ANP-10269NP-A
Revision 0

The ACH-2 CHF Correlation for the U.S. EPR

Topical Report

by

D. A. Farnsworth

R. L. Harne

December 2007

AREVA NP Inc.

Non-Proprietary

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

December 5, 2007

Mr. Ronnie L. Gardner, Manager
AREVA NP
3315 Old Forrest Road
P.O. Box 10935
Lynchburg, VA 24506-0935

SUBJECT: FINAL SAFETY EVALUATION REPORT FOR ANP-10269P, "THE ACH-2 CHF CORRELLATION FOR U.S. EPR TOPICAL REPORT" (TAC NO. MD0026)

Dear Mr. Gardner:

By letter dated November 30, 2006 (NRC's ADAMS Accession Number ML063390039), as supplemented by letters dated May 29, 2007 (ML071500525), and August 15, 2007 (ML072620333), AREVA NP (AREVA) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review proprietary and non-proprietary versions of Topical Report (TR) ANP-10269, Revision 0, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report." By letter dated September 27, 2007, a draft safety evaluation (SE) regarding our approval of ANP-10269(P) was provided for your review and comments (ML072630042). The staff has received verbal comments from AREVA regarding proprietary information inadvertently included in the draft SE and typographical errors. We have corrected the typographical errors and removed the proprietary information in the final SE enclosed with letter. AREVA also informed us of the existence of typographical errors in Section 7.1.1 of the topical report and proposed to correct them in the approved version of the SE. The staff agrees with AREVA's proposal to correct the errors in the approved version of the TR.

The staff has found that ANP-10269(P), Revision 0 is acceptable for referencing in licensing applications for U.S. EPR to the extent specified and under the limitations delineated in the TR and in the enclosed SE. The SE defines the basis for acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in regulatory applications, our review will ensure that the material presented applies to the specific application involved. Regulatory applications that deviate from this TR will be subject to further review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that AREVA publish the accepted version of this TR within three months of receipt of this letter. The accepted version shall incorporate this letter and the enclosed SE after the title page. Also, the accepted version must contain historical review information, including NRC requests for additional information and your responses. The accepted versions shall include a "-A" (designating accepted) following the TR identification symbol.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, AREVA will be expected to revise the TR appropriately, or justify its continued applicability for subsequent referencing.

If you have any questions, please contact me at gxt2@nrc.gov or (301) 415-3361.

Sincerely,

Getachew Tesfaye, Sr. Project Manager
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Division of New Reactor Licensing
Office of New Reactors

Project No. 733

Enclosure: Final Safety Evaluation

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FINAL SAFETY EVALUATION BY THE OFFICE OF NEW REACTORS
ANP-10269P, REVISION 0, "THE ACH-2 CHF CORRELATION
FOR THE U.S. EVOLUTIONARY PRESSURIZED WATER REACTOