XN-NF-512(NP)

XN-3 CRITICAL POWER CORRELATION

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JULY 1979

RICHLAND, WA 99352

EXXON NUCLEAR COMPANY, Inc.

7908210577 758 234

XN-NF-512 (NP)

Issue Date: 07/20/79

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758 235

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758 236

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

758 234

APPENDICES A - D

TABLE OF CONTENTS

758 239

The following symbols are used to report test results:

- P - Operating pressure, psia
- G - Mass velocity, 10^6 lb/hr-ft^2
- HIN - Inlet enthalpy, Btu/lb
- HBT - Average bundle enthalpy at location of boiling transition, Btu/lb
- POWER - Btu/sec
- CPR - Ratio of predicted-to-measured bundle power

1.0 INTRODUCTION AND SUMMARY

In order to assess the thermal margin of high power density boiling water reactor (BWR) fuel, Exxon Nuclear Company (ENC) has developed the XN-3 Critical Power Correlation. The XN-3 Correlation extends and may be used to supersede the XN-2 Correlation,[2] which is an NRC-approved correlation (Ref. 9) for determination of critical power margins in BWRs. The data base of the XN-3 Correlation has been expanded from that supporting the XN-2 Correlation to include boiling transition data acquired by ENC on full-length (12 ft) test assemblies. Although the updates made in deriving XN-3 from the XN-2 Correlation are minor, the XN-3 Correlation is more accurate in predicting the trends of the data. This report presents the XN-3 Correlation and the data base that is used for its verification.

The XN-3 Correlation is comprised of a base correlation with correctors for pressure, local rod power peaking, grid spacer type, and nonuniform axial power distribution effects. For a given axial and local peaking distribution, the XN-3 Correlation predicts, from the independent variables of assembly average fluid flow, enthalpy, and pressure, the minimum heat flux required to produce boiling transition. The XN-3 Correlation is applied iteratively to determine the critical assembly power, which is defined as the minimum power required to produce boiling transition.

The XN-3 Correlation data base is comprised of 896 data points taken with 20 different test assemblies. The test assemblies include both partial and full-length rods, both uniform and nonuniform axial heat flux profiles, grid spacers that are prototypic of BWR fuel designs (typical grids) as well as "wart" type spacers (minimum grids), and a variety of rod diameters, assembly hydraulic diameter, rod-to-wall spacings, and rod-to-rod spacings. The data base was compiled from data taken at three different test laboratories: Battelle-Northwest, Columbia University, and CISE in Milan, Italy.

Table 1.1 shows the range of operating conditions and bundle geometries which now comprise the XN-3 Correlation data base. The range of test conditions envelopes both steady state and MCPR limiting operational transients for boiling water reactors.

The test data base and correlation address the effects upon boiling transition due to operating pressure level, mass velocity, enthalpy, axial power peaking and distribution, local power peaking and distribution, rod diameter, assembly hydraulic diameter, and heated length. The correlation distinguishes between minimum and typical grids. To encompass all the various effects, the XN-3 Correlation is comprised of a total of eleven correlating coefficients for nonuniform axial data. The typical grid data has 446 degrees of freedom as estimated by Satterthwaite's formula,[7] indicating that the data base has not been correlated by an excess number of parameters.

The XN-3 Correlation has been used to predict the critical power for each test point in the data base. The ratio (CPR) of the predicted critical power to the measured critical power has been determined for each test point and used as a basis in determining the ability of the correlation to predict critical power. The CPR predictions for each test point have been statistically combined to determine the overall mean and standard deviation, thereby characterizing the frequency distribution of the data comparison. The prediction of assembly critical power may be characterized by a normal distribution with a mean of 1.0016 and standard deviation of 0.0427 for the typical

Table 1.1

Test Conditions	
Pressure	590 - 1515 psia
Mass velocity	0.25 - 2.0 Mlb/hr-ft^2
Inlet subcooling	0 - 485 Btu/lbm
Bundle average quality at boiling transition	0 - 0.80
Maximum local power peaking	1.0 - 1.31
Secondary local power peaking	1.0 - 1.09
Axial power peaking	Uniform - 1.5 skewed to exit

Geometry	Test
Length	6 - 12 ft
Rod-to-rod spacing	0.152 - 0.178 in.
Rod-to-channel spacing	0.123 - 0.153 in.
Rod diameter	0.484 - 0.591 in.
Bundle hydraulic diameter	0.472 - 0.531 in.

grid data, and a mean of 1.0025 and standard deviation of 0.0331 for the minimum grid data. A statistical summary of the test comparison is provided in Table 1.2. Comparisons of the predicted and measured assembly critical powers are shown in Figures 1.1 and 1.2 for the typical and minimum grid data, respectively.

The XN-3 Correlation has also been used to predict the number of rods experiencing boiling transition (predict multiple indications) for each test point in the data taken on assemblies with typical grids and uniform axial profiles. The probability of boiling transition for each rod was determined from the critical power prediction for that rod. The probabilities for all the rods in the test assembly, as predicted by XN-3, were then summed to yield the prediction of the total number of rods experiencing boiling transition. The ratio of the predicted to the observed number of rods in boiling transition, the multiple boiling transition ratio (MBTR), was used as a basis in determining the ability of the XN-3 Correlation to predict the occurrence of boiling transition throughout the entire test assembly and, therefore, the occurrence of multiple indications of boiling transition. The average MBTR was determined to be [ ] for the data analyzed, indicating that the XN-3 prediction of the number of rods in boiling transition is expected to be [ ] higher than that expected from testing experience over the range of data correlated.

In summary, it was determined that the XN-3 Correlation can be used to predict assembly critical power and conservatively predict the frequency of individual rod boiling transitions. The uncertainty associated with the XN-3 critical power prediction is distributed normally and over-all means and standard deviations have been determined for the typical grid and minimum

Table 1.2

Statistical Summary of XN-3 Data Comparison

Typical Grid Data

Test Group	N	CPR $\bar{X}$	CPR S
ENC-I			
ENC-II			
ENC-III			
ENC-IV			
Overall	726	1.002	0.043

Minimum Grid Data

Test Group	N	CPR $\bar{X}$	CPR S
ENC-I			
CISE			
Overall	170	1.002	0.033

$$CPR = \frac{\text{Predicted critical power}}{\text{Measured critical power}}$$

N = Number of data points

$\bar{X}$ = Mean

S = Standard deviation

758 245

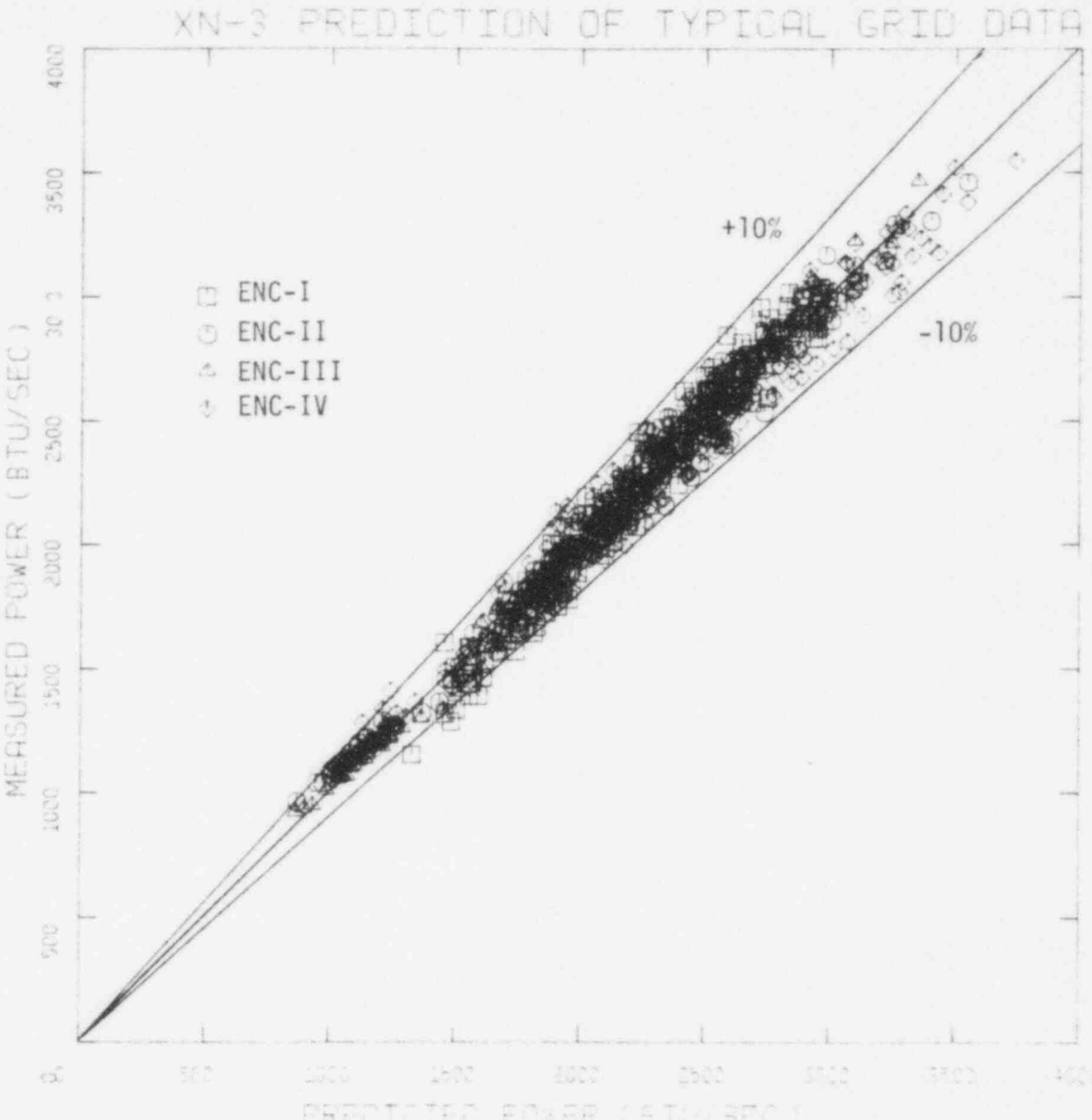

Figure 1.1 XN-3 Prediction of typical grid data.

