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A STATISTICAL MARGIN TO DNB SAFETY ANALYSIS APPROACH FOR LOFT

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ABSTRACT

A method was developed and used for LOFT thermal safety analysis to estimate the statistical margin to DNB for the hot rod, and to base safety analysis on desired DNB probability limits. This method is an advanced approach using response surface analysis methods, a very efficient experimental design, and a 2nd-order response surface equation with a 2nd-order error propagation analysis to define the MDNBR probability density function. Calculations for limiting transients were used in the response surface analysis thereby including transient interactions and trip uncertainties in the MDNBR probability density.

INTRODUCTION

The standard thermal safety analysis approach used for PWRs and LOFT has been the hot spot-hot channel or conservative deterministic analysis approach. This safety analysis approach assumes all plant and physical parameter uncertainties and errors simultaneously equal or exceed 95% probability bounds in the worst direction for the occurrence of Departure from Nucleate Boiling (DNB) when a reactor transient occurs. Additionally, reactor trips are set at worst-case values in which all uncertainties and errors are added to the nominal trippoints. Although the safety goal for Incidents of Moderate Frequency or Condition II transients is a probability of 95% or greater for no occurrence of DNB on the hot fuel rod [1], this probability cannot be calculated using the hot spot-hot channel approach. The use of the hot spot-hot channel approach has resulted in restrictive limits on LOFT operation and an inability to show that the reactor can operate safely in some test configurations because of an inability to estimate the thermal safety margins.

Methods have been developed for statistically combining all uncertainties and potential errors to obtain relief from the stacked conservatisms and lack of realism inherent in the hot spot-hot channel approach. The methods determine the probability density (or probability distribution) for the hot rod MDNBR (minimum DNB heat flux ratio) in order to evaluate the probability for DNB on the hot rod. The DNB safety margin can then be estimated and safety analysis can be based on satisfying a desired bound or limit for the probability of DNB (typically a 5% probability, or a probability greater than 95% that DNB does not occur).

An example of a MDNBR probability distribution is in Figure 1. When the 5% probability bound corresponds to the desired MDNBR limit, the nominal value of MDNBR is then considered a limit for the nominal value of MDNBR for safety analysis performed using nominal conditions and nominal parameter values as input. The margin between this nominal MDNBR limit and the desired limit at the 5% probability bound is a minimum safety margin to allow for the statistical combination of uncertainties in reactor conditions, parameters, and trips.

This concept of a nominal MDNBR limit for a maximum probability of obtaining a MDNBR less than a defined MDNBR limit was developed and is used by Westinghouse in their "Improved Thermal Design Procedure" and is accepted for the licensing of their current generation nuclear steam supply system [2,3].

DEFINING A NOMINAL LIMIT FOR MDNBR

The probability distribution for MDNBR needs to be determined in order to calculate a statistical margin from DNB and a nominal MDNBR limit. The probability distribution for the output of an algebraic analytical function can be easily determined by error propagation or Monte Carlo sampling methods. But, complex computer models are needed to reasonably calculate the transient thermal-hydraulic conditions and the approach to DNB in a LOFT fuel bundle. To obtain the MDNBR probability distribution using complex computer models with a minimum number of runs and costs, and to obtain information about the MDNBR and its relationship to the input parameters, the Response Surface Analysis Method was used. The Westinghouse Improved Thermal Design Procedure used a simplified response surface analysis approach [2].

A response surface is a multidimensional surface defined by the output or response of an analytical model as a function of its multivariable input. In the response surface analysis approach, the response surface is fit by an algebraic function, the response surface equation. The response surface equation is then used as a substitute for the computer models in the statistical analysis.

Definition of the response surface requires obtaining a suitable population of output points from the computer models. The key to a good response surface definition, and thus a good response surface equation, is the plan by which the values of the input variables are chosen. A plan for choosing parameter values to use in experimental testing and statistical analysis is called "Statistical Design and Analysis of Experiments" or just "Experimental Design." Many different types of experimental designs could be used, but the type of experimental design used needs to be one which will at least:

1. Provide adequate coverage of the response surface.
2. Minimize the number of runs required to generate an adequate response surface.
3. Provide sensitivity information for the relative importance of the input parameters.

