XN-NF-734(NP)(A)
Issue Date: 2/28/85

CONFIRMATION OF XN-3 CRITICAL POWER CORRELATION

FOR 9x9 FUEL ASSEMBLIES

This is the NRC approved version of Document XN-NF-734(NP) and and has been prepared in accordance with NRC guidance.

EXXON NUCLEAR COMPANY, INC.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

February 1, 1985

Mr. J. C. Chandler, Lead Engineer
Reload Fuel Licensing
Exxon Nuclear Company, Inc.
2101 Horn Rapids Road
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Dear Mr. Chandler:

Subject: Acceptance for Referencing of Licensing Topical Report XN-NF-734(P), "Confirmation of the XN-3 Critical Power Correlation for 9x9 Fuel Assemblies"

We have completed our review of the subject topical report submitted by Exxon Nuclear Company, Inc. (Exxon). We find the report to be acceptable for referencing in license applications to the extent specified and under the limitations delineated in the report and the associated NRC evaluation, which is enclosed. The evaluation defines the basis for acceptance of the report.

We do not intend to repeat our review of the matters described in the report and found acceptable when the report appears as a reference in license applications, except to assure that the material presented is applicable to the specific plant involved. Our acceptance applies only to the matters described in the report.

In accordance with procedures established in NUREG-0390, it is requested that Exxon publish accepted versions of this report, proprietary and non-proprietary, within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed evaluation between the title page and the abstract. The accepted versions shall include an -A (designating accepted) following the report identification symbol.

Should our criteria or regulations change such that our conclusions as to the acceptability of the report are invalidated, Exxon and/or the applicants

Enclosure

SAFETY EVALUATION FOR THE

CONFIRMATION OF THE EXXON NUCLEAR COMPANY XN-3 CRITICAL POWER CORRELATION FOR 9X9 FUEL ASSEMBLIES

Prepared by

Core Performance Branch

December 1984

1.0 INTRODUCTION

As part of the process of developing the capability to license fuel for nuclear reactor core reloads, Exxon Nuclear Company has pursued a program aimed at the development of a correlation to predict the onset of transition boiling (critical heat flux). A large number of experimental measurements of critical heat flux have been performed using heated rod diameters, power distributions and spacers that are typical of current generation boiling water reactors. The data has been mathematically correlated to provide a mechanism for predicting the onset of transition boiling. The correlation has progressed through the XN-1, XN-2 and XN-3 correlations to its present form which is denoted XN-3 (Revision 1). This form of the correlation has been previously reviewed and approved by the staff (Reference 5) for use by Exxon with a mean of .997 and a standard deviation of 0.041 to develop design limits. The purpose of XN-NF-734(P) is to present additional data which justifies the use of this correlation for 9x9 fuel assemblies.

2.0 XN-3 CORRELATION (REVISION 1)

The XN-3 Correlation is an empirical representation of the planar averaged fluid conditions at which boiling transition has been experimentally detected. The minimum heat flux required to produce boiling transition is predicted from the fluid conditions of pressure, mass velocity and enthalpy averaged over the assembly at the planes of interest. The correlation contains correctors for the effects on boiling transition due to a non-uniform axial heat flux profile.

The XN-3 (Revision 1) correlation has been revised to provide an additional correlation which predicts the onset of transition boiling in interior rods, and the previous version of the XN-3 correlation has been restricted to peripheral rods. This revision appears to have been motivated by the data resulting from a new series of tests involving a 5x5 array of heated rods

(ENC-IV test series, tasks JP/8 and JP/9). The previous version was based exclusively on data taken from tests with rod arrays no larger than 4x4.

Revision 1 to the XN-3 correlation presents three separate and distinct correlations for predicting the onset of transition boiling. These apply to peripheral and interior rods of assemblies with "typical" spacers while the third applies only to assemblies with "minimal" spacers. This review does not consider the case of minimal spacers which are not used in the current BWR designs.

The XN-3 (Revision 1) correlation data base (Reference 1) is comprised of 1501 data points taken with 26 different test assemblies. The test assemblies include both partial and full length rods; both uniform and non-uniform axial heat flux profiles; grid spacers that are prototypic of BWR fuel designs (typical grids) as well as "Wart" type spacers (minimum grids); 4x4 rod configurations and 5x5 rod configurations; and a variety of rod diameters, assembly hydraulic diameters, rod-to-wall spacings and rod to rod spacings.