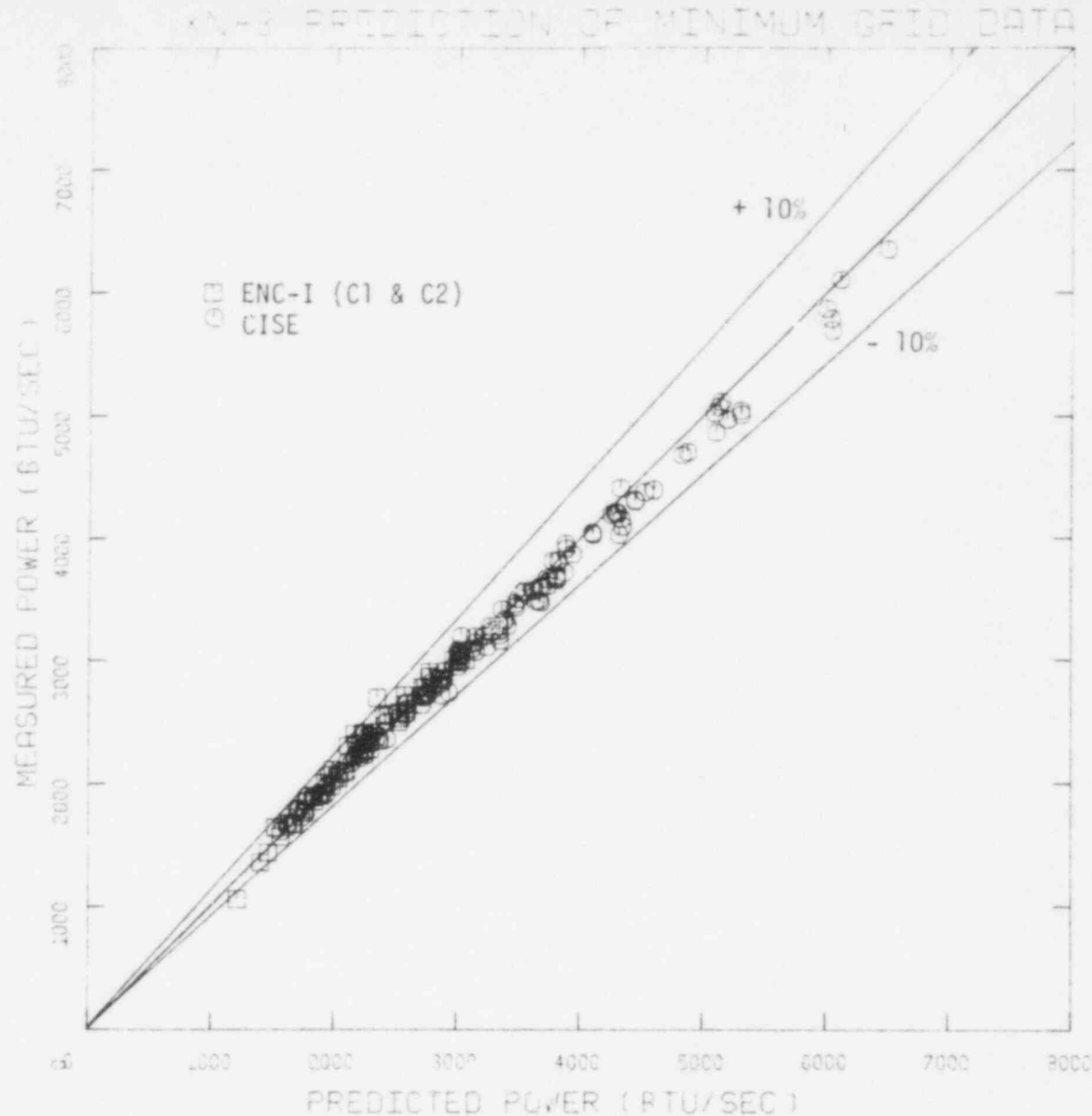

Figure 1.2 XN-3 Predic ion of minimum grid data.

grid data comparisons. Application of the XN-3 Correlation as a normal distribution has been found to overpredict the number of rods in boiling transition; i.e., more multiple indicators of boiling transition are predicted to occur than are observed in the test results. Therefore, it is concluded that the XN-3 Correlation overpredicts the expected number of rods that would experience boiling transition.

758 248

2.0 BASIC CHARACTERISTICS OF THE XN-3 CORRELATION

The XN-3 Correlation uses the assembly averaged values of coolant flow, enthalpy and pressure to predict the critical heat flux (CHF) for a particular rod. The corresponding assembly critical power is determined by iteration and is equal to the assembly power when the XN-3 heat flux and the rod heat flux are equal. The correlation may be applied to both uniform or non-uniform axial heat flux profiles. The form of the correlation is [

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2.1 XN-3 BASE CORRELATION FOR TYPICAL GRIDS

758 249

2.2 XN-3 BASE CORRELATION FOR MINIMUM GRIDS

758 250

2.3 NONUNIFORM AXIAL HEAT FLUX FACTOR (F-Factor)

758 251

2.4 SECONDARY LOCAL PEAKING CORRECTION FACTOR

A secondary local peaking correction factor is applied in the XN-3 Correlation to account for the effect on boiling transition due to the grouping of high-powered rods. [

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758 252

2.5 PROCEDURE FOR USING THE XN-3 CORRELATION TO PREDICT CRITICAL POWER

The following steps are required to predict the experimental critical power to reach boiling transition for either a nonuniform or uniform axial heat flux distribution:

(i) Calculate the local bundle average cross sectional values of coolant flow and enthalpy at each node, and from these and the operating pressure calculate the critical heat flux q''_{XN-3} from the XN-3 Correlation.

(ii) The F-factor is calculated using Eq. (8) and (9).

[

758 253

]

The value of the F-factor is equal to unity for a uniform axial heat flux distribution and can be substantially greater than unity for nonuniform heat flux distributions in the upper section of the bundle where heat flux is decreasing with length. Convert the XN-3 uniform critical heat flux at each node to the corresponding value of the nonuniform heat flux by dividing by F.

(iii) Correct the critical heat flux for S, if appropriate. S is calculated from [

]

(iv) The assembly critical power is predicted for either the nonuniform or the uniform heat flux distribution when $q''_{XN-3} = q''_{\ell_c}$ at a single node and $q''_{XN-3} > q''_{\ell_c}$ at all other axial nodes.

758 254

(v) If $q''_{XN-3} > q''_{\ell_c}$ or if $q''_{XN-3} < q''_{\ell_c}$ at any node then the bundle power is increased for the case of $q''_{xn-3} > q''_{\ell_c}$ and decreased for $q''_{XN-3} < q''_{\ell_c}$ until the criteria for critical power (Statement (iv)) are satisfied. Both local enthalpy and q''_{local} are allowed to increase or decrease with bundle power and the q''_{XN-3} is calculated using bundle-averaged enthalpy corresponding to the modified power.

(vi) The CPR is calculated as the bundle power causing q''_{XN-3} to just equal q''_{ℓ_c} divided by the operating bundle power.

758 255

3.0 EXPERIMENTAL DATA SUPPORTING XN-3 CRITICAL POWER CORRELATION

The 896 data points supporting the XN-3 Critical Power Correlation have been compiled from five sources:

(1) The Exxon Nuclear Critical Heat Flux Test Program(1) (ENC-I).

(2) The Exxon Nuclear Cosine Axial Profile Critical Heat Flux Test Program(3) (ENC-II).

(3) The Exxon Nuclear Upskew Axial Profile Critical Heat Flux Test Program(4) (ENC-III).

(4) The Exxon Nuclear Full Length Uniform Axial Critical Heat Flux Test Program (ENC-IV).

(5) The CISE Critical Heat Flux Test Program(5) (CISE).

The geometry and results of analysis of the data from these test groups are reported in the following sections.

3.1 ENC CRITICAL HEAT FLUX TEST PROGRAM(1) (ENC-I)

The ENC-I test program was comprised of nine separate test groups. Various bundle geometries and local peaking distributions were tested although the heated length of all test assemblies was less than, or equal to, seven feet. This test program was comprised of assemblies with both typical and minimum grids. The operating conditions for each test point, the predicted critical power, and the salient features of the test bundles are provided in Appendix A.