It is also desirable to have a response surface for which all 1st-order effects and the important 2nd-order effects, including interaction effects between input factors, are identified.

A "Resolution IV" fractional factorial design was used for the LOFT MDNBR response surface analysis. A Resolution IV design is one for which:

1. No 1st-order terms are confounded with any other 1st-order terms or 2nd-order terms.
2. Important 2nd-order terms are only confounded with higher order terms.
3. All higher-order interactions are assumed to be insignificant.

Confounding refers to when the effect of some factors are confused or indistinguishable from the effect of other factors. This property of a Resolution IV design is an accepted compromise in order to reduce the number of trials and the cost of the experiment.

The particular experimental design chosen for the LOFT MDNBR response surface analysis is a folded-over Plackett-Burman design [4] supplemented with star-points. Star-points are output values obtained by the perturbation of only a single input factor with all other input factors set at their nominal values. The star-points are defined for perturbed factor levels outside the levels used in the Plackett-Burman design, such as at 3 standard deviations away from nominal. The star-point calculations can be done first to serve as a sensitivity study to pare the number of factors in the design. This experimental design requires 4 n + 7 trials, where n is the number of input factors. Eighteen input factors were considered in the LOFT MDNBR design, requiring 79 runs. This design is a very economical design, and it has been shown to be effective for response surface analysis for propagation of errors through complex thermal-hydraulic computer models [5,6].

The steps in the response surface analysis for defining the LOFT MDNBR probability density and nominal MDNBR limit is summarized as follows [7]:

1. Define the limiting transient (that transient within the event probability class resulting in the lowest values for MDNBR). The LOFT response surface analysis is based on a transient rather than a steady state analysis as used for the Westinghouse Improved Thermal Design Procedure [2]. The steady state analysis is unable to include the effect on the MDNBR of the transient and trippoint interactions. Therefore, worst-case trippoints must still be used with the Improved Thermal Design Procedure.
2. Obtain or conservatively estimate for the important input parameters:
    a. Mean value (nominal value)
    b. Probability density function
    c. Standard deviation.

    Instrumentation channels usually have a normal probability density function. Parameters for which only a known or controlled range of potential values exist, were conservatively assumed to have a uniform probability density function. In a uniform probability density, all values have an equal probability, and the known bounds of the function are only $\pm \sqrt{3}$ standard deviations from the mean.
3. Define which input parameter combinations are suspected to have important two-factor interactions in order to assign the variables in the experimental design to minimize confounding amoung these interactions.
4. Set up the experimental design to set up the input parameter values to use in the computer calculations for the response surface points.
5. Run the computer models for the LOFT primary coolant system (PCS) response and fuel bundle thermal-hydraulic response to calculate MDNBR with input parameters established according to the experimental design.
6. Normalize the MDNBR calculation results to the MDNBR for all-nominal input and fit the resulting normalized MDNBR points in the response surface to a 2nd-order polynomial response surface equation. Normalizing the MDNBR values facilitates the statistical analysis of the response surface equation and the definition of the probability density function for the response surface. The computed output of the computer models may be nonlinear with respect to some parameter variations. Thus, a linear response surface equation and linear error propagation may not be satisfactory, and at least a 2nd-order equation and 2nd-order error propagation is required.
7. Use the best-fit response surface equation in a 2nd-order error propagation analysis to define the characteristics of the probability density. The computer program SOERP [8] enables the accomplishment of the difficult 2nd-order error propagation.
8. Define the probability density function which best fits the response surface equation 2nd-order error propagation results, and determine the 5% probability bound for the normalized MDNBR probability density function (using the PDFPLOT [9] computer program).
9. Define the nominal MDNBR limit for the normalized MDNBR probability density function with the desired limit on the MDNBR at the 5% probability bound.

