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May 3, 1994
JHT/94-066

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

Subject: Submittal of Accepted Version of Topical Report BAW-10187P-A, "Statistical Core Design for B&W -Designed 177 FA Plants."

Gentlemen:

Enclosed are twenty copies of topical report BAW-10187P-A and twelve copies of BAW-10187-A. These reports will serve as the accepted versions, proprietary and non-proprietary, of BAW-10187P which was recently reviewed and found to be acceptable by the NRC staff. BWFC will use this report in future licensing applications where statistical core design is used as the approved methodology for performing thermal-hydraulic calculations.

A copy of the NRC acceptance letter and accompanying safety evaluation is included between the title page and abstract of the report. A copy of the NRC acceptance letter and safety evaluation for Appendix F to BAW-10187P is also enclosed.

B&W Fuel Company (BWFC) requested that BAW-10187P be withheld from public disclosure and provided an affidavit supporting that request with the November 16, 1992 submittal of the topical report. Since the accepted version of BAW-10187P does not include any new information beyond that previously submitted, BWFC does not intend to submit another affidavit defending the proprietary nature of the report. It is requested, however, that the NRC approved version of BAW-10187P be treated as proprietary for the reasons in the original submittal noted above.

Very truly yours,

J H Taylor

J. H. Taylor, Manager
Licensing Services

cc: L. I. Kopp, NRC
L. E. Phillips, NRC
R. C. Jones, NRC
G. C. Schwenk, NRC
R. B. Borsum

BAW-10187-A
March 1994

STATISTICAL CORE DESIGN FOR B&W DESIGNED 177 FA PLANTS

by

A. B. Copsey

B&W FUEL CO.
P. O. Box 10935
Lynchburg, Virginia 24506-0935

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

J H

MAR 2 1994

March 17, 1994

Mr. J. H. Taylor
Manager, Licensing Services
B&W Fuel Company
3315 Old Forest Road
P.O. Box 10935
Lynchburg, VA 24506-0935

Dear Mr. Taylor:

SUBJECT: ACCEPTANCE FOR REFERENCING OF APPENDIX F TO TOPICAL REPORT BAW-10187P, "STATISTICAL CORE DESIGN FOR B&W-DESIGNED 177 FA PLANTS" (TAC NO. M88899)

We have reviewed Appendix F to topical report BAW-10187P submitted by B&W Fuel Company by letter dated February 25, 1994. We find Appendix F to be acceptable for referencing in license applications to the extent specified and under the limitations stated in the enclosed safety evaluation. The evaluation defines the basis for accepting the inclusion of Appendix F to the topical report.

We will not repeat our review of the matters described in topical report BAW-10187P or Appendix F and found acceptable when the report appears as a reference in license applications, except to ensure that the material presented applies to the specific plant involved. Our acceptance applies only to the matters described in the report. In accordance with procedures established in NUREG-0390, "Topical Report Review Status," the NRC requests that B&W publish an accepted version of the report within three (3) months of receiving this letter. The accepted version shall incorporate this letter and the enclosed evaluation between the title page and the abstract and include an "-A" (designating accepted) after the report identification symbol.

If the NRC's criteria or regulations change so that its conclusions as to the acceptability of the report are invalidated, B&W and the applicants referencing the topical report should revise and resubmit their respective documentation, or submit justification for the continued applicability of the topical report without revising their respective documentation.

Sincerely,

Timothy E. Collins for

Martin J. Virgilio, Acting Director
Division of Systems Safety and Analysis

Enclosure:
BAW-10187P Appendix F Safety Evaluation

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

ENCLOSURE

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION
RELATING TO APPENDIX F TO TOPICAL REPORT BAW-10187P,
"STATISTICAL CORE DESIGN FOR B&W-DESIGNED 177 FA PLANTS"
B&W FUEL COMPANY

1. INTRODUCTION

In a letter of March 24, 1993 (Ref. 1), the U.S. Nuclear Regulatory Commission (NRC) accepted topical report BAW-10187P, "Statistical Core Design for B&W-Designed 177 FA Plants" (Ref. 2) for referencing in licensing applications subject to the limitations delineated in the NRC safety evaluation report. Application of the statistical core design (SCD) method described in BAW-10187P resulted in a departure from nucleate boiling ratio (DNBR) statistical design limit (SDL) of 1.237 for the hottest fuel pin. Subsequently, B&W Fuel Company (BWFC) submitted Appendix F to BAW-10187P entitled "Exit Limited SCD Analysis" for NRC review (Ref. 3).

2. EVALUATION

In the original submittal of topical report BAW-10187P, the assumption was made that the SDL did not vary significantly with axial power shape. Subsequent studies, however, have indicated that there are some conditions under which the SDL is sensitive to axial power shape (Ref. 3). This sensitivity was found to exist if the minimum DNBR is located at or near the core exit.

To obtain an SDL that is conservative for all axial power shapes, a series of LYNXT computer code cases were run by BWFC and response surface models were generated, each representing a different axial power shape. A maximum hot pin SDL that bounded all cases, including core exit limited cases, was found to be 1.313. A sufficient number of cases and different axial power shapes were evaluated using approved methods to ensure that this limit provides the limiting hot pin 95 percent protection at a 95 percent confidence level against departure from nucleate boiling and that similar protection is provided to all other fuel pins on a core-wide basis. Therefore, the staff finds a hot pin SDL of 1.313 acceptable.

3. CONCLUSIONS

The staff finds the application of the information in Appendix F to BAW-10187P acceptable for referencing in license applications for B&W-designed 177 FA (fuel assembly) plants subject to the same limitations delineated in the NRC safety evaluation report for BAW-10187P (Ref. 1). The previously approved hot pin SDL of 1.237 has been increased to 1.313 to conservatively bound all axial power shapes.

4. REFERENCES

(1) Letter from A. C. Thadani (NRC) to J. H. Taylor (BWFC), "Acceptance for Referencing of Topical Report BAW-10187P, Statistical Core Design for B&W-Designed 177 FA Plants," (TAC No. M85118), March 24, 1993.

(2) BAW-10187P, "Statistical Core Design for B&W-Designed 177 FA Plants," B&W Fuel Company, November 1992.

(3) Letter from J. H. Taylor (BWFC) to Document Control Desk (NRC), JHT/94-35, transmitting Appendix F to BAW-10187P, February 25, 1994.

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

March 24, 1993

Mr. J. H. Taylor
Manager, Licensing Services
B&W Fuel Company
3315 Old Forest Road
P.O. Box 10935
Lynchburg, VA 24506-0935

Dear Mr. Taylor:

SUBJECT: ACCEPTANCE FOR REFERENCING OF TOPICAL REPORT BAW-10187P, "STATISTICAL CORE DESIGN FOR B&W-DESIGNED 177 FA PLANTS" (TAC NO. M85118)

We have reviewed the topical report submitted by B&W Fuel Company by letter dated November 16, 1992 as requested by letter dated February 9, 1993. We find the report to be acceptable for referencing in license applications to the extent specified and under the limitations stated in the enclosed safety evaluation. The evaluation defines the basis for accepting the report.

We will not 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 ensure that the material presented applies to the specific plant involved. Our acceptance applies only to the matters described in the report. In accordance with procedures established in NUREG-0390, "Topical Report Review Status," the NRC requests that B&W publish an accepted version of the report within three (3) months of receiving this letter. The accepted version shall incorporate this letter and the enclosed evaluation between the title page and the abstract and include an "-A" (designating accepted) after the report identification symbol.