The measured and predicted critical powers of the ENC-I data group are compared in Figure 3.1. The mean CPR for the [ ] typical grid data points was [ ] with a standard deviation of [ ]. The [ ] minimum grid data points were predicted with a mean CPR of [ ] and a standard deviation of

758 256

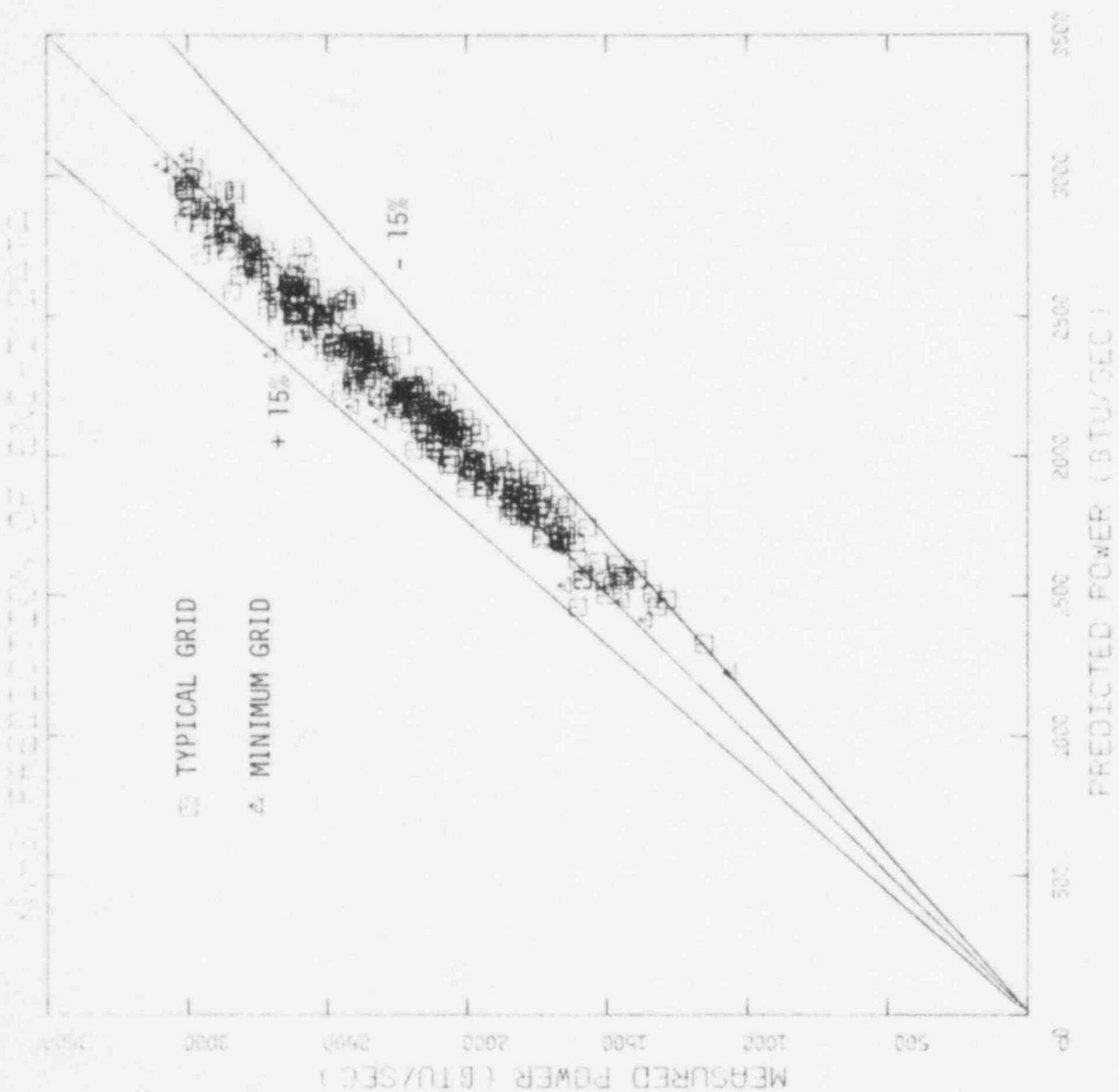

Figure 3.1 XN-3 prediction of ENC-I data.

758 257

[

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3.2 ENC COSINE AXIAL PROFILE CRITICAL HEAT FLUX TEST PROGRAM[3] (ENC-II)

The ENC-II test group was comprised of a full-length 4x4 rod array bundle with both nonuniform axial and radial power distributions. The spacer and rod bundle geometry are prototypic of BWR fuel designs. The test was performed at Columbia University under the direction of the Department of Chemical Engineering.

The measured and predicted critical powers are compared in Figure 3.2. The mean CPR was determined to be [ ] with a standard deviation of [ ] for the total of [ ]data points. [

]

The salient features of the bundle geometry and the test results are given in Appendix B.

3.3 ENC UPSKEW AXIAL PROFILE CRITICAL HEAT FLUX TEST PROGRAM[4] (ENC-III)

The ENC-III test bundle was identical to that used for the ENC-II group with the single exception of a different axial profile, [

]

This test was also conducted at Columbia University.

The measured and predicted critical powers are compared in Figure 3.3. The mean CPR was determined to be [ ] with a standard deviation of

758 258

[ ] for the total of [ ] data points. The values of the mean CPRs and standard deviation for the ENC-II and ENC-III test groups indicate that the XN-3 Critical Power Correlation predicts the effects of nonuniform axial power distribution on boiling transition.

The salient features of the bundle geometry and the test results are given in Appendix B.