Input parameters that are not to be included in the experimental design are set at fixed off-nominal values.

LOFT RESPONSE SURFACE ANALYSIS RESULTS

Two limits for MDNBR were defined for LOFT safety analysis. The consequence limit for LOFT Operational Transients (Condition I events) or Incidents of Moderate

Frequency (Condition II events) is the MDNBR corresponding to the 95% probability bound (with a 95% confidence) of the population of LOFT fuel bundle DNB test data as correlated by the LOFT-3 DNB heat flux correlation [10]. This MDNBR limit is 1.14.

The consequence limits for LOFT Infrequent Faults or Limiting Faults (Condition III and IV events) are limits on fuel cladding temperature which will not be reached unless DNB or clad dryout occurs. A limit for DNBR still needs to be defined at which the fuel rod surface would be assumed to reach DNB conditions for fuel rod heatup analysis. A conservative approach is to assume DNB occurs whenever and wherever the probability of DNB reaches or exceeds 5%. The desired limit on MDNBR for this approach is 1.0 with the DNB heat flux and its uncertainty included in the MDNBR probability distribution. The DNB heat flux uncertainty is not included in the MDNBR probability distribution for the first limit discussed above. This statistical safety analysis does not extend into the fuel rod heatup analysis, but only defines the probability of DNB on the fuel rod surface.

Table I presents the results of the LOFT MDNBR response surface analyses [11]. The fit of the response surface equation to the MDNBR response surface for the limiting Incident of Moderate Frequency (a control rod withdrawal accident) is shown in Figure 2. The previously discussed Figure 1 is the normalized MDNBR probability distribution for the CRWA response surface analysis. Figure 1 shows the MDNBR probability distribution is skewed towards values of MDNBR below the nominal value. Thus, most uncertainties result in a lower MDNBR.

TABLE I

LOFT MDNBR RESPONSE SURFACE ANALYSIS RESULTS (FULL FLOW OPERATION)

	Operational Transients	Condition II Events	Condition III and IV Events
Limiting transient	CRWA[a.]	CRWA[a.]	Rapid loss of flow[b.]
Desired DNBR limit	1.14[c.]	1.14[c.]	1.0
MDNBR probability density function	Pearson Type VI	Pearson Type VI	Normal
Normalized MDNBR mean	.968	.968	.969
Normalized MDNBR standard deviation	.0459	.0459	.0927[d.]
Normalized MDNBR 5% probability bound	.8778	.8778	.8164
Nominal MDNBR limit	1.30	1.30	1.23
MDNBR, all-nominal input	1.86	1.80	1.25
MDNBR worst combination potential nominal conditions	1.76	1.59	---
MDNBR deterministic analysis	1.27	1.17	0.89

a. Control rod withdrawal accident

b. Without flywheel assisted coastdown

c. 95% probability bound of LOFT-3 DNB heat flux correlation

d. MDNBR probability density includes DNB heat flux uncertainty

Table I identifies the limiting transient used for the response surface analysis, the desired limit on MDNBR at the 5% probability bound of the MDNBR probability distribution, the MDNBR probability density function and its normalized mean and standard deviation, the normalized MDNBR at the 5% probability bound, and the resulting limit for nominal MDNBR.

The standard deviation for the rapid loss of flow is more than twice the standard deviation for the CRWA because the DNB heat flux uncertainty is included in the former distribution. The DNB heat flux uncertainty accounts for 67% of the total variance for the rapid loss of flow MDNBR probability distribution.

The nominal MDNBR is 1.30 when MDNBR at the 5% probability bound is 1.14 for the CRWA MDNBR probability distribution. The nominal MDNBR is 1.23 when MDNBR at the 5% probability bound is 1.0 for the rapid loss of flow MDNBR probability distribution.

