Westinghouse Electric Corporation
Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

December 9, 1993
CAW-93-553

Document Control Desk
US Nuclear Regulatory Commission
Washington, DC 20555

Attention: Dr. Thomas Murley, Director

APPLICATION FOR WITHHOLDING PROPRIETARY
INFORMATION FROM PUBLIC DISCLOSURE

Subject: North Atlantic Energy Service Corporation Letter and Application for Withholding Proprietary Information from Public Disclosure to Document Control Desk.

Dear Dr. Murley:

The proprietary information for which withholding is being requested in the above-referenced letter is further identified in Affidavit CAW-93-553 signed by the owner of the proprietary information, Westinghouse Electric Corporation. The affidavit, which accompanies this letter, sets forth the basis on which the information may be withheld from public disclosure by the Commission and addresses with specificity the considerations listed in paragraph (b)(4) of 10 CFR Section 2.790 of the Commission's regulations.

Accordingly, this letter authorized the utilization of the accompanying Affidavit by the North Atlantic Energy Service Corporation and Yankee Atomic Electric Company.

Correspondence with respect to the proprietary aspects of the application for withholding or the Westinghouse affidavit should reference this letter, CAW-93-553, and should be addressed to the undersigned.

Very truly yours,

Nicholas J. Liparulo, Manager
Nuclear Safety and Regulatory Activities

Enclosures

cc: Kevin Bohrer / NRC (12H5)

Proprietary Information Notice

Transmitted herewith are proprietary and/or non-proprietary versions of documents furnished to the NRC in connection with requests for generic and/or plant-specific review and approval.

In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

Copyright Notice

The reports transmitted herewith each bear a Westinghouse copyright notice. The NRC is permitted to make the number of copies for the information contained in these reports which are necessary for its internal use in connection with generic and plant-specific reviews and approvals as well as the issuance, denial, amendment, transfer, renewal, modification, suspension, revocation, or violation of a license, permit, order, or regulation subject to the requirements of 10 CFR 2.790 regarding restrictions on public disclosure to the extent such information has been identified as proprietary by Westinghouse, copyright protection not withstanding. With respect to the non-proprietary versions of these reports, the NRC is permitted to make the number of copies beyond these necessary for its internal use which are necessary in order to have one copy available for public viewing in the appropriate docket files in the public document room in Washington, DC and in local public document rooms as may be required by NRC regulations if the number of copies submitted is insufficient for this purpose. The NRC is not authorized to make copies for their personal use or for members of the public who make use of the NRC public document rooms. Copies made by the NRC must include the copyright notice in all instances and the proprietary notice if the original was identified as proprietary.

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared Henry A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Corporation ("Westinghouse") and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

Henry A. Sepp

Henry A. Sepp, Manager
Strategic Licensing Issues

Sworn to and subscribed
before me this 14th day
of December, 1993.

Lorraine M. Piplica
Notary Public

Notarial Seal
Lorraine M. Piplica, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires Dec. 14, 1995
Member, Pennsylvania Association of Notaries

(1) I am Manager, Strategic Licensing Issues, in the Nuclear and Advanced Technology Division, of the Westinghouse Electric Corporation and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Energy Systems Business Units.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Energy Systems Business Units in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked in "Revised Thermal Design Procedure," WCAP-11397-P-A (Proprietary), April 1989, for information in support of North Atlantic Energy Service Corporation's submittal to the Commission, transmitted via letter, North Atlantic, NYN-93020, dated February 2, 1993, "Request for NRC Review and Approval of Analysis Methodologies to be Applied to Seabrook Station", and Application for Withholding Proprietary Information from Public Disclosure, Nicholas J. Liparulo, W, Manager Nuclear Safety and Regulatory Activities to the attention of Dr. T. Murley, Director, Office of NRR. The proprietary information as submitted for use by the Yankee Atomic Electric Company for the Westinghouse reload cores is expected to be applicable in other licensee submittals in response to certain NRC requirements for justification of statistical thermal design procedures.

This information is part of that which will enable Westinghouse to:

(a) Justify the statistical methodology associated with the Revised Thermal Design Procedures.

(b) Assist its customers to obtain licenses.

(c) Optimize reactor design and performance while maintaining a high level of fuel integrity.

Further this information has substantial commercial value as follows:

(a) Westinghouse plans to sell the use of similar information to its customers for purposes of future fuel upgrades.

(b) Westinghouse can sell support and defense of the product to its customers in the licensing process.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar improved core thermal performance methodology and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for developing the enclosed improved core thermal performance methodology.

Further the deponent sayeth not.

Westinghouse
Commercial Nuclear Fuel Division

Westinghouse Class 3

WCAP-11397-A

REVISED THERMAL DESIGN PROCEDURE

A. J. Friedland
S. Ray

Original Version: February 1987
Approved Version: April 1989

Approved: E H Novendstern

E. H. Novendstern, NFD
Manager, Thermal-Hydraulic Design and Fuel Licensing

WESTINGHOUSE ELECTRIC CORPORATION
Commercial Nuclear Fuel Division
P.O. Box 3912
Pittsburgh, Pennsylvania 15320

WCAP-11397-A

TABLE OF CONTENTS

SECTION A

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

JAN 1 7 1989

Mr. W. J. Johnson, Manager
Nuclear Safety Department
Westinghouse Electric Corporation
Box 355
Pittsburgh, PA 15230-0355

Dear Mr. Johnson:

SUBJECT: ACCEPTANCE FOR REFERENCING OF LICENSING TOPICAL REPORT WCAP-11397, "REVISED THERMAL DESIGN PROCEDURE"

We have completed our review of the subject topical report submitted by Westinghouse by letter dated March 16, 1987. 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 Westinghouse publish accepted versions of the report, proprietary and non-proprietary, within 3 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, Westinghouse and/or the applicants referencing the topical report will be expected to revise and resubmit their respective documentation, or submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

Ashok C. Thadani, Assistant Director
for Systems
Division of Engineering & Systems Technology
Office of Nuclear Reactor Regulation

Enclosure:
Topical Report Enclosure

SECTION B

SAFETY EVALUATION BY THE OFFICE OF NRR

RELATING TO TOPICAL REPORT WCAP-11397

REVISED THERMAL DESIGN PROCEDURE

WESTINGHOUSE ELECTRIC CORPORATION

1. INTRODUCTION

The subject topical report WCAP-1397, describes a revised thermal design procedure (RTDP) for predicting the departure from nucleate boiling ratio (DNBR) design limit in Westinghouse pressurized water reactors (PWRs). This is a modification of the existing improved thermal design procedure (ITDP) methodology (Ref. 1) which has been reviewed and approved by the NRC (Ref. 2). As with the ITDP, the RTDP is also based on consideration of system uncertainties in plant operating parameters, fabrication parameters, nuclear and thermal parameters, and the use of the appropriate departure from nucleate boiling (DNB) correlation for the plant.

The DNB design basis remains the same, namely, that there must be at least a 95 percent probability at a 95 percent confidence level that the limiting power fuel rod will not experience DNB during normal operation and anticipated operational occurrences. Parameter uncertainties or variances obtained from the evaluation of data are determined at a 95 percent confidence level.

With the ITDP methodology, these system uncertainties were statistically combined separately from the DNB correlation uncertainty. The two were then combined directly rather than statistically to determine the DNBR limit. The proposed RTDP methodology would combine the system and correlation uncertainties statistically rather than deterministically. This is similar to the statistical DNBR evaluation methodologies developed by the other PWR vendors and approved by the NRC.

The staff review encompassed the original submittal as well as responses to staff requests for additional information (Ref. 3). The staff was assisted in this review by our consultants at Pacific Northwest Laboratories.

2.0 SUMMARY OF TOPICAL REPORT

The topical report describes the mathematical relationships used in both the approved ITDP and the proposed RTDP and presents a sample calculation of a representative plant using both methods to illustrate the difference between them. In addition, a description of how fuel rod bow is accounted for in both methodologies is given and the effect on rod bow penalty is compared. Finally, a discussion as to how sensitivity factors are determined for various statepoints over an appropriate range of conditions is given.

3.0 EVALUATION

The existing ITDP method of protecting against DNB in Westinghouse pressurized water reactors was reviewed extensively by the NRC and a staff evaluation was issued in 1978 (Ref. 2). Because the ITDP resulted in a large reduction in DNBR margin as compared to the traditional method, referred to by Westinghouse as the fixed value method, the staff examined all the parameters to assure that all uncertainties had been appropriately considered. The general methodology for the RTDP will be implemented in the same manner as for the ITDP. Sensitivity factors will be determined for each new correlation, set of design parameters, or range of applicability. The design parameter variances will be determined on a plant specific basis by the identical procedure currently used for the ITDP.

However, since the RTDP extends the ITDP methodology in that the DNB correlation will be statistically combined with the system uncertainties, the adequacy of the relationship of the DNBR uncertainty factor to changes in the values of the design parameters given by

$$dy/y = S_i dx_i/x_i$$

was evaluated. The procedure used to check the validity is the same as that previously used and evaluated by the NRC and was based on test calculations performed by Westinghouse using the THINC-IV computer program. These test results indicate that, with the sensitivity factors used, the above relationship

provides a conservative model for changes in DNBR, as calculated by THINC-IV, for small changes in parameter values. Therefore, no uncertainty allowance is required for this equation with the sensitivity parameters used in the topical report. However, if sensitivity factors change as a result of correlation changes or changes in the application or use of the THINC-IV code, the uncertainty allowance must be re-evaluated.

A linearity approximation was made in the ITDP to obtain Equation (2-9) in the topical report. This equation is used to determine the statistical parameters for the DNBR uncertainty factor from the design parameters. There is a corresponding linearity assumption in the derivation of Equation (2-17) in the report for the RTDP which must be validated. In investigating the adequacy of the linear approximations, Westinghouse compared results both with and without the assumption of linearity. The cases tested were those suggested by the NRC in the evaluation of the ITDP (Ref. 2). In every case, the linearity assumption gave more conservative results than the calculation which did not assume linearity. Based on this, the staff feels it is reasonable to expect the linear approximations to be conservative and, therefore, acceptable.

In the existing ITDP, fuel rod bow is accounted for by a correlation which relates the upper 95 percent tolerance limit for the standard deviation of channel closure for the worst span and burnup. This is combined with a relation between DNBR penalty and channel closure. The DNBR penalty is then combined statistically with the CHF correlation uncertainty to calculate a limit DNBR. The rod bow penalty is the percent difference between this limit DNBR and the limit DNBR with no rod bow. The analysis in the proposed RTDP methodology is performed in the same way except that the DNBR correlation uncertainty is statistically combined with the plant parameter and other uncertainties for both the unbowed and bowed cases. This results in a slight decrease in the rod bow penalty compared to the ITDP methodology. For example, for 17 x 17 standard fuel at the rod limiting burnup of 24 GWD/MTU, the ITDP resulted in a rod bow penalty of 1.1 percent whereas the RTDP resulted in a rod bow penalty of 1.0 percent using the WRB-1 correlation. The staff considers

the effect of the small difference to be negligible and, therefore, finds the rod bow treatment described in the topical report acceptable.

4.0 STAFF POSITION

The RTDP procedure for calculating DNB limits, as presented in WCAP-11397, is acceptable for use in licensing applications. It provides a reasonable approximation to the proposed statistical basis. As with the existing ITDP, however, certain restrictions must be imposed on the implementation of the method because of the sensitivity of the method to changes in the correlations and codes used. These restrictions are:

1. Sensitivity factors used for a particular plant and their ranges of applicability should be included in the Safety Analysis Report or reload submittal.

2. Any changes in DNB correlation, THINC-IV correlations, or parameter values listed in Table 3-1 of WCAP-11397 outside of previously demonstrated acceptable ranges require re-evaluation of the sensitivity factors and of the use of Equation (2-3) of the topical report.

3. If the sensitivity factors are changed as a result of correlation changes or changes in the application or use of the THINC code, then the use of an uncertainty allowance for application of Equation (2-3) must be re-evaluated and the linearity assumption made to obtain Equation (2-17) of the topical report must be validated.

4. Variances and distributions for input parameters must be justified on a plant-by-plant basis until generic approval is obtained.

5. Nominal initial condition assumptions apply only to DNBR analyses using RTDP. Other analyses, such as overpressure calculations, require the appropriate conservative initial condition assumptions.

6. Nominal conditions chosen for use in analyses should bound all permitted methods of plant operation.

7. The code uncertainties specified in Table 3-1 (± 4 percent for THINC-IV and ± 1 percent for transients) must be included in the DNBR analyses using RTDP.

The statistical method as presented includes no explicit design margin to accommodate unknowns. Such a margin could reduce or eliminate the impact of core related problems which are discovered after a core is designed and after a plant is operating. Although no particular margin is quantified, margin is inherent in the overall procedure used with the revised thermal design procedure. This margin is available to offset the effects of yet-to-be-discovered design problems. However, if newer procedures are proposed which substantially reduce thermal margin, then a design margin to accommodate unknowns should be explicitly identified.

The parameter ranges do not cover the range required for part loop operation. If the method is to be used for analysis of part loop operation, the topical report must be amended to cover this wider range.

5.0 REFERENCES

1. Chelemer, H., Bowman, L. H., and Sharp, D.R., "Improved Thermal Design Procedure, "WCAP-8567-P, July 1975.

2. Letter from D. F. Ross, Jr. (NRC) to C. Eicheldinger (W), "Staff Evaluation of WCAP-7956, WCAP-8054, WCAP-8567, and WCAP-8762," April 19, 1978.

3. Friedland, A. J., and Ray, S., "Revised Thermal Design Procedure," WCAP-11397, Addendum 1, June 1988.

SECTION C

Westinghouse
Electric Corporation

Power Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

NS-NRC-87-3209
March 16, 1987

Mr. James Lyons, Chief
Technical & Operations Support Branch
Office of Nuclear Reactor Regulations
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ATTENTION: Document Control Desk

ATTENTION: Carl H. Berlinger, Chief
Reactor Systems Branch
Division of PWR Licensing-A

SUBJECT : Submittal of Westinghouse Topical, WCAP-11397, "Revised Thermal Design Procedure", for Review and Approval

Reference: 1. Chelemer, H., Boman, L.H., and Sharp, D.R., "Improved Thermal Design Procedure," WCAP-8567-P (Proprietary) and WCAP-8568 (Non-proprietary), July 1975.

Dear Mr. Lyons:

Enclosed are twenty-five (25) copies of the topical report, "Revised Thermal Design Procedure", WCAP-11397 (Proprietary).

The enclosed topical has been submitted to revise the Improved Thermal Design Procedure, Reference 1. Our objective is to provide a more realistic prediction of the DNBR limit which satisfies the design criterion, by removing some of the conservatism in the Improved Thermal Design Procedure methodology. The procedure described in this report will be applied in our standard reactor design methodology and referenced in future licensing applications.

It is requested that the review of this topical be completed in the third quarter of 1987 so that Westinghouse can extend their analytical capabilities as the need arises.