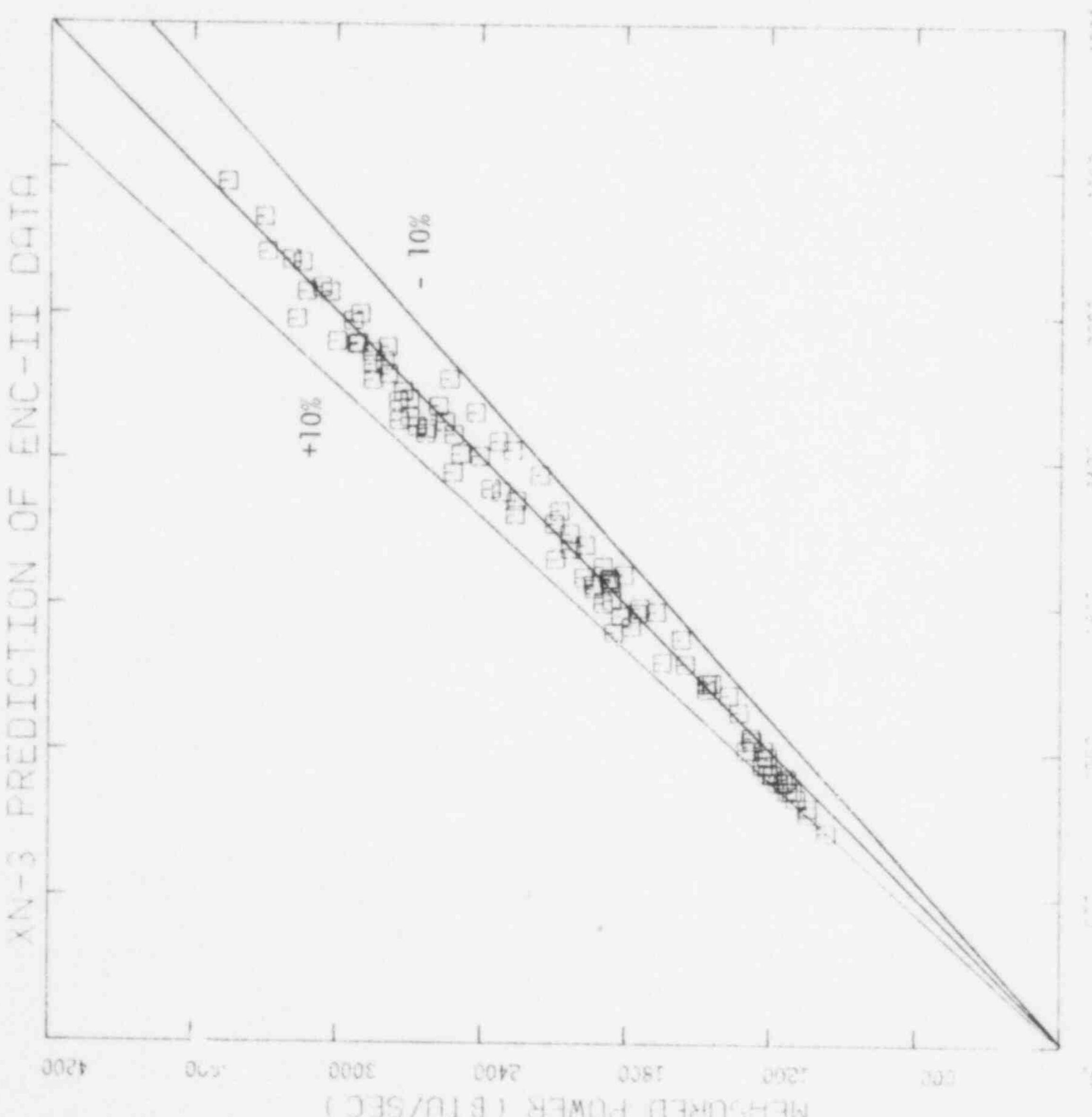

Figure 3.2 XN-3 prediction of ENC-II data.

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260

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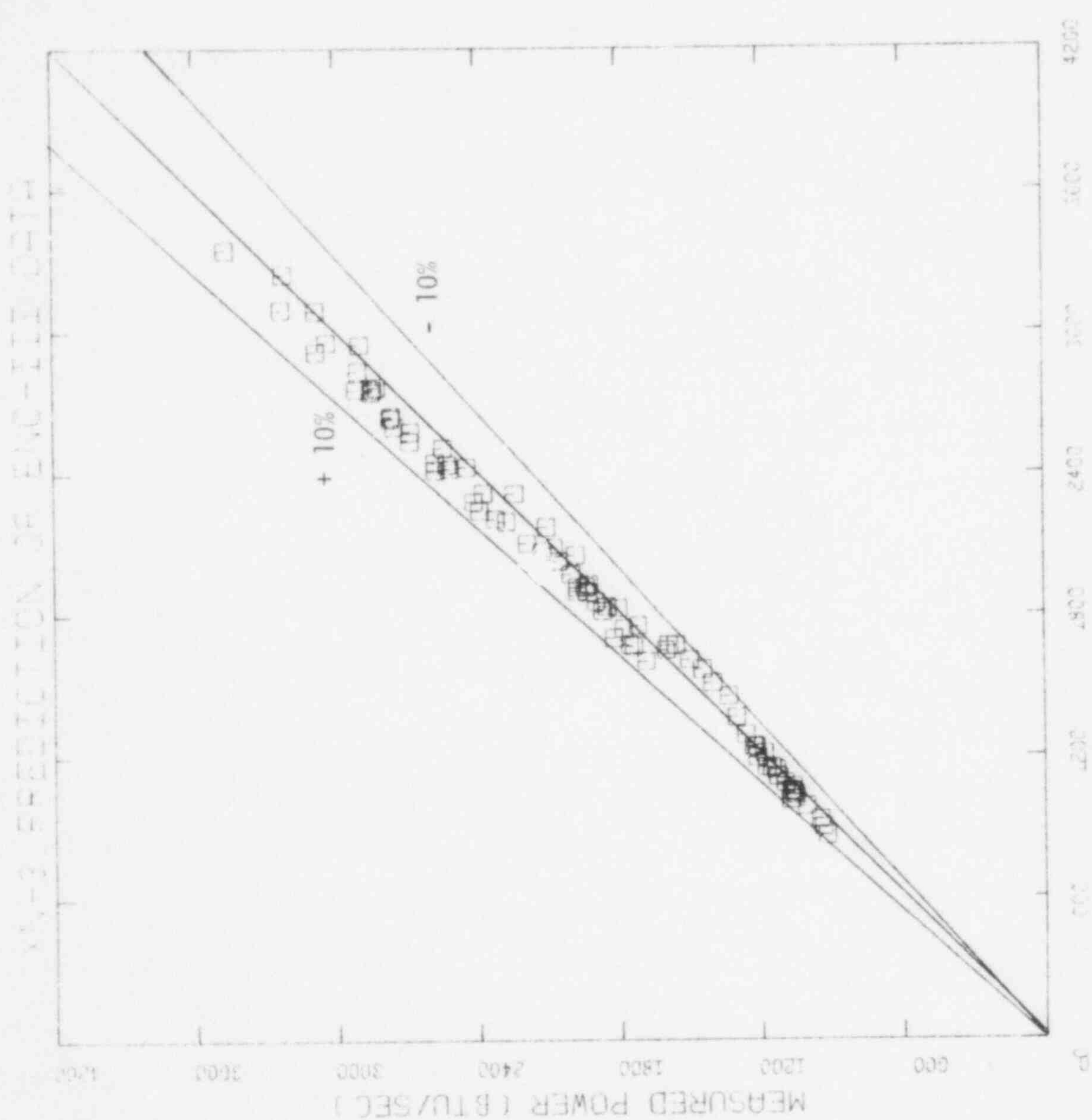

Figure 3.3 XN-3 prediction of ENC-III data.

3.4 ENC FULL-LENGTH UNIFORM AXIAL CRITICAL HEAT FLUX TEST PROGRAM (ENC-IV)

The ENC-IV data group is comprised of data from three separate test assemblies, all[ ]full-length rods and with a uniform axial profile and a nonuniform radial power distribution. The maximum radial peaking in the assemblies varies from [ ] These tests were run at Columbia University.