If the NRC's criteria or regulations change such that its conclusions as to the acceptability of the report are invalidated, B&W and the applicants referencing the topical report should revise and resubmit their respective documentation, or submit justification for the continued applicability of the topical report without revising their respective documentation.

Sincerely,

A. Thadani

Ashok C. Thadani, Director
Division of Systems Safety and Analysis

Enclosure:
BAW-10187P Safety Evaluation

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

ENCLOSURE 1
SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION
RELATING TO TOPICAL REPORT BAW-10187P,
"STATISTICAL CORE DESIGN FOR B&W-DESIGNED 177 FA CORES,"
B&W FUEL COMPANY

1. INTRODUCTION

In a letter of November 16, 1992 (Ref. 1), Babcock and Wilcox Fuel Company (BWFC) submitted the topical report BAW-10187P, "Statistical Core Design for B&W-Designed 177 FA Cores" (Ref. 2). In a letter of February 9, 1993 (Ref. 3), BWFC asked the U.S. Nuclear Regulatory Commission (NRC) to review BAW-10187P. This topical report presents the methodology and justification for applying uncertainties to the BWFC departure from nucleate boiling ratio (DNBR) limit by using a statistical rather than a deterministic method. The statistical core design (SCD) method is a thermal-hydraulic analysis technique that gives additional DNBR margin by statistically combining core and fuel element uncertainties. Topical reports BAW-10145P-A (Ref. 4) and BAW-10170P-A (Ref. 5) presented similar methodologies for application to B&W 205 FA (fuel assembly) plants and Westinghouse 193 FA plants, respectively. The subject topical report extends the statistical design technique for application to B&W-designed 177 FA plants.

2. SUMMARY OF TOPICAL REPORT

The traditional thermal-hydraulic design of pressurized-water reactors has maintained core thermal protection during normal operations and anticipated operational occurrences (AOOs) by avoiding departure from nucleate boiling (DNB) during these conditions. The minimum DNBR for each condition or transient was calculated with the core parameters all held at conservative levels assuming that worst-case conditions were experienced during the event. This minimum DNBR was then compared to the DNBR limit associated with the critical heat flux correlation being used. These comparisons were made on the most power-limiting fuel pin only.

The SCD described in BAW-10187P retains the traditional criterion that the core should be protected by designing to avoid DNB but changes the treatment of the uncertainties present in the DNBR calculation. It combines some of these uncertainties statistically, and leaves others at conservative levels. SCD uses the DNBR calculated for the most power-limiting pin to quantify the protection afforded to the entire core. This quantification is based on best estimates and uncertainties of these estimates are taken into consideration.

The report discusses the definition of the core variables used and the determination of their uncertainties, the response surface modeling (RSM), the Monte Carlo propagation of uncertainties, and the application of the SCD to the B&W-designed 177 FA plants.

3. TECHNICAL EVALUATION OF REPORT

Since topical reports BAW-10145P-A and BAW-10170P-A presented a similar methodology for application to B&W 205 FA plants and Westinghouse 193 FA plants, respectively, the review of BAW-10187P concentrated primarily on any differences from the methodology in these previously approved reports. The primary differences found were in the core state variables and in the experimental design used in the RSM.

Two core state variables present in the previously approved SCD were not included in this method. The two variables are the axial power peak and the location of the axial peak. The main reason stated by BWFC for excluding these two variables is that their nonlinear behavior increases the RSM fit uncertainty. By excluding these two variables, the RSM fit error is reduced. The staff concurs that these two variables may be excluded from the determination of the RSM, but requires them to continue to be input to thermal-hydraulic codes at their most adverse allowable level rather than at their nominal value.

The experimental design that was used was the same as the design used in the previously approved reports, except that a full central composite design (CCD) was used in this case rather than the fractional CCD used previously in BAW-10170P-A. The rationale for previously using a fractional design was primarily economic since computer costs were rather expensive at that time. A fractional experimental design requires less data but more easily misses detecting nonlinear effects and yields a larger RSM fit uncertainty. Therefore, the staff finds the use of a full design acceptable.

The overall uncertainty on DNBR is obtained by calculating the DNBR many times for a given set of nominal inputs while allowing these variables to vary randomly over their uncertainty ranges. This "propagation of uncertainties" methodology is the same as that used in BAW-10170P-A except for the trial size and the computer programming language. In BAW-10170P-A, the propagation of uncertainties computer code was written in BASIC to run on a PC and the number of trials was 3,000. In BAW-10187P, the propagation of uncertainties code was written in FORTRAN to run on a workstation and the number of trials was increased to 60,000. The staff finds this acceptable since the 20-fold increase in trials significantly reduces the statistical uncertainty.

Other slight differences exist in the RSM equation form. However, the staff concurs that the RSM used in BAW-10187P can adequately predict the plant response during the propagation of uncertainties and is acceptable.

4. SUMMARY AND CONCLUSIONS

The staff finds the application of BAW-10187P acceptable for referencing in license applications subject to the same limitations delineated in the NRC technical evaluations for the previously approved reports. Specifically, the hot pin statistical design limit of 1.237 is acceptable with the following restrictions:

(1) The component uncertainties and their distributions are to be reviewed on a plant-specific basis to determine their applicability.

(2) The "bounding" assembly-wise power distribution assumed in the core-wide SDL calculation should be shown to bound the expected operating power distributions on a cycle-specific basis.

(3) All core state variables that were not included in the statistical design must continue to be input to thermal-hydraulic computer codes at their most adverse allowable level rather than at their nominal value.

(4) The response surface model should be validated and revised (as necessary) when applied to new fuel assembly designs and extended operating conditions, and with new computer codes and DNB correlations. The approved codes are LYNXT, LYNX1, and LYNX2, and the approved correlation is the BWC DNB correlation.

5. REFERENCES

(1) Letter from J. H. Taylor (BWFC) to Document Control Desk (NRC), "Submittal of Topical Report BAW-10187P, Statistical Core Design for B&W-Designed 177 FA Plants, November 1992," JHT/92-250, November 16, 1992.

(2) BAW-10187P, "Statistical Core Design for B&W-Designed 177 FA Plants," B&W Fuel Company, November 1992.

(3) Letter from J. H. Taylor (BWFC) to Document Control Desk (NRC), Request for NRC Review of BAW-10187P, JHT/93-037, February 9, 1993.

(4) BAW-10145P-A, "Statistical Core Design Applied to the Babcock-205 Core," Babcock & Wilcox, September 1985.

(5) BAW-10170P-A, "Statistical Core Design for Mixing Vane Cores," Babcock & Wilcox, December 1988.

B&W FUEL COMPANY
Lynchburg, Virginia

Topical Report
BAW-10187-A

March 1994

STATISTICAL CORE DESIGN FOR B&W DESIGNED 177 FA PLANTS

A. B. Copsey

ABSTRACT

Statistical Core Design (SCD) is a thermal-hydraulic analysis technique that provides an increase in core thermal (DNB) margin by treating core state and bundle uncertainties statistically. The traditional method of treating uncertainties is to assume the worst level of each uncertainty simultaneously. Applying statistical techniques allows for a realistic assessment of core DNB protection.

The uncertainty distribution for each of the applicable variables is subjected to a Monte Carlo propagation analysis to determine an overall statistical DNBR penalty which is used to establish a Statistical Design Limit (SDL). The variables treated in this manner are then input to the thermal-hydraulic analysis computer codes at their nominal levels. Variables not treated in deriving the SDL continue to be input at their most adverse allowable level. The SCD technique is a widely accepted method that is utilized to reduce some of the extreme conservatism of traditional methods while still allowing for the traditional compounding of variables not amenable to statistical treatment.

The SDL of 1.313 (subject to core specific verification) developed in this report provides 95 percent protection at a 95 percent confidence level against hot pin DNB. The corresponding corewide protection on a pin-by-pin basis using real peaking distributions is greater than 99.9 percent.

ACKNOWLEDGEMENT

The author would like to express his appreciation to Dave Farnsworth, Richard Harne and George Meyer for instruction and consultation in the application of statistical methods for core DNB protection. I would also like to thank Isaac Mensah and Ethel Miller for their help and review of the current work.

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1. Introduction and Methodology

This report discusses the application of Statistical Core Design (SCD) to the B&W designed 177 fuel assembly (FA) plants. It is the third B&W application of SCD. The earlier applications were for the B&W designed 205 FA plants (Reference 4) and the BWFC refueled plants with mixing vane cores (Reference 2). In addition, other utilities and fuel vendors have submitted similar SCD methodologies for licensing application approval. The methodology of SCD for B&W designed 177 FA plants is similar to the approved methodology of SCD for mixing vane cores. The response surface model (RSM) and statepoints are necessarily different, but the experimental design, propagation of uncertainties (monte carlo technique), and application are essentially the same.

1.1. Introduction

Statistical techniques can be applied to many areas of reactor design and analysis. The B&W-developed Statistical Core Design method is a specific application of these techniques to determine Departure from Nucleate Boiling (DNB) limitations in reactor core designs. The purpose of B&W's SCD is threefold: first, to increase the core operating margin or allowable power; second, to quantify the DNB protection; and finally, to allow for future expansion of the technique. Before we discuss the actual SCD methodology, a brief background is presented on the need for Statistical Core Design for DNB protection.

In a nuclear reactor core, the energy generated by the uranium dioxide fuel pellets leaves the fuel rod surfaces in the form of heat flux. This heat flux is removed from the surface by the coolant system flow. The normal mode of heat transfer to the coolant at high power densities is nucleate boiling (a very efficient mode of heat transfer), with heat transfer coefficients to around 50,000 Btu/Hr-Ft^2-F.

As the capacity of the coolant to accept heat from the fuel rod surface and transfer it by bubble detachment to the coolant stream degrades, a continuous layer of steam (a film) starts to blanket the tube. The steam film acts as an insulator, and the heat transfer coefficient drops drastically to around 500 Btu/Hr-Ft^2-F. This is because the heat transfer mechanism is then primarily conduction through the steam layer. Reactor cores must be protected against possible damage that could result from the high clad temperatures that are experienced in the transition to (and in) film boiling.

The heat flux at which the steam film starts to form is termed the Critical Heat Flux (CHF) or Departure from Nucleate Boiling (DNB) point. For design purposes, the Departure from Nucleate Boiling Ratio (DNBR) is used as an indicator of the margin to DNB. The DNBR is the ratio of the predicted CHF to the actual heat flux at the same condition. Thus, the DNBR is a measure of the thermal margin to film boiling and its associated high temperatures. The greater the DNBR value (above 1.0), the greater the thermal margin.

The CHF cannot be predicted from first principles, so it is empirically correlated from out of reactor experiments as a function of the local thermal-hydraulic conditions, the geometry, and the power distribution (of the experiments). Since a CHF correlation is essentially a least squares surface fit to experimental data, it has an associated uncertainty. This uncertainty is quantified in a DNBR design limit. A calculated DNBR above this design limit ensures protection against film boiling. Consistent with the specified acceptable fuel design limit of Standard Review Plan 4.4 (NUREG 0800), a calculated DNBR value greater than this design limit provides assurance that there is at least a 95% probability at the 95% confidence level that a departure from nucleate boiling will not occur on that specific fuel pin.

The calculated core DNBR to compare to this design limit is determined by thermal-hydraulic analyses utilizing the LYNX (COBRA type) computer codes. The code output is, ultimately, a minimum DNBR for a given core state. A further complication is that some of the input variables required by the LYNX code have another set of uncertainties.

Traditional design philosophy for core DNB protection has followed an extremely conservative approach. Essentially, all variables are assumed to occur at their worst possible conditions simultaneously. This approach is a compounding of uncertainties. Thus, in the thermal-hydraulic analyses, the uncertainties in the inputs are compounded to obtain a minimum DNBR which is then compared to a design limit that assumes that the CHF correlation itself is performing at its worst.

This is where a statistical approach can be of benefit. The occurrence of each of the uncertainties at its most detrimental limit is obviously unrealistic. The extent to which the compounding approach is unrealistic can be evaluated as can a more realistic combination of the uncertainties. This is done using statistical methods.

First, the important variables, their uncertainties, and their distributions must be identified. Next, the individual uncertainties are propagated through a model in order to obtain an overall uncertainty on the calculated DNBR. Once this DNBR uncertainty is obtained, a Statistical Design Limit (SDL) DNBR is established to replace the CHF correlation limit DNBR. Finally, the thermal-hydraulic codes are run with nominal input conditions, and the resulting minimum DNBR is compared to the SDL to determine the core DNBR margin (at any given core state).

The difference in this approach is that in the propagation of many uncertainties, the true "expected" uncertainty penalty is found. Further, using these statistical methods, the DNBR protection that is provided is quantified for both the core and for the hot pin.

1.2. Methodology

The SCD methodology consists of four basic steps: (1) definition of variables and determination of uncertainties, (2) response surface modeling, (3) Monte Carlo propagation of uncertainties, and (4) application. The following paragraphs examine each of these steps in more detail.

DNB is not an observable parameter in an operating reactor; it must be inferred from parameters that are observable. The observable parameters can be categorized as core variables and as bundle variables. The core variables describe the overall core condition: core power, the percentage of rated power that the core is producing; core flow, the percentage of design system flow that is available for heat transfer; inlet temperature, the coolant temperature at the core inlet; and system pressure, the primary system pressure at the core outlet. The bundle variables describe the conditions in specific fuel assemblies: radial peaking factor, the power produced in an assembly normalized to the power produced by an average assembly in the core. Each of these five variables is observable either explicitly or implicitly during core operation. Furthermore, when they are input to the LYNX thermal-hydraulic analyses, they determine the thermal-hydraulic performance of the assemblies within the core at any given core state.

The explicitly observed, or directly measured, variables such as pressure or temperature usually have comparatively well-defined uncertainties associated with them. Typically, these uncertainties result from detector and instrumentation string errors. On the other hand, the uncertainties in the implicit variables, those not directly measured, such as assembly power distribution, are not so straightforward. They must usually be calculated by mathematical models and secondary measurement sources.

In any event, once the variables and uncertainties are defined, they need to be translated to an overall uncertainty on DNB ratio. This is done by calculating the DNBR many times for a given set of nominal inputs while allowing these variables to vary randomly over their uncertainty ranges. This is known as propagation of uncertainties with a Monte Carlo analysis. For instance, in one determination of DNBR, the temperature may be higher than nominal (within its uncertainty) while the pressure might be very close to nominal. In the next determination, both might be slightly below nominal; and so forth. When a sufficient number of these determinations are made, one obtains a distribution of DNBR values about a nominal or expected value. This distribution defines the overall random uncertainty in the calculation of DNBR and is based on the range of the individual uncertainties considered.

An accurate determination of the overall uncertainty requires us to calculate the DNBR many times (in the BWFC application, 60,000 times) for many nominal core statepoints. This could be done by running 60,000 LYNX analyses for each nominal condition while randomly varying the inputs within their uncertainty ranges. For obvious reasons, this is a rather impractical approach. Instead, a Response Surface Model (RSM) is developed. The RSM is essentially an equation that defines DNBR as a function of the core and bundle variables. It is not a physically based equation, but much like a linear least squares fit of an experiment. The RSM is a fit of a five variable surface, and it contains linear, cross, quadratic, cubic, and ratio terms. Nevertheless, the evaluation of 60,000 DNBR's for a dozen or more nominal statepoints using this single equation makes efficient Monte Carlo propagation possible.

The RSM is developed statistically by running a mathematical experiment with 210 to 220 LYNX cases analogous to a test matrix. The input to these cases is a carefully chosen set based on an experimental design technique termed central composite design. The resulting DNBR's from each case represent the experimental points. The coefficients in the RSM are then optimized using multiple regression methods. The requirements imposed upon the RSM are that it must give a relatively accurate DNBR prediction over a wide range of input variables and that it must allow for very accurate propagation of the variable uncertainties for the determination of the overall DNBR uncertainty. The primary purpose of the response surface is propagation of uncertainties, not absolute calculation of DNBR.

Once the uncertainty in calculated DNBR is determined, it is possible to define statistically a new limiting DNBR called the Statistical Design Limit (SDL) to replace the CHF correlation limit. The determination of the SDL is directly analogous to the determination of the correlation limit: in fact, the same equation is used. The SDL, however, is significantly higher than the correlation limit since it contains allowances for all of the propagated uncertainties as well as the original CHF uncertainty. Then, when the minimum DNBR is calculated (with nominal inputs to the LYNX code) to be at the SDL, the actual DNBR with uncertainty considered will be above the true limiting DNBR of 1.0 with at least a 95 percent probability at a 95 percent confidence level. Less limiting pins will have a correspondingly higher protection probability, and one can then proceed to quantify the number of pins in the core in danger of being at DNB for any given peaking distribution, and adjust the SDL accordingly. When at least 95 percent hot pin protection with 99.9 percent or greater core-wide protection is obtained, the goal of quantifying and assuring adequate core protection from film boiling has been met.

1.3. Summary

Statistical Core Design (SCD) is a thermal-hydraulic analysis technique that provides an increase in core thermal (DNB) margin by treating core state and bundle uncertainties statistically. The traditional method of treating uncertainties is to assume that the worst levels of all of the uncertainties occur simultaneously. Applying statistical techniques allows for a realistic assessment of core DNB protection.

The uncertainty distribution for each of the applicable variables is subjected to a Monte Carlo propagation analysis to determine an overall statistical DNBR penalty that is used to establish a Statistical Design Limit (SDL). The variables treated in this manner are then input to the thermal-hydraulic analysis computer codes at their nominal levels. Variables not treated in deriving the SDL continue to be input at their most adverse allowable levels. The SCD technique is a widely accepted method that is utilized to reduce some of the undue conservatism of traditional methods while still allowing for the traditional compounding of variables not amenable to statistical treatment.

The SDL of 1.313 (subject to core-specific verification) developed in this report provides 95 percent protection at a 95 percent confidence level against hot pin DNB. The corresponding corewide protection on a pin-by-pin basis using real peaking distributions is greater than 99.9 percent.

2. Response Surface Model

2.1. Response Surface Model Development

This section presents the development of the response surface model (RSM) for the Mark-B Statistical Core Design (SCD). The following subsections describe the core state variables, the form of the response surface equation, and the matrix of test cases used to determine the RSM coefficients. The LYNXT model and inputs are discussed, and the final RSM is presented. The final subsection evaluates the validity of the final response surface, including direct comparisons to LYNXT analyses over a range of core operating conditions. The model development is similar to the methodology developed in Reference 2. The primary differences are the specific plant parameters and the form of the response surface model equation.

2.1.1. Response Surface Model

The determination of a core state requires specification of the core state vector. The core state vector consists of five observable independent variables that describe the global and local state of the core (with respect to CHF or DNBR) from a thermal-hydraulic point of view. The core state variables are:

Q - Fraction of reactor thermal power

W - Fraction of nominal RCS flow

P - System pressure, psia

[C]

R - Hot pin radial peaking factor

Two core state variables present in the Mark-BW SCD were not included in the Mark-B SCD. The two variables are the axial peak (A or F_z) and the axial peak location (Z). The reasons for excluding the two variables is that the uncertainty associated with the variables is not included in all of the DNBR analyses, their effect on overall core margin is small, and their nonlinear behavior increases the RSM fit uncertainty.

The basic Response Surface Model (RSM) for Mark-BW plants given in Reference 2 consists of a quadratic with cross products in the seven state variables. The coefficients for the Mark-BW RSM are one constant coefficient, seven linear coefficients, seven quadratic coefficients and twenty one cross product coefficients. It is important to avoid RSM fit biases since they can cause errors in the propagation of uncertainties analysis. In order to avoid a bias in the Mark-B RSM the following was done:

1. The experimental design that was used was the same used in the Mark-BW SCD, except in the Mark-BW SCD a fractional design was used while a full design was used in the Mark-B SCD. A fractional experimental requires less data but more easily misses detecting nonlinear effects.
2. A stepwise regression was performed using the first, second and third order parameters as well as the first order cross products and ratios of the five state variables.
3. A detailed residual analysis was performed.

This approach to develop the RSM is similar to the Reference 2 approach since the end product from both approaches is a regression equation and the end product is independent of the approach.

2.1.2. RSM Design Matrix

In order to determine the initial RSM coefficients, an excess of the number of the coefficient values of the dependent variable for differing core states must be found. One of the most efficient state vectors for use in finding the coefficients are defined by the experimental design matrix described in Reference 2. The design consist of three levels for each variable:

- the factorial portion, which is a complete 2^K factorial design
- the axial portion, which is two points on the axis of each design variable with values equal to the minimum and maximum of the design variable, and
- the central value, where all of the design variables are at their midpoint value.

The values of the 2^K factorial design portion are determined by:

[

C

]

For example, the range of fraction of reactor thermal power from Table 2-1 is 0.6. So the factorial value for reactor thermal power is 1.0 ± 0.1342. In order to avoid missing nonlinear effects in the extreme of the variable range, all of the combinations for each of the three values are considered. The experimental design matrix is illustrated in Figure 2-1 for three independent variables (X_1, X_2, and X_3).

In general, an experimental design is chosen so that a design is orthogonal as possible. The SAS computer program was used to aid in setting up the design matrix. SAS is a widely used computer package for statistical design and analysis. The SAS scripts and results used in the experimental design development are given in Appendix B. For the five dimensional state vector the number of required points is the sum of the number of center points, factorial points, and axial points. The number of points (NP) is

[C]

As described previously, a full experimental design was used to reduce the possibility of a fit bias.

2.1.3. Design Matrix Ranges

The physical ranges of the independent variables represent those of actual reactor operation. The flow range is somewhat larger than that encountered for a specific reactor in order to accommodate variation between reactors and three loop operation. The center point results in a DNBR substantially above 1.0. However, after the uncertainties are propagated, the overall results are, in effect, normalized by the use of coefficients of variation rather than standard deviations. Therefore the results are applicable over the full DNBR range.

The ranges of all variables except for inlet temperature are their actual physical values. [C] The ranges and center points are discussed and shown in Table 2-1.

2.2. Model Determination

This section describes the actual process used to determine the RSM. The fitting code (Section 2.2.1) takes the results of the LYNXT core model (Section 2.2.2) run on each point of the RSM design matrix (Section 2.1.2) and provides the final RSM (Section 2.2.3) which is then verified against the original LYNXT matrix and against additional LYNXT check point cases.