Also listed in Table I is a comparison of values for nominal MDNBR calculated for normal operating conditions, for a worst combination of potential operating conditions, and for MDNBR calculated by the hot spot-hot channel approach for LOFT limiting transients. This comparison shows the hot spot-hot channel approach indicated very little safety margin may exist (even after operating limitations were tightened), while the actual margin is significant. The MDNBR calculation for the worst combination of potential initial conditions also included a loosening of some operating and trippoint restrictions. For Condition-III and most Condition-IV events, the hot spot-hot channel analysis indicates DNB will probably occur, whereas the probability for DNB on the hot rod is found to be less than 5%. Thus the use of the statistical margin to DNB analysis approach reveals a significant safety margin exists when the hot spot-hot channel analysis indicated little or no safety margin may be left.

Another comparison was made for a LOFT low flow operating condition for a CRWA for which the hot spot-hot channel analysis calculated a MDNBR of 1.13, slightly less than the 1.14 limit for a Condition II event, but for which the nominal MDNBR is 1.51 [8]. From the MDNBR probability distribution for the CRWA, during LOFT low flow operation including the DNB heat flux uncertainty, it was determined that the actual probability for DNB on the hot rod was less than 0.05%, and the probability that MDNBR was less than 1.14 was only 0.5%.

These comparisons clearly illustrate the gross conservatism in the use of the hot spot-hot channel safety analysis approach, and the large safety margins that are demonstrated by use of a statistical DNB analysis approach.

APPLICABILITY OF THE STATISTICAL MARGIN TO DNB ANALYSIS

Sensitivity analyses were done to explore the applicability of the LOFT statistical margin to DNB safety analysis method and the use of nominal MDNBR limits for LOFT transient analyses [12]. A potential disadvantage of the response surface method is that the range of applicability may be limited to the range of input parameter values assumed for the experimental design, a limit of 3 standard deviations or less from nominal. Therefore, analyses were run for input parameter values at and beyond the 3 standard deviation range to examine the accuracy and applicability of the response surface equations and the nominal MDNBR limits.

Figure 3 shows MDNBR as calculated by the response surface equation and by the computer models (using the COBRA IV-I code) as a function of one of the significant input parameters for the CRWA, initial reactor power. The multiple points at each power level show the variations due to changes in other significant input parameters. The 2nd-order response surface equation is not able to cover the inflection in the MDNBR calculated by the computer models due to the mitigating influence of the high pressure scram for a CRWA from low initial powers. As a result, the response surface equation continues to predict a trend of decreasing MDNBR as a function of decreasing initial power. The response surface equation is, therefore, very conservative for initial powers less than 2 standard deviations from nominal. As a result of this study, it can be concluded that this response surface equation is accurate only over the +3, -2 standard deviation range for initial power, but is conservative for initial powers below nominal.

The difference between the computer calculated MDNBRs and those calculated by the response surface equation are within about 1% for variations in the other input parameters, with some of those parameters varied as much as six standard deviations away from nominal. These comparisons, and comparisons done for the rapid loss of flow transient and for LOFT low flow operation, show that the response surface equations are reasonably accurate over ± 3 standard deviations about nominal, and that for extrapolation beyond these bounds to 4 to 6 standard deviations about nominal the response surface equations are still sufficiently accurate (within 3%) or at least conservative. Thus the statistical margin to DNB analysis method can be applied for conditions somewhat outside the bounds of the experimental design of the response surface analysis.

If the probability densities or values of important input parameters are significantly changed, the response surface and its statistical analysis must be re-examined. If the response surface and the response surface equation are still valid, but the probability density functions of some parameters have changed, then it is only necessary to redo the error propagation analysis. If the response surface is no longer valid, the response surface analysis will have to be redone. However, with the use of the response surface sensitivity information available from the response surface analysis, it may be necessary to only redo a portion of the original analysis. For weak parameters, some sensitivity analysis and an appropriate conservative adjustment to the nominal MDNBR statistical limit may suffice.