The measured and predicted critical powers are compared in Figure 3.4. The mean CPR for this test group was determined to be [ ] with a standard deviation of [ ] for a total of[ ] data points. The agreement between the XN-3 Correlation and this data demonstrates the ability to separate the influence of a nonuniform axial profile on the phenomena of boiling transition and demonstrates the ability of the XN-3 Correlation to predict boiling transition in assemblies with[

]

The salient features of the bundle geometry and the test results are given in Appendix C.

3.5 CISE CRITICAL HEAT FLUX TEST PROGRAM[5] (CISE)

The CISE heat flux test program was comprised of six 4x4 rod array test bundles of a BWR-type geometry, all 12-feet long and with a uniform axial power distribution. The radial power distribution was varied between each test both in terms of the magnitude of the radial power peaking and the location within the bundle of the high-powered rods, as shown in Appendix D. The magnitude of the radial peaking varied from 1.02 to 1.26, but was maintained at 1.20 for four of the tests, while the location of the

758 262

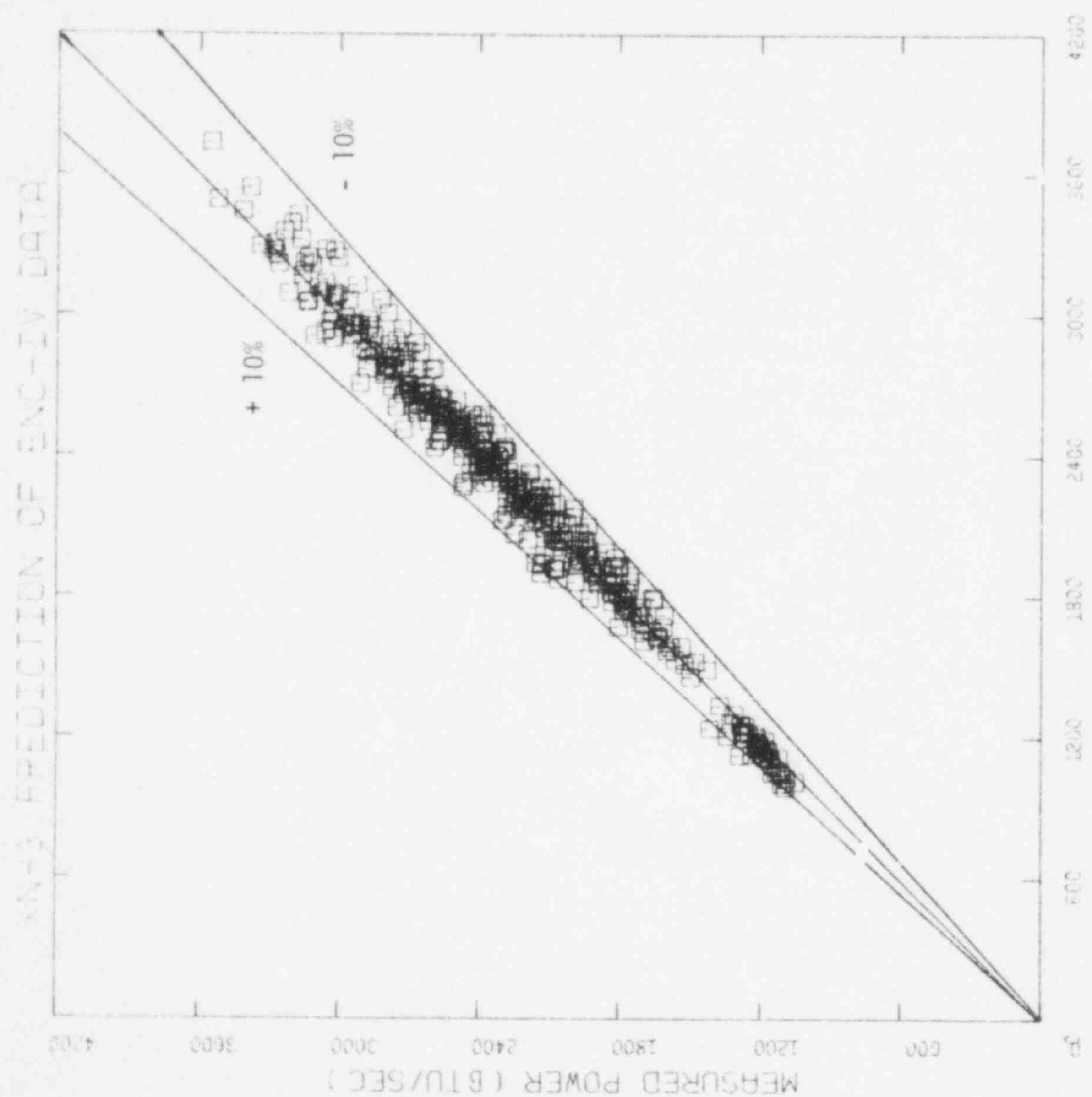

Figure 3.4 XN-3 prediction of ENC-IV data.

758 263

high-powered rods were varied. The radial power distributions tested encompass all the bundle local power distributions anticipated for full-power BWR fuel during reactor operation.

In predicting the CISE data, the test points with a mass velocity within the range of the XN-3 Correlation ($0.25 \leq G \times 10^6$ lb/hr-ft^2) have been included. The minimum grid form of the XN-3 Correlation was used as the design of the CISE test grid spacer is prototypic of minimum grids. Table 3.1 also shows that the mean CPR predictions are all close to 1.0, indicating that the data is well predicted by the minimum gird formulation.

The measured and predicted critical powers for the CISE data set are compared in Figure 3.5. The mean CPR of the CISE data set was determined to be [ ]with a standard deviation [ ] of [ ]for the total of 120 test points.

The salient features of the test bundle geometry and the test results are provided in Appendix D.

