for the effect of the local fluid energy on DNB and which is used directly as input into the TUE-1 correlation is the local quality. The local quality is used to establish the range of fluid energies over which the correlation can be considered valid. The range of the local quality is provided on page 2-5 of RXE-88-102-P.

Similarly, a parameter which reflects the inlet temperature and which represents the effect of inlet temperature on DNB is the inlet fluid energy with respect to saturation conditions. For this reason, the range of inlet subcooling in terms of Btu/lbm is more appropriate for defining a limiting range. The range of the inlet subcooling is given on page 2-5 of RXE-88-102-P.

4. NRC Request: To allow for a more quantitative measure of the bias, please provide fits of QDNB predicted as a function of QDNB measured for each test section and for all data combined. The intercept of the fits should have the value 0.0, with a slope of 1.0.

TU Electric Response: The fits of QDNB predicted as a function of QDNB measured for all data combined and for each test section individually have been performed using linear regression. The results of the linear regression fits are summarized in Table 1. Plots of predicted CHF versus measured heat flux for all test data combined and for each test section are provided in Figures 2 through 21. Two lines are shown on each plot. The top line represents the locus of points corresponding to a MDNBR of 1.16, which is the 95/95 limit for the TUE-1 DNB correlation. The other line represents the locus of points corresponding to a MDNBR of 1.0.

5. NRC Request: The correlation does not extrapolate outside the ranges of the experimental data base, and under certain conditions the correlation predicts negative values of the DNB heat flux. In view of these concerns, please describe the controls in the VIPRE-01 code to deal with such circumstances and also explain what is done when the VIPRE-01 calculated conditions exceed any of the experimental data base ranges, including the correlation and the Tong F-factor.

TU Electric Response: The VIPRE-01 code will terminate with a fatal error message if a negative critical heat flux is calculated. There are no controls within VIPRE-01 to flag when calculated conditions may be outside the range of applicability of the correlation. It is the responsibility of the user to ensure that the correlation has not been used outside its range of applicability. Should any of the calculated conditions exceed the range of the TUE-1 correlation, DNB would be assumed to occur.

6. NRC Request: Is there any intent to apply the TUE-1 correlation to fuel assemblies that have been reconstituted to include one or more dummy fuel rods? If so, define the configuration limits for such applications and justify the applicability of the experimental data base.

TU Electric Response: The TUE-1 correlation is considered to be applicable to reconstituted fuel assemblies with the limitation that the TUE-1 correlation cannot be applied to rods which share a single subchannel with two or more "cold" rods. ("Cold" rods are either guide thimble tubes, instrument thimble tubes, or reconstituted fuel rods.) This limitation is necessary because the

experimental data base does not include any test sections which simulate this configuration. The test sections in the TUE-1 correlation data base were designed to represent Westinghouse 15X15 and 17X17 fuel assemblies. Some of the test sections included an unheated rod to simulate a guide thimble tube or an instrument thimble tube. A "cold wall factor" is included in the TUE-1 correlation to account for the DNB behavior of a heated rod which shares a subchannel with an unheated rod as exhibited in the tests. The cold wall effect of a reconstituted fuel rod is considered to be comparable to the cold wall effect of the thimble tubes. Therefore, as long as the configuration of the reconstituted fuel assemblies does not include two or more unheated rods sharing a single subchannel, the experimental data base is cosidered to be representative of the fuel assembly and the TUE-1 correlation is applicable.

TABLE 1.

TEST SECTION NUMBER	NUMBER OF DATA POINTS	FIGURE NUMBER	SLOPE "m"	STD. ERROR OF "m"	Y INTERCEPT "b"	STD. ERROR OF "b"	R^2
ALL	934	2	0.92521	0.00802	0.04022	0.00487	0.93458
124	34	3	0.49569	0.07041	0.45141	0.06345	0.60764
125	33	4	0.56143	0.08606	0.43789	0.08299	0.57857
127	37	5	0.60838	0.10133	0.30744	0.09199	0.50739
131	37	6	0.86961	0.06641	0.05932	0.03167	0.83048
132	36	7	0.81511	0.07688	0.05845	0.03540	0.76778
134	38	8	1.09186	0.05874	-0.04428	0.02714	0.90565
139	38	9	0.93280	0.06286	0.03141	0.02953	0.85950
140	32	10	0.64434	0.08522	0.26891	0.07300	0.65581
146	38	11	0.82746	0.07195	0.07832	0.03593	0.78605
148	69	12	0.95622	0.03573	0.02506	0.01723	0.91445
153	41	13	1.17559	0.08458	-0.06700	0.04113	0.83202
157	78	14	0.85608	0.03555	0.09511	0.02252	0.88412
158	66	15	0.67323	0.04017	0.18308	0.02656	0.81445
160	66	16	0.65900	0.03852	0.22935	0.02644	0.82058
161	67	17	0.93811	0.05669	0.[illegible]2030	0.02554	0.80815
162	68	18	0.97977	0.02625	0.[illegible]2125	0.01277	0.95477
163	41	19	0.63544	0.07604	0.23757	0.04933	0.64162
164	69	20	0.99791	0.03054	0.00781	0.01385	0.94094
166	46	21	0.99344	0.08582	0.01251	0.04309	0.75283

FIGURE 1.

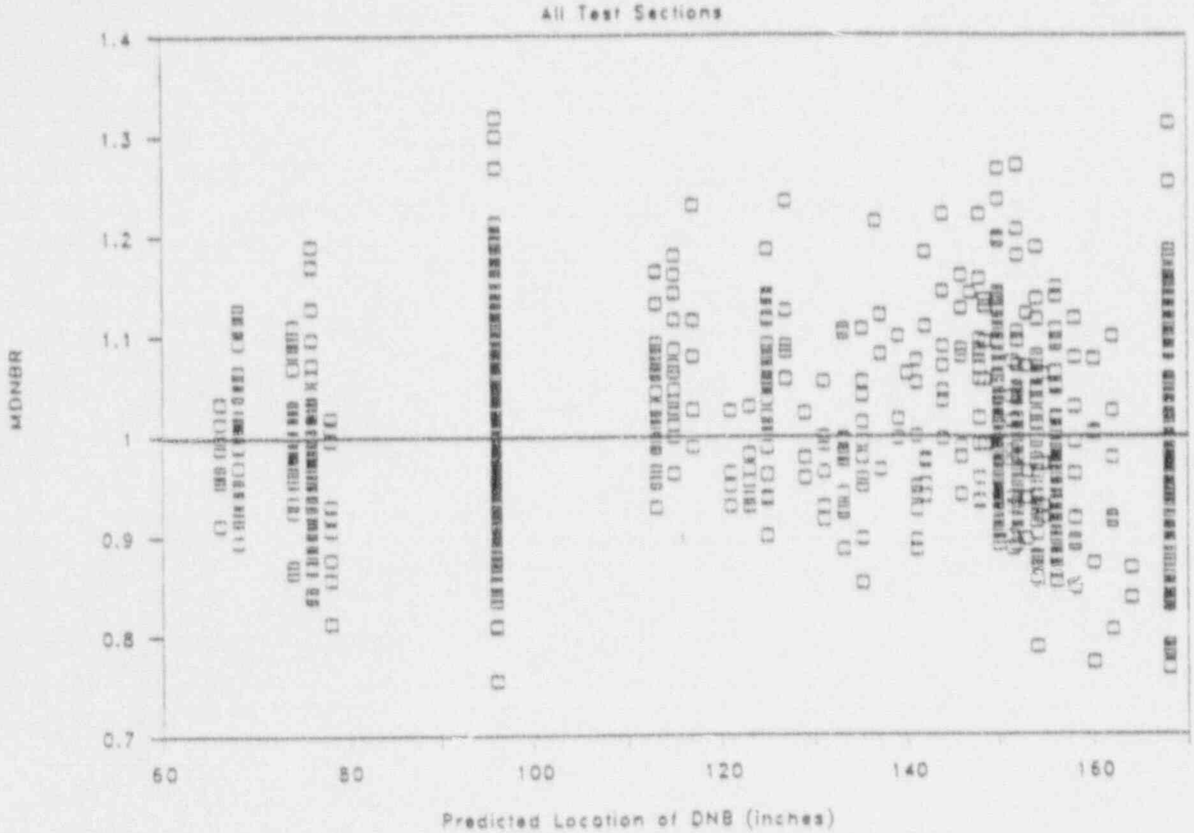


FIGURE 2.