XN-NF-734(P) presents data from two sources (References 2 and 3) in order to justify the use of XN-3 for 9x9 bundles. The data base contains 241 data points obtained by ENC in 5x5 rod test sections at Columbia University and in 9x9 test sections at the ATLAS test facility. These test sections include uniform and non-uniform axial profiles of full length rods, with grid spacers prototypical of BWR designs with and without water holes. The range of operating conditions considered is shown in Table 1.0.

3.0 XN-3 COMPARISON TO (9X9) DATA BASE

Exxon has used XN-3 to predict the critical power for each of the 241 test points in the expanded 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 0.959 and standard deviation of 0.041.

Table 1.0

TEST CONDITIONS FOR 9X9 DATA

	Range
Pressure (psia)	595 - 1215
Mass Velocity ($MLb/hrft^2$)	.242 - 1.609
Inlet Subcooling (BTU/Lbm)	0 - 203
Bundle Average Steam Quality at Boiling Transition	.2 - .8
Maximum Local Power Peaking	1.135 - 1.177
S Factor	1.02 - 1.031
Axial Power Peaking	Uniform - 1.40 chopped cosine

Examining the ENC data from Columbia and comparing it with data from the ATLAS facility shows the mean of the ENC data is 0.957 while the mean of the ATLAS data is 0.965.

4.0 STAFF EVALUATION

The staff has reviewed XN-3 (Revision 1) comparisons to experimental data and finds that it accurately reproduces this data base. Although the extended data base consists of only 241 test points they do cover the expected range of conditions and the data base contains the range of geometries for current Exxon 9x9 fuel designs. In reviewing this data base the staff was concerned that the fuel rod pitch of 0.572 inches which Exxon plans to use in future reloads in BWR/3-5 applications was not explicitly included. The staff submitted the following question in this regard to Exxon:

> The fuel rod pitch identified for the ENC 9x9 fuel in XN-NF-81-21(P), Revision 2, is 0.572 inch. The rod pitch in the test sections used for verification of the XN-3 correlation for 9x9 fuel applications is 0.563 inch. Please explain the discrepancy and justify the use of the atypical test sections for validation of the XN-3 correlation for 9x9 fuel applications.

Exxon provided the following response:

<u>ENC Response</u>

"The rod pitch in the test sections is typical of 9x9 fuel for BWR/6 applications; the fuel design reported in the generic fuel design analysis is for the slightly larger lattice associated with BWR/3-5 applications.

Phenomenologically, boiling transition for BWRs is dominated by stripping the liquid layer due to high steam velocities. The influence of rod size and rod pitch upon this phenomenon was not apparent in the original data upon which the XN-3 correlation is based, although a range of rod sizes and pitches was evaluated in the original documentation. Based on observation of the original correlation data, the impact of a fuel rod pitch of 0.563 inch rather than 0.572 inch in extending the applicability of the correlation of 9x9 designs is relatively unimportant.

The trends noted in the XN-3 data base show a slight conservatism at the lower pitch values relative to the XN-3 predictions. This consistent conservatism is also shown in the impact of hydraulic diameter. When these parameters are considered together, however, there are no readily observable trends. This lack of trends is shown by comparing the correlation error as a function of the ratio of the rod pitch to the hydraulic diameter. These trend analyses indicate that the effect of rod pitch and hydraulic diameter are insignificant to conservative in the ranges of these parameters typical of BWR fuel.

The rod pitch covered in the test sections ranges from 0.563 inch to 0.738 inch. The 0.572 inch fuel rod pitch characteristic of the 9x9 fuel fabricated for BWR/3-5 applications is bracketed by the range of hydraulic diameters covered in the test sections, 0.450 to 0.525 inch. The fuel rod outside diameter of the 9x9 fuel for all BWR applications is covered explicitly in the data base. The data presented in XN-NF-734(P) extend the limits of applicability of the XN-3 correlation to cover the 9x9 lattice configurations to be fabricated for BWR/3-5 and BWR/6 applications."

The staff agress in principle with the Exxon response, however, we find that it would provide insufficient justification for using XN-3 with a mean of 0.959 as calculated for the 9x9 data set. However, since in Reference 4 Exxon has agreed to use the previously approved mean of 0.997 for XN-3 instead of the 0.959 calculated for the 9x9 data it will be conservative to apply XN-3 as previously approved for 8x8 assemblies. Thus, the staff concludes that XN-3 as approved in

Reference 5 may be used by Exxon in developing its design limits for reload cores containing Exxon 9x9 provided the ranges of applicability given in Table 2 are not exceeded.