758 264

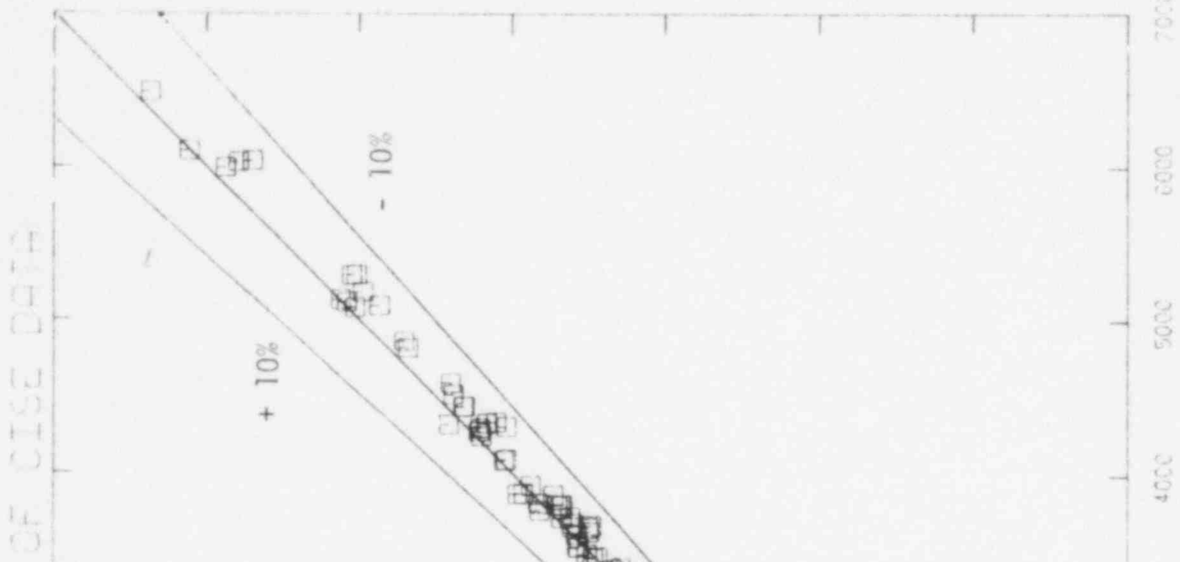

Figure 3.5 XN-3 prediction of CISE data.

758 265

Table 3.1

Summary of CISE Test Predictions

Test Section	Data Points	Mean CPR	Standard Deviation
PELCO B	30		
PELCO C	21		
PELCO D	18		
PELCO E	16		
PELCO F	19		
PELCO G	16		

758 266

4.0 STATISTICAL EVALUATION OF THE XN-3 CRITICAL POWER CORRELATION

The CPR predictions for each data point were statistically combined to determine the mean CPR prediction and the standard deviation. The mean ($\bar{x}$) and standard deviation (s) were used to characterize the frequency distribution of the XN-3 test predictions. In the determination of the overall standard deviation, the variation between data sets was also considered.

For an individual set of data. let x_i be the i^{th} value of the ratio of predicted-to-measured critical power, with $i = 1, 2, \ldots n_j$; where j is the number of data points in the j^{th} test group. The mean, $\bar{x}_j$, and the standard deviation, s_j, are calculated by the formulas:

$$\bar{x}_j = \sum_{i=1}^{n_j} \frac{x_i}{n_j}$$

$$s^2 = \frac{1}{n_j - 1}\left\{\sum_{i=1}^{n_j} x_i^2 - n_j\left(\sum_{i=1}^{n_j} x_i\right)^2\right\}$$

$$s = \sqrt{s^2}$$

The overall mean ($\bar{X}$)and within-group standard deviation (S) are determined by a weighted combination of the test group means and standard deviations where the weights are determined by the number of data points within each group. The overall standard deviation is then determined from the within-group standard deviation and the standard deviation between data. The result of this analysis is an overall mean CPR prediction of 1.0116 and

758 267

an overall standard deviation of 0.0427 for typical grid data (726 data points) and a mean of 1.0025 and standard deviation of 0.0331 for minimum grid data (164 data points).*

A statistical summary of the CPR predictions for each data set is provided in Table 4.1.

Histograms of the CPR predictions are shown in Figures 4.1 and 4.2 for the typical and minimum grid data, respectively. Superimposed on the histograms are normal distributions with means and standard deviations equal to those determined by statistical analysis. The histograms of the XN-3 test predictions are seen to be more sharply peaked than the fitted normal distributions. That is, there are a larger number of observations close to CPR equal to 1.0 than predicted by the fitted normal distribution and a fewer number of observations in the tails than predicted by the fitted normal distributions. [

]

The overprediction of the probability of boiling transition is further demonstrated by predicting the number of rods in boiling transition. For each test point in the typical grid uniform axial data base, the number of

*The ENC I, C2 data (6 points) was not used in the statistical data reduction because of the nonprototypic geometry of the test assembly.

Table 4.1

Statistical Summary of XN-3 Data Predictions

Test Group	Test Section	N	CPR	Standard Deviation
ENC-I	HB			
	A1			
	A2			
	B1			
	B2			
	C1*			
	C2*			
	D			
	E			
ENC-II	--			
ENC-III	--			
ENC-IV	JP/1			
	JP/2			
	JP/3			
CISE	PELCO B*			
	PELCO C*			
	PELCO D*			
	PELCO E*			
	PELCO F*			
	PELCO G*			

* Minimum grid base correlation.