This submittal contains Westinghouse proprietary information of trade secrets, commercial, or financial information which we consider priviledged or confidential pursuant to 10CFR9.5 (4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure.

This material is for your internal use only and may be used for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the express written approval of Westinghouse. Correspondence with respect to the Application for Withholding should reference AW-87-022, and should be addressed to R. A. Wiesemann, Manager of Regulatory and Legislative Affairs, Westinghouse Electric Corporation, P. O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

W. J. Johnson, Manager
Nuclear Safety Department

/pj

Enclosure(s)

Westinghouse Electric Corporation

Power Systems

Box 355
Pittsburgh Pennsylvania 15230 0355

March 16, 1987
AW-87-022

Mr. Herbert M. Berkow
Standardization & Special Projects Branch
Division of PWR Licensing-B
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Reference: LETTER JOHNSON TO LYONS, NS-NRC-87-3209, DATED MARCH, 1987

Dear Mr. Berkow:

SUBJECT: WCAP-11397, "Revised Thermal Design Procedure"

The subject report transmitted by the referenced letter contains information proprietary to the Westinghouse Electric Corporation.

The material will not be employed as a part of a license application or other action identified in 10CFR2.790(a) at this time. It will be separately submitted with an Application for Withholding accompanied by an Affidavit meeting the requirements of 10CFR2.790(b) prior to such use.

Accordingly, we request that the material be treated as proprietary information within the provisions of 10CFR9.5(4), "Freedom of Information Act Regulations". If there is a need to make public disclosure of the material prior to a separate Westinghouse submittal for docket in accordance with the provisions of 10CFR2.790(a), please notify Westinghouse prior to making a disclosure determination.

Correspondence with respect to the proprietary aspects of this submittal should reference AW-87-022 and should be addressed to the undersigned.

Very truly yours,

Robert A. Wiesemann, Manager
Regulatory & Legislative Affairs

cc: E. C. Shomaker, Esq.
Office of the General Council, NRC

SECTION D

ABSTRACT

A Revised Thermal Design Procedure (RTDP) is developed which satisfies the design criterion that protects against Departure from Nucleate Boiling (DNB) in a PWR core. Variations in plant operating parameters, nuclear and thermal parameters, fuel fabrication parameters, and DNB correlation predictions are considered statistically to obtain a DNB uncertainty factor. Applying this factor leads to a limiting DNBR value to be used for accident analysis. Since the uncertainties are all included in the uncertainty factor, the accident analysis is done with input parameters at their nominal or best estimate values.

RTDP revises the previous procedure, called the Improved Thermal Design Procedure (ITDP), in that DNB correlation uncertainties are combined statistically with the ITDP uncertainties instead of being treated separately. This provides a more realistic prediction of the DNBR limit which satisfies the design criterion.

The mathematical relationships are derived and a sample calculation is presented using numerical values for a 3 loop plant with 17x17 standard rod array fuel assemblies, and the WRB-1 DNB correlation. This Revised Thermal Design Procedure retains the capability of readily and realistically accommodating additional parameters which affect DNB or changes in the values or uncertainties of parameters.

ACKNOWLEDGEMENTS

The authors would like to thank E. H. Novendstern for guiding this project, H. Chelemer for his helpful comments on the statistical methods, and J. R. Reid who performed many of the calculations. The discussions with R. C. Anderson and K. L. Basehore of Virginia Power are also greatly appreciated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECTION 1

INTRODUCTION

A Revised Thermal Design Procedure (RTDP) is presented in this topical report for purposes of realistically predicting the Departure from Nucleate Boiling Ratio (DNBR) design limit in Westinghouse PWR's. This procedure removes some of the conservatism in the Improved Thermal Design Procedure (ITDP) methodology[1]* while satisfying the design criterion that protects against DNB in a PWR core. The DNB thermal design criterion is that the probability that DNB will not occur on the most limiting fuel rod is at least 95% (at a 95% confidence level) for any Condition I or II event.

With ITDP methodology, system uncertainties are statistically combined separately from the DNB correlation uncertainty. The two are then combined directly, rather than statistically, to determine the DNBR limit.

The system and correlation uncertainties are independent variables, and in the revised procedure they are statistically combined to more realistically predict the DNBR limit by removing some of the unnecessary conservatism in ITDP. The RTDP is a natural extension of the ITDP and is similar to the approach developed by Virginia Power[2].

The development of the mathematical relationships for the revised procedure is given in Section 2 and a sample plant analysis is shown in Section 3. Section 4 describes the application to fuel rod bow, and the justification for the use of sensitivity factors is presented in Section 5.

* Superscripts in brackets refer to list of References

SECTION 2

MATHEMATICAL RELATIONSHIPS

RTDP is essentially an extension of ITDP. The mathematical relationships used in ITDP are derived in the first part of this section. The second part shows the extension of these relationships for RTDP.

2.1 ITDP Methodology

The following is a summary of the methodology used in ITDP.[1]

For a DNB correlation such as WRB-1[3] the statistical parameters of the data base are obtained: mean ($m_{M/P}$), and standard deviation ($s_{M/P}$), where M/P is the ratio of measured-to-predicted heat fluxes at the point of minimum DNBR. When ITDP is used, the DNBR Correlation Limit (CL) is set so that with 95% confidence there is at least a 95% probability that DNB will not occur for a statepoint with DNBR ≥ CL. CL is given by

$$CL = \frac{1}{m_{M/P} - Ks_{M/P}} \qquad (2\text{-}1)$$

where K is obtained from tables prepared by Owen[4] and is a function of the confidence level, the probability, and the number of data points in the DNB data set.

In order to relate the variations in design parameters to DNBR variations, an uncertainty factor, y, defined by the following equation, is used:

$$y = DNBR(variable)/DNBR(nominal) \qquad (2\text{-}2)$$

The value of DNBR(nominal) is determined by considering the values of all the design parameters to be at their nominal or best estimate values. The value of DNBR(variable) is based on values of the design parameters including their uncertainties and deviations from nominal values. Consequently, in any particular application, DNBR(nominal) will have a single determinable value while DNBR(variable) will be a random variable.

The DNBR uncertainty factor is considered to be affected by changes in the values of the design parameters according to a relation of the form

$$\frac{dy}{y} = s_1 \frac{dx_1}{x_1} + s_2 \frac{dx_2}{x_2} + \ldots s_m \frac{dx_m}{x_m} \qquad (2\text{-}3)$$

where

x_i is the value of the i^{th} design parameter,

dx_i is the differential change in the value of x_i,

dy is the differential change in y resulting from the differential changes dx_i.

The factor s_i represents the sensitivity factor associated with the i^{th} parameter. If all the parameters in Equation (2-3) are held constant except for one, then it is clear from Equation (2-3) that if the x_i are independent

$$s_i = \frac{\partial y}{y} \Big/ \frac{\partial x_i}{x_i} = \frac{\partial(\ln y)}{\partial(\ln x_i)} \qquad (2\text{-}4)$$

Thus the value of s_i can be interpreted as representing the percentage change in DNBR resulting from a one percent change in x_i, all other parameters being held constant.

Integrating Equation (2-3), considering the s_i values fixed, and taking antilogarithms gives

$$y = C\, x_1^{s_1}\, x_2^{s_2} \ldots x_m^{s_m} \qquad (2\text{-}5)$$

where C is obtained from the constant of integration.

In order to evaluate the uncertainty factor to be used in the design value of the DNBR, it is necessary to obtain a relationship between it and the uncertainties in the design parameters used to determine DNBR.

Consider each of the independent design parameters x_i as being distributed about a mean value μ_i. If y is expanded in a Taylor's series about the μ_i the following expression is obtained

$$y-\mu_y = \frac{\partial y}{\partial x_1}(x_1-\mu_1) + \frac{\partial y}{\partial x_2}(x_2-\mu_2) + \ldots \frac{\partial y}{\partial x_m}(x_m-\mu_m) \qquad (2\text{-}6)$$

$$+ \text{ higher order terms}$$

The partial derivatives in Equation (2-6) are evaluated at the point where all the x_i are at their mean values μ_i. The value of y at this point is represented by μ_y.

From Equation (2-5)

$$\mu_y = C\, \mu_1^{s_1}\ \mu_2^{s_2}\ \ldots\ \mu_m^{s_m} \qquad (2\text{-}7)$$

If the pertubations from the mean values are small, the higher order terms in Equation (2-6) will be considerably smaller in magnitude than the first order terms and can be ignored. Under these conditions, the variance of y determined using Equation (2-6) results in the following expression [5]:

$$\sigma_y^2 = \left(\frac{\partial y}{\partial x_1}\right)^2 \sigma_1^2 + \left(\frac{\partial y}{\partial x_2}\right)^2 \sigma_2^2 + \ldots \left(\frac{\partial y}{\partial x_m}\right)^2 \sigma_m^2 \qquad (2\text{-}8)$$

Using Equation (2-5) and (2-7) in Equation (2-8) leads to the equation

$$\left(\frac{\sigma_y}{\mu_y}\right)^2 = s_1^2 \left(\frac{\sigma_1}{\mu_1}\right)^2 + s_2^2 \left(\frac{\sigma_2}{\mu_2}\right)^2 + \ldots s_m^2 \left(\frac{\sigma_m}{\mu_m}\right)^2 \qquad (2\text{-}9)$$

The ratio σ/μ is called the coefficient of variation. Equation (2-9) enables the coefficient of variation of the DNBR uncertainty factor y to be determined in terms of the sensitivity factors s_i defined by Equation (2-4) and coefficients of variation σ_i/μ_i of the design parameters x_i used in evaluating DNBR.

The central limit theorem of statistics indicates that the probability distribution function for y will approach a normal distribution with mean μ_y and standard deviation σ_y even if the individual distributions of the x_i are not normal. It should be noted that Equation (2-9) is subject to the restrictions that the x_i are independently distributed and that the variations in the x_i can be considered small. In addition the sensitivity factors s_i are considered to be constant, thus independent of the x_i.

In order to satisfy the DNB thermal design criterion, an ITDP DNBR design limit value DL_I is determined such that the probability that CL, the Correlation Limit DNBR (given by Equation (2-1)) is exceeded is 95% with 95% confidence. The governing variables are considered to be at such levels that with each at its mean value the DNBR value on the peak power rod is DL_I. This results in the following relation for the design limit DNBR:

$$DL_I = \frac{CL}{1 - 1.645\,\sigma_y} \qquad (2\text{-}10)$$

where the values 1 and 1.645 represent the mean value of y and the standardized normal variate corresponding to a 95% probability, respectively.

2.2 RTDP Methodology

RTDP utilizes the DNB correlation statistical characteristics, $m_{M/P}$ and $s_{M/P}$, and the uncertainty factor statistical parameters, μ_y and σ_y, calculated in the same manner as in the ITDP.

The statistically combined system and correlation design limit DNBR for RTDP (DL_R) is selected such that for a statepoint with mean DNBR at the DL_R, there is a 95% probability that the DNBR(variable) for the limiting fuel rod exceeds the correlation P/M(variable) with 95% confidence. DNB will not occur if

[ ] (a,c) (2-11)

Using Equation (2-2) gives

[ ] (a,c) (2-12)

Rearranging Equation (2-12) results in

[ ] (a,c) (2-13)

RTDP uses a parameter z defined by

z =[ ] (a,c) (2-14)

[ ] If z is (a,c) expanded in a Taylor's series about the mean value, the following expression is obtained

[ ](a,c)(2-15)

The partial derivatives in Equation (2-15) are evaluated at the point where each variable is at its mean value. The value of z at this point is represented by μ_z.

From Equation (2-14)

[ ] (a,c) (2-16)

If the perturbations are small, the higher order terms in Equation (2-15) will be considerably smaller in magnitude than the first order terms and as a result can be ignored. This being the case, the variance of z determined using Equation (2-15) results in the following expression[5].

[ ] (a,c) (2-17)

[ ] (a,c)

[ ] (a,c) (2-18)

[ ] (a,c)

Using Equation (2-14) and (2-16) in Equation (2-17) leads to the equation

[ ] (a,c) (2-19)

[ ] (a,c)

From Equations (2-13) and (2-14), with[ ] If this is the case (a,c)

[ ] (a,c) (2-20)

[ ] (a,c) (2-21)

Substituting Equation (2-16) in (2-21) and noting that

[ ] (a,c) (2-22)

results in

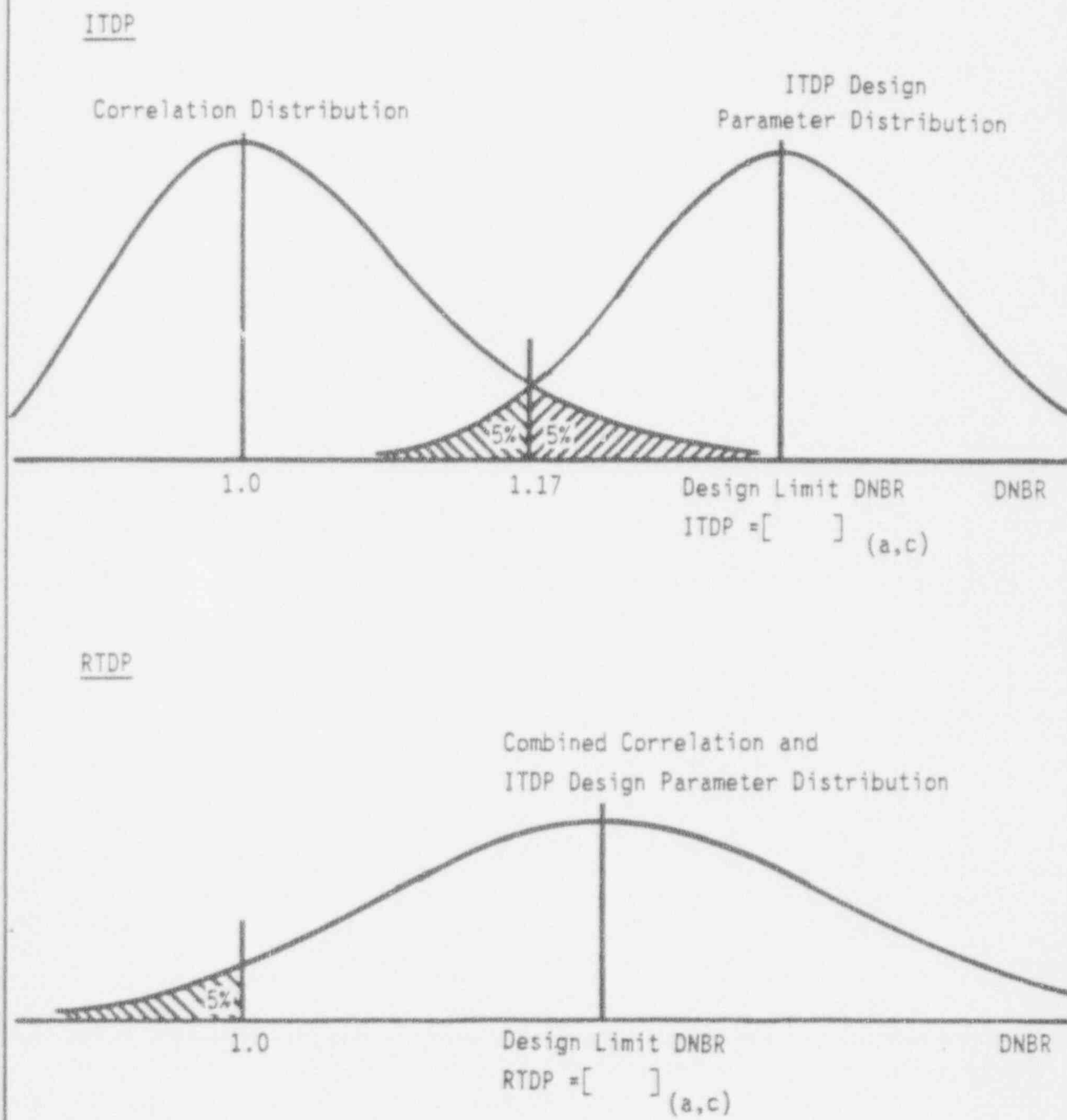
DL_R = [ ] (a,c) (2-23)

Figure 2-1 schematically illustrates the calculation of the design limit DNBR using RTDP compared with that using ITDP

It should be noted that Equation (2-19) is subject to the restrictions that the x_i [ ] are independently distributed and that the variations in the x_i [ ] can be considered small. In addition, the sensitivity factors s_i are considered to be constant and independent of the x_i. (a,c) (a,c)

Figure 2-1

ILLUSTRATIVE COMPARISON OF RTDP WITH ITDP FOR A DNB CORRELATION WITH $\mu_{M/P}$ = 1.0 AND LIMIT DNBR = 1.17



SECTION 3

SAMPLE CALCULATION

A representative plant will be analyzed using both ITDP and RTDP to illustrate the difference between them. The selected plant is a three-loop plant with 17x17 standard fuel. Nominal plant operating conditions are listed in Table 3-1.