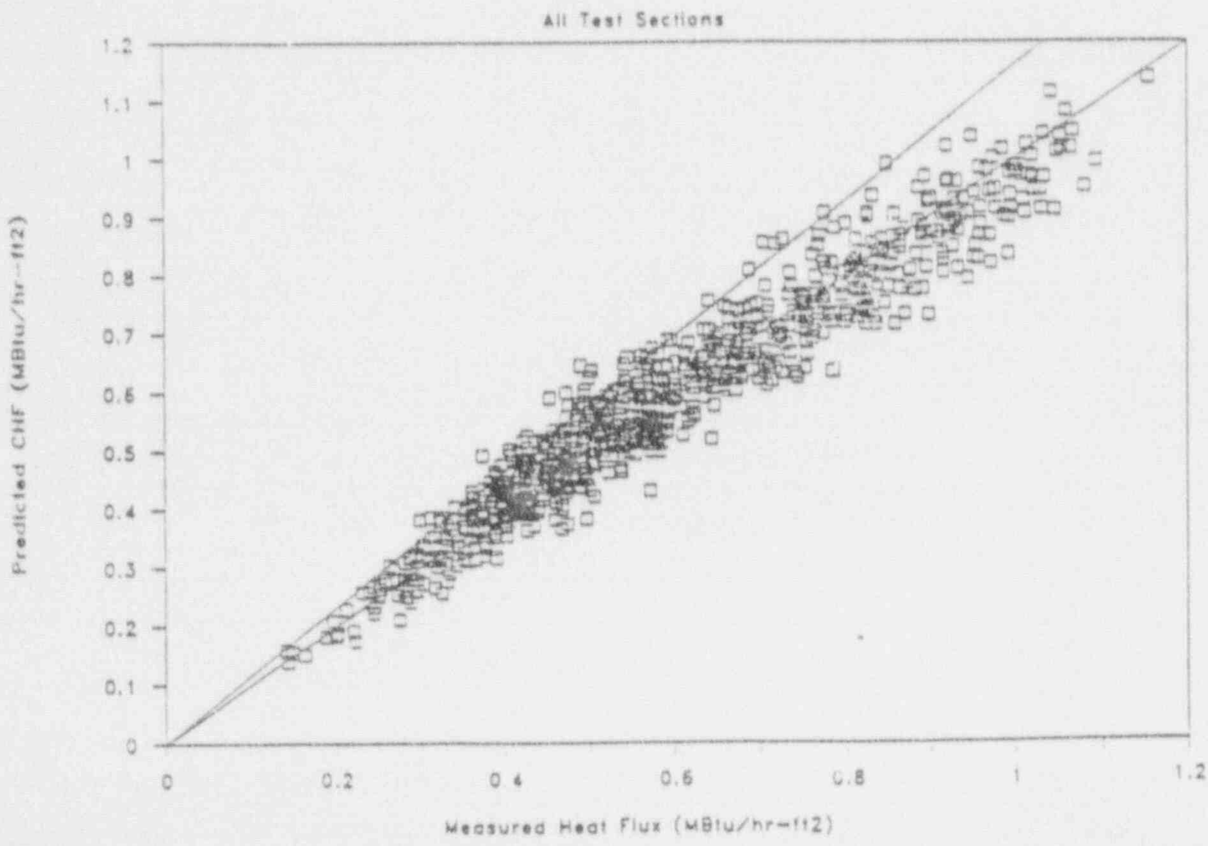


FIGURE 3.

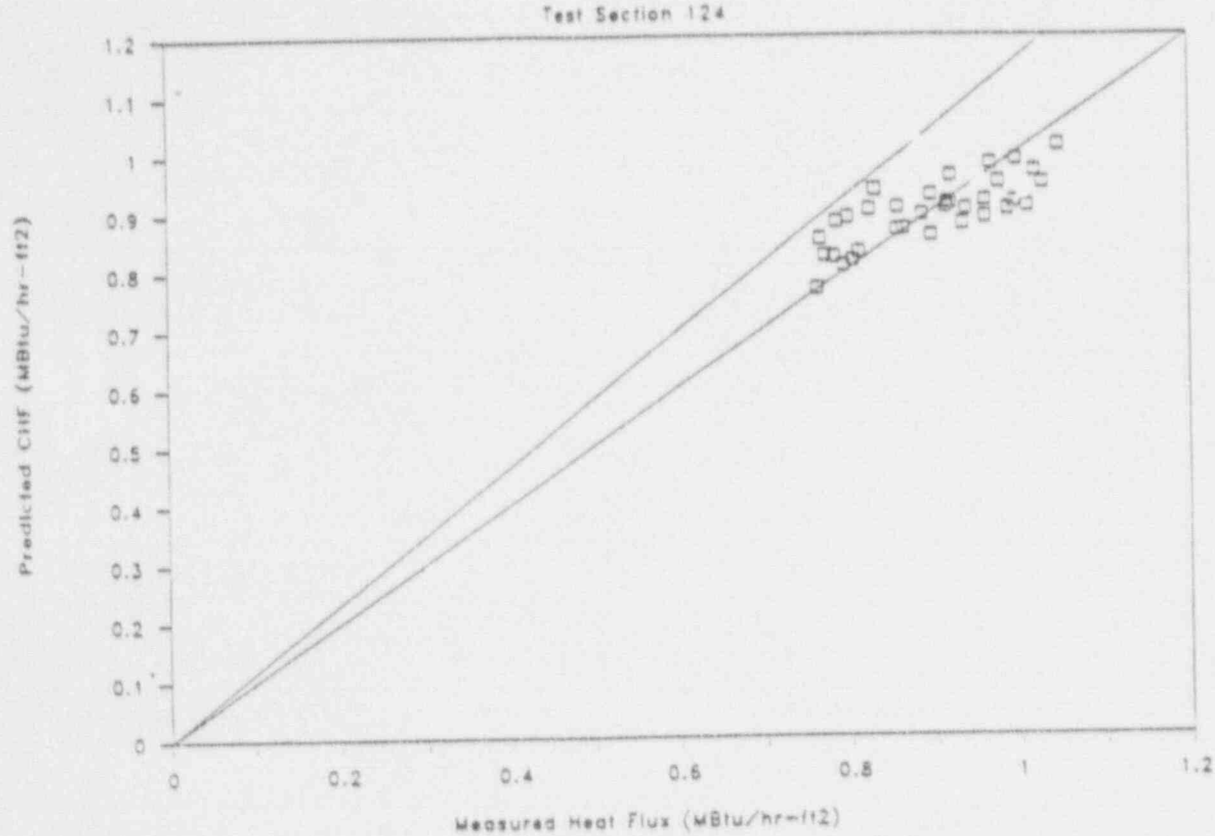


FIGURE 4.