Sensitivity calculations were also done for transients different from the limiting transients used for the response surface analyses, such as a Condition II loss of steam load accident, or a normal flow coastdown transient [8,12]. The variation in MDNBR for variations in the input parameters were compared to those for the limiting transients. These sensitivity calculations showed that the variance of the MDNBR for the alternate transients would not be larger than for the limiting transients. Thus, the resulting limit for nominal MDNBR is not greater than for the limiting transient, and the limit on nominal MDNBR determined for the limiting transient is also applicable to alternate but less severe transients.

These nominal MDNBR limits do not apply to transients that are phenomenologically very different from the limiting transients used for the response surface analysis (which are power-cooling mismatch transients), such as a control rod ejection accident or a loss of coolant resulting in core uncovery.

A third set of sensitivity calculations were done to define how sensitive the MDNBR probability distribution is to potential or expected changes in the probability densities of significant input parameters [8]. Several different changes were assumed in the variance and/or the probability density function of an input parameter. An example of the results of this sensitivity study is shown in the comparison of MDNBR probability distributions in Figure 4. The effect of an increase in the operating band for primary coolant pressure on the MDNBR probability distribution, shown in Figure 4, is minimal. The resulting limit on nominal MDNBR is unaffected. The same type of result was obtained for all other potential input parameter differences examined. These sensitivity tests for the effect of potential or likely changes in input parameter probability densities on the LOFT MDNBR probability densities show that the LOFT MDNBR probability density functions are robust, that is they are unlikely to be significantly affected by slight changes in the form or spread of the input parameter probability densities. These sensitivity studies show that the nominal MDNBR limits are satisfactory for LOFT safety analysis use for conditions within the demonstrated bounds of applicability of the response surface equations.

SUMMARY AND CONCLUSIONS

Limits on LOFT hot fuel rod MDNBR calculated using nominal input conditions and parameter values were established based on maintaining desired limits on the probability of DNB. The nominal MDNBR limits were developed using an advanced statistical analysis approach using response surface analysis methods, a very efficient experimental design, and a 2nd-order response surface equation. Calculations for limiting transients were used in the response surface analysis thereby including transient interactions and trippoint uncertainties in the MDNBR probability density.

Sensitivity analyses were done which show that the limiting transient can be used to define a MDNBR probability density and nominal MDNBR limit that is enveloping for the other transients. Sensitivity studies also demonstrated that the MDNBR probability densities are insignificantly effected by potential uncertainties in the input variable probability densities.

The use of the nominal MDNBR limits and performance of core thermal analysis using potential nominal conditions and input parameter values for LOFT operation has shown that previously restrictive tripsetting and operating limitations can be eased while still demonstrating that significant safety margins exist.