A sensitivity study was performed using the THINC-IV computer program.[6,7] Sensitivities of DNBR to changes in plant parameters were determined for a range of statepoints covering various operating conditions with minimum DNBR values near the expected DL_R. The most limiting statepoint was selected as the one for which the sensitivities resulted in the highest DL_R. The resulting sensitivities are shown in Table 3-1.

Plant parameter uncertainties are also listed in Table 3-1. These are determined on a plant-specific basis.

For the WRB-1 correlation, the statistical analysis of the data base results in [3]

[ ] (a,c)

When ITDP is used, the Correlation Limit obtained from Equation (2-1) is

CL = 1.17

The ITDP analysis for the representative plant using the sensitivities calculated above is given in Table 3-1. The resulting DNBR design limit values from Equation (2-10) are:

DL_I = [ ] (typical cell) (a,c)
DL_I = [ ] (thimble cell) (a,c)

TABLE 3-1

DESIGN LIMIT DNBR USING ITDP

Parameter	Nominal or Best Estimate (μ)	σ	σ/μ	Typical Cell S	Typical Cell $S^2(\frac{\sigma}{\mu})^2$	Thimble Cell S	Thimble Cell $S^2(\frac{\sigma}{\mu})^2$
Power	100%						
T_{in}	553.6°F						
Pressure	2280 psia						
Flow	100%						
Bypass	0.965						
$F^N_{\Delta H}$	1.49						
$F^E_{\Delta H,1}$	1.0						
THINC 4	1.0						
Transient Code	1.0						

$$\frac{\sigma_y}{\mu_y} = \sqrt{\Sigma\ S_i^2\ \left(\frac{\sigma_i}{\mu_i}\right)^2} =$$

$$\text{DNBR Design Limit} = \frac{\text{Correlation Limit}}{1 - 1.645\ (\sigma_y/\mu_y)}$$

$$= \frac{1.17}{1 - 1.645\ (\sigma_y/\mu_y)} =$$

(a,c)

When RTDP is used, the analysis in Table 3-1 gives for a typical cell,

[ ] (a,c)

From Equations (2-18) and (2-19):

[ ] (a,c)

From Equation (2-23),

DL_R = [ ] (a,c)

Similarly, for a thimble cell,

[ ] (a,c)

[ ] (a,c)

DL_R = [ ] (a,c)

The DNBR design limits using RTDP are compared to those using ITDP in Table 3-2.

TABLE 3-2

COMPARISON OF DESIGN LIMIT DNBR'S

	Design Limit DNBR		
	ITDP	RTDP	
Typical Cell	[	]	
Thimble Cell			(a,c)

SECTION 4

FUEL ROD BOW

Rod bow is accounted for with current methodology[8] by a correlation based on reactor data which relates S_W (the upper 95% tolerance limit for the standard deviation of channel closure for the worst span) and burnup. This is combined with a relation between DNBR penalty and channel closure, a Monte Carlo type calculation being performed to generate the DNBR penalty statistics. The DNBR penalty is combined statistically with the correlation uncertainty and the results are used to calculate a limit DNBR. The percent difference between this limit DNBR and the limit DNBR with no rod bow is the rod bow penalty.

With the new methodology, the analysis is performed in the same way except that for both the unbowed and bowed cases, the DNBR correlation uncertainty is statistically combined with the plant parameter and other uncertainties. This results in a slight decrease in the rod bow penalty compared to the previous methodology.

A sample calculation was performed for 17x17 standard fuel, high flow conditions, at the rod bow limiting burnup of 24,000 MWD/MTU,[9] using the WRB-1 correlation. With the previous methodology, the rod bow penalty was [ ]$^{(a,c)}$. With the new methodology, for the plant conditions evaluated in Section 3, the rod bow penalty was [ ]$^{(a,c)}$.

SECTION 5

SENSITIVITY FACTORS

Sensitivity factors were determined over a wide range of statepoints covering various operating conditions with minimum DNBR values near the expected DL_R. The most limiting statepoint was selected as the one for which the sensitivities resulted in the highest DL_R. This leads to conservative results in terms of setting the limits on the core operating conditions determined by the DNB limitation.

This procedure differs from that described in Reference 1, in which a range of DNBR values was covered and the largest numerical value of each sensitivity factor over the DNBR range of interest was chosen for use in the DNB analysis.

Since RTDP extends the ITDP methodology in that the DNB correlation uncertainties are statistically combined with the ITDP uncertainties, the following evaluations were necessary with regard to this new methodology:

(a) Verification of the adequacy of Equation (2-3) in predicting changes in DNBR.

(b) Verification of the adequacy of the linearity approximation made to obtain Equation (2-17).

The above evaluations were performed by using procedures previously evaluated by the NRC in Reference 10 and are discussed below.

As a check on the form of Equation (2-3), a pair of test cases was executed using the THINC-IV program. One case used values of the design parameters at nominal conditions while the second case used values at extreme conditions. For the latter case, significant changes were made in all of the parameters in which uncertainties were being considered in the DNB design procedure.

The ratio of the minimum DNBR's for the two cases was 0.80 for both typical and thimble cells as determined by the THINC program. Alternatively, the minimum DNBR for the second case can be estimated from the value for the first case by a relationship obtained by integrating Equation 2-3 assuming that the sensitivity factors, s_i, are constant, and taking the ratio of the results as applied to the two cases:

$$\frac{y}{\mu_y} = \left(\frac{x_1}{\mu_1}\right)^{s_1} \left(\frac{x_2}{\mu_2}\right)^{s_2} \cdots \left(\frac{x_m}{\mu_m}\right)^{s_m} \qquad (5\text{-}1)$$

where the μ_i and x_i represent the parameter values from the first and second cases, respectively. Substituting the numerical values for the x_i, μ_i and s_i gave values for y/μ_y of 0.76 (typical cell) and 0.77 (thimble cell). These represent the calculated ratio of the minimum DNBR's assuming the parameters are related to the DNBR by Equation (2-3) with constant s_i values. Comparing these values (0.76 and 0.77) with the values obtained from comparing the two THINC cases (0.80 and 0.80) indicates that the assumptions used in developing Equation (2-3) are conservative. Therefore, no uncertainty allowance is required for Equation (2-3) with the sensitivity factors given in Table 3-1 for the WRB-1 correlation with RTDP.

A linearity approximation was made to obtain Equation (2-9), the equation used to determine the statistical parameters for the DNBR uncertainty factor from the variation in the design parameters. There is a corresponding linearity assumption in the derivation of Equation (2-17).

This approximation was tested by choosing the value of each of the parameters to be one standard deviation from its nominal value (in the direction leading to a decrease in DNBR) and using Equation (5-2) to determine the combined effect on the DNBR.

[ ] (a,c) (5-2)

Note that no linearity relationship is used in this calculation. The calculation results in a z value which is 0.74 times the nominal value for a thimble cell.

The same combined effect is also determined using Equation (2-15) neglecting terms of second order and higher, which considers the relationship between the DNBR uncertainty factor and the design parameters to be linear. This leads to

[ ] (a,c) (5-3)

The value of 0.70 is obtained for the ratio of the resulting z to the nominal value.

The comparisons were repeated at several other values of the parameters (i.e., $\pm\ \sigma/2$, $\pm\ \sigma$, $\pm\ 2\ \sigma$) and the results are given in Table 5-1. In every case, the linearity assumption gave more conservative results than the calculation which did not assume linearity. This confirms that the linearity assumption is somewhat conservative.

TABLE 5-1

EVALUATION OF LINEARITY ASSUMPTION

Assumed Deviation of each x_i Value From Mean			z/μ_z * Equation (5-3) (Assumes Linearity)	z/μ_z * Equation (5-2) (Does not assume Linearity)
Typical:	1/2 σ	adverse	0.85	0.86
	"	beneficial	1.15	1.16
	1 σ	adverse	0.70	0.74
	"	beneficial	1.30	1.34
	2 σ	adverse	0.41	0.54
	"	beneficial	1.59	1.79
Thimble:	1/2 σ	adverse	0.86	0.87
	"	beneficial	1.14	1.15
	1 σ	adverse	0.72	0.75
	"	beneficial	1.28	1.32
	2 σ	adverse	0.43	0.56
	"	beneficial	1.57	1.74

* z is calculated using values of parameters which deviate from the nominal value by the amount specified in the first column.
μ_z is calculated using nominal values of parameters.

SECTION 6

CONCLUSIONS

Based on the results of this study, the following conclusions were reached;

- The Revised Thermal Design Procedure given here satisfies the design criterion that protects against Departure from Nucleate Boiling in a PWR core.

- The procedure described in this report will be applied in the standard reactor design process and referenced in future licensing applications.

SECTION 7

NOMENCLATURE

C	Constant of integration
CL	Correlation limit DNBR
DL_I	Design limit DNBR using ITDP
DL_R	Design limit DNBR using RTDP
DNB	Departure from nucleate boiling
DNBR	Ratio of the expected DNB heat flux to the actual local heat flux
K	Owen's Factor for 95% probability with 95% confidence
M/P	Ratio of measured-to-predicted heat fluxes in DNB test at the point of minimum DNBR
$m_{M/P}$	Mean of measured-to-predicted heat flux ratio in DNB data set
m	Number of design parameters affecting DNBR uncertainty factor
n	Sample size
$s_{M/P}$	Standard deviation of measured-to-predicted heat flux ratio in DNB data set
s_i	Sensitivity factor of i^{th} parameter
x_i	i^{th} parameter
y	DNBR uncertainty factor = DNBR(variable)/DNBR(nominal)
z	[ ]$^{(a,c)}$
μ	Mean
σ	Standard deviation

SECTION 8

REFERENCES

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2. Anderson, R.C., "Statistical DNBR Evaluation Methodology," VEP-NE-2, July 1985.

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9. Letter dated 6/18/86, C.H. Berlinger (NRC) to E. P. Rahe, Jr. (Westinghouse), "Request for Reduction in Fuel Assembly Burnup Limit for Calculation of Maximum Rod Bow Penalty"

10. Letter dated 4/19/78, D. F. Ross, Jr. (NRC) to C. Eicheldinger (Westinghouse)," Staff Evaluation of WCAP-7956, WCAP-8054, WCAP-8567, and WCAP-8762".

SECTION E

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June 13, 1986
NS-NRC-88-3346

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

ATTN: Mr. Marvin W. Hodges, Reactor Systems Branch Chief
Division of Engineering & System Technology

SUBJECT: Responses to NRC Questions on WCAP-11397, "Revised Thermal Design Procedure" [Non-Proprietary]

REFERENCE: (1) Letter from M. W. Hodges (NRC) to W. J. Johnson (W), (Questions on WCAP-11397), "Revised Thermal Design Procedure" dated April 4, 1988.

Dear Mr. Hodges:

Enclosed are:

Twelve (12) copies of WCAP-11397, Addencum 1, "Responses to Additional Questions on Revised Thermal Design Procedure" [Non-Proprietary].

The enclosed information is being submitted in response to additional NRC questions, Reference (1), as a result of the Staff's and their consultants review of the subject Topical.

Very truly yours,

W. J. Johnson

W. J. Johnson, Manager
Nuclear Safety Department

/mlt
Enclosure

WCAP-11397
Addendum 1

REVISED THERMAL DESIGN PROCEDURE

A. J. Friedland
S. Ray

June 1988

Approved: E. H. Novendstern
E. H. Novendstern, Manager
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RESPONSE TO NRC QUESTIONS ON WCAP-11397,

REVISED THERMAL DESIGN PROCEDURE"

1. *Explain what is meant by DNBR(variable) and P/M(variable) in the Revised Thermal Design Procedure (RTDP) development on page 5. Apparently they are both random variables, but it is unclear which sources of uncertainty are included in each. Does the DNBR(variable) only contain the uncertainty from the design parameters for a given nominal set of conditions? Does P/M(variable) only contain uncertainty from the correlation for a given nominal set of conditions? What are the means and standard deviations (values or notation) for each of these random variables? Is the "(variable)" descriptor assumed on the P/M's and M/P's in equations (2-12) through (2-14)?*

<u>RESPONSE TO QUESTION 1</u>:

In the development on page 5:

DNBR(variable) only contains the uncertainties from the design parameters for a given nominal set of conditions.

P/M(variable) only contains uncertainty from the correlation for a given nominal set of conditions.

y is defined as DNBR(variable)/DNBR(nominal).
y has a mean of 1.0 (μ_y = 1.0) and a standard deviation designated σ_y.

The reciprocal of P/M(variable) is M/P(variable), with mean $\mu_{M/P}$ and standard deviation $\sigma_{M/P}$.

The "(variable)" descriptor is assumed on the P/M's and M/P's in equation (2-12) through (2-14).