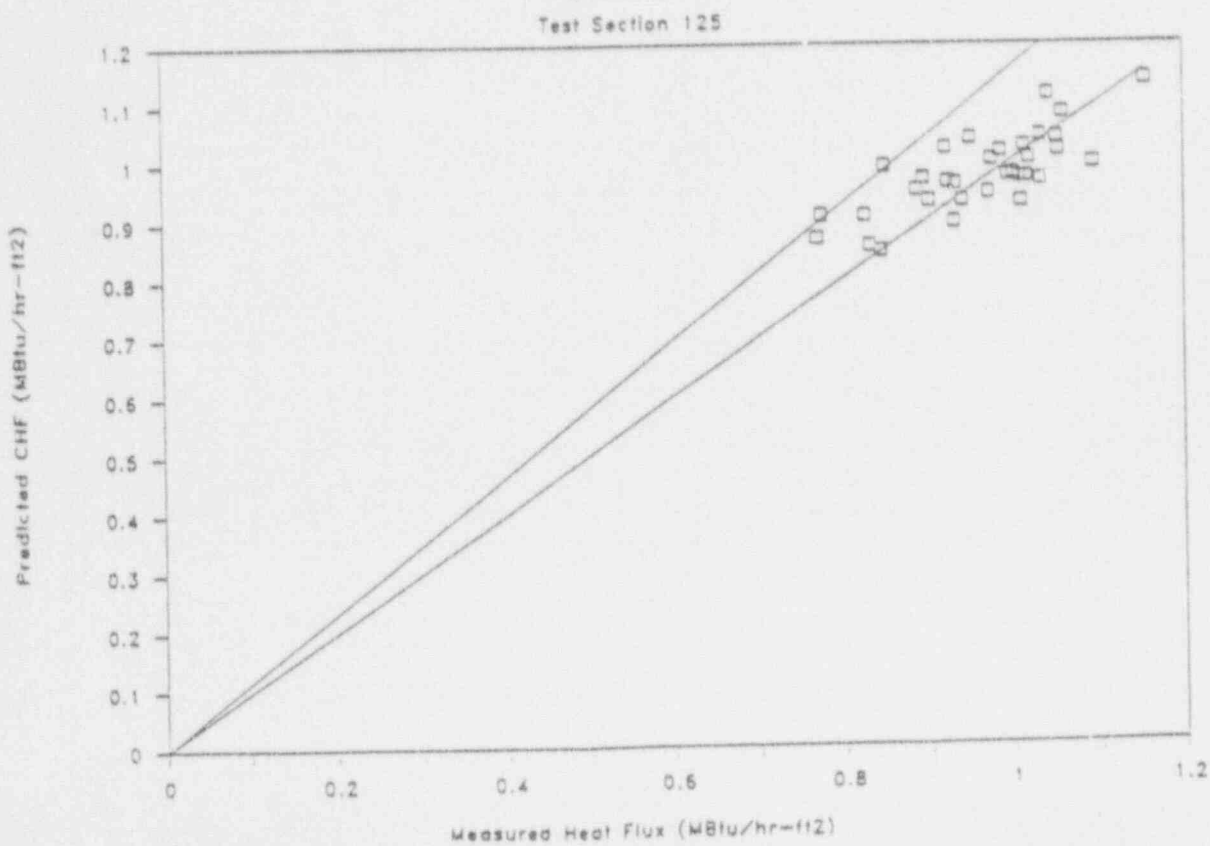
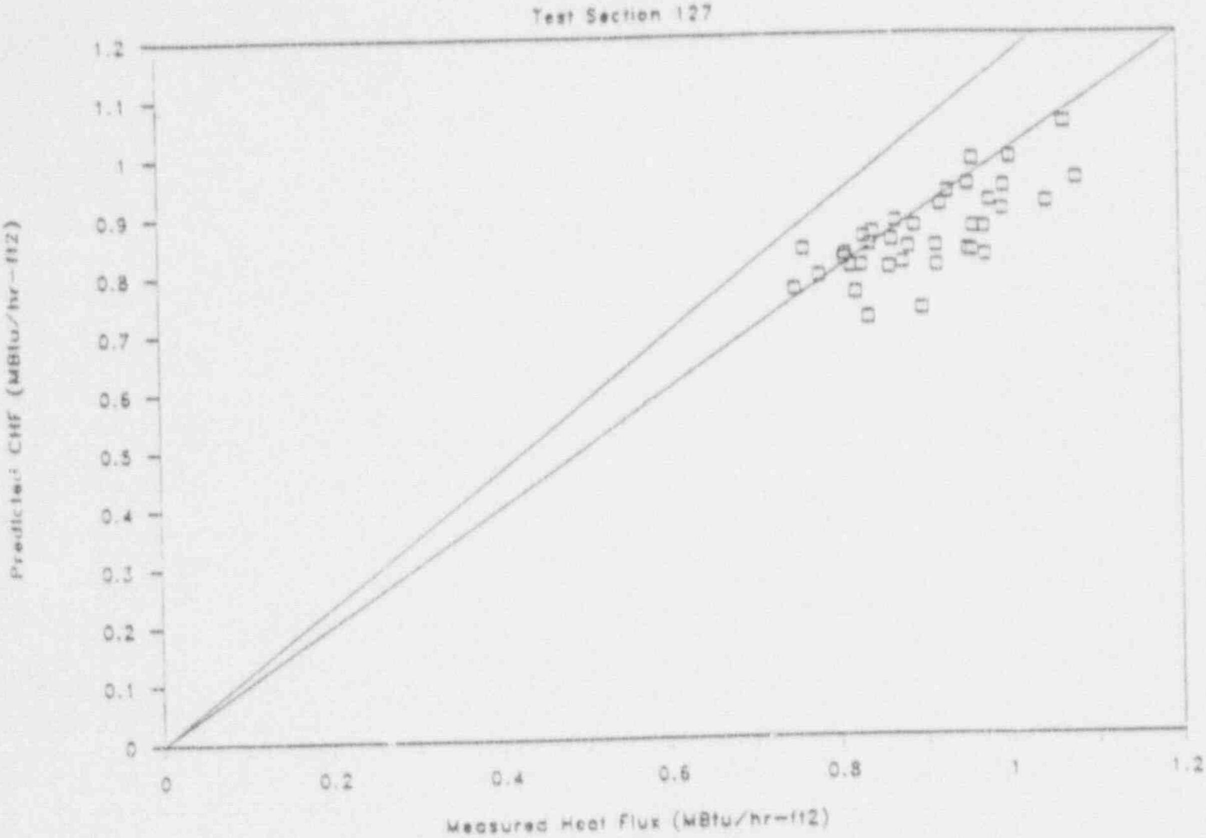


FIGURE 5.



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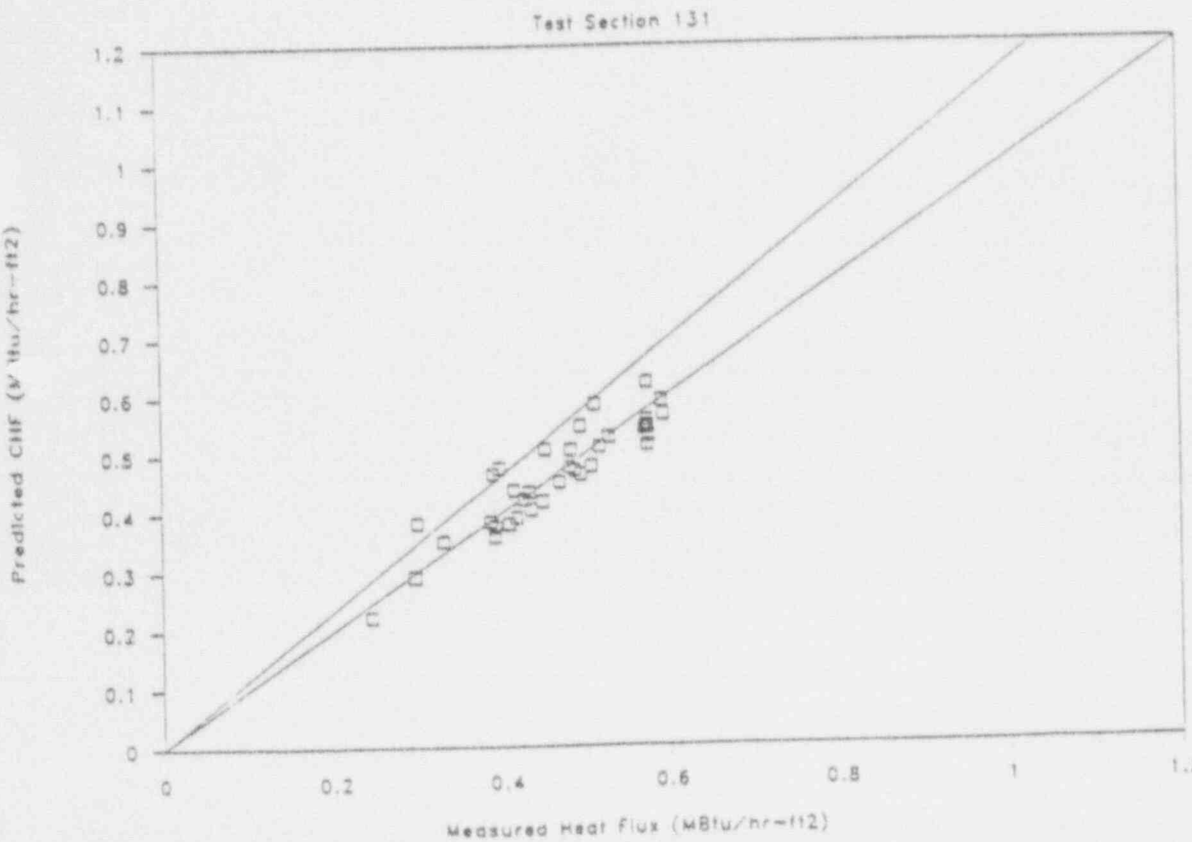

FIGURE 7.

Test Section 132

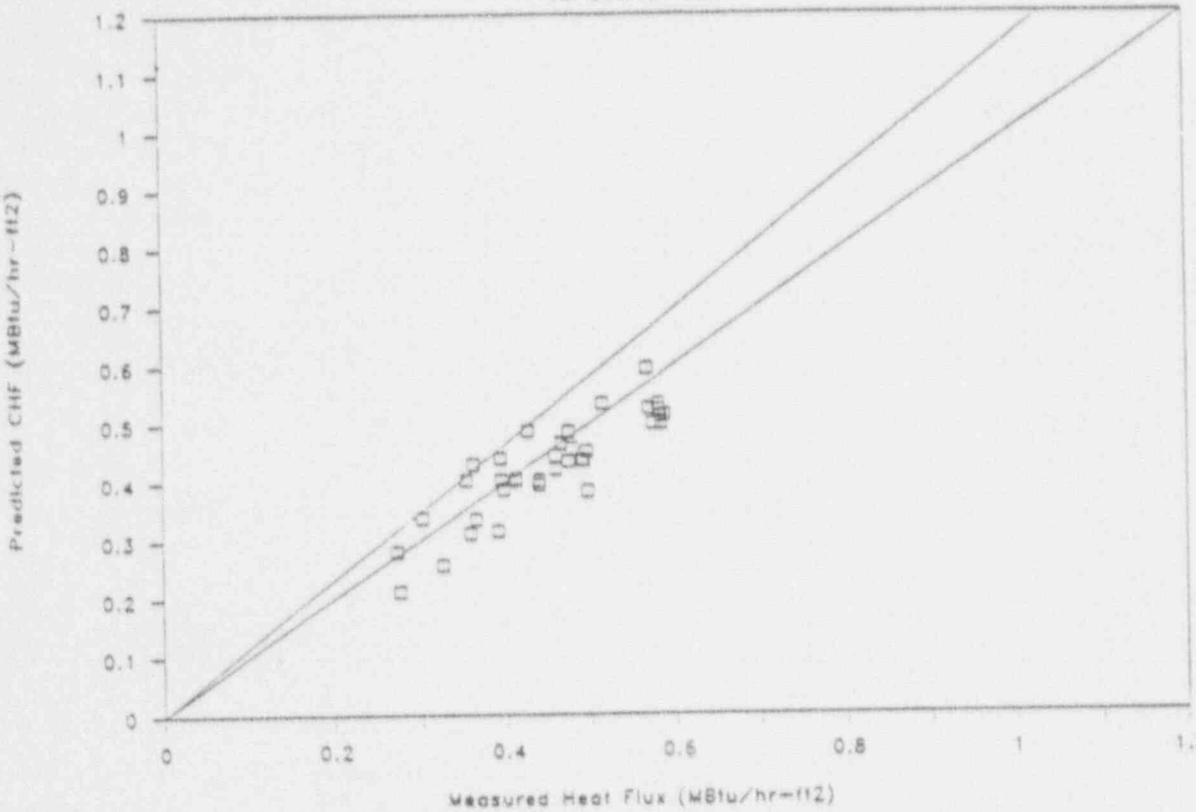

FIGURE 8.

Test Section 134

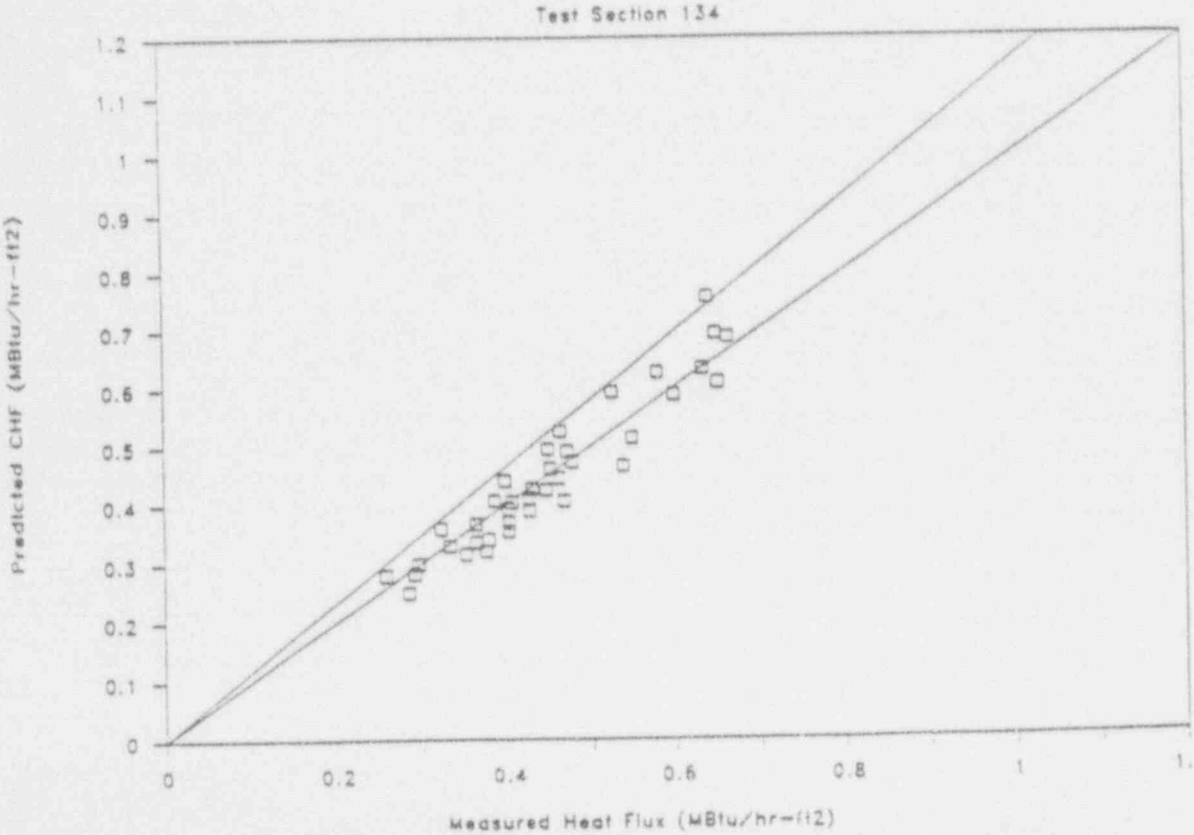

FIGURE 9.

Test Section 139

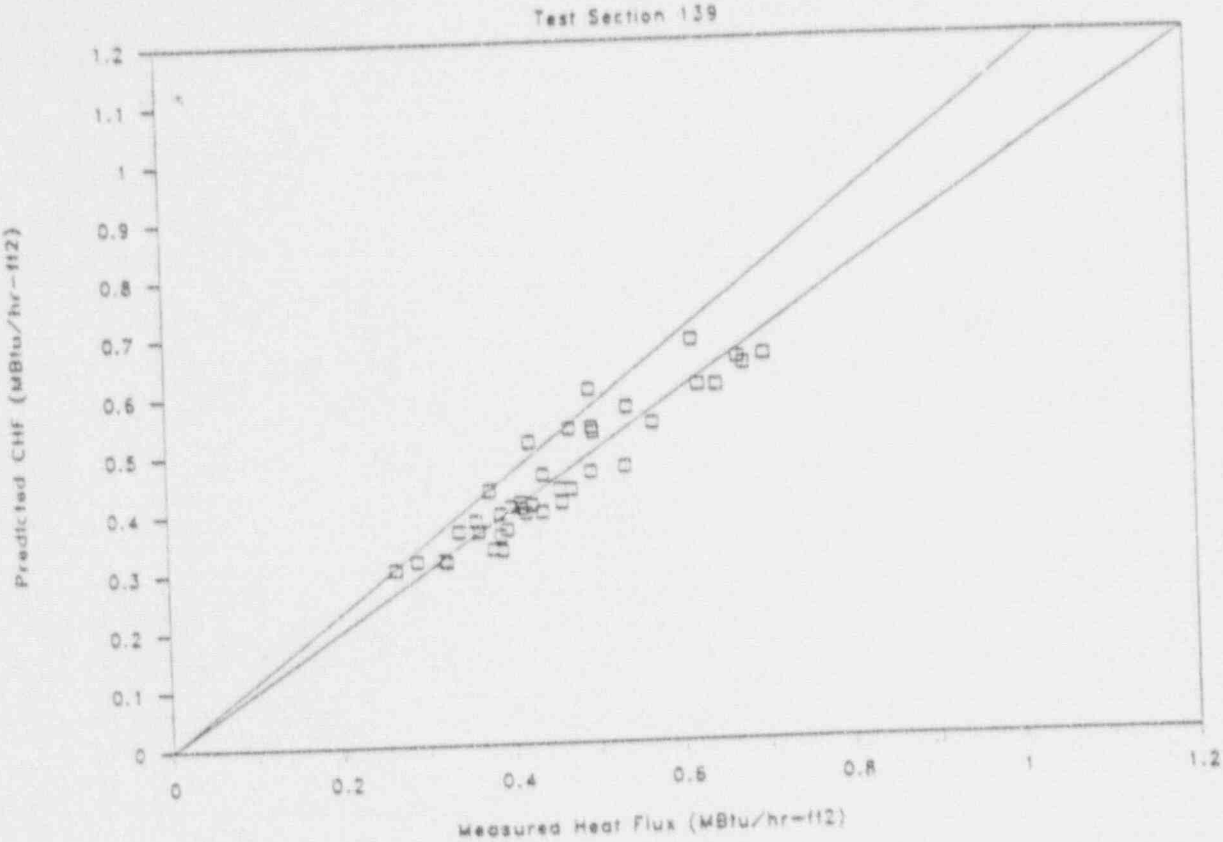

FIGURE 10.