Table 2

RANGES OF APPLICABILITY FOR
XN-3 (REVISION 1 FOR 9X9 ASSEMBLIES

Mass Velocity Mlb/hr-ft**2	Range of enthalpy at boiling transition BTU/lbm
0.25	953.0 - 1112.0
0.50	834.8 - 946.2
0.75	741.9 - 858.0
1.00	668.0 - 802.0
1.25	629.6 - 758.5
1.50	618.5 - 750.4

5.0 REFERENCES

1. R. B. Macduff and T. W. Patten, XN-3 CRITICAL POWER CORRELATION, XN-NF-512(P)(A), Revision 1, October 1982.

2. S. Pimpoutkar and M. Gross, The Thermal-Hydraulic Performance of an 81 Rod Bundle Under Boiling Water Reactor Conditions, 1979 Meeting of the European Two-Phase Flow Group, ISPRA, June 5 - June 7.

3. R. B. Macduff, Exxon Nuclear Critical Heat Flux Data Base For Boiling Water Reactor Fuel - Data Supporting 9x9 BWR Fuel, XN-NF-81-15, Supplement 1, August 1983.

4. Letter, J. C. Chandler (ENC) to C. O. Thomas (NRC), dated November 19, 1984 (JCC:154:84).

5. Memorandum, L. S. Rubenstein to R. L. Tedesco "Review of Exxon Nuclear Company's XN-3 Critical Power Correlation", June 17, 1982.

XN-NF-734(NP)(A)

CONFIRMATION OF XN-3 CRITICAL POWER CORRELATION FOR 9x9 FUEL ASSEMBLIES

SEPTEMBER 1983

EXXON NUCLEAR COMPANY, Inc.

XN-NF-734(NP)(A)

CONFIRMATION OF XN-3 CRITICAL POWER CORRELATION

FOR 9x9 FUEL ASSEMBLIES

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CONFIRMATION OF XN-3 CRITICAL POWER CORRELATION FOR 9x9 FUEL ASSEMBLIES

1.0 INTRODUCTION AND SUMMARY

This document reports the data and analysis which confirm the applicability of the XN-3 critical power correlation[1] for 9x9 fuel designs. The analysis of 241 data points obtained by ENC at Columbia University and from the open literature[2] demonstrates the adequate, yet conservative capability of XN-3 to predict critical power for 9x9 fuel assemblies. Three different assemblies representative of 9x9 fuel designs have been considered. The designs include uniform and non-uniform axial profiles of full length rods, grid spacers prototypic of BWR designs, and [ ] The range of operating conditions considered is shown in Table 1.1.

The XN-3 correlation has been used to predict the critical power for each point in the 9x9 data base. The ratio (CPR) of the predicted critical power to the measured critical has been determined for each test point. Comparison of the predicted and measured critical powers is shown in Figure 1.1; in general measured critical powers are slightly greater than predicted critical powers which demonstrate the conservative nature of the XN-3 correlation in 9x9 fuel.

Statistically, the data were characterized to determine an overall mean and standard deviation. The mean CPR for the 9x9 data is 0.959 with a standard deviation of 0.041. The distribution of the data is approximately normal.

The data were statistically evaluated with the result that the mean of the data [ ] from the ATLAS test reported in the open literature[2] could not be considered different from the mean of the data [ ] from the Columbia University tests. [ ]

Table 1.1 Test Conditions for 9x9 Data

	Range
Pressure (psia)	595 - 1215
Mass Velocity (MLb/hrft^2)	.242 - 1.609
Inlet Subcooling (BTU/Lbm)	0 - 203
Bundle Average Steam Quality at Boiling Transition	.2 - .8
Maximum Local Power Peaking	1.135 - 1.177
S Factor	1.02 - 1.031
Axial Power Peaking	Uniform - 1.40 chopped cosine