ACKNOWLEDGEMENT

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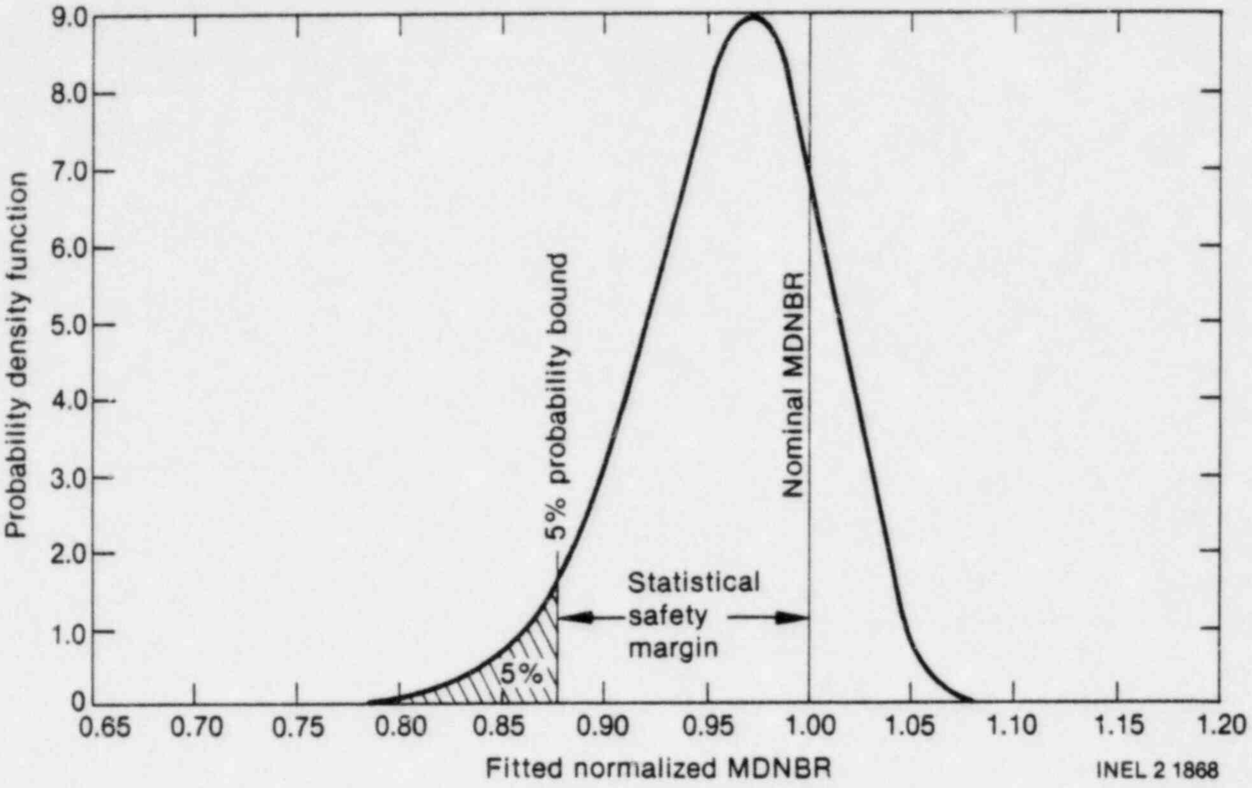

Figure 1. Normalized MDNBR Probability Distribution for the CRWA Response Surface.

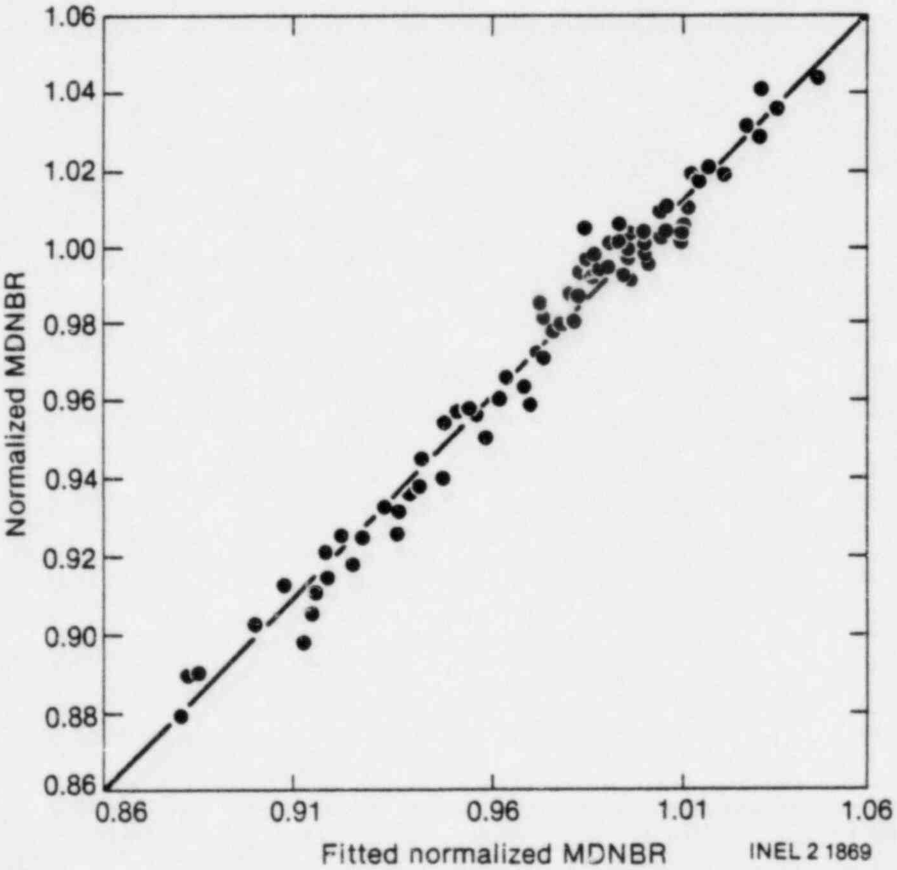

Figure 2. CRWA MDNBR Response Surface Equation, Fitted Correlation vs. Observed Data.

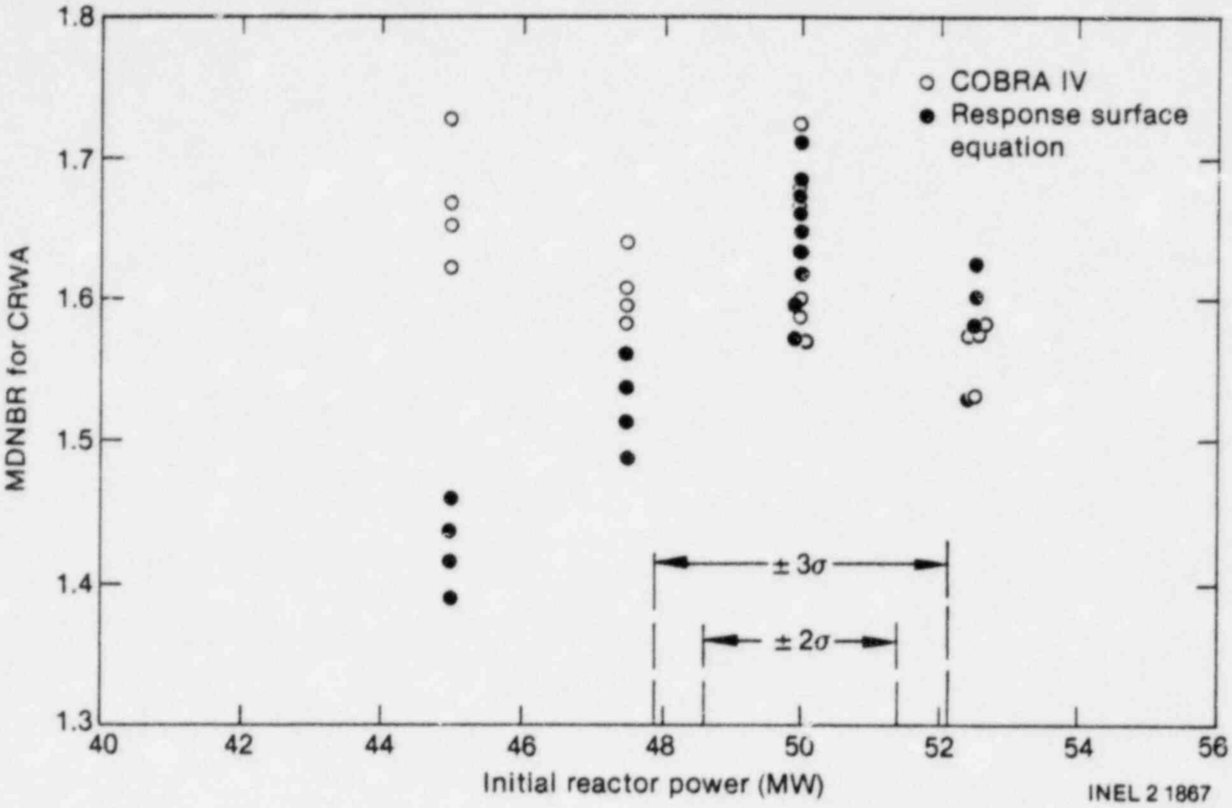

Figure 3. MDNBR Comparisons for CRWA Response Surface Equation and COBRA IV.