2. *How is z in equation (2-14) interpreted? It does not appear to be completely analogous to y, which was an uncertainty factor. Is z just a DNBR random variable containing both correlation and design parameter uncertainties?*

RESPONSE TO QUESTION 2:

Z is defined by equation (2-14) and is a DNBR random variable containing both correlation and design parameter uncertainties, as inferred in the question.

3. *The expression in equation (2-18) is described as an upper 95% confidence limit on the standard deviation associated with the uncertainty in the correlation. However, K/1.645 is in general larger than (df/chi-square)**0.5, the appropriate multiplier to obtain an upper 95% confidence limit. The two quantities are equal when the true mean of M/P is known (which is not the case). Still, the use of K/1.645 provides for the revised design limit (DL_K) equaling the correlation limit (CL) when there is no uncertainty in the design parameters. Is this the reason for doing what was done in equation (2-18)? Or was it to allow for treating the true variance of M/P as unknown? In any case, please explain the rationale for equation (2-18) and the corresponding description.*

RESPONSE TO QUESTION 3:

The term K/1.645 is used in equation (2-18) to account for the uncertainty in the mean of M/P as well as the uncertainty in the standard deviation of M/P.

The resulting $\sigma_{M/P}$ is that for a normal distribution which has the same upper 95% tolerance limit as is given by Owen's table.

For known μ and σ, upper 95% tolerance limit (UTL) = $\mu + 1.645\sigma$

For sample $\bar{x}$ and s, UTL = $\bar{x} + ks$

For equal UTL's $\mu + 1.645\sigma = \bar{x} + ks$

$$\sigma = \frac{\bar{x} - \mu + ks}{1.645}$$

$$\therefore \frac{K}{1.645} s = \sigma \text{ if } \mu = \bar{x}$$

4. *As noted in the previous question, an "upper confidence limit" is placed on sigma(M/P). Presumably this was not done to sigma(y) because it is being treated as known. Clearly, it is not known exactly because error propagation methods (which are approximate and make certain assumptions) were used to derive it. Also, there are situations where the individual parameter variances may not be justifiably treated as known. The treatment of sigma(y) as known leads to DL_R, but something different would be obtained if sigma(y) were treated as unknown. Please discuss and support your treatment of sigma(y).*

RESPONSE TO QUESTION 4:

σ_y is treated identically to the way it is treated in ITDP (WCAP-8567). The NRC review (Ref. 10 of WCAP-11397) of WCAP-8567 states:

> "The proposed design basis is that there must be at least a 95% probability that the minimum DNBR of the limiting power rod is greater than or equal to the DNBR limit of the correlation being used; parameter uncertainties or variances obtained from the evaluation of data are determined at a 95% confidence level. Implementation of the procedure involves assumptions that errors in correlations or postulated functions are random variables where repeated use of a correlation with identical conditions gives identical results. Also, distributions of uncertainties for variables such as power, flow or temperature are not well known so that the functional forms of the uncertainty distributions must be assumed. Therefore, a rigorous statistical statement of the type implied in the proposed DNBR design basis cannot be obtained.
>
> "However, Westinghouse has either chosen distribution functions which are typical of observed distributions or which give conservative variances. Also, biases in correlations have been reduced insofar as practical. Therefore, although a rigorous statistical statement cannot be made, the Westinghouse method provides a reasonable approximation to such a statistical statement."

For RTDP, the design parameter variances will be determined on a plant specific basis by the identical procedure currently used for ITDP.

5. *The last sentence of the first paragraph of Section 1 states the design criterion that is the basis for the RTDP discussed in the submittal. The "95% probability at 95% confidence" portion of the criterion is typically implemented via use of a one-sided tolerance interval based on the normal distribution. A description of a 95%/95% tolerance interval and how it differs from a 95% confidence interval is given in the Appendix.*

A tolerance interval is a statement about a single distribution. Although the RTDP figure and caption on the bottom of page 8 suggest that the RTDP method is considering a single distribution that combines the correlation and design parameter uncertainties, the development on page 6 seems to indicate otherwise. Specifically, Eq. (2-18) computes a tolerance interval for the "correlation uncertainty" distribution, while Eq. (2-20) is the result of a 95% confidence interval on the combined distribution where a "tolerance interval inflated" variance is used for the correlation uncertainty. This RTDP approach is similar to, but not quite the same as what would be obtained if a 95%/95% tolerance interval was computed on the combined distribution under the assumption that sigma(y) is known without error.

Please explain the rationale for the RTDP development steps referred to above, and explain how it satisfies the "95% probability at 95% confidence" portion of the design criterion from Section 1.

RESPONSE TO QUESTION 5:

The approach used in RTDP is the same as that in ITDP with M/P included among the independent variables. The response to question 4 includes the NRC comments on the statistical approach used in ITDP.

6. *Discussions throughout the submittal imply that m(M/P) and s(M/P) are calculated over the set of M/P values corresponding to the data used to develop the correlation. Two comments are made relative to this.*

   (a) *It is inappropriate to compute a mean and standard deviation in this fashion unless it can be demonstrated that the M/P values are a random sample from a common population. This will usually not be the case for a given correlation and its corresponding data base and region of applicability. If the M/P values do not come from a common population, the mean and standard deviation may vary significantly over various subregions of the region of applicability. (This will require computing different safety limits in different subregions, or choosing the largest safety limit if the whole region is to be covered using only a single value.)*

(b) *It in inappropriate to evaluate and measure the performance of a correlation using the same data used to develop it, especially if empirical fitting techniques such as least squares are used. Performance measures (e.g., means and standard deviations of P/M) should be computed from data not used to develop the correlation. If such "extra" data are not available, data-splitting or cross-validation techniques should be used to evaluate and measure performance, with the resulting means and standard deviations used in calculating the design limit.*

Although this submittal covers general methodology, the above points must be recognized when applying the methodology to specific applications. Please discuss how your approach for applying the RTDP accounts for the two issues raised above.

RESPONSE TO QUESTION 6:

The DNB correlation statistics are the same as those which were used to develop the DNBR correlation limits in the previous ITDP methodology which have been accepted by the NRC. For the WRB-2 correlation, for example (Ref. 6-1), the NRC SER presented a statistical analysis of the test data and concluded that while the data do not all represent a single population, the error introduced into variance estimates by assuming that the data are all from the same population is negligible. Similar results are obtained for the WRB-1 correlation (Ref. 3 of WCAP-11397) applied to "R" grid data.

The evaluation of DNB correlation is handled in separate topicals, as in the above examples. The RTDP derivation treats the data as coming from a common population, and assumes that the error introduced by this assumption is negligible as shown in the appropriate correlation topical report.

(Ref. 6-1, WCAP-10444-P-A, "Reference Core Report - Vantage 5 Fuel Assembly," September 1985)

7. *The first paragraph of Section 5 (page 14) is not completely clear regarding how you propose to obtain the sensitivity factors. Do you propose choosing as the sensitivity factors those values corresponding to the limiting statepoint (the one with the highest DL_R, as specified on page 14)? This seems to be a reasonable approach (given that enough statepoints are examined), but conflicts with the description of sensitivity factors given in Section 2.1. One page 3, the sensitivity factors were described as being percentage changes in DNBR resulting from 1% changes in the x_i. Since no mention is made of the sensitivity factors depending on the s_i or the correlation, the implication is that they are independent of the x_i and the correlation. Hence, the apparent conflict with the proposal on page 14.*

Please clarify your proposal for determining the sensitivity factors for a given application, including how you will determine the number and location of statepoints to be considered. Explain why this approach is an improvement over the approach mentioned in the second paragraph on page 14.

RESPONSE TO QUESTION 7:

We will choose as the sensitivity factors those values corresponding to the limiting statepoint (the one with the highest DL_R, as specified on page 14). The statement on page 3 that the sensitivity factors are percentage changes in DNBR resulting from 1% changes in the x_i, applies at the limiting statepoint. The sensitivity factors do depend somewhat on the x_i and the correlation, so some of them may be higher at some other statepoints. However, as noted in Refs. 1 and 10 of WCAP-11397, the observed variations in sensitivity factors are generally small over a wide range of conditions. Selecting the sensitivities at the limiting statepoint is sufficient to assure a conservative DL_R.

As is currently done for ITDP, sensitivity factors are determined for various statepoints over a range of conditions for which the RTDP methodology will be applicable. With RTDP, the sensitivity factors at each statepoint are used to calculate a DL_R value. The highest of these is used as the design limit DNBR. This approach removes some unnecessary conservatism from the approach mentioned in the second paragraph on page 14, which combines worst sensitivities from different statepoints.

8. *The discussion before and after equation (5-1) deals with a single investigation of the validity of using equation (2-3). In general, "proof by example" is dangerous, especially when only one example is used. Presumably results could differ for different correlations, different values of the correlation input variables, different design parameters, and different values of the design parameters. Justify that (2-3) is a conservative approximation under other possible circumstances?*

RESPONSE TO QUESTION 8:

As noted on page 14, the procedure used to check the form of Eq. (2-3) was the same as that previously evaluated by the NRC in Ref. 10. The form of the equation is based on observation and experience with the THINC computer program and the Westinghouse DNB correlations, which generally show small variation in the S_i over a wide range of conditions. The numerical example which was made at nominal plant conditions is considered to be a check rather than a proof of the methodology. A similar check was made with one test case at the limiting statepoint conditions where the sensitivities resulted in the highest DL_R and the second case with all design parameters one standard deviation from the limiting statepoint conditions in the direction leading to a decrease in DNBR. The combined effect on DNBR of these deviations is considerably greater than 1.645 times the RMS of the individual DNBR standard deviations. If Eq. (5-1) were exact with constant S_i then it would be expected to agree exactly with the THINC analyses, since the S_i were evaluated near the limiting statepoints. This was found to be the case with both the THINC analyses and Eq. (5-1) showing the limiting statepoint ratio of perturbed to nominal DNBR to be 0.834 for the typical cell and 0.847 for the thimble cell. Similar evaluations will be performed if there are any changes to the DNBR correlation or in the limiting statepoint.

9. *In equation (5-3), shouldn't each of the s(x-mi) terms be divided by the corresponding mi?*

RESPONSE TO QUESTION 9:

Yes. The equation was misprinted and should read:

$$\frac{Z}{\mu_z} = \frac{S_1(x_1-\mu_1)}{\mu_1} + \frac{S_2(x_2-\mu_2)}{\mu_2} + \ldots + \frac{Sm(x m-\mu m)}{\mu_m} + \frac{(M/P)}{\mu_{M/P}} \quad (5\text{-}3)$$

The calculated results in Table 5-1 are correct. The misprint will be corrected in the approved version of the topical.

10. The discussion and comparisons on pages 15-16 of WCAP-11397 are concerned with investigating the adequacy of the linear approximations in equations (2-6) and (2-15). As in question 8, we have concerns about the sufficiency of your investigation. In this case you did consider several values of (or changes in) the x_i, but all are for the same set of design parameters (with a fixed set of means and standard deviations). Please justify your conclusion that the linear approximations are adequate and conservative for all possible different combinations of design parameters.

RE ONSE TO QUESTION 10:

The cases tested are those suggested in the NRC evaluation of WCAP-8567 (Ref. 10 of WCAP-11397). They provide a confirmatory check that the linear approximation is reasonable and conservative.

It can be shown that, in general, if all the deviations are in the direction leading to a decrease in DNBR, and all S_i are numerically greater than or equal to unity as is generally true, then the linear approximation is conservative. This is shown by expanding Z in a Taylor's series about the μ_i and including second order terms.

The values of the variables which are major contributors to defining the lower 95% limit of Z/μ_z will be mostly in the direction of negative deviations of Z from μ_z. Therefore, it is reasonable to expect the linear approximations to be conservative.

11. The submittal does not discuss how the general methodology will be implemented in specific applications. Clearly the sensitivity factors need to be determined for each new correlation, set of design parameters, or range of applicability. It is not clear whether it will be necessary to check the various assumptions and approximations of the RTDP for each application. Finally, the submittal does not discuss how the design parameter variances will be determined. Please discuss these issues regarding the application of the general RTDP methodology to specific applications. The reviewers need to know whether it is just the general methodology that is under review, or if the implementation and verification aspects for specific applications are also to be reviewed/approved.

RESPONSE TO QUESTION 11:

The general methodology for RTDP will be implemented in the same manner as for ITDP. Sensitivity factors will be determined for each new correlation, set of design parameters, or range of applicability. The design parameter variances will be determined on a plant specific basis by the identical procedure currently used for ITDP.

12. *The first-order error propagation formula (2-8) assumes that the random variables $x_1, \ldots, x_m$ are statistically independent. While this assumption was mentioned in the submittal, its reasonableness was not discussed. Please provide such a discussion, making reference to specific design parameters and giving reasons why the parameters are mutually independent.*

13. *Please clarify your statement on page 4 that "The central limit theorem of statistics indicates that the probability distribution function for y will approach a normal distribution with mean mu(y) and standard deviation sigma(y) even if the individual distributions of the s_i are not normal." Clearly the central limit theorem is not applicable to equation (2-5). Are you basing this statement on the assumption of (2-5) being adequately approximated by (2-6)? Also, since x_i are not identically distributed, a more restrictive form of the central limit theorem must be satisfied. Finally, the convergence to normality of a linear combination of random variables is dependent on the number of variables and their individual distributions. Please consider all of the above points in clarifying and supporting your statements concerning the central limit theorem and an approximate normal distribution for y.*

RESPONSE TO QUESTIONS 12 AND 13:

Questions 12 and 13 deal with the ITDP development, which has been covered in the NRC review and evaluation of WCAP-8567 (Ref. 10 of WCAP-11397). The RTDP development is identical to the ITDP development in these areas.

14. *The development of the revised design limit (DL_R) assumes that every design parameter is distributed with a mean value equal to its nominal value. Will this always be the case, or is it possible that biases might exist? If so, how does the RTDP handle the bias and how would DL_R change?*

RESPONSE TO QUESTION 14:

Biases might exist in design parameters. In such cases, the bias is included separately in the DNBR analysis. The bias is not included in development of DL_R.