Test Section 140

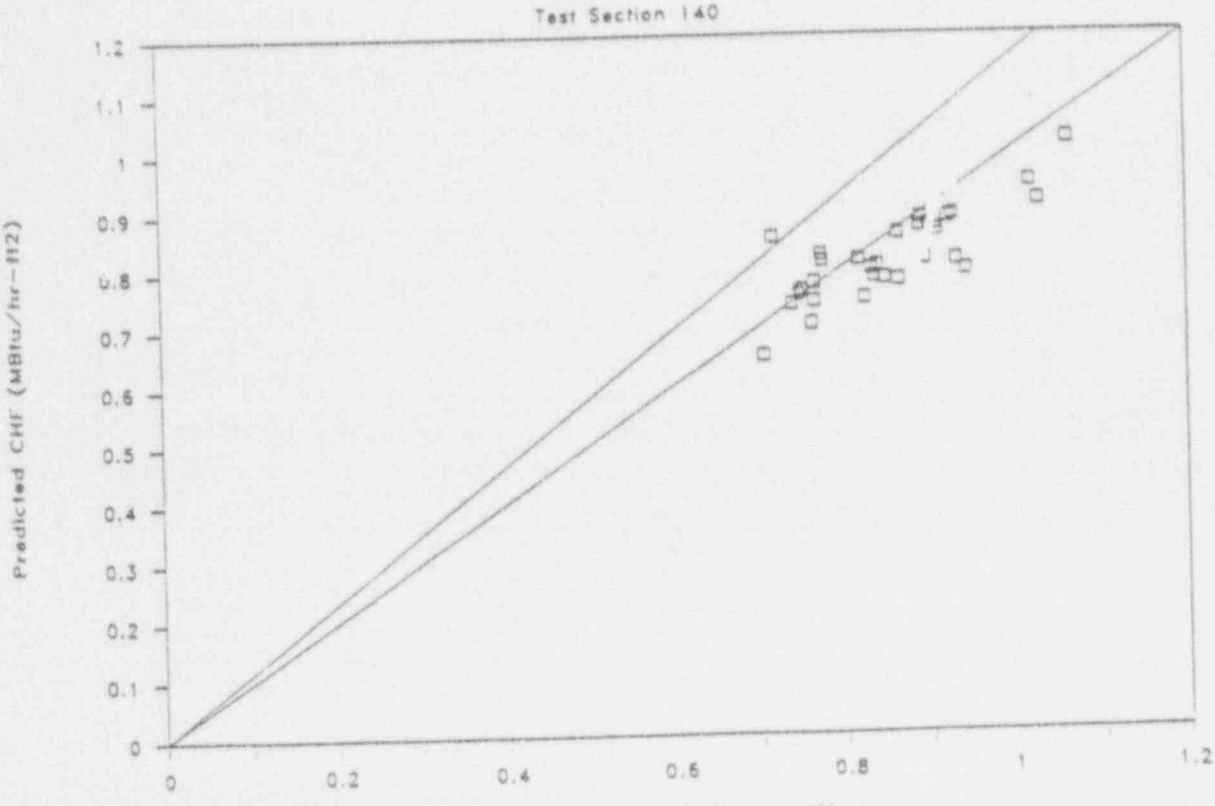

FIGURE 11.

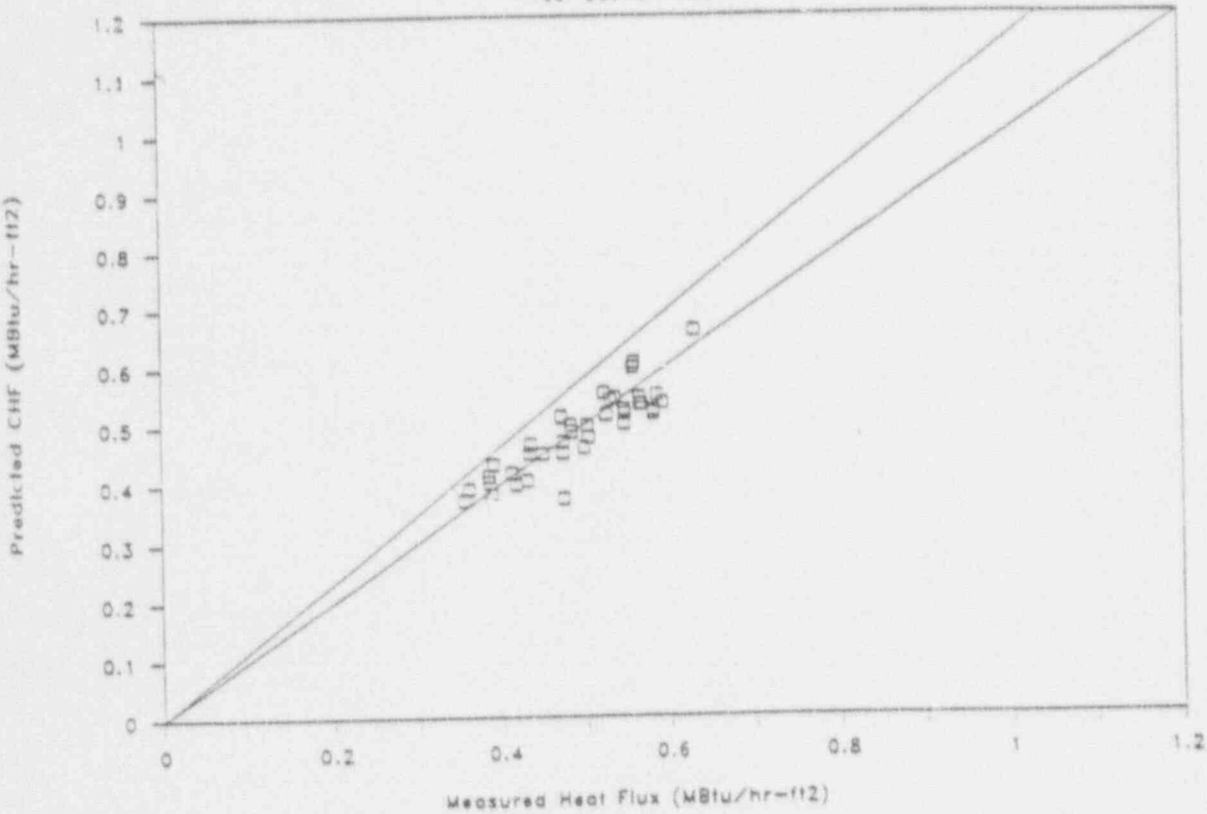

FIGURE 12.

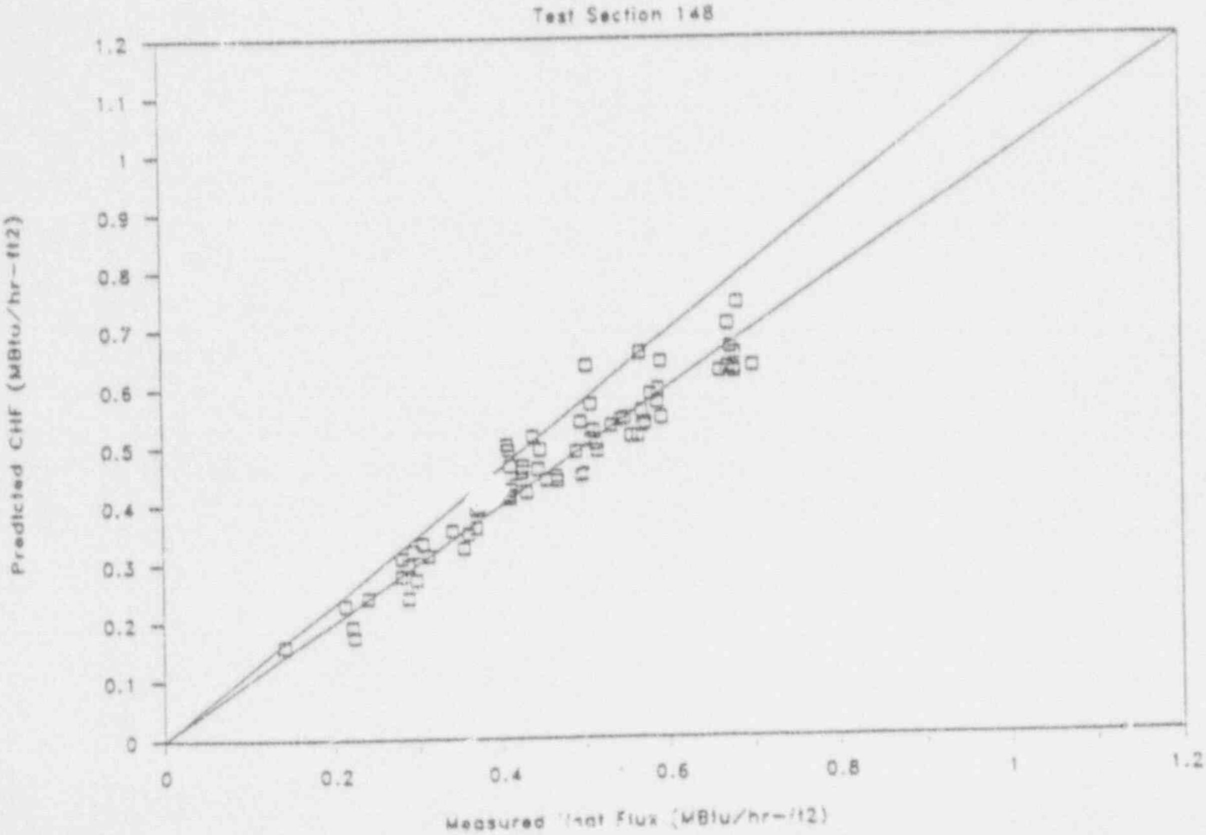

FIGURE 13.