2.2.1. RSM Fitting Code

The statistics computer program used for both regression and residual analysis is SAS. SAS is a widely used general purpose statistics and data manipulation computer program. The input decks used to generate and evaluate the RSM are included in Appendix A. The scheme used in the RSM regression work is as follows:

1. Read the data from the LYNXT runs (SAS script RSM01.SAS)
2. Perform a stepwise regression to determine the optimal model (SAS script RSM02.SAS)
3. Perform a residual analysis (SAS script RSM08.SAS)

2.2.2. LYNXT Model for RSM Determination

A standard, twelve-channel, eighth-core symmetric LYNXT (Reference 1) model is used. The base model described here is the BWFC standard for core steady-state and transient analysis except that all required inputs that will be propagated in the Monte Carlo analysis are nominal. That is, no pin hot channel factors, flow uncertainty factors, etc., are used. The reason for this modification to the standard model is that the final RSM will accurately model the overall sensitivity of DNBR with respect to the core state variables with no inclusion of arbitrary localized effects.

The base twelve-channel model is shown in Figure 2-2. Ten subchannels of the eighth-core symmetric hot bundle are modeled. The eleventh channel is comprised of the remaining portion of this symmetric hot bundle. Channel twelve is composed of the remainder of the eighth-core.

The nominal design thermal power for the Mark-B 177-FA plants is 2772 MWt or 2568 MWt. The RSM has been based on the LYNXT DNBR predictions for the higher 2772 MWt core design. The RSM is applicable to the lower power level, 2568 MWt, since nominal design thermal power is included in the power state variable (Q) described below. There are five state variables that are modified in the LYNXT deck in order to generate the data used in the RSM development. The method in which they are modified is discussed below.

Power (Q) : The fraction of reactor thermal power is input as an average heat flux into the LYNXT program. The average heat flux input into LYNXT is the fraction of reactor thermal power relative to the 1.12 overpower multiplied by the base average heat flux. The average heat flux is calculated by:

[

C

]

Flowrate (W): The flowrate used in the RSM is fraction of nominal RCS flow. The input for LYNXT is not flowrate, but mass flux (G_{in}). Mass flux is calculated by

[

C

]

[

C]

System Pressure (P): The system pressure is directly input into the LYNXT program.

[

C

]

Peak Pin Power: The pin power is input in the LYNXT program. [

C

]

[

C

]

2.2.3. Final RSM for Propagation

Using the LYNXT model described in the previous section, the RSM was generated using SAS with the scripts shown in Appendix A. The Analysis of Variance (ANOVA) data is shown in Table 2-2. The correlation coefficient (R^2) is [C] indicating that the regression fit predicts the data very well. The "Root MSE" parameter shown in Table 2-2 is used to calculate the RSM uncertainty as follows:

[

C,D

]

The RSM uncertainty is one of the uncertainty parameters on DNBR. The RSM uncertainty is conservatively increased to [C,D] for use in the SCD Monte Carlo analysis.

The parameters in the RSM are determined by the technique of stepwise regression. Stepwise regression adds the most "statistically important" parameters to the regression equation. Using this technique the optimal RSM is determined with the minimal number of parameters and coefficients. The selected parameters and the parameter estimates are shown in Table 2-3. The

RSM has [C] parameters, including the intercept. The RSM is shown in Figures 2-3 through 2-7. These figures show the response of each of the five state variables when the remaining four state variables are at the midpoint values. For example, Figure 2-3 shows the variation of DNBR as a function of fraction of reactor thermal power when the remaining parameters are at the midpoint values shown in Table 2-1.

A residual analysis is performed next. The residuals are the difference between the actual DNBR values from LYNXT and the predicted DNBR value from the RSM. If the residuals are unbiased then the form of the RSM from the stepwise regression is acceptable. A list of the state variable values, the actual DNBR values from LYNXT, the predicted DNBR value from the RSM, and the residual is shown in Table 2-4. The peak absolute value of the residual is [C] This peak residual does not occur at an extreme location in the experimental design matrix. This, along with the residual plots indicate that the regression equation does not show a fit bias. Residual plots are shown in Figures 2-8 through 2-12. The residual plots show the residuals plotted as a function of each of the state variables. If a trend has been observed in any of the residual plots then a detailed analysis would have been performed to assure that a bias did not exist. None of the residual plots show a trend. A histogram of the residuals is shown in Figure 2-13. The residuals are normally distributed and do not exhibit a skew. A plot of the predicted DNBR versus the observed DNBR is shown in Figure 2-14. This plot shows that the RSM is not biased with respect to DNBR level and illustrates the goodness of fit.

Additional LYNXT cases were analyzed in order to act as validation cases. These validation cases are not part of the data used to generate the RSM. A comparison of the actual DNBR from the check cases and the predicted DNBR from the RSM provide an assurance that the RSM accurately predicts the LYNXT results. The validation cases are a 2^K factorial design, similar to the factorial portion of the experimental design matrix. The value of the power, flow, and radial parameters was arbitrarily chosen to be [C] of the distance between the midpoint value and the axial values. For example, the value of core power used in the validation runs was [

C] The results of the validation runs are shown in Table 2-5. To validate the model, a statistical test was performed to determine if the standard deviation of the residuals from the regression analysis is the same as the standard deviation of the validation error. The validation error is defined similarly to the residual, the difference between the actual validation DNBR from LYNXT and the DNBR predicated by the RSM. The value of F for this test is

[C]

The test statistic for this case is

[C]

The "best-fit" parameters and variables used in the RSM are listed in Table 2-3. In addition, the RSM is listed below in equation form:

[

C

]

[

c

]

Table 2-1: RSM Design Matrix, Center Points and Ranges

[

C

]

Table 2-2: Analysis of Variance of the RSM

[

c

]

Table 2-3: Parameter Estimates for the RSM

[

c

]

Table 2-4: Residuals, Actual and Predicted Values for the RSM
(Sorted by Residual)

[

c

]

Table 2-5: LYNXT Validation Cases Compared with the RSM
(Sorted by Residual)

[

c

]

Figure 2-1: Experimental Design Matrix for Three Variables

[

c

]

Figure 2-2: Base Twelve Channel LYNXT Model

[

c

]

[c]

[c]

[c]

[c]

[c]

[c]

[c]

[c]

[c]

[c]

[c]

[c]

[c]

3. Propagation of Uncertainties

3.1. Distribution Modeling

This section presents the development and verification of the normal and uniform distribution models for eventual Monte Carlo propagation of the various uncertainties.

3.1.1. Normal Distribution for Propagation

Each Monte Carlo propagation of each uncertainty through the RSM requires generation of a point on the normal distribution curve. Thus if, for one statepoint, 30,000 propagations of six uncertainties are desired, 180,000 points on the normal distribution curve must be generated.

Since no analytical generator exists, it is convenient to approximate the normal distribution using a function. A FORTRAN subroutine called GAUSS.F was written to approximate the normal distribution. The subroutine uses a random number generator (GGUB.F) to generate the normal deviates, N[0,1]. A listing of the subroutines is included in Appendix C.

3.1.2. Uniform Distribution for Propagation

The generation of a uniform distribution is relatively trivial (in comparison to the normal distribution). The objective in this case is to generate a continuous uniform distribution with a mean of zero and range of one, U[0,1] to be consistent with the normal distribution developed above. A FORTRAN subroutine called UNIFORM.F was written to approximate the uniform distribution. The subroutine uses a random number generator (GGUB.F) to generate the uniform deviates. A listing of the subroutine is included in Appendix C.