Westinghouse
Commercial Nuclear Fuel Division
P.O. Box 355
Pittsburgh, PA 15230-0355

WCAP-11397-P-A

REVISED THERMAL DESIGN PROCEDURE

A. J. Friedland
S. Ray

Original Version: February 1987
Approved Version: April 1989

Approved: Earl H. Novendstern

E. H. Novendstern, NFD
Manager, Thermal-Hydraulic Design and Fuel Licensing

WESTINGHOUSE ELECTRIC CORPORATION
Commercial Nuclear Fuel Division
P.O. Box 3912
Pittsburgh, Pennsylvania 15320

WCAP-11397-P-A

TABLE OF CONTENTS

SECTION A

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

JAN 1 7 1989

Mr. W. J. Johnson, Manager
Nuclear Safety Department
Westinghouse Electric Corporation
Box 355
Pittsburgh, PA 15230-0355

Dear Mr. Johnson:

SUBJECT: ACCEPTANCE FOR REFERENCING OF LICENSING TOPICAL REPORT WCAP-11397, "REVISED THERMAL DESIGN PROCEDURE"

We have completed our review of the subject topical report submitted by Westinghouse by letter dated March 16, 1987. 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 Westinghouse publish accepted versions of the report, proprietary and non-proprietary, within 3 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, Westinghouse and/or the applicants referencing the topical report will be expected to revise and resubmit their respective documentation, or submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

Ashok C. Thadani, Assistant Director
for Systems
Division of Engineering & Systems Technology
Office of Nuclear Reactor Regulation

Enclosure:
Topical Report Enclosure

SECTION B

SAFETY EVALUATION BY THE OFFICE OF NRR

RELATING TO TOPICAL REPORT WCAP-11397

REVISED THERMAL DESIGN PROCEDURE

WESTINGHOUSE ELECTRIC CORPORATION

1. INTRODUCTION

The subject topical report WCAP-1397, describes a revised thermal design procedure (RTDP) for predicting the departure from nucleate boiling ratio (DNBR) design limit in Westingnouse pressurized water reactors (PWRs). This is a modification of the existing improved thermal design procedure (ITDP) methodology (Ref. 1) which has been reviewed and approved by the NRC (Ref. 2). As with the ITDP, the RTDP is also based on consideration of system uncertainties in plant operating parameters, fabrication parameters, nuclear and thermal parameters, and the use of the appropriate departure from nucleate boiling (DNB) correlation for the plant.

The DNB design basis remains the same, namely, that there must be at least a 95 percent probability at a 95 percent confidence level that the limiting power fuel rod will not experience DNB during normal operation and anticipated operational occurrences. Parameter uncertainties or variances obtained from the evaluation of data are determined at a 95 percent confidence level.

With the ITDP methodology, these system uncertainties were statistically combined separately from the DNB correlation uncertainty. The two were then combined directly rather than statistically to determine the DNBR limit. The proposed RTDP methodology would combine the system and correlation uncertainties statistically rather than deterministically. This is similar to the statistical DNBR evaluation methodologies developed by the other PWR vendors and approved by the NRC.

The staff review encompassed the original submittal as well as responses to staff requests for additional information (Ref. 3). The staff was assisted in this review by our consultants at Pacific Northwest Laboratories.

2.0 SUMMARY OF TOPICAL REPORT

The topical report describes the mathematical relationships used in both the approved ITDP and the proposed RTDP and presents a sample calculation of a representative plant using both methods to illustrate the difference between them. In addition, a description of how fuel rod bow is accounted for in both methodologies is given and the effect on rod bow penalty is compared. Finally, a discussion as to how sensitivity factors are determined for various statepoints over an appropriate range of conditions is given.

3.0 EVALUATION

The existing ITDP method of protecting against DNB in Westinghouse pressurized water reactors was reviewed extensively by the NRC and a staff evaluation was issued in 1978 (Ref. 2). Because the ITDP resulted in a large reduction in DNBR margin as compared to the traditional method, referred to by Westinghouse as the fixed value method, the staff examined all the parameters to assure that all uncertainties had been appropriately considered. The general methodology for the RTDP will be implemented in the same manner as for the ITDP. Sensitivity factors will be determined for each new correlation, set of design parameters, or range of applicability. The design parameter variances will be determined on a plant specific basis by the identical procedure currently used for the ITDP.

However, since the RTDP extends the ITDP methodology in that the DNB correlation will be statistically combined with the system uncertainties, the adequacy of the relationship of the DNBR uncertainty factor to changes in the values of the design parameters given by

$$dy/y = S_i dx_i/x_i$$

was evaluated. The procedure used to check the validity is the same as that previously used and evaluated by the NRC and was based on test calculations performed by Westinghouse using the THINC-IV computer program. These test results indicate that, with the sensitivity factors used, the above relationship

provides a conservative model for changes in DNBR, as calculated by THINC-IV, for small changes in parameter values. Therefore, no uncertainty allowance is required for this equation with the sensitivity parameters used in the topical report. However, if sensitivity factors change as a result of correlation changes or changes in the application or use of the THINC-IV code, the uncertainty allowance must be re-evaluated.

A linearity approximation was made in the ITDP to obtain Equation (2-9) in the topical report. This equation is used to determine the statistical parameters for the DNBR uncertainty factor from the design parameters. There is a corresponding linearity assumption in the derivation of Equation (2-17) in the report for the RTDP which must be validated. In investigating the adequacy of the linear approximations, Westinghouse compared results both with and without the assumption of linearity. The cases tested were those suggested by the NRC in the evaluation of the ITDP (Ref. 2). In every case, the linearity assumption gave more conservative results than the calculation which did not assume linearity. Based on this, the staff feels it is reasonable to expect the linear approximations to be conservative and, therefore, acceptable.

In the existing ITDP, fuel rod bow is accounted for by a correlation which relates the upper 95 percent tolerance limit for the standard deviation of channel closure for the worst span and burnup. This is combined with a relation between DNBR penalty and channel closure. The DNBR penalty is then combined statistically with the CHF correlation uncertainty to calculate a limit DNBR. The rod bow penalty is the percent difference between this limit DNBR and the limit DNBR with no rod bow. The analysis in the proposed RTDP methodology is performed in the same way except that the DNBR correlation uncertainty is statistically combined with the plant parameter and other uncertainties for both the unbowed and bowed cases. This results in a slight decrease in the rod bow penalty compared to the ITDP methodology. For example, for 17 x 17 standard fuel at the rod limiting burnup of 24 GWD/MTU, the ITDP resulted in a rod bow penalty of 1.1 percent whereas the RTDP resulted in a rod bow penalty of 1.0 percent using the WRB-1 correlation. The staff considers

the effect of the small difference to be negligible and, therefore, finds the rod bow treatment described in the topical report acceptable.

4.0 STAFF POSITION

The RTDP procedure for calculating DNB limits, as presented in WCAP-11397, is acceptable for use in licensing applications. It provides a reasonable approximation to the proposed statistical basis. As with the existing ITDP, however, certain restrictions must be imposed on the implementation of the method because of the sensitivity of the method to changes in the correlations and codes used. These restrictions are:

1. Sensitivity factors used for a particular plant and their ranges of applicability should be included in the Safety Analysis Report or reload submittal.

2. Any changes in DNB correlation, THINC-IV correlations, or parameter values listed in Table 3-1 of WCAP-11397 outside of previously demonstrated acceptable ranges require re-evaluation of the sensitivity factors and of the use of Equation (2-3) of the topical report.

3. If the sensitivity factors are changed as a result of correlation changes or changes in the application or use of the THINC code, then the use of an uncertainty allowance for application of Equation (2-3) must be re-evaluated and the linearity assumption made to obtain Equation (2-17) of the topical report must be validated.

4. Variances and distributions for input parameters must be justified on a plant-by-plant basis until generic approval is obtained.

5. Nominal initial condition assumptions apply only to DNBR analyses using RTDP. Other analyses, such as overpressure calculations, require the appropriate conservative initial condition assumptions.

6. Nominal conditions chosen for use in analyses should bound all permitted methods of plant operation.

7. The code uncertainties specified in Table 3-1 (± 4 percent for THINC-IV and ± 1 percent for transients) must be included in the DNBR analyses using RTDP.

The statistical method as presented includes no explicit design margin to accommodate unknowns. Such a margin could reduce or eliminate the impact of core related problems which are discovered after a core is designed and after a plant is operating. Although no particular margin is quantified, margin is inherent in the overall procedure used with the revised thermal design procedure. This margin is available to offset the effects of yet-to-be-discovered design problems. However, if newer procedures are proposed which substantially reduce thermal margin, then a design margin to accommodate unknowns should be explicitly identified.

The parameter ranges do not cover the range required for part loop operation. If the method is to be used for analysis of part loop operation, the topical report must be amended to cover this wider range.

5.0 REFERENCES

1. Chelemer, H., Bowman, L. H., and Sharp, D.R., "Improved Thermal Design Procedure, "WCAP-8567-P, July 1975.

2. Letter from D. F. Ross, Jr. (NRC) to C. Eicheldinger (W), "Staff Evaluation of WCAP-7956, WCAP-8054, WCAP-8567, and WCAP-8762," April 19, 1978.

3. Friedland, A. J., and Ray, S., "Revised Thermal Design Procedure," WCAP-11397, Addendum 1, June 1988.

SECTION C

Westinghouse Electric Corporation
Power Systems
Box 355
Pittsburgh Pennsylvania 15230-0355

NS-NRC-87-3209
March 16, 1987

Mr. James Lyons, Chief
Technical & Operations Support Branch
Office of Nuclear Reactor Regulations
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ATTENTION: Document Control Desk

ATTENTION: Carl H. Berlinger, Chief
Reactor Systems Branch
Division of PWR Licensing-A

SUBJECT : Submittal of Westinghouse Topical, WCAP-11397, "Revised Thermal Design Procedure", for Review and Approval

Reference: 1. Chelemer, H., Boman, L.H., and Sharp, D.R., "Improved Thermal Design Procedure," WCAP-8567-P (Proprietary) and WCAP-8568 (Non-proprietary), July 1975.

Dear Mr. Lyons:

Enclosed are twenty-five (25) copies of the topical report, "Revised Thermal Design Procedure", WCAP-11397 (Proprietary).

The enclosed topical has been submitted to revise the Improved Thermal Design Procedure, Reference 1. Our objective is to provide a more realistic prediction of the DNBR limit which satisfies the design criterion, by removing some of the conservatism in the Improved Thermal Design Procedure methodology. The procedure described in this report will be applied in our standard reactor design methodology and referenced in future licensing applications.

It is requested that the review of this topical be completed in the third quarter of 1987 so that Westinghouse can extend their analytical capabilities as the need arises.

This submittal contains Westinghouse proprietary information of trade secrets, commercial, or financial information which we consider priviledged or confidential pursuant to 10CFR9.5 (4). Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosure.

This material is for your internal use only and may be used for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Office of Nuclear Reactor Regulation without the express written approval of Westinghouse. Correspondence with respect to the Application for Withholding should reference AW-87-022, and should be addressed to R. A. Wiesemann, Manager of Regulatory and Legislative Affairs, Westinghouse Electric Corporation, P. O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

W. J. Johnson, Manager
Nuclear Safety Department

/pj

Enclosure(s)

Westinghouse Electric Corporation

Power Systems

Box 355
Pittsburgh Pennsylvania 15230 0355

March 16, 1987
AW-87-022

Mr. Herbert M. Berkow
Standardization & Special Projects Branch
Division of PWR Licensing-B
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Reference: LETTER JOHNSON TO LYONS, NS-NRC-87-3209, DATED MARCH, 1987

Dear Mr. Berkow:

SUBJECT: WCAP-11397, "Revised Thermal Design Procedure"

The subject report transmitted by the referenced letter contains information proprietary to the Westinghouse Electric Corporation.

The material will not be employed as a part of a license application or other action identified in 10CFR2.790(a) at this time. It will be separately submitted with an Application for Withholding accompanied by an Affidavit meeting the requirements of 10CFR2.790(b) prior to such use.

Accordingly, we request that the material be treated as proprietary information within the provisions of 10CFR9.5(4), "Freedom of Information Act Regulations". If there is a need to make public disclosure of the material prior to a separate Westinghouse submittal for docket in accordance with the provisions of 10CFR2.790(a), please notify Westinghouse prior to making a disclosure determination.

Correspondence with respect to the proprietary aspects of this submittal should reference AW-87-022 and should be addressed to the undersigned.

Very truly yours,

Robert A. Wiesemann, Manager
Regulatory & Legislative Affairs

cc: E. C. Shomaker, Esq.
Office of the General Council, NRC

SECTION D

ABSTRACT

A Revised Thermal Design Procedure (RTDP) is developed which satisfies the design criterion that protects against Departure from Nucleate Boiling (DNB) in a PWR core. Variations in plant operating parameters, nuclear and thermal parameters, fuel fabrication parameters, and DNB correlation predictions are considered statistically to obtain a DNB uncertainty factor. Applying this factor leads to a limiting DNBR value to be used for accident analysis. Since the uncertainties are all included in the uncertainty factor, the accident analysis is done with input parameters at their nominal or best estimate values.

RTDP revises the previous procedure, called the Improved Thermal Design Procedure (ITDP), in that DNB correlation uncertainties are combined statistically with the ITDP uncertainties instead of being treated separately. This provides a more realistic prediction of the DNBR limit which satisfies the design criterion.

The mathematical relationships are derived and a sample calculation is presented using numerical values for a 3 loop plant with 17x17 standard rod array fuel assemblies, and the WRB-1 DNB correlation. This Revised Thermal Design Procedure retains the capability of readily and realistically accommodating additional parameters which affect DNB or changes in the values or uncertainties of parameters.

ACKNOWLEDGEMENTS

The authors would like to thank E. H. Novendstern for guiding this project, H. Chelemer for his helpful comments on the statistical methods, and J. R. Reid who performed many of the calculations. The discussions with R. C. Anderson and K. L. Basehore of Virginia Power are also greatly appreciated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECTION 1

INTRODUCTION

A Revised Thermal Design Procedure (RTDP) is presented in this topical report for purposes of realistically predicting the Departure from Nucleate Boiling Ratio (DNBR) design limit in Westinghouse PWR's. This procedure removes some of the conservatism in the Improved Thermal Design Procedure (ITDP) methodology[1]* while satisfying the design criterion that protects against DNB in a PWR core. The DNB thermal design criterion is that the probability that DNB will not occur on the most limiting fuel rod is at least 95% (at a 95% confidence level) for any Condition I or II event.

With ITDP methodology, system uncertainties are statistically combined separately from the DNB correlation uncertainty. The two are then combined directly, rather than statistically, to determine the DNBR limit.

The system and correlation uncertainties are independent variables, and in the revised procedure they are statistically combined to more realistically predict the DNBR limit by removing some of the unnecessary conservatism in ITDP. The RTDP is a natural extension of the ITDP and is similar to the approach developed by Virginia Power[2].

The development of the mathematical relationships for the revised procedure is given in Section 2 and a sample plant analysis is shown in Section 3. Section 4 describes the application to fuel rod bow, and the justification for the use of sensitivity factors is presented in Section 5.

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* Superscripts in brackets refer to list of References

SECTION 2

MATHEMATICAL RELATIONSHIPS

RTDP is essentially an extension of ITDP. The mathematical relationships used in ITDP are derived in the first part of this section. The second part shows the extension of these relationships for RTDP.

2.1 ITDP Methodology

The following is a summary of the methodology used in ITDP.[1]

For a DNB correlation such as WRB-1[3] the statistical parameters of the data base are obtained: mean ($m_{M/P}$), and standard deviation ($s_{M/P}$), where M/P is the ratio of measured-to-predicted heat fluxes at the point of minimum DNBR. When ITDP is used, the DNBR Correlation Limit (CL) is set so that with 95% confidence there is at least a 95% probability that DNB will not occur for a statepoint with DNBR ≥ CL. CL is given by

$$CL = \frac{1}{m_{M/P} - Ks_{M/P}} \qquad (2\text{-}1)$$

where K is obtained from tables prepared by Owen[4] and is a function of the confidence level, the probability, and the number of data points in the DNB data set.