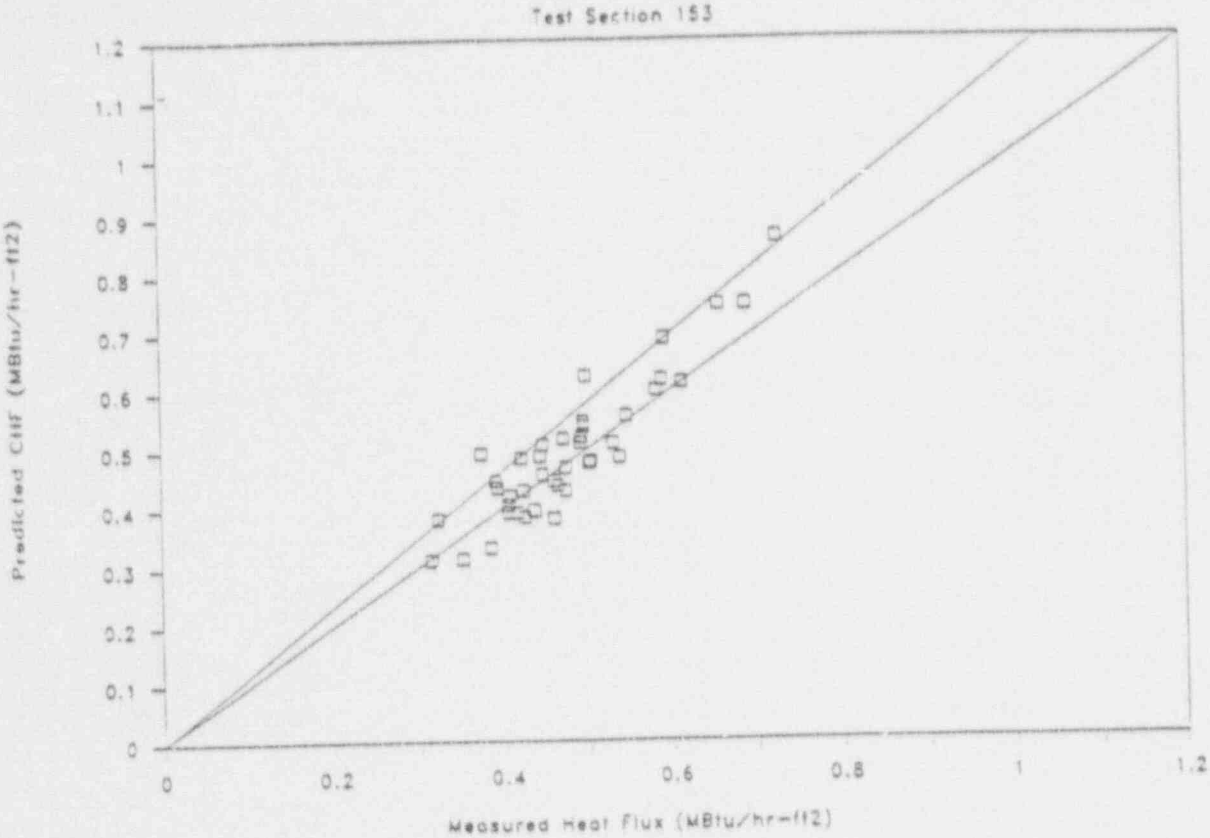

FIGURE 14.

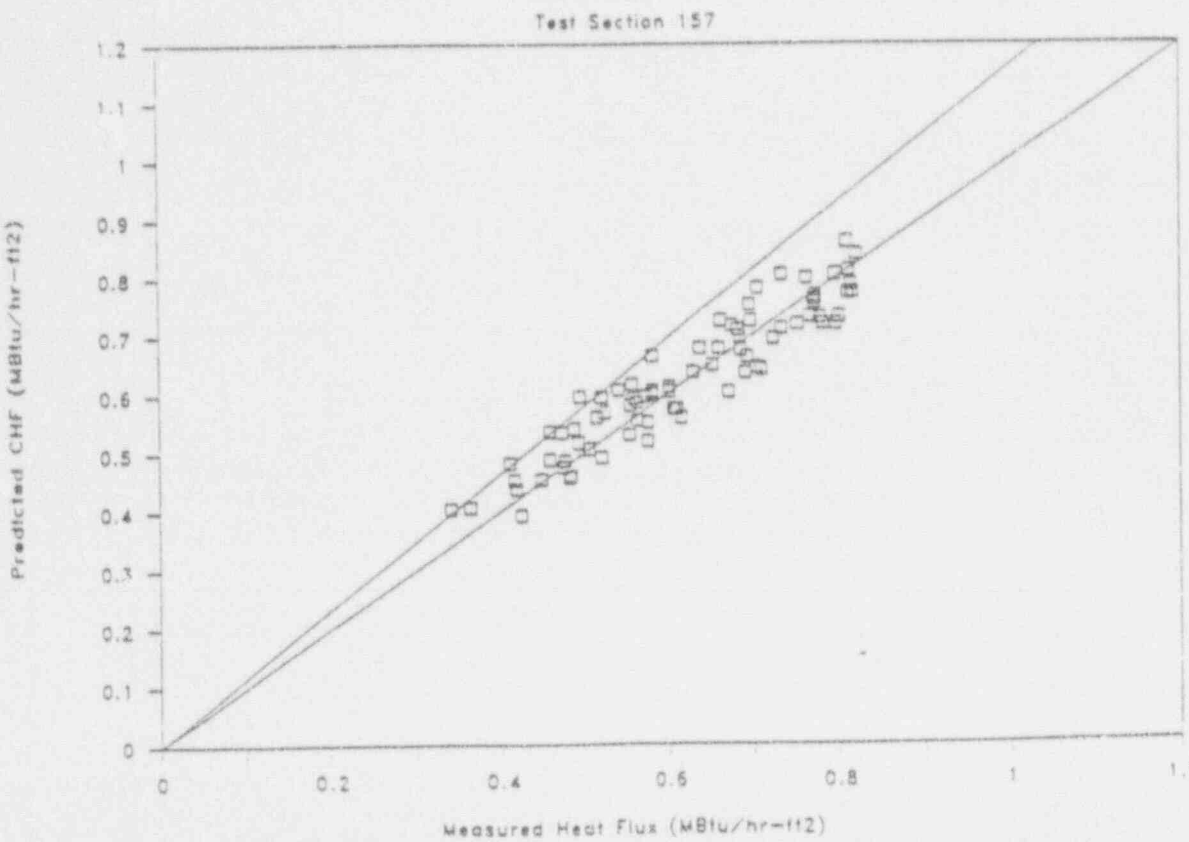

FIGURE 15.

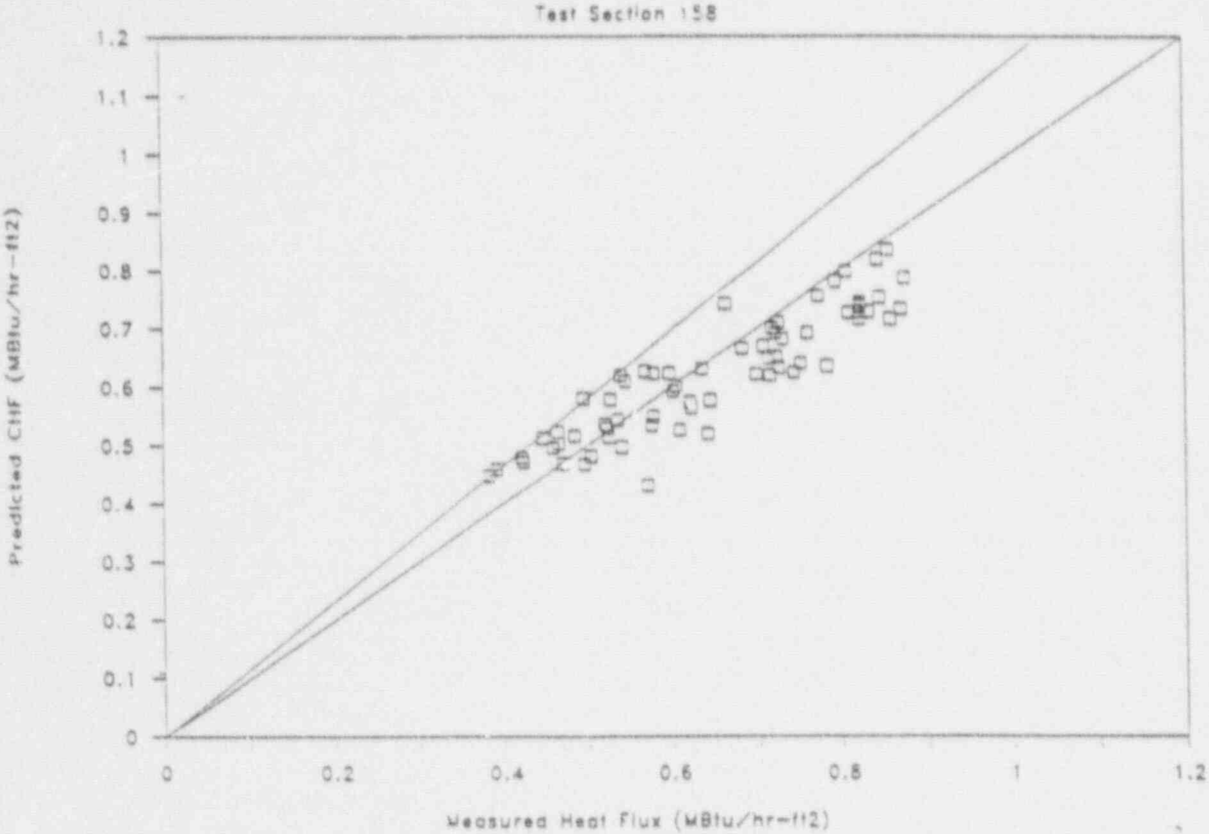

FIGURE 16.