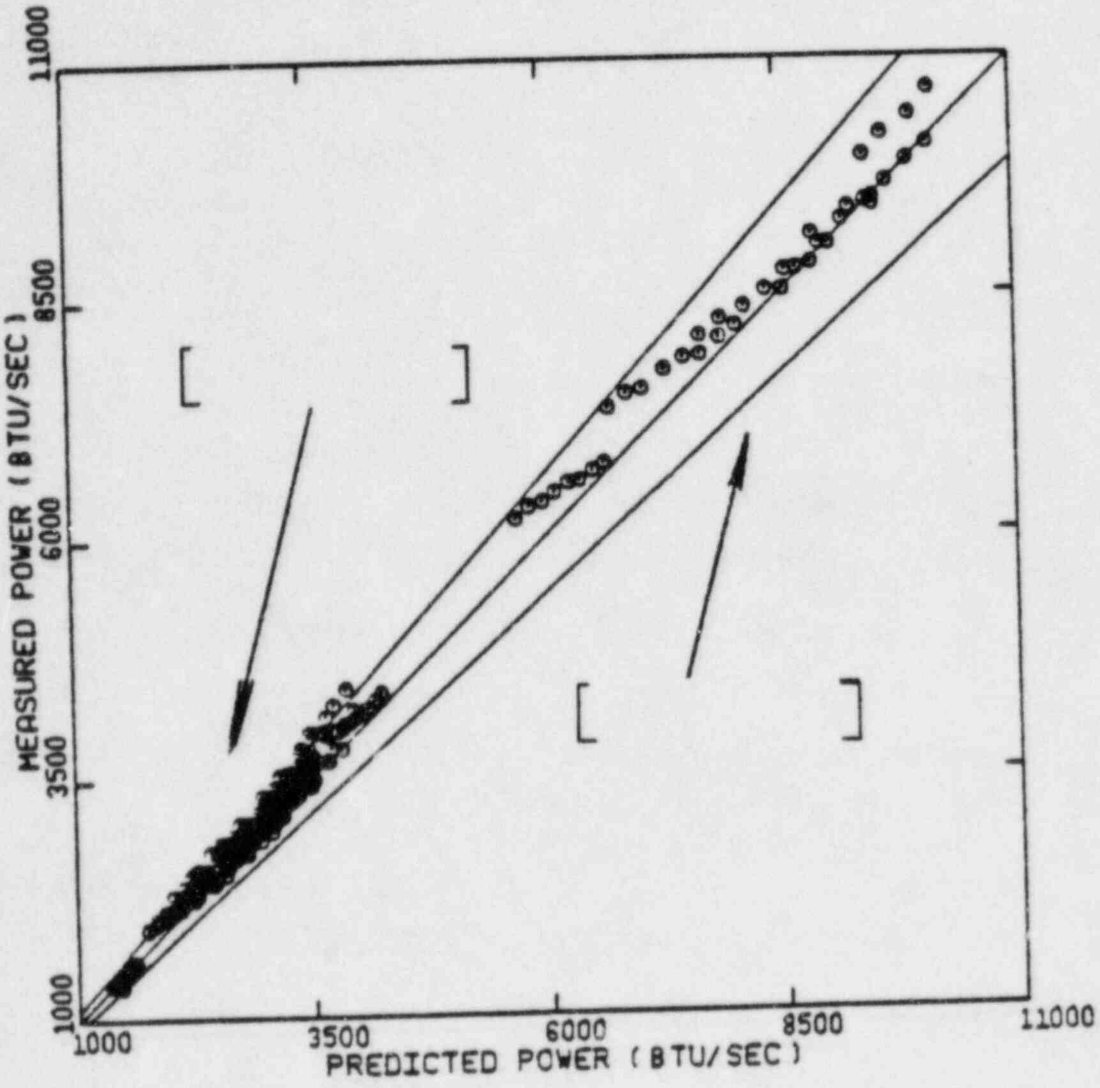

FIGURE 1.1 XN3 PREDICTION OF 9X9 DATA

2.0 EXPERIMENTAL DATA SUPPORTING XN-3 CRITICAL POWER CORRELATION FOR 9x9 APPLICATIONS

The data come from two sources. Exxon Nuclear Company sponsored critical heat flux tests at Columbia University while other tests were conducted in the ATLAS facility and reported in Reference (2). The test section description and rod layout are reported in Reference (3) for each of the sections. Appendix A shows cross sections of the rod layout of the ENC-sponsored tests. Relative rod power and pertinent bundle geometry are included. Appendix B shows the cross section of the 9x9 test section at the ATLAS facility, the geometry and axial power profile. Further, in Appendices A and B, each data point is presented including the measured bundle power, the predicted bundle power, and critical power ratio.

The measured versus predicted critical powers are shown in Figures 2.1, 2.2 and 2.3. The data from section JP-10 are shown in Figure 2.1. The mean CPR for the [ ] points is [ ] with a standard deviation of [ ] The measured and predicted critical powers for test section JP-11 [ ] are compared in Figure 2.2. The mean CPR for the [ ] points is [ ] with a standard deviation of [ ]

The measured versus predicted critical power for the ATLAS data is shown in Figure 2.3. The mean CPR for the [ ] data points is [ ] with a standard deviation of [ ]