3.1.3. Verification of the Distributions

In order to verify the normal distribution, nine sample distributions of 2000 points each were generated with the above algorithm with a mean of one and a standard deviation of two, N[1,2]. As can be seen in Table 3-1, these sample distributions exhibit excellent attributes of normality. In reference to the ANSI standard on normality, it can be seen that in no case can normality be rejected at the ±5 percent level. The upper and lower D' limits are 25320 and 25130 respectively. All of the calculated D' statistics for each of the nine samples are within the D' limits, indicating normality.

The uniform distribution was verified qualitatively since a test analogous to D' for uniform distributions is not known to exist. The uniform distribution was arbitrarily chosen to be from -5 to 7, or U[1,6]. A histogram of a uniform distribution calculated with the UNIFORM.F subroutine is shown in Figure 3-1. The univariate statistics are given in Table 3-2. The mean [C] and the resulting distribution shown in Figure 3-1 is very flat.

3.2. Propagation Modeling

In the first part of this section, the Monte Carlo model for propagation of various uncertainties with either the normal or uniform distributions is defined. Next, the specific uncertainties, their components, and distributions are presented.

3.2.1. Uncertainty Propagation Model

The uncertainty of a given independent variable, X, using its mean, uncertainty, and type of distribution is defined by the triple:

$$\{ \mu_X, \pm\Delta X, N[\mu,\sigma] \text{ or } U[\mu,R/2] \}$$

For the current work, the uncertainty must then be put into the proper form using the previously developed distributions. Then the value of the variable (at its instantaneous value) within the distribution must be found so the DNBR can be evaluated by the RSM. The distribution spread is calculated as follows.

Normal: Assume that the extremes of the symmetric range, Δ_X, are at the 95% K-factor level. Then the standard deviation of the normal distribution, σ_X, is

$$\sigma_X = \left[\frac{\Delta_X}{K_{95\%,95\%}}\right]$$

$$\sigma_X = \left[\frac{\Delta_X}{1.645}\right]$$

and the propagation model as a function of the distribution mean, μ_X, and standard deviation, σ_X, is given by

$$X_i = \mu_X + N[0,1] \cdot \sigma_X$$

$$X_i = N[\mu_X, \sigma_X]$$

Uniform: Assume that the extremes of the symmetric range, Δ_X, are at the parameter uncertainty. Then the propagation model as a function of the distribution mean, μ_X, and the range, Δ_X, is given by

$$X_i = \mu_X + U[0,1] \cdot \Delta_X$$

$$X_i = U[\mu_X, \Delta_X]$$

3.2.2. Uncertainties for Propagation

The uncertainties are propagated through the RSM to arrive at a final Statistical Design Limit (SDL). The SDL defines the new LYNXT design analysis. That is, if an uncertainty (such as a 2 degree temperature error) has been propagated in determining the final SDL, it need no longer be considered in the LYNXT design case, and the nominal value can be used. The RSM, through which the uncertainties are propagated, results in a minimum core DNB ratio, D, for each core state input vector: Q, W, P, T, and R. All applicable uncertainties, including those on D, will be treated. If an uncertainty is not treated, [C,D] it must be considered in the LYNXT model.

Further, if an uncertainty is treated at an inferior level, the remaining portion of that uncertainty will be compounded in the LYNXT model. Thus, for instance, if a 65 psia pressure error has been propagated, but it is later found that the actual error is 80 psia, the remaining 15 psia will be compounded in the core analysis. For this reason, the conservative values of each applicable uncertainty are treated.

Finally, for a slight added conservatism, appropriate uncertainties are propagated with a uniform distribution when it is questionable that a normal distribution can be justified. A brief discussion of each uncertainty to be propagated follows.

1. Q (CORE POWER) - 1 Uncertainty - [C,D]

2. W (CORE FLOW) - 2 Uncertainties - [C,D]

3. P (CORE PRESSURE) - 1 Uncertainty - [C,D]

4. T [C,D]- 1 Uncertainty - [C,D]

5. R (RADIAL PEAKING FACTOR) - 4 Uncertainties - [C,D]

6. D (Uncertainties on DNBR) - 3 Uncertainties - [C,D]

[

C,D

]

These uncertainties and their distributions must be verified for each separate application (core). [C] A summary of the above is shown in Tables 3-3 through 3-6.

[

C

]

Table 3-1: Statistics for the Normal Distribution Function for nine Random samples of size 2000

[

c

]

Table 3-2: Univariate Statistics of the Uniform Distribution

[

c

]

Table 3-3: Nominal Values and Ranges for the State Parameters that are used in the SCD for B&W 2772 MWt Plants

[

C,D

]

Table 3-4:
Nominal Values and Ranges for the State Parameters that are used in the SCD for B&W 2568 MWt Plants

[

C,D

]

Table 3-5: Uncertainty Parameters that are used in the SCD for B&W 2772 MWt Plants

[

C,D

]

Table 3-6: Uncertainty Parameters that are used in the SCD for B&W 2568 MWt Plants

[

C,D

]

C]

4. DNBR Protection in Statistical Core Design

4.1. Hot Pin Protection

In this section the RSM, the propagation models, and the uncertainties for propagation are used to find the SDL and coefficient of variation (C_V) for several typical and limiting core states. The maximum C_V (which results in the maximum hot pin SDL) is then used in the core-wide protection analysis of the next section.

4.1.1. Hot Pin Protection Model

A hot pin protection computer code, SDLHOT, was written to perform the work described in this section. SDLHOT propagates uncertainties on the core state variables (Q, W, P, T, and R) through an RSM to arrive at an SDL for 95 percent hot pin protection at the given input statepoint. In the analysis, each state variable has separate uncertainties with either a normal or uniform distribution. Additionally, separate DNBR uncertainties may be included. The statepoints are read from a disk file, after which Monte Carlo propagation of a user specified number of trials is performed. Each resulting DNBR is written to an output disk file for documentation and later analysis. Final statistics, statepoint information, and the resulting SDL are then reported.

For the current work, SDLHOT uses the RSM from Section 2.2.3, the state and DNBR uncertainties of section 3.2.2, and a [C] point Monte Carlo propagation. A source listing and verification of SDLHOT is contained in Appendix C.

4.1.2. Core States for Hot Pin Protection

Eleven limiting core states were run in SDLHOT. Further, the eleven core states were repeated. The states analyzed are summarized below. [C]

[

C

]

1.

[C

]

2.

[C

]

3.

[C

]

4.

[C

]

5.

[C

]

6.

[C

]

7.

[C]

8.

[C]

9.

[C]

10.

[C]

11.

[C]

4.1.3. Hot Pin Protection Results

The results of running the eleven core statepoints and five repeats through SDLHOT are summarized in Table 4-2. The results presented in the table were repeated five times to assure consistency with the distribution function generators. The limiting hot pin SDL was found to be [C] from Case 6. Next, the equations used to calculate the hot pin SDL in SDLHOT are described. The C_V (coefficient of variation) for Case 6 was [C]. The C_V is defined as the standard deviation of the DNBR deviates to the mean of the DNBR deviates. To transform the limiting statepoint C_V using the monte carlo sample of [C] to a hot pin C_V for core protection the Chi Square multiplier is used. The limiting statepoint is essentially a sample from the core protection population. The definition of Chi Square for this case is:

[

C

]

To transform the [C] C_V from the limiting statepoint to a core protection C_V the root of the ratio of the χ^2 to the degrees of freedom is used. Thus,

[

C

]

The hot pin SDL is then determined by

[

C

]

where $K_{95\%,95\%}$ is the one sided tolerance factor for 95 percent protection at the 95 percent confidence level.