In order to relate the variations in design parameters to DNBR variations, an uncertainty factor, y, defined by the following equation, is used:

$$y = DNBR(variable)/DNBR(nominal) \qquad (2\text{-}2)$$

The value of DNBR(nominal) is determined by considering the values of all the design parameters to be at their nominal or best estimate values. The value of DNBR(variable) is based on values of the design parameters including their uncertainties and deviations from nominal values. Consequently, in any particular application, DNBR(nominal) will have a single determinable value while DNBR(variable) will be a random variable.

The DNBR uncertainty factor is considered to be affected by changes in the values of the design parameters according to a relation of the form

$$\frac{dy}{y} = s_1 \frac{dx_1}{x_1} + s_2 \frac{dx_2}{x_2} + \ldots s_m \frac{dx_m}{x_m} \qquad (2\text{-}3)$$

where

x_i is the value of the i^{th} design parameter,

dx_i is the differential change in the value of x_i,

dy is the differential change in y resulting from the differential changes dx_i.

The factor s_i represents the sensitivity factor associated with the i^{th} parameter. If all the parameters in Equation (2-3) are held constant except for one, then it is clear from Equation (2-3) that if the x_i are independent

$$s_i = \frac{\partial y}{y} \bigg/ \frac{\partial x_i}{x_i} = \frac{\partial(\ln y)}{\partial(\ln x_i)} \qquad (2\text{-}4)$$

Thus the value of s_i can be interpreted as representing the percentage change in DNBR resulting from a one percent change in x_i, all other parameters being held constant.

Integrating Equation (2-3), considering the s_i values fixed, and taking antilogarithms gives

$$y = C\, x_1^{s_1}\, x_2^{s_2} \ldots x_m^{s_m} \qquad (2\text{-}5)$$

where C is obtained from the constant of integration.

In order to evaluate the uncertainty factor to be used in the design value of the DNBR, it is necessary to obtain a relationship between it and the uncertainties in the design parameters used to determine DNBR.

Consider each of the independent design parameters x_i as being distributed about a mean value μ_i. If y is expanded in a Taylor's series about the μ_i the following expression is obtained

$$y-\mu_y = \frac{\partial y}{\partial x_1}(x_1-\mu_1) + \frac{\partial y}{\partial x_2}(x_2-\mu_2) + \ldots \frac{\partial y}{\partial x_m}(x_m-\mu_m) \qquad (2\text{-}6)$$

+ higher order terms

The partial derivatives in Equation (2-6) are evaluated at the point where all the x_i are at their mean values μ_i. The value of y at this point is represented by μ_y.

From Equation (2-5)

$$\mu_y = C\, \mu_1^{s_1}\, \mu_2^{s_2} \ldots \mu_m^{s_m} \tag{2-7}$$

If the pertubations from the mean values are small, the higher order terms in Equation (2-6) will be considerably smaller in magnitude than the first order terms and can be ignored. Under these conditions, the variance of y determined using Equation (2-6) results in the following expression [5]:

$$\sigma_y^2 = \left(\frac{\partial y}{\partial x_1}\right)^2 \sigma_1^2 + \left(\frac{\partial y}{\partial x_2}\right)^2 \sigma_2^2 + \ldots \left(\frac{\partial y}{\partial x_m}\right)^2 \sigma_m^2 \tag{2-8}$$

Using Equation (2-5) and (2-7) in Equation (2-8) leads to the equation

$$\left(\frac{\sigma_y}{\mu_y}\right)^2 = s_1^2 \left(\frac{\sigma_1}{\mu_1}\right)^2 + s_2^2 \left(\frac{\sigma_2}{\mu_2}\right)^2 + \ldots s_m^2 \left(\frac{\sigma_m}{\mu_m}\right)^2 \tag{2-9}$$

The ratio σ/μ is called the coefficient of variation. Equation (2-9) enables the coefficient of variation of the DNBR uncertainty factor y to be determined in terms of the sensitivity factors s_i defined by Equation (2-4) and coefficients of variation σ_i/μ_i of the design parameters x_i used in evaluating DNBR.

The central limit theorem of statistics indicates that the probability distribution function for y will approach a normal distribution with mean μ_y and standard deviation σ_y even if the individual distributions of the x_i are not normal. It should be noted that Equation (2-9) is subject to the restrictions that the x_i are independently distributed and that the variations in the x_i can be considered small. In addition the sensitivity factors s_i are considered to be constant, thus independent of the x_i.

In order to satisfy the DNB thermal design criterion, an ITDP DNBR design limit value DL_I is determined such that the probability that CL, the Correlation Limit DNBR (given by Equation (2-1)) is exceeded is 95% with 95% confidence. The governing variables are considered to be at such levels that with each at its mean value the DNBR value on the peak power rod is DL_I. This results in the following relation for the design limit DNBR:

$$DL_I = \frac{CL}{1 - 1.645\, \sigma_y} \tag{2-10}$$

where the values 1 and 1.645 represent the mean value of y and the standardized normal variate corresponding to a 95% probability, respectively.

2.2 RTDP Methodology

RTDP utilizes the DNB correlation statistical characteristics, $m_{M/P}$ and $s_{M/P}$, and the uncertainty factor statistical parameters, μ_y and σ_y, calculated in the same manner as in the ITDP.

The statistically combined system and correlation design limit DNBR for RTDP (DL_R) is selected such that for a statepoint with mean DNBR at the DL_R, there is a 95% probability that the DNBR(variable) for the limiting fuel rod exceeds the correlation P/M(variable) with 95% confidence. DNB will not occur if

$$\left[\text{DNBR (variable)} \geq \text{P/M(variable)}\right] \quad (a,c) \qquad (2-11)$$

Using Equation (2-2) gives

$$\left[(DL_R) * y \geq (P/M)\right] \quad (a,c) \qquad (2-12)$$

Rearranging Equation (2-12) results in

$$\left[(DL_R) * y * (M/P) \geq 1.0\right] \quad (a,c) \qquad (2-13)$$

RTDP uses a parameter z defined by

$$z = \left[(DL_R) * y * (M/P)\right] \quad (a,c) \qquad (2-14)$$

[The analysis of z in the RTDP is comparable to the analysis of y in the ITDP. Consider each of the independent parameters y and M/P as being distributed about a mean value.] If z is expanded in a Taylor's series about the mean value, the following expression is obtained (a,c)

$$\left[z - \mu_z = \frac{\partial z}{\partial y}(y - \mu_y) + \frac{\partial z}{\partial (M/P)}(M/P - \mu_{M/P}) + \text{higher order terms}\right](a,c) \qquad (2-15)$$

The partial derivatives in Equation (2-15) are evaluated at the point where each variable is at its mean value. The value of z at this point is represented by μ_z.

From Equation (2-14)

$$\left[\mu_z = (DL_R) * \mu_y * \mu_{M/P} \right] \quad (a,c) \qquad (2\text{-}16)$$

If the perturbations are small, the higher order terms in Equation (2-15) will be considerably smaller in magnitude than the first order terms and as a result can be ignored. This being the case, the variance of z determined using Equation (2-15) results in the following expression[5].

$$\left[\sigma_z^2 = \left(\frac{\partial z}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial z}{\partial (M/P)}\right)^2 \sigma_{M/P}^2 \right] \quad (a,c) \qquad (2\text{-}17)$$

[$\sigma_{M/P}$ corresponds to the standard deviation associated with the DNB correlation being used (at an upper 95% confidence level) and is obtained as follows:] (a,c)

$$\left[\sigma_{M/P} = s_{M/P} \frac{K}{1.645} \right] \quad (a,c) \qquad (2\text{-}18)$$

[where $s_{M/P}$ is the standard deviation associated with the data set and K is the Owen's factor from Reference 4. The mean associated with the correlation, $\mu_{M/P}$, is taken as equal to the mean of the data set, $m_{M/P}$, since K includes the effect of the uncertainties in both $s_{M/P}$ and $m_{M/P}$.] (a,c)

Using Equation (2-14) and (2-16) in Equation (2-17) leads to the equation

$$\left[\left(\frac{\sigma_z}{\mu_z}\right)^2 = \left(\frac{\sigma_y}{\mu_y}\right)^2 + \left(\frac{\sigma_{M/P}}{\mu_{M/P}}\right)^2 \right] \quad (a,c) \qquad (2\text{-}19)$$

[where $(\sigma_y/\mu_y)^2$ is calculated from Equation (2-9).] (a,c)

From Equations (2-13) and (2-14), with [mean DNBR at the DL_R, there is 95% probability that $z \geq 1$ with 95% confidence.] If this is the case
(a,c)

$$\left[\mu_z - 1.645\, \sigma_z \geq 1 \right] \quad (a,c) \qquad (2\text{-}20)$$

$$\left[\mu_z \geq \frac{1}{1 - 1.645\, \sigma_z/\mu_z} \right] \quad (a,c) \qquad (2\text{-}21)$$

Substituting Equation (2-16) in (2-21) and noting that

$$\left[\ \mu_y = 1.0\ \right]^{(a,c)} \qquad (2\text{-}22)$$

results in

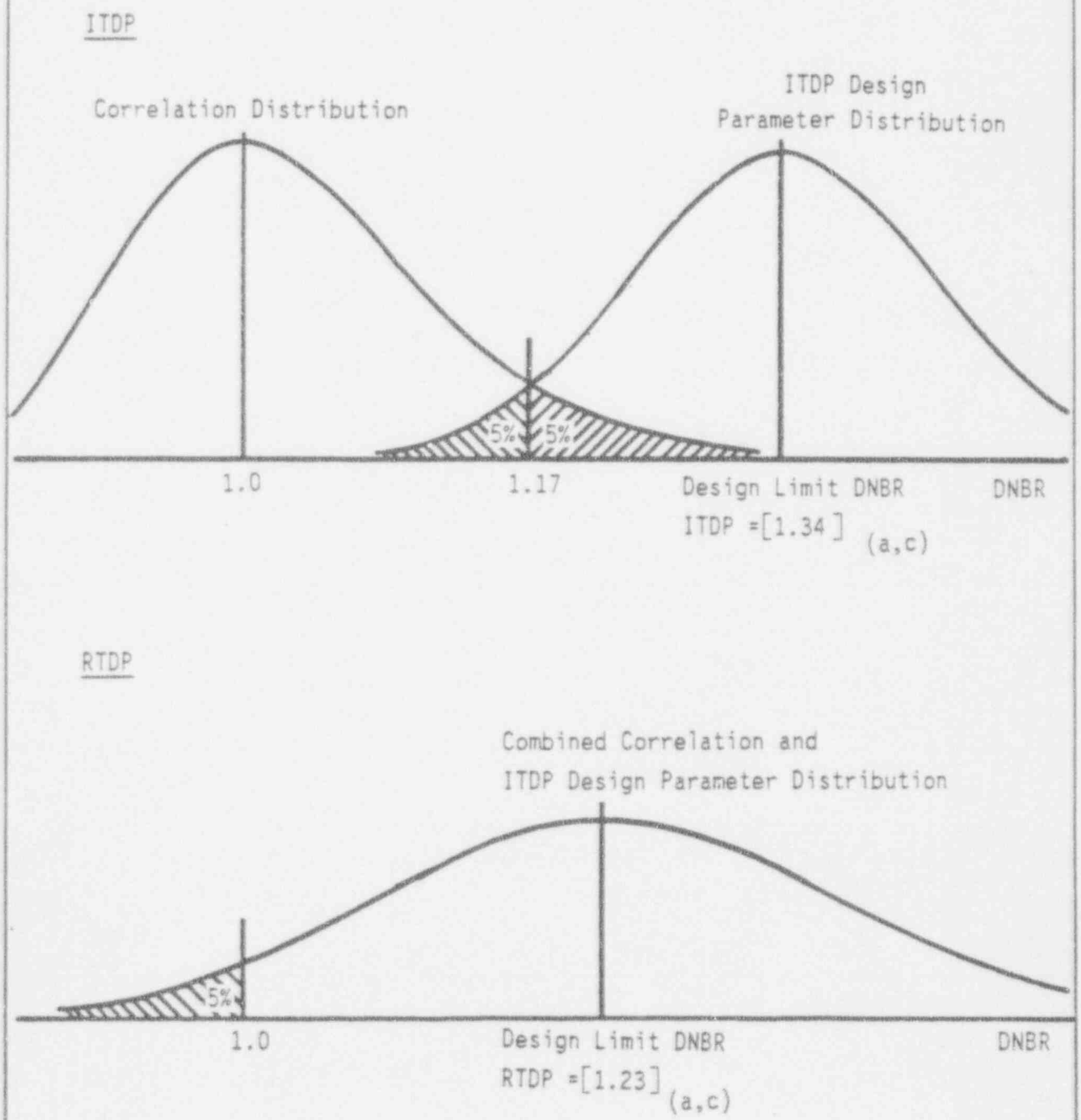
$$DL_R = \left[\frac{1}{\mu_{M/P}(1 - 1.645\ \sigma_z/\mu_z)}\right]_{(a,c)} \qquad (2\text{-}23)$$

Figure 2-1 schematically illustrates the calculation of the design limit DNBR using RTDP compared with that using ITDP.

It should be noted that Equation (2-19) is subject to the restrictions that the x_i [and M/P] are (a,c)
independently distributed and that the variations in the x_i [and in M/P] can be considered (a,c)
small. In addition, the sensitivity factors s_i are considered to be constant and independent of the x_i.

Figure 2-1

ILLUSTRATIVE COMPARISON OF RTDP WITH ITDP FOR A DNB CORRELATION WITH $\mu_{M/P}$ = 1.0 AND LIMIT DNBR = 1.17



SECTION 3

SAMPLE CALCULATION

A representative plant will be analyzed using both ITDP and RTDP to illustrate the difference between them. The selected plant is a three-loop plant with 17x17 standard fuel. Nominal plant operating conditions are listed in Table 3-1.

A sensitivity study was performed using the THINC-IV computer program.[6,7] Sensitivities of DNBR to changes in plant parameters were determined for a range of statepoints covering various operating conditions with minimum DNBR values near the expected DL_R. The most limiting statepoint was selected as the one for which the sensitivities resulted in the highest DL_R. The resulting sensitivities are shown in Table 3-1.

Plant parameter uncertainties are also listed in Table 3-1. These are determined on a plant-specific basis.

For the WRB-1 correlation, the statistical analysis of the data base results in [3]

[

$m_{M/P}$ = 1.0079

$s_{M/P}$ = 0.0859

n = 1108 (misprint in Reference 3 corrected)

K = 1.724 from Reference 4.