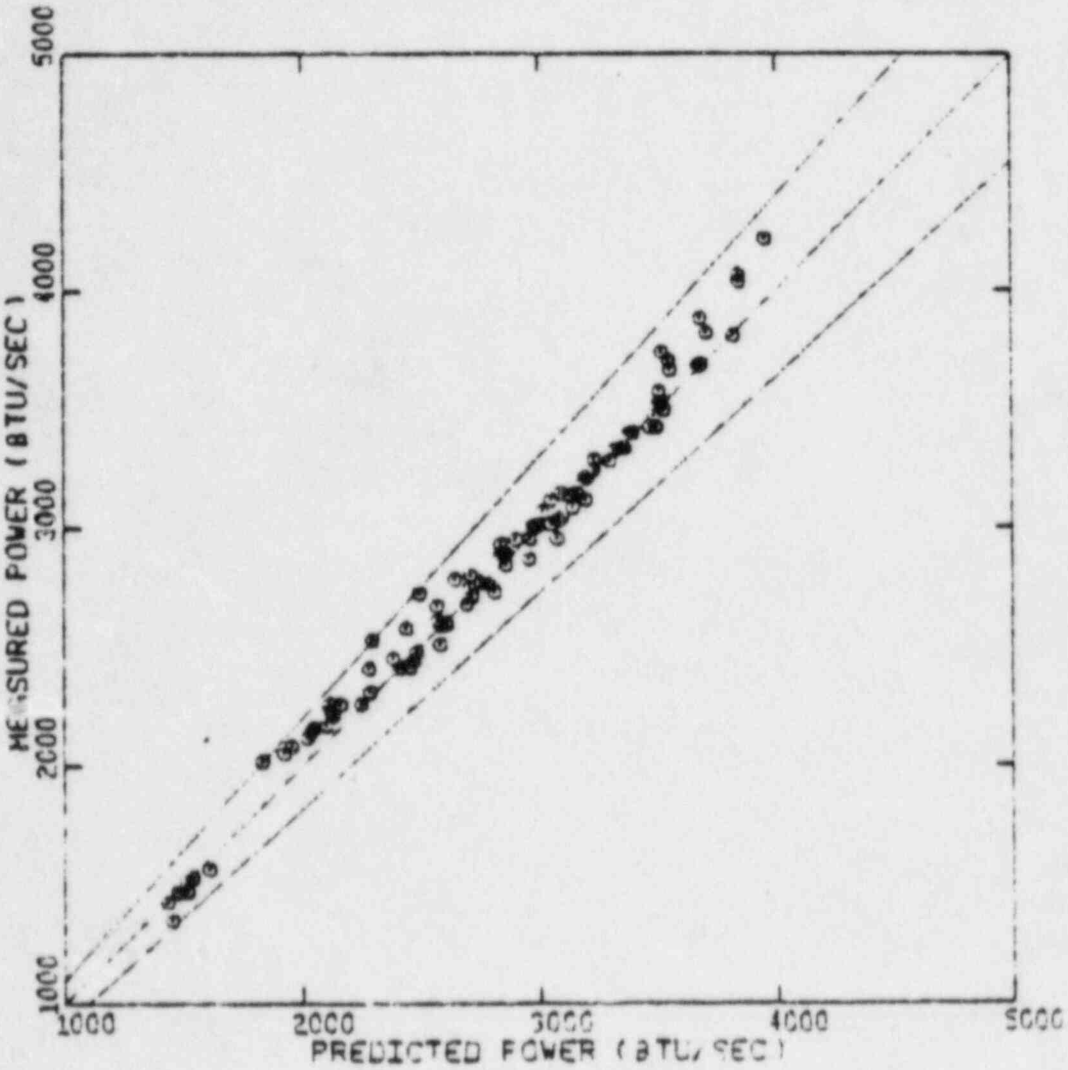

FIGURE 2.1 XN3 PREDICTION OF JP-10 DATA

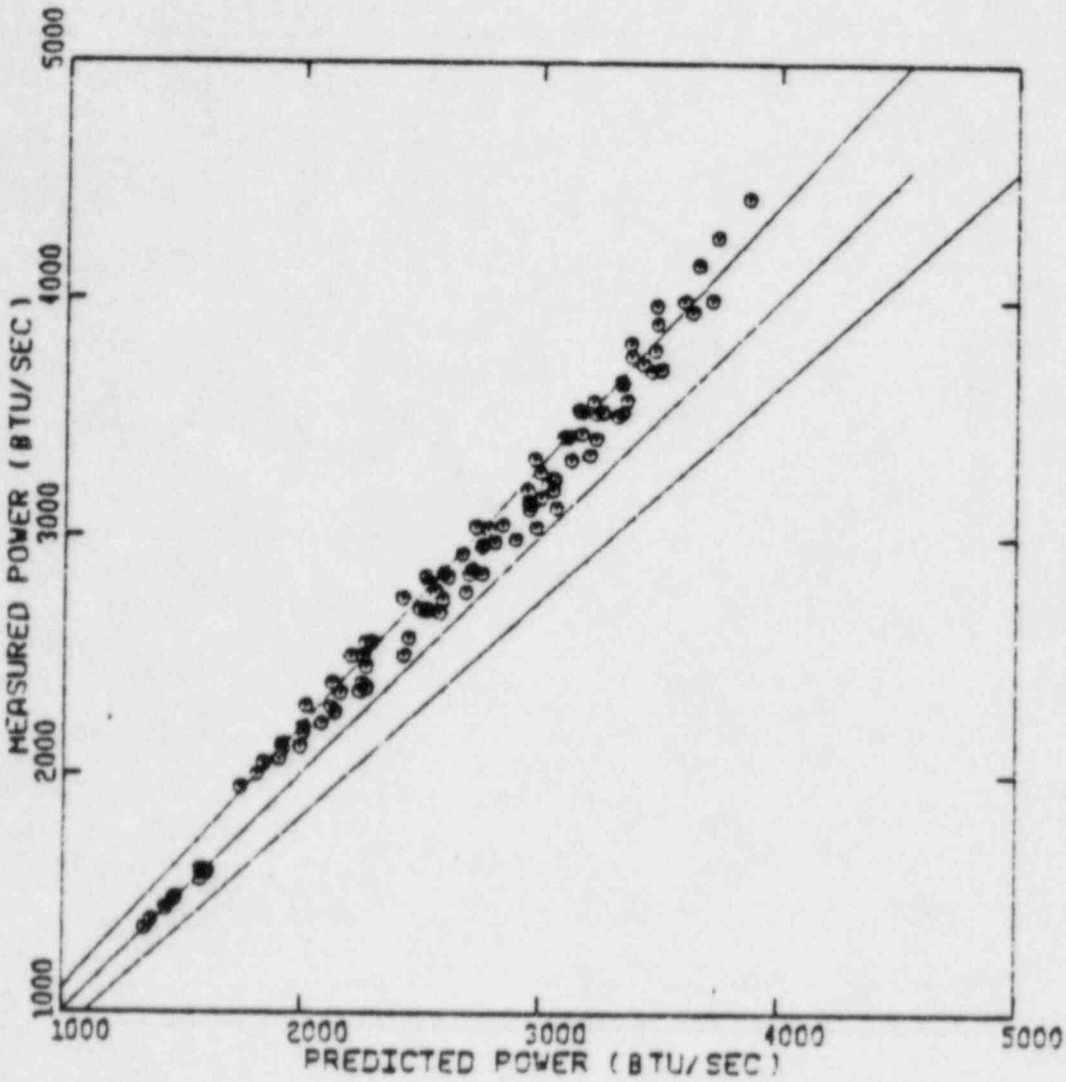

FIGURE 2.2 XN3 PREDICTION OF JP-11 DATA

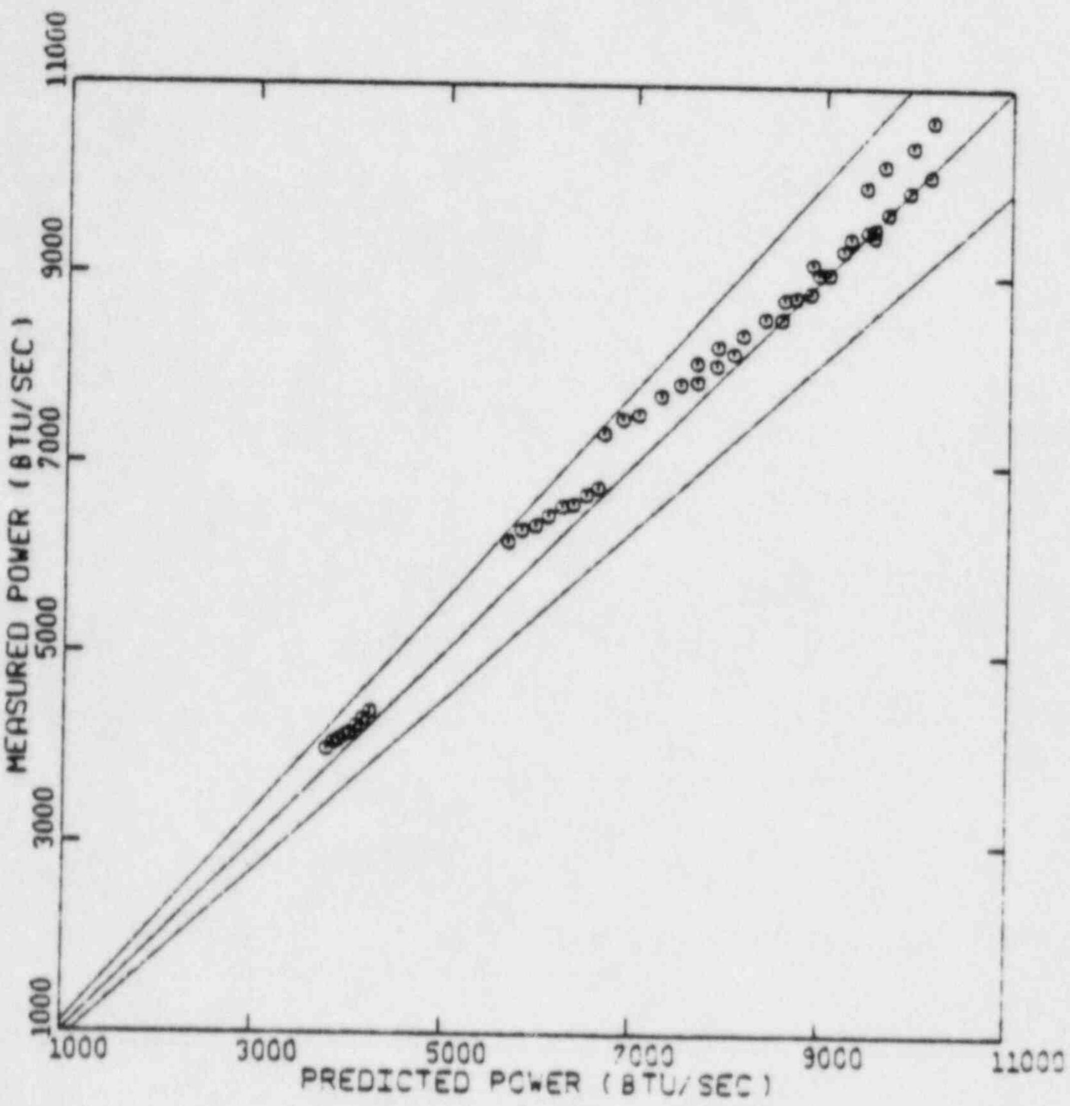

FIGURE 2.3 XN3 PREDICTION OF ATLAS DATA

3.0 DATA REDUCTION METHOD

3.1 UNIFORM AXIAL ASSEMBLIES

The procedure detailed in Reference (1) using an explicit critical power relationship for uniform axial assemblies was applied for analysis of test sections JP-10 and JP-11. The critical heat flux was corrected, where appropriate, for the S factor.

3.2 NON-UNIFORM AXIAL ASSEMBLY

The data presented in Reference (2) required reduction from graphical presentation. The flow and pressure were known as the quantities given in the test and represent rounded values of the actual experimental flows. Power and inlet subcooling were taken from a graphical presentation. The power is expected to be a correct representation within [ ] and the subcooling is expected to be a correct representation within [ ]

The data were converted from metric (SI) units to English engineering units and an [ ] analysis was performed for this non-uniform axial case. The F-factor as described in Reference (1) corrected the correlation prediction to account for the non-uniform axial. The reduced data is shown in Appendix B.

4.0 STATISTICAL EVALUATION

The CPR predictions for each data point were statistically combined to determine the mean CPR prediction and the standard deviation. The mean (x) and standard deviation (s) are used to characterize the frequency distribution of the XN-3 predictions. The overall standard deviation takes into consideration the variation among data sets. The mean and standard deviation of a given data set are calculated by standard statistical expressions. The overall mean and standard deviation are determined by a weighted combination of the test section means and standard deviations. The weights are determined by the number of data points within each group. The overall standard deviation is determined from the standard deviation of each data set and the standard deviation between data sets. The result of this analysis for the 241 data points is a mean of 0.959 and a standard deviation of 0.041. Table 4.1 provides a statistical summary of the CPR predictions.