The D-prime test for normality was performed on the DNBR distribution output file for the limiting state. The distribution was found to be normal at the 5 percent level. A histogram of the limiting core state DNBR distribution is shown in Figure 4-1.

4.2. Core-wide Protection

In this section the DNBR protection analysis is completed to verify the final SDL for application. A core protection model is developed, starting from the limiting hot pin C_V of section 4.1.3 (case 6), that calculates the applicable core protection SDL for various core radial peaking distribution states. The limiting core protection SDL then becomes the design SDL for application if it is higher than the hot pin SDL.

4.2.1. Core-wide Protection Model

The SDLCORE computer code was written to perform the core protection DNBR analysis. SDLCORE determines the SDL for the core based on a given core statepoint (Q, W, T, P, and R), radial peaking distribution, and C_V. The BWFC core protection criterion states that when the hottest pin in the core, analyzed under the limiting hot pin state, is at the SDL, no more than one tenth of one percent of the total pins in the core will be in DNB. Thus, any peaking distribution can be substituted for the single hot pin peak and the core analyzed for DNB protection using any given SDL until the criterion is met. SDLCORE starts with the hot pin SDL of section 2.1.3 and iterates on SDL, if necessary, until the protection criterion is met. A source listing of SDLCORE is given in Appendix D.

The main inputs to SDLCORE are the core state variables, the limiting (design) C_V, the number of fuel assemblies and pins in the core, and the core peaking distribution. The first three of these inputs are, for SDLCORE, deterministic. The core state variables that produced the limiting hot pin C_V are used with this C_V. The radial peaking distribution model is detailed below. The actual core peaking distributions are discussed in the next section.

The definition of core state for this analysis differs from the hot pin definition of core state only in the core peaking distribution. Core radial peaking distributions are calculated on a bundle basis at various times throughout each cycle. The bundle basis distributions must be translated into pin basis distributions for calculation of DNBR protection on a core-wide basis. This translation relies upon the hot pin radial peaking distribution of section 2.2.2.

The standard LYNXT model utilized an [C]

While acceptable for determination of a hot pin DNBR (or SDL), this model is unacceptable for a core-wide analysis. [C] This technique is slightly conservative in that the [C

] Table 4-1 shows the relative intrabundle peaking factors to be applied to each bundle.

4.2.2. Core States for Core-wide Protection

The limiting core radial power distribution for core DNBR protection cannot be determined explicitly. It must be determined by examination of the possible distributions that might occur. A characteristic limiting distribution would consist of several relatively high power bundles (with only a small decrease in power from the highest to lowest) rather than one very high power bundle (followed by a high falloff in peaking from bundle to bundle).

The typical "design peaking" distribution used for thermal-hydraulic analyses is a very highly peaked distribution chosen to minimize the hot pin DNBR value. This may not be limiting for core-wide protection, therefore, representative predicted peaking distributions for the core of interest are evaluated. For the purposes of this methodology description, six core peaking distributions from typical Mark-B cores were examined (cycle eight of Davis-Besse and cycle nine of Crystal River). They were the beginning of cycle (BOC), end of cycle (EOC), and the time-in-life that yielded the highest pin peak. The time-in-life that yielded the highest pin peak was termed MOC.

The peaking distributions thus examined are shown in eighth core symmetry form in Appendix E. The limiting distribution for corewide DNBR protection was found to be that of cycle eight of Davis-Besse, BOC. This limiting distribution is shown in Figure 4-2.

4.2.3. Core-wide Protection Results

The SDLCORE results for the six peaking distributions of the previous section are shown in Table 4-3. The limiting corewide SDL of [C] was found to occur for the distribution at the beginning of cycle (BOC) for Davis Besse Cycle 8. Two interesting observations arise from these results. First, the least limiting SDL occurs at initial startup (BOC of the fresh core). This initial peaking distribution is most like the usual "design peaking" distribution, and thus indicates a need to look at "real" peaking distributions. Second, the fact that the core-wide SDL is significantly less limiting than the hot pin SDL, indicates that the hot pin SDL can be used with a high level of confidence as a conservative means of meeting the corewide protection criterion. The hot pin SDL (1.237) is higher than the core-wide SDL [C]. Thus, the hot pin SDL is applied to the entire core.

Table 4-1: Generic Local Peaking Factors

[

C

]

Table 4-2: SDL Hot Pin Protection Results

[

c

]

Table 4-3: Corewide Protection Results

[

c

]

[C]

Figure 4-2: Assembly Peaking Factors for Limiting Corewide SDL

Peak Pin Power, Davis Besse Cycle 8, BOC

[

c

]

5. APPLICATION

This chapter outlines the application of the Statistical Core Design method for the DNBR protection of a specific core. The two basic steps in the application process are modification of the thermal-hydraulic analysis code inputs to be consistent with the SCD method and verification of the basis of the Statistical Design Limit to the specific core.

5.1. Thermal-Hydraulic Analysis Model for SCD

The LYNXT thermal-hydraulic computer code (Reference 1) is used in design analysis to determine the minimum core DNBR for all applicable core states. In traditional (Maximum Design) analyses, the statepoint inputs to the analysis code are chosen to be the most adverse possible values (within their given uncertainties) about the nominal statepoint. Thus, for a nominal inlet temperature of [C] degrees with an uncertainty of [C] degrees, the Maximum Design inlet temperature would be [C] degrees. This modification of the nominal statepoint is repeated for all applicable input variables, and results in a compounding of uncertainties. The resultant Maximum Design DNBR is then compared to the CHF correlation design limit to determine the DNBR margin.

The modification of the input model to the analysis code for SCD is simple and straightforward. Nominal values are input for all variables for which uncertainties have been treated statistically. Variables with untreated uncertainties are compounded as in the Maximum Design analyses. For variables with only partial treatment of uncertainties, the untreated part of the uncertainty is compounded. The minimum DNBR resulting from this input statepoint is then compared with the statistically derived SDL to determine the DNBR margin.

Next the specific changes to the LYNXT input deck are described. The usual procedure is to modify an input deck that was used for Maximum Design analysis so that it can be used for SCD analysis. The uncertainties described in Section 1.2.2 that are now included in the SDL are removed from the LYNXT input deck. The following are the modifications needed to change a Maximum Design LYNXT input deck to an SCD LYNXT input deck.

- The heat balance uncertainty is removed from the heat flux value (which is the input to LYNXT). [C]

- The mass flux is increased by the flow uncertainty and the core bypass uncertainty.

- The core pressure is increased by the pressurizer uncertainty.

- The inlet temperature is reduced by the temperature uncertainty.

- The radial peaking factor is reduced by the calculational uncertainty and the local/rod bundle spacing uncertainty. In addition, the rod power hot channel factors are set to 1.

An example of the application of SCD is shown in Figure 5-1. A thermal overpower statepoint was used in this example. First the case was run using Maximum Design analysis techniques (non-SCD). The minimum DNBR of [C] CHF design limit used in Maximum Design analysis. Next the thermal design statepoint LYNXT input deck is modified so that it can be used for SCD analysis. The modifications follow the description above. The minimum DNBR of [C] The [C] points margin can be broken down into retained margin and additional margin provided by SCD to increase operational flexibility. The retained margin can be used to cover penalties and offsets such as transition core penalties, rod bow penalties, flux depression at the grid, grid modifications, etc. The third case that was run is similar to the SCD case, except that the radial design peaking was increased. This is one use for the additional margin available with SCD. The additional margin was reduced from [C] points from the base SCD case to 4 points. This example shows one of the possible application benefits of using SCD methodology.