] (a,c)

When ITDP is used, the Correlation Limit obtained from Equation (2-1) is

CL = 1.17

The ITDP analysis for the representative plant using the sensitivities calculated above is given in Table 3-1. The resulting DNBR design limit values from Equation (2-10) are:

DL_I = [1.352] (typical cell) (a,c)
DL_I = [1.339] (thimble cell) (a,c)

TABLE 3-1

DESIGN LIMIT DNBR USING ITDP

Parameter	Nominal or Best Estimate (μ)	σ	σ/μ	Typical Cell S	Typical Cell $S^2(\frac{\sigma}{\mu})^2$	Thimble Cell S	Thimble Cell $S^2(\frac{\sigma}{\mu})^2$
Power	100%	1.0%	0.0100	-2.24	.000502	-2.12	.000449
T_{in}	553.6°F	2.0°F	0.0036	-7.49	.000727	-6.60	.000564
Pressure	2280 psia	15 psia	0.0066	1.81	.000143	1.53	.000102
Flow	100%	2.25%	0.0225	1.48	.001109	1.31	.000869
Bypass	0.965	0.577%	0.0060	1.48	.000078	1.31	.000061
$F^N_{\Delta H}$	1.49	0.0365	0.0245	-2.31	.003203	-2.20	.002905
$F^E_{\Delta H,1}$	1.0	1.824%	0.0182	-1.26	.000528	-1.22	.000495
THINC 4	1.0	0.02	0.0200	1.0	.000400	1.0	.000400
Transient Code	1.0	0.005	0.0050	1.0	.000025	1.0	.000025
$\frac{\sigma_y}{\mu_y} = \sqrt{\Sigma\, S_i^2 \left(\frac{\sigma_i}{\mu_i}\right)^2}$ =				0.0819		0.0766	

$$\text{DNBR Design Limit} = \frac{\text{Correlation Limit}}{1 - 1.645\,(\sigma_y/\mu_y)} = \frac{1.17}{1 - 1.645\,(\sigma_y/\mu_y)} =$$

	Typical Cell	Thimble Cell
DNBR Design Limit	1.352	1.339

(a,c)

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When RTDP is used, the analysis in Table 3-1 gives for a typical cell,

[$\sigma_y/\mu_y = 0.0819$] (a,c)

From Equations (2-18) and (2-19):

$$\left[\begin{aligned}\frac{\sigma_z}{\mu_z} &= \sqrt{(.0819)^2 + \left(\frac{.0859}{1.0079} \times \frac{1.724}{1.645}\right)^2}\\ &= 0.1212\end{aligned}\right] \text{(a,c)}$$

From Equation (2-23),

$$DL_R = \left[\frac{1}{(1.0079)\ (1-1.645 \times 0.1212)} = 1.239\right] \text{(a,c)}$$

Similarly, for a thimble cell,

[$\sigma_y/\mu_y = 0.0766$] (a,c)

$$\left[\begin{aligned}\frac{\sigma_z}{\mu_z} &= \sqrt{(0.0766)^2 + \left(\frac{.0859}{1.0079} \times \frac{1.724}{1.645}\right)^2}\\ &= 0.1177\end{aligned}\right] \text{(a,c)}$$

$$DL_R = \left[\frac{1}{(1.0079)\ (1-1.645 \times 0.1177)} = 1.230\right] \text{(a,c)}$$

The DNBR design limits using RTDP are compared to those using ITDP in Table 3-2.

TABLE 3-2

COMPARISON OF DESIGN LIMIT DNBR'S

	Design Limit DNBR		
	ITDP	RTDP	
Typical Cell	[1.352	1.239]	
Thimble Cell	1.339	1.230]	(a,c)

SECTION 4

FUEL ROD BOW

Rod bow is accounted for with current methodology[8] by a correlation based on reactor data which relates S_W (the upper 95% tolerance limit for the standard deviation of channel closure for the worst span) and burnup. This is combined with a relation between DNBR penalty and channel closure, a Monte Carlo type calculation being performed to generate the DNBR penalty statistics. The DNBR penalty is combined statistically with the correlation uncertainty and the results are used to calculate a limit DNBR. The percent difference between this limit DNBR and the limit DNBR with no rod bow is the rod bow penalty.

With the new methodology, the analysis is performed in the same way except that for both the unbowed and bowed cases, the DNBR correlation uncertainty is statistically combined with the plant parameter and other uncertainties. This results in a slight decrease in the rod bow penalty compared to the previous methodology.

A sample calculation was performed for 17x17 standard fuel, high flow conditions, at the rod bow limiting burnup of 24,000 MWD/MTU,[9] using the WRB-1 correlation. With the previous methodology, the rod bow penalty was [1.1%]$^{(a,c)}$. With the new methodology, for the plant conditions evaluated in Section 3, the rod bow penalty was [1.0%]$^{(a,c)}$.

SECTION 5

SENSITIVITY FACTORS

Sensitivity factors were determined over a wide range of statepoints covering various operating conditions with minimum DNBR values near the expected DL_R. The most limiting statepoint was selected as the one for which the sensitivities resulted in the highest DL_R. This leads to conservative results in terms of setting the limits on the core operating conditions determined by the DNB limitation.

This procedure differs from that described in Reference 1, in which a range of DNBR values was covered and the largest numerical value of each sensitivity factor over the DNBR range of interest was chosen for use in the DNB analysis.

Since RTDP extends the ITDP methodology in that the DNB correlation uncertainties are statistically combined with the ITDP uncertainties, the following evaluations were necessary with regard to this new methodology:

(a) Verification of the adequacy of Equation (2-3) in predicting changes in DNBR.

(b) Verification of the adequacy of the linearity approximation made to obtain Equation (2-17).

The above evaluations were performed by using procedures previously evaluated by the NRC in Reference 10 and are discussed below.

As a check on the form of Equation (2-3), a pair of test cases was executed using the THINC-IV program. One case used values of the design parameters at nominal conditions while the second case used values at extreme conditions. For the latter case, significant changes were made in all of the parameters in which uncertainties were being considered in the DNB design procedure.

The ratio of the minimum DNBR's for the two cases was 0.80 for both typical and thimble cells as determined by the THINC program. Alternatively, the minimum DNBR for the second case can be estimated from the value for the first case by a relationship obtained by integrating Equation 2-3 assuming that the sensitivity factors, s_i, are constant, and taking the ratio of the results as applied to the two cases:

$$\frac{y}{\mu_y} = \left(\frac{x_1}{\mu_1}\right)^{s_1} \left(\frac{x_2}{\mu_2}\right)^{s_2} \cdots \left(\frac{x_m}{\mu_m}\right)^{s_m} \tag{5-1}$$

where the μ_i and x_i represent the parameter values from the first and second cases, respectively. Substituting the numerical values for the x_i, μ_i and s_i gave values for y/μ_y of 0.76 (typical cell) and 0.77 (thimble cell). These represent the calculated ratio of the minimum DNBR's assuming the parameters are related to the DNBR by Equation (2-3) with constant s_i values. Comparing these values (0.76 and 0.77) with the values obtained from comparing the two THINC cases (0.80 and 0.80) indicates that the assumptions used in developing Equation (2-3) are conservative. Therefore, no uncertainty allowance is required for Equation (2-3) with the sensitivity factors given in Table 3-1 for the WRB-1 correlation with RTDP.

A linearity approximation was made to obtain Equation (2-9), the equation used to determine the statistical parameters for the DNBR uncertainty factor from the variation in the design parameters. There is a corresponding linearity assumption in the derivation of Equation (2-17).

This approximation was tested by choosing the value of each of the parameters to be one standard deviation from its nominal value (in the direction leading to a decrease in DNBR) and using Equation (5-2) to determine the combined effect on the DNBR.

$$\left[\frac{z}{\mu_z} = \left(\frac{x_1}{\mu_1}\right)^{s_1} \left(\frac{x_2}{\mu_2}\right)^{s_2} \cdots \left(\frac{x_m}{\mu_m}\right)^{s_m} \left(\frac{M/P}{\mu_{M/P}}\right) \right]^{(a,c)} \qquad (5\text{-}2)$$

Note that no linearity relationship is used in this calculation. The calculation results in a z value which is 0.74 times the nominal value for a thimble cell.

The same combined effect is also determined using Equation (2-15) neglecting terms of second order and higher, which considers the relationship between the DNBR uncertainty factor and the design parameters to be linear. This leads to

$$\left[\frac{z}{\mu_z} = \frac{s_1(x_1 - \mu_1)}{\mu_1} + \frac{s_2(x_2 - \mu_2)}{\mu_2} + \cdots \frac{s_m(x_m - \mu_m)}{\mu_m} + (M/P)/\mu_{M/P} \right]^{(a,c)} \qquad (5\text{-}3)$$

The value of 0.70 is obtained for the ratio of the resulting z to the nominal value.

The comparisons were repeated at several other values of the parameters (i.e., $\pm\sigma/2$, $\pm\sigma$, $\pm 2\sigma$) and the results are given in Table 5-1. In every case, the linearity assumption gave more conservative results than the calculation which did not assume linearity. This confirms that the linearity assumption is somewhat conservative.

TABLE 5-1

EVALUATION OF LINEARITY ASSUMPTION

Assumed Deviation of each x_i Value From Mean			z/μ_z * Equation (5-3) (Assumes Linearity)	z/μ_z * Equation (5-2) (Does not assume Linearity)
Typical:	1/2 σ	adverse	0.85	0.86
	"	beneficial	1.15	1.16
	1 σ	adverse	0.70	0.74
	"	beneficial	1.30	1.34
	2 σ	adverse	0.41	0.54
	"	beneficial	1.59	1.79
Thimble:	1/2 σ	adverse	0.86	0.87
	"	beneficial	1.14	1.15
	1 σ	adverse	0.72	0.75
	"	beneficial	1.28	1.32
	2 σ	adverse	0.43	0.56
	"	beneficial	1.57	1.74

* z is calculated using values of parameters which deviate from the nominal value by the amount specified in the first column.
μ_z is calculated using nominal values of parameters.

SECTION 6

CONCLUSIONS

Based on the results of this study, the following conclusions were reached;

- The Revised Thermal Design Procedure given here satisfies the design criterion that protects against Departure from Nucleate Boiling in a PWR core.

- The procedure described in this report will be applied in the standard reactor design process and referenced in future licensing applications.

SECTION 7

NOMENCLATURE

C	Constant of integration
CL	Correlation limit DNBR
DL_I	Design limit DNBR using ITDP
DL_R	Design limit DNBR using RTDP
DNB	Departure from nucleate boiling
DNBR	Ratio of the expected DNB heat flux to the actual local heat flux
K	Owen's Factor for 95% probability with 95% confidence
M/P	Ratio of measured-to-predicted heat fluxes in DNB test at the point of minimum DNBR
$m_{M/P}$	Mean of measured-to-predicted heat flux ratio in DNB data set
m	Number of design parameters affecting DNBR uncertainty factor
n	Sample size
$s_{M/P}$	Standard deviation of measured-to-predicted heat flux ratio in DNB data set
s_i	Sensitivity factor of i^{th} parameter
x_i	i^{th} parameter
y	DNBR uncertainty factor = DNBR(variable)/DNBR(nominal)
z	[DNBR uncertainty parameter = $DL_R * y * M/P$]$^{(a,c)}$
μ	Mean
σ	Standard deviation

SECTION 8

REFERENCES

1. Chelemer, H., Boman, L.H., and Sharp, D.R., "Improved Thermal Design Procedure," WCAP-8567-P (Proprietary), July 1975 and WCAP-8568 (Non-proprietary), July 1975.

2. Anderson, R.C., "Statistical DNBR Evaluation Methodology," VEP-NE-2, July 1985.

3. Motley, F. E., et al., "New Westinghouse Correlation WRB-1 for Predicting Critical Heat Flux in Rod Bundles with Mixing Vane Grids," WCAP-8762-P-A (Proprietary), July 1984 and WCAP-8763 (Non-proprietary), July 1976.

4. Owen, D.B., "Factors for One-Sided Tolerance Limits and for Variable Sampling Plans," SCR-607, March 1963.

5. Jaech, J.L., "Statistical Methods in Nuclear Material Control," TID-26298, 1973.

6. Chelemer, H., Chu, P.T., and Hochreiter, L.E., "THINC-IV - An Improved Program for Thermal Hydraulic Analysis of Rod Bundle Cores," WCAP-7956, (Non-proprietary), June 1973.

7. Hochreiter, L.E., and Chelemer, H., "Application of the THINC-IV Program to PWR Design," WCAP-8054 (Proprietary) and WCAP-8195 (Non-proprietary), September 1973.

8. Skaritka, J. (Ed.), "Fuel Rod Bow Evaluation," WCAP-8691, Rev. 1 (Proprietary), and WCAP-8692, Rev. 1 (Non-Proprietary), July 1979.

9. Letter dated 6/18/86, C.H. Berlinger (NRC) to E. P. Rahe, Jr. (Westinghouse), "Request for Reduction in Fuel Assembly Burnup Limit for Calculation of Maximum Rod Bow Penalty"

10. Letter dated 4/19/78, D. F. Ross, Jr. (NRC) to C. Eicheldinger (Westinghouse)," Staff Evaluation of WCAP-7956, WCAP-8054, WCAP-8567, and WCAP-8762".

SECTION E

WESTINGHOUSE PROPRIETARY CLASS 2

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June 13, 1986
NS-NRC-88-3346

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

ATTN: Mr. Marvin W. Hodges, Reactor Systems Branch Chief
Division of Engineering & System Technology

SUBJECT: Responses to NRC Questions on WCAP-11397, "Revised Thermal Design Procedure" [Non-Proprietary]

REFERENCE: (1) Letter from M. W. Hodges (NRC) to W. J. Johnson (W), (Questions on WCAP-11397), "Revised Thermal Design Procedure" dated April 4, 1988.

Dear Mr. Hodges:

Enclosed are:

Twelve (12) copies of WCAP-11397, Addendum 1, "Responses to Additional Questions on Revised Thermal Design Procedure" [Non-Proprietary].

The enclosed information is being submitted in response to additional NRC questions, Reference (1), as a result of the Staff's and their consultants review of the subject Topical.

Very truly yours,

W. J. Johnson

W. J. Johnson, Manager
Nuclear Safety Department

/mlt
Enclosure

WCAP-11397
Addendum 1

REVISED THERMAL DESIGN PROCEDURE

A. J. Friedland
S. Ray

June 1988

Approved: E. H. Novendstern
E. H. Novendstern, Manager
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RESPONSE TO NRC QUESTIONS ON WCAP-11397, "REVISED THERMAL DESIGN PROCEDURE"

1. *Explain what is meant by DNBR(variable) and P/M(variable) in the Revised Thermal Design Procedure (RTDP) development on page 5. Apparently they are both random variables, but it is unclear which sources of uncertainty are included in each. Does the DNBR(variable) only contain the uncertainty from the design parameters for a given nominal set of conditions? Does P/M(variable) only contain uncertainty from the correlation for a given nominal set of conditions? What are the means and standard deviations (values or notation) for each of these random variables? Is the "(variable)" descriptor assumed on the P/M's and M/P's in equations (2-12) through (2-14)?*

RESPONSE TO QUESTION 1:

In the development on page 5:

DNBR(variable) only contains the uncertainties from the design parameters for a given nominal set of conditions.