[

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[

]

TABLE 4.1

Section	N	(X)	(S)
JP-10			
JP-11			
ATLAS			
Overall	241	.959	.041

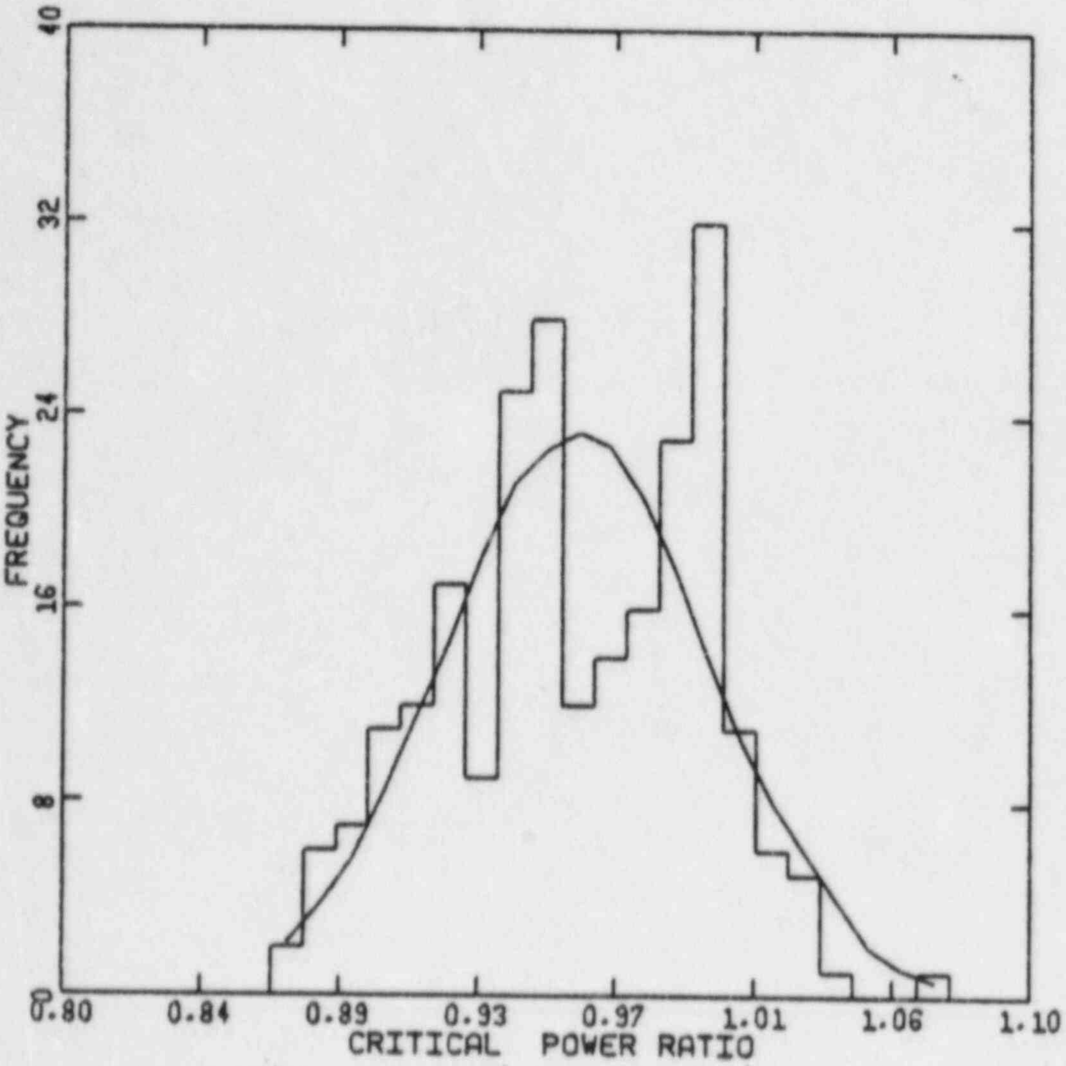

FIGURE 4.1 HISTOGRAM AND NORMAL DISTRIBUTION

4.0 REFERENCES

(1) R. B. Macduff and T. W. Patten, XN-3 CRITICAL POWER CORRELATION, XN-NF-512(P)(A), Revision 1, October 1982.

(2) S. Pimputkar and M. Gross, The Thermal Hydraulic Performance of an 81 Rod Bundle Under Boiling Water Reactor Conditions, 1979 Meeting of the European Two-Phase Flow Group, ISPRA, June 5 - June 7.

(3) R. B. Macduff, Exxon Nuclear Critical Heat Flux Data Base For Boiling Water Reactor Fuel - Data Supporting 9x9 BWR Fuel, XN-NF-81-15, Supplement 1, August 1983.

(4) [ ]

APPENDIX A

EXXON SPONSORED CHF TEST RESULTS FOR 9x9 APPLICATION

(This appendix consists entirely of proprietary material and has been deleted for this document.)

APPENDIX B

ATLAS CHF TEST RESULTS

FOR 9x9 APPLICATION

(This appendix consists entirely of proprietary material and has been deleted for this document.)

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