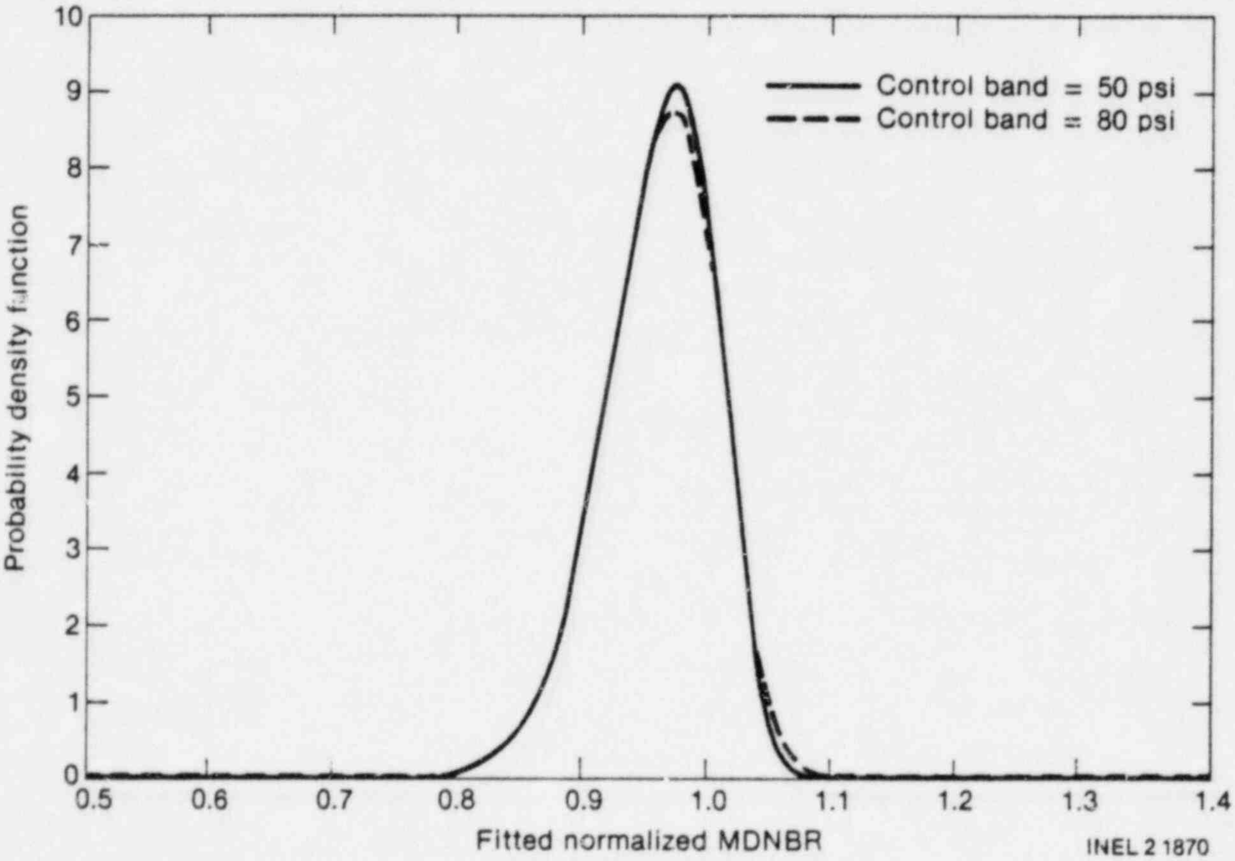

Figure 4. Overlay Plots, CRWA Normalized MDNBR Probability Density