The thermal-hydraulic analysis code and CHF correlation should be consistent with those used in determination of the SDL. Thus, for application of the results of this report, the BWC CHF correlation must be used with either the LYNXT code or an equivalent.

A portion of the additional DNB margin may be retained by adding a given value to the SDL. The resulting (higher) limiting DNBR limit is the Thermal Design Limit (TDL). The retained margin represented by the TDL can be then used to offset effects not treated in the SDL development, such as transition core effects, or to provide flexibility in the fuel cycle design.

5.2. Core Specific Verification

The SDL determined in this work is based on the LYNXT thermal-hydraulic computer code, the BWC CHF correlation, the uncertainties detailed in section 3.2.2, and the core peaking distributions of section 4.2.2. For a specific application, each of these bases must be verified.

Verification of the codes and CHF correlation is not dependent on plant-specific parameters and is therefore provided generically. Verification of the uncertainties assumed for plant-specific parameters will be performed for each plant application.

The evaluation of core peaking indicates that the use of the hot pin SDL will be conservative for realistic power distributions. For plant-specific applications this applicability will be re-evaluated.

[C]

Appendix A: SAS Scripts used in the RSM Development and Analysis

SAS script RSM01.SAS: Read the data from the LYNXT runs

SAS script RSM02.SAS: Perform a stepwise regression to determine the optimal model

SAS script RSM08.SAS: Perform a residual analysis

Pages A-2 through 15 are totally proprietary (c).

Appendix B: SAS Scripts used in the SCD Experimental Design Development

SAS Script to Generate the Experimental Design Data

[

c

]

Appendix C: Hot Pin Protection Computer Program

This section discusses the hot pin protection programs.

[C]

Pages C-2 through C-17 are totally proprietary (c).

Appendix D: Core Protection Computer Program

This Appendix lists the source code for the corewide protection program SDLHOT.BAS. The computer program is described in Reference 2. The primary differences between the Reference 2 version of the program (Mark-BW) and the version listed in this appendix (Mark-B) are as follows.

Pages D-2 through D-6 are totally proprietary (c).

Appendix E: Corewide Bundle Peaking Distributions

This Appendix contains the core wide bundle peaking distributions used to calculate the core wide SDL. The following figures show the peak pin power, average assembly power, and peak to average power. The peak pin power is the value used in the SDLCORE.BAS program described in Appendix D.

Pages E-2 through E-7 are totally proprietary (c).

Appendix F: Exit Limited SCD Analysis

Introduction

In the Statistical Core Design (SCD) method for the B&W Designed 177 Fuel Assembly (FA) Plants discussed in the main body of this report, the Statistical Design Limit (SDL) did not vary significantly with axial power shape. In a February 9, 1993 letter to the NRC, BWFC acknowledged that the axial power peak and axial peak location are not well behaved variables. They were excluded from the Response Surface Model (RSM) for this reason. At that time BWFC had found that the SDL did not vary significantly with these variables. In work performed subsequent to that letter, BWFC has determined that, for some power shapes, the SDL does indeed show a sensitivity to axial power peak and peak location. For core conditions that result in a very limiting DNBR (low value) and where the minimum DNBR is located at or near the core exit, a higher SDL may be required.

This appendix discusses the application of Statistical Core Design methodology to the B&W designed 177 fuel assembly plants utilizing the Mark-B fuel assembly. It extends the analysis discussed in Sections 2-4 of this report to cases where the minimum DNBR is located at or near the core exit.
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In previous SCD analyses the sensitivity of axial power peak and axial power peak location on the Statistical Design Limit (SDL) was determined by including statepoints with different axial power shapes. For example, a sensitivity study in a previous analysis analyzed statepoints with axial power peaks of [C] A correlation between the axial power shape and the SDL was not observed. The SDL difference between the [C] axial power shape cases was very small, only about 1%.

Discussion

Sensitivity studies performed after the original analysis show that a sensitivity does exist between axial power shape and SDL under certain conditions. For cases that have a limiting DNBR (low value), the SDL is higher when the minimum DNBR is located at or very near the core exit. An additional sensitivity study was performed in which many LYNXT cases were run for a statepoint at an axial peak of [C] and for normalized axial peak locations of [C] (inlet peak) and [C] (outlet peak). The two cases were selected because an inlet axial peak of [C] yields a minimum DNBR at the core exit while an outlet axial peak of [C] yields a minimum DNBR well below the core exit. The sensitivities of the parameters were analyzed by running three LYNXT cases for each parameter. For example, three LYNXT cases were run at 110%, 112% and 114% of full power. The relative change in DNBR between the 114% power case and 110% power case was [C]% for the inlet peaked [C] case and 2.0% for the outlet peaked [C] case. Since the magnitude of the SDL is directly related to the change in DNBR as a function of a state variable, the SDL values will differ. Therefore, a study was performed to determine the maximum SDL for a wide range of axial power shapes (F_z, Z) that include cases where the minimum DNBR is located at or near the core exit and cases where the minimum DNBR is well below the core exit.

In order to calculate an SDL that is conservative for all axial power shapes, the methodology described in Sections 2, 3 and 4 was applied. For this analysis twelve sets of LYNXT cases were run and twelve Response Surface Models (RSM) were generated, one RSM for each axial power shape (F_z and Z combination). The values of axial power (F_z) analyzed were [C] The values of axial power location (Z) analyzed were [C]. An SDL was calculated for each of the twelve axial power and axial power location RSMs for the eleven statepoints shown in Chapter 4. Each of these cases was repeated five additional times to assure uniformity, totalling 792 SDL values. The limits ensure, at a 95% confidence level, that the limiting pin is protected against DNB and that similar protection is provided to all other pins on a core-wide basis. The limiting (maximum) hot pin SDL for all 792 values was [C]. The corewide SDL, calculated using the methodology from Chapter 4, is [C]. Therefore the bounding SDL for Mark-B applications is [C].

Additional retained margin can be added to the SDL to yield a Thermal Design Limit (TDL). The retained margin provided by the TDL can be used to offset effects not treated in the SDL development, such as transition core effects, or other cycle specific needs. For example, a [C] TDL provides a minimum of [C] DNB points (where 1 DNB point is 0.01) of retained margin. The relationship between the TDL and the corresponding SDLs is shown in Figure F1.

The reload safety evaluation for a particular core, including development of the cycle-specific core protective and operating limits, is based on preserving margin to the TDL. The TDL for a particular core design will be the sum of the applicable SDL and the degree of retained margin that is judged to be appropriate. The SDL that is used in generic analysis for a range of axial power distributions is [C] even though each axial power distribution has an SDL associated with it that is less than or equal to the [C] value. For particular analyses that do not have cases with the minimum DNBR at the core exit (for example, the [C] case used in Sections 2, 3, and 4), additional margin exists for the range of conditions in Tables 3-3 and 3-4. For conditions outside the range of applicability of the SDL, either a non-SCD analysis would be performed or a new SDL would be calculated using the methods presented in Sections 2-4 of this report and this Appendix.

Conclusion

Using the same methodology that resulted in the original SDL of [C], an analysis was done which expanded the range of axial power shapes. The resulting (maximum) SDL for Mark-B applications was found to be [C].

Figure F1:
Application of the Statistical Design Limit and Thermal Design Limit for Statistical Core Design