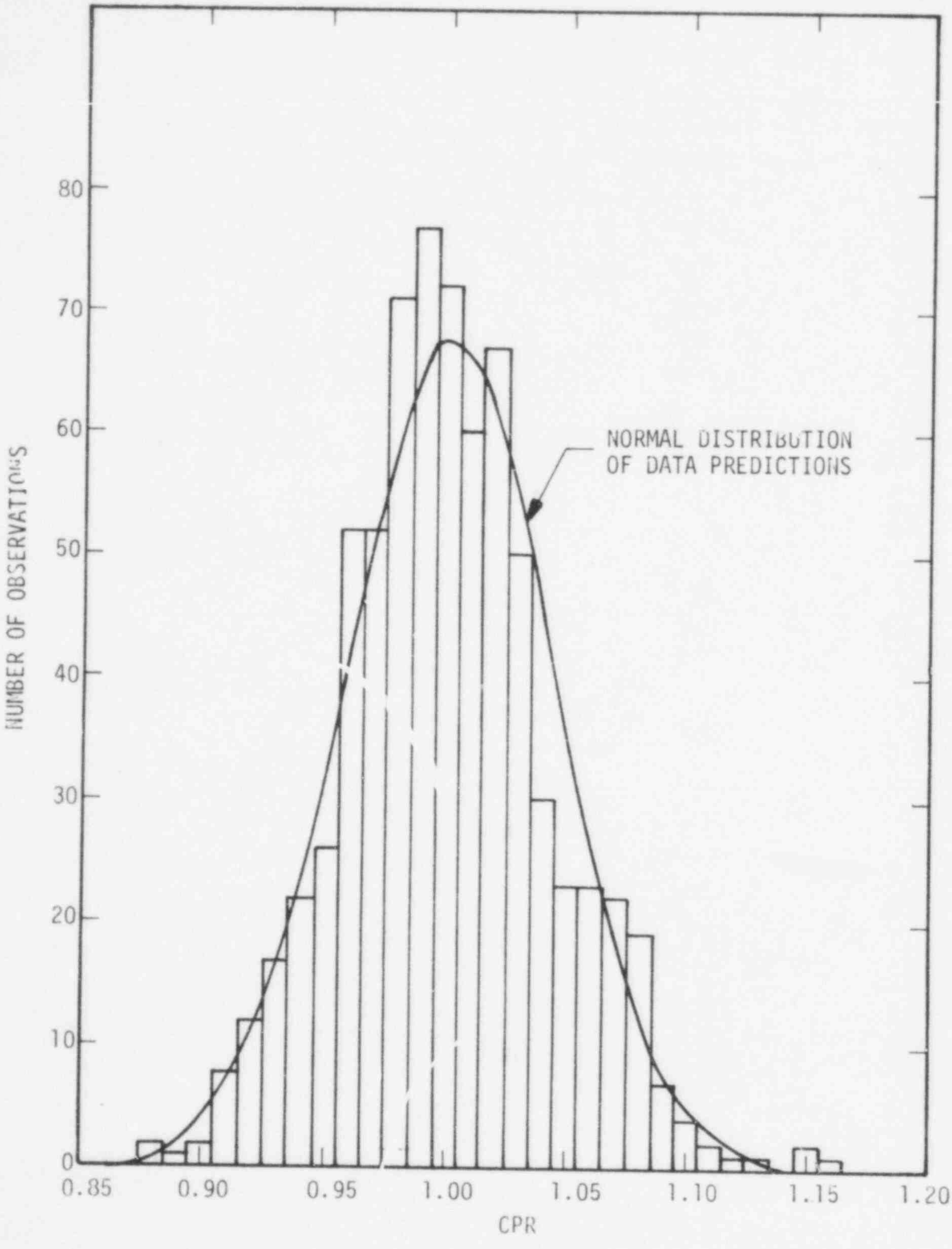

Figure 4.1 Histogram of XN-3 predictions for typical grid data.

758 240

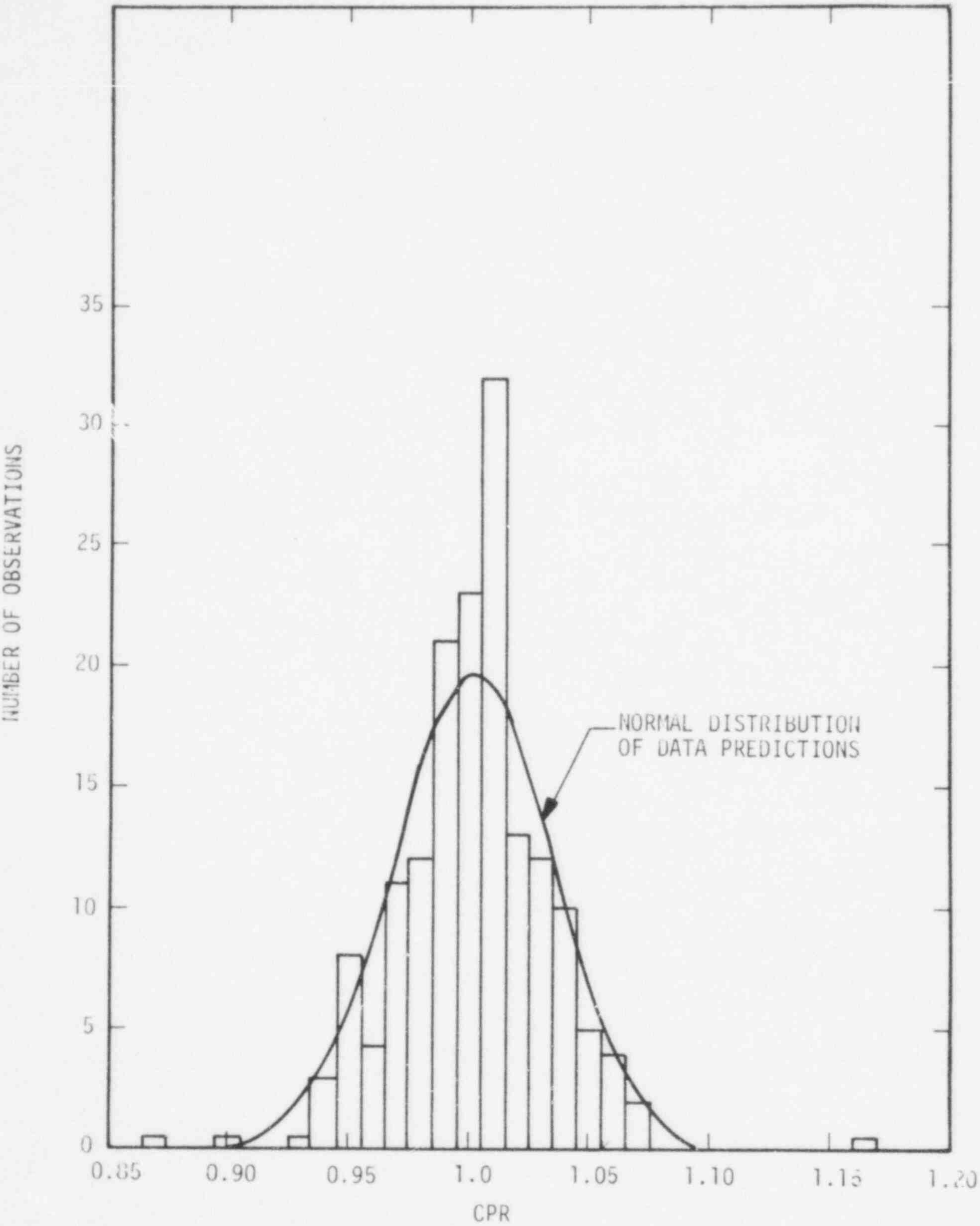

Figure 4.2 Histogram of XN-3 predictions for minimum grid data.

rods in boiling transition was predicted and compared to the number observed. The ratio of the number of rods predicted to the number of rods observed in boiling transition (MBTR) was determined for each test point. The average MBTR was [ ]indicating that use of the XN-3 Correlation overestimates the number of rods in boiling transition by [ ]

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Appendices A - D are deleted.

XN-NF-512 (NP)

Issue Date: 07/20/79

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275