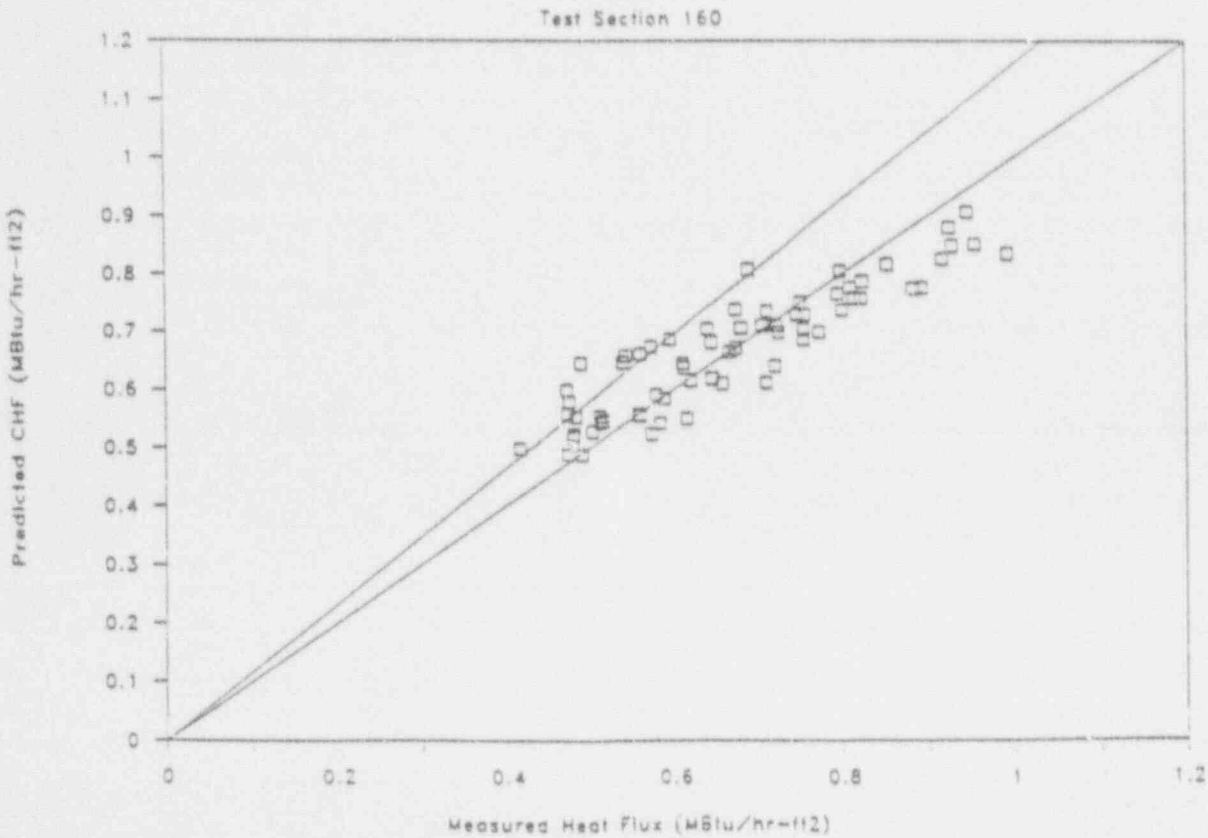

FIGURE 17.

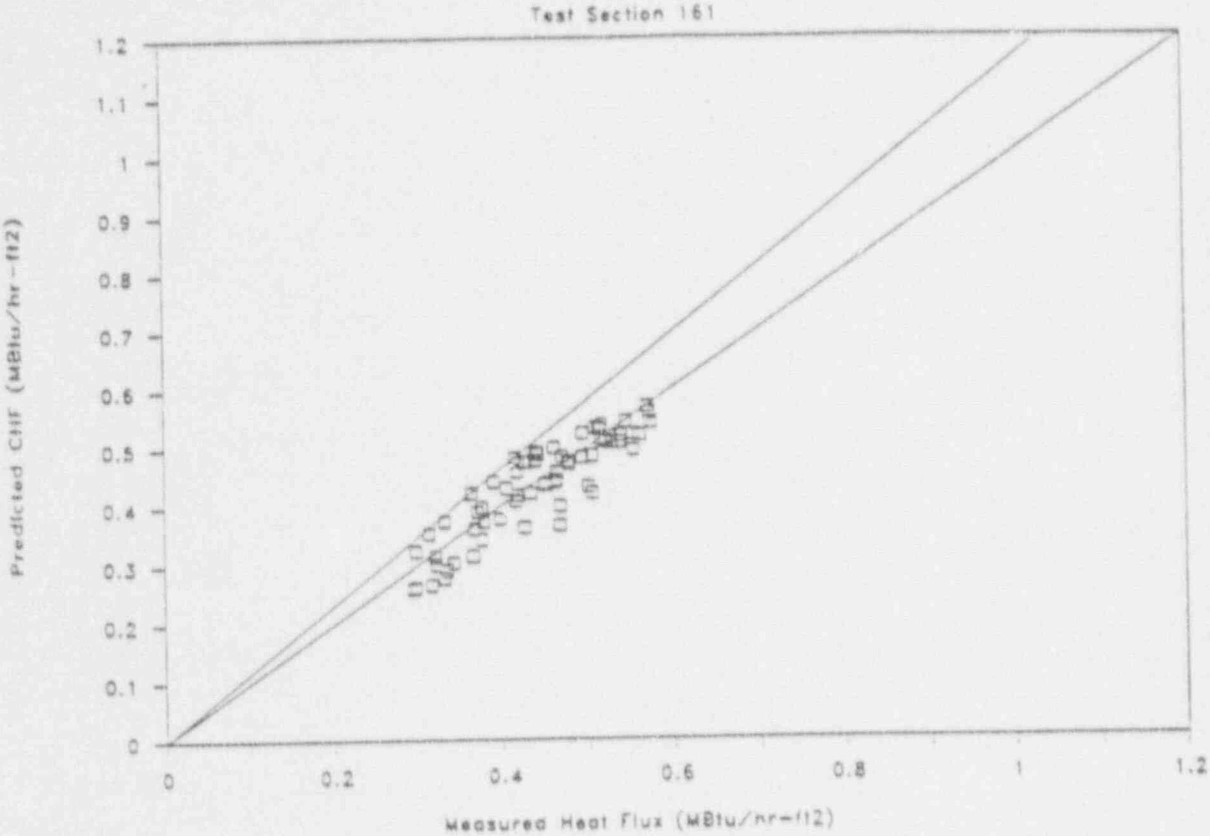

FIGURE 18.