P/M(variable) only contains uncertainty from the correlation for a given nominal set of conditions.

y is defined as DNBR(variable)/DNBR(nominal).
y has a mean of 1.0 ($\mu_y = 1.0$) and a standard deviation designated σ_y.

The reciprocal of P/M(variable) is M/P(variable), with mean $\mu_{M/P}$ and standard deviation $\sigma_{M/P}$.

The "(variable)" descriptor is assumed on the P/M's and M/P's in equation (2-12) through (2-14).

2. *How is z in equation (2-14) interpreted? It does not appear to be completely analogous to y, which was an uncertainty factor. Is z just a DNBR random variable containing both correlation and design parameter uncertainties?*

RESPONSE TO QUESTION 2:

Z is defined by equation (2-14) and is a DNBR random variable containing both correlation and design parameter uncertainties, as inferred in the question.

3. *The expression in equation (2-18) is described as an upper 95% confidence limit on the standard deviation associated with the uncertainty in the correlation. However, K/1.645 is in general larger than (df/chi-square)**0.5, the appropriate multiplier to obtain an upper 95% confidence limit. The two quantities are equal when the true mean of M/P is known (which is not the case). Still, the use of K/1.645 provides for the revised design limit (DL_R) equaling the correlation limit (CL) when there is no uncertainty in the design parameters. Is this the reason for doing what was done in equation (2-18)? Or was it to allow for treating the true variance of M/P as unknown? In any case, please explain the rationale for equation (2-18) and the corresponding description.*

RESPONSE TO QUESTION 3:

The term K/1.645 is used in equation (2-18) to account for the uncertainty in the mean of M/P as well as the uncertainty in the standard deviation of M/P.

The resulting $\sigma_{M/P}$ is that for a normal distribution which has the same upper 95% tolerance limit as is given by Owen's table.

For known μ and σ, upper 95% tolerance limit (UTL) = $\mu + 1.645\sigma$

For sample $\bar{x}$ and s, UTL = $\bar{x} + ks$

For equal UTL's $\mu + 1.645\sigma = \bar{x} + ks$

$$\sigma = \frac{\bar{x} - \mu + ks}{1.645}$$

$$\therefore \quad \frac{K}{1.645}\, s = \sigma \text{ if } \mu = \bar{x}$$

4. *As noted in the previous question, an "upper confidence limit" is placed on sigma(M/P). Presumably this was not done to sigma(y) because it is being treated as known. Clearly, it is not known exactly because error propagation methods (which are approximate and make certain assumptions) were used to derive it. Also, there are situations where the individual parameter variances may not be justifiably treated as known. The treatment of sigma(y) as known leads to* DL_R, *but something different would be obtained if sigma(y) were treated as unknown. Please discuss and support your treatment of sigma(y).*

RESPONSE TO QUESTION 4:

σ_y is treated identically to the way it is treated in ITDP (WCAP-8567). The NRC review (Ref. 10 of WCAP-11397) of WCAP-8567 states:

> "The proposed design basis is that there must be at least a 95% probability that the minimum DNBR of the limiting power rod is greater than or equal to the DNBR limit of the correlation being used; parameter uncertainties or variances obtained from the evaluation of data are determined at a 95% confidence level. Implementation of the procedure involves assumptions that errors in correlations or postulated functions are random variables where repeated use of a correlation with identical conditions gives identical results. Also, distributions of uncertainties for variables such as power, flow or temperature are not well known so that the functional forms of the uncertainty distributions must be assumed. Therefore, a rigorous statistical statement of the type implied in the proposed DNBR design basis cannot be obtained.
>
> "However, Westinghouse has either chosen distribution functions which are typical of observed distributions or which give conservative variances. Also, biases in correlations have been reduced insofar as practical. Therefore, although a rigorous statistical statement cannot be made, the Westinghouse method provides a reasonable approximation to such a statistical statement."

For RTDP, the design parameter variances will be determined on a plant specific basis by the identical procedure currently used for ITDP.

5. *The last sentence of the first paragraph of Section 1 states the design criterion that is the basis for the RTDP discussed in the submittal. The "95% probability at 95% confidence" portion of the criterion is typically implemented via use of a one-sided tolerance interval based on the normal distribution. A description of a 95%/95% tolerance interval and how it differs from a 95% confidence interval is given in the Appendix.*

A tolerance interval is a statement about a single distribution. Although the RTDP figure and caption on the bottom of page 8 suggest that the RTDP method is considering a single distribution that combines the correlation and design parameter uncertainties, the development on page 6 seems to indicate otherwise. Specifically, Eq. (2-18) computes a tolerance interval for the "correlation uncertainty" distribution, while Eq. (2-20) is the result of a 95% confidence interval on the combined distribution where a "tolerance interval inflated" variance is used for the correlation uncertainty. This RTDP approach is similar to, but not quite the same as what would be obtained if a 95%/95% tolerance interval was computed on the combined distribution under the assumption that sigma(y) is known without error.

Please explain the rationale for the RTDP development steps referred to above, and explain how it satisfies the "95% probability at 95% confidence" portion of the design criterion from Section 1.

RESPONSE TO QUESTION 5:

The approach used in RTDP is the same as that in ITDP with M/P included among the independent variables. The response to question 4 includes the NRC comments on the statistical approach used in ITDP.

6. *Discussions throughout the submittal imply that m(M/P) and s(M/P) are calculated over the set of M/P values corresponding to the data used to develop the correlation. Two comments are made relative to this.*

   (a) *It is inappropriate to compute a mean and standard deviation in this fashion unless it can be demonstrated that the M/P values are a random sample from a common population. This will usually not be the case for a given correlation and its corresponding data base and region of applicability. If the M/P values do not come from a common population, the mean and standard deviation may vary significantly over various subregions of the region of applicability. (This will require computing different safety limits in different subregions, or choosing the largest safety limit if the whole region is to be covered using only a single value.)*

(b) It in inappropriate to evaluate and measure the performance of a correlation using the same data used to develop it, especially if empirical fitting techniques such as least squares are used. Performance measures (e.g., means and standard deviations of P/M) should be computed from data not used to develop the correlation. If such "extra" data are not available, data-splitting or cross-validation techniques should be used to evaluate and measure performance, with the resulting means and standard deviations used in calculating the design limit.

Although this submittal covers general methodology, the above points must be recognized when applying the methodology to specific applications. Please discuss how your approach for applying the RTDP accounts for the two issues raised above.

RESPONSE TO QUESTION 6:

The DNB correlation statistics are the same as those which were used to develop the DNBR correlation limits in the previous ITDP methodology which have been accepted by the NRC. For the WRB-2 correlation, for example (Ref. 6-1), the NRC SER presented a statistical analysis of the test data and concluded that while the data do not all represent a single population, the error introduced into variance estimates by assuming that the data are all from the same population is negligible. Similar results are obtained for the WRB-1 correlation (Ref. 3 of WCAP-11397) applied to "R" grid data.

The evaluation of DNB correlation is handled in separate topicals, as in the above examples. The RTDP derivation treats the data as coming from a common population, and assumes that the error introduced by this assumption is negligible as shown in the appropriate correlation topical report.

(Ref. 6-1, WCAP-10444-P-A, "Reference Core Report - Vantage 5 Fuel Assembly," September 1985)

7. *The first paragraph of Section 5 (page 14) is not completely clear regarding how you propose to obtain the sensitivity factors. Do you propose choosing as the sensitivity factors those values corresponding to the limiting statepoint (the one with the highest DL_R, as specified on page 14)? This seems to be a reasonable approach (given that enough statepoints are examined), but conflicts with the description of sensitivity factors given in Section 2.1. One page 3, the sensitivity factors were described as being percentage changes in DNBR resulting from 1% changes in the x_i. Since no mention is made of the sensitivity factors depending on the s_i or the correlation, the implication is that they are independent of the x_i and the correlation. Hence, the apparent conflict with the proposal on page 14.*

Please clarify your proposal for determining the sensitivity factors for a given application, including how you will determine the number and location of statepoints to be considered. Explain why this approach is an improvement over the approach mentioned in the second paragraph on page 14.

RESPONSE TO QUESTION 7:

We will choose as the sensitivity factors those values corresponding to the limiting statepoint (the one with the highest DL_R, as specified on page 14). The statement on page 3 that the sensitivity factors are percentage changes in DNBR resulting from 1% changes in the x_i, applies at the limiting statepoint. The sensitivity factors do depend somewhat on the x_i and the correlation, so some of them may be higher at some other statepoints. However, as noted in Refs. 1 and 10 of WCAP-11397, the observed variations in sensitivity factors are generally small over a wide range of conditions. Selecting the sensitivities at the limiting statepoint is sufficient to assure a conservative DL_R.

As is currently done for ITDP, sensitivity factors are determined for various statepoints over a range of conditions for which the RTDP methodology will be applicable. With RTDP, the sensitivity factors at each statepoint are used to calculate a DL_R value. The highest of these is used as the design limit DNBR. This approach removes some unnecessary conservatism from the approach mentioned in the second paragraph on page 14, which combines worst sensitivities from different statepoints.

8. *The discussion before and after equation (5-1) deals with a single investigation of the validity of using equation (2-3). In general, "proof by example" is dangerous, especially when only one example is used. Presumably results could differ for different correlations, different values of the correlation input variables, different design parameters, and different values of the design parameters. Justify that (2-3) is a conservative approximation under other possible circumstances?*

RESPONSE TO QUESTION 8:

As noted on page 14, the procedure used to check the form of Eq. (2-3) was the same as that previously evaluated by the NRC in Ref. 10. The form of the equation is based on observation and experience with the THINC computer program and the Westinghouse DNB correlations, which generally show small variation in the S_i over a wide range of conditions. The numerical example which was made at nominal plant conditions is considered to be a check rather than a proof of the methodology. A similar check was made with one test case at the limiting statepoint conditions where the sensitivities resulted in the highest DL_R and the second case with all design parameters one standard deviation from the limiting statepoint conditions in the direction leading to a decrease in DNBR. The combined effect on DNBR of these deviations is considerably greater than 1.645 times the RMS of the individual DNBR standard deviations. If Eq. (5-1) were exact with constant S_i then it would be expected to agree exactly with the THINC analyses, since the S_i were evaluated near the limiting statepoints. This was found to be the case with both the THINC analyses and Eq. (5-1) showing the limiting statepoint ratio of perturbed to nominal DNBR to be 0.834 for the typical cell and 0.847 for the thimble cell. Similar evaluations will be performed if there are any changes to the DNBR correlation or in the limiting statepoint.

9. *In equation (5-3), shouldn't each of the s(x-mu) terms be divided by the corresponding mu?*

RESPONSE TO QUESTION 9:

Yes. The equation was misprinted and should read:

$$\frac{Z}{\mu_z} = \frac{S_1(\chi_1-\mu_1)}{\mu_1} + \frac{S_2(\chi_2-\mu_2)}{\mu_2} + \ldots + \frac{Sm(\chi m-\mu m)}{\mu_m} + \frac{(M/P)}{\mu_{M/P}} \qquad (5\text{-}3)$$

The calculated results in Table 5-1 are correct. The misprint will be corrected in the approved version of the topical.

10. *The discussion and comparisons on pages 15-16 of WCAP-11397 are concerned with investigating the adequacy of the linear approximations in equations (2-6) and (2-15). As in question 8, we have concerns about the sufficiency of your investigation. In this case you did consider several values of (or changes in) the x_i, but all are for the same set of design parameters (with a fixed set of means and standard deviations). Please justify your conclusion that the linear approximations are adequate and conservative for all possible different combinations of design parameters.*

RESPONSE TO QUESTION 10:

The cases tested are those suggested in the NRC evaluation of WCAP-8567 (Ref. 10 of WCAP-11397). They provide a confirmatory check that the linear approximation is reasonable and conservative.

It can be shown that, in general, if all the deviations are in the direction leading to a decrease in DNBR, and all S_i are numerically greater than or equal to unity as is generally true, then the linear approximation is conservative. This is shown by expanding Z in a Taylor's series about the μ_i and including second order terms.

The values of the variables which are major contributors to defining the lower 95% limit of Z/μ_z will be mostly in the direction of negative deviations of Z from μ_z. Therefore, it is reasonable to expect the linear approximations to be conservative.

11. *The submittal does not discuss how the general methodology will be implemented in specific applications. Clearly the sensitivity factors need to be determined for each new correlation, set of design parameters, or range of applicability. It is not clear whether it will be necessary to check the various assumptions and approximations of the RTDP for each application. Finally, the submittal does not discuss how the design parameter variances will be determined. Please discuss these issues regarding the application of the general RTDP methodology to specific applications. The reviewers need to know whether it is just the general methodology that is under review, or if the implementation and verification aspects for specific applications are also to be reviewed/approved.*

RESPONSE TO QUESTION 11:

The general methodology for RTDP will be implemented in the same manner as for ITDP. Sensitivity factors will be determined for each new correlation, set of design parameters, or range of applicability. The design parameter variances will be determined on a plant specific basis by the identical procedure currently used for ITDP.

12. *The first-order error propagation formula (2-8) assumes that the random variables $x_1, \ldots, x_m$ are statistically independent. While this assumption was mentioned in the submittal, its reasonableness was not discussed. Please provide such a discussion, making reference to specific design parameters and giving reasons why the parameters are mutually independent.*

13. *Please clarify your statement on page 4 that "The central limit theorem of statistics indicates that the probability distribution function for y will approach a normal distribution with mean mu(y) and standard deviation sigma(y) even if the individual distributions of the s_i are not normal." Clearly the central limit theorem is not applicable to equation (2-5). Are you basing this statement on the assumption of (2-5) being adequately approximated by (2-6)? Also, since x_i are not identically distributed, a more restrictive form of the central limit theorem must be satisfied. Finally, the convergence to normality of a linear combination of random variables is dependent on the number of variables and their individual distributions. Please consider all of the above points in clarifying and supporting your statements concerning the central limit theorem and an approximate normal distribution for y.*

RESPONSE TO QUESTIONS 12 AND 13:

Questions 12 and 13 deal with the ITDP development, which has been covered in the NRC review and evaluation of WCAP-8567 (Ref. 10 of WCAP-11397). The RTDP development is identical to the ITDP development in these areas.

14. *The development of the revised design limit (DL_R) assumes that every design parameter is distributed with a mean value equal to its nominal value. Will this always be the case, or is it possible that biases might exist? If so, how does the RTDP handle the bias and how would DL_R change?*

RESPONSE TO QUESTION 14:

Biases might exist in design parameters. In such cases, the bias is included separately in the DNBR analysis. The bias is not included in development of DL_R.