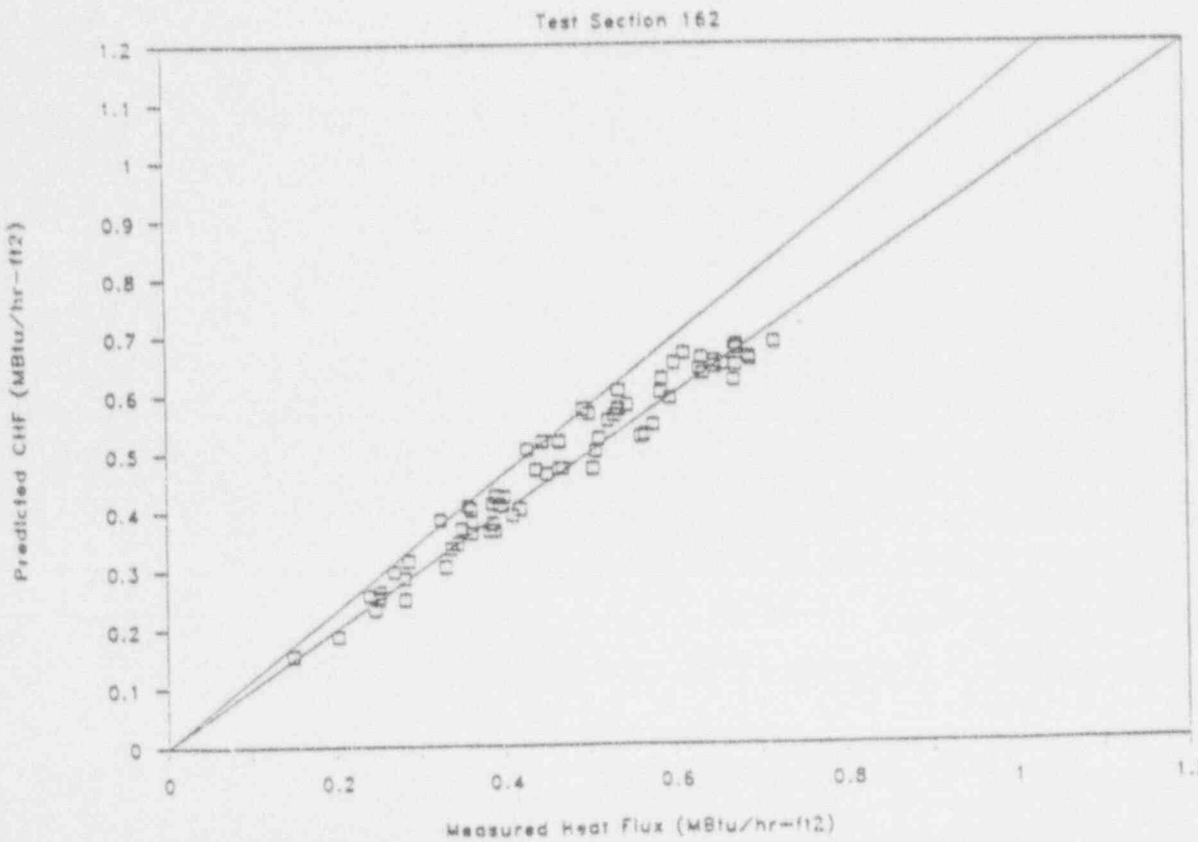

FIGURE 19.

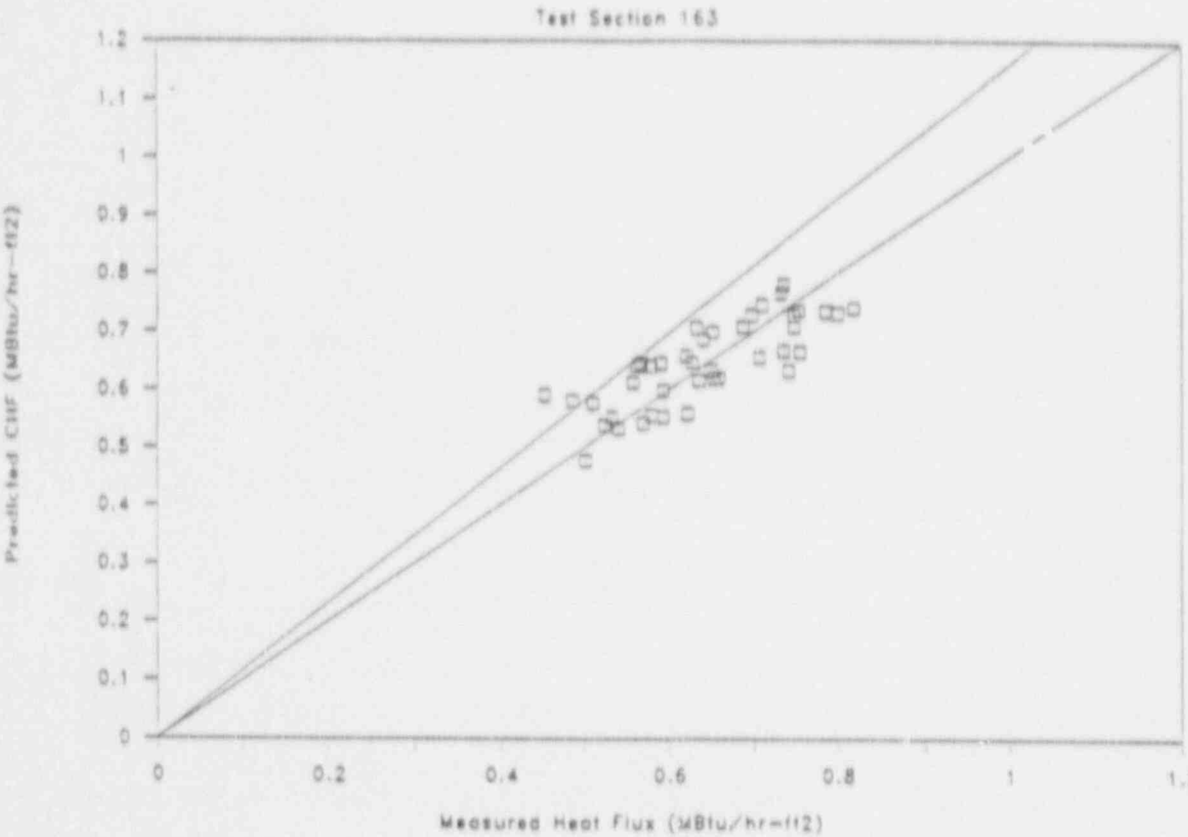

FIGURE 20.

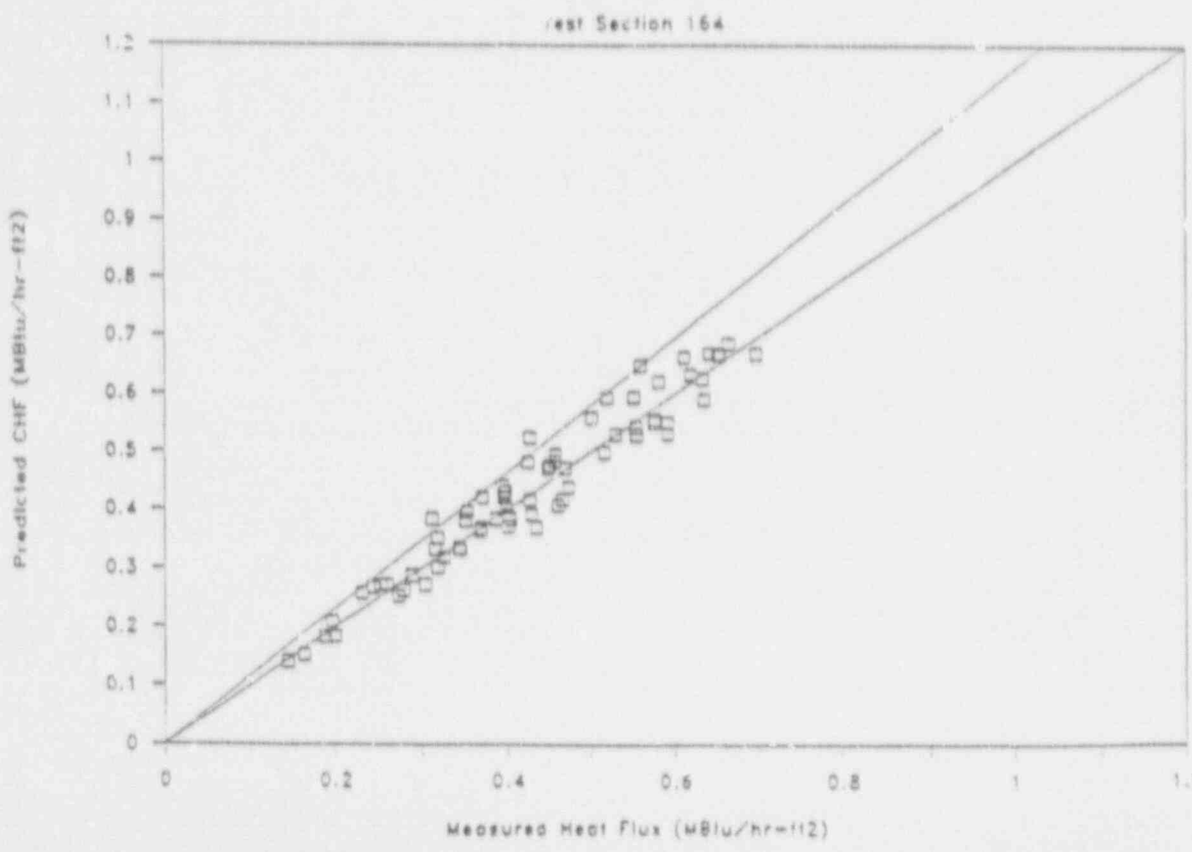

FIGURE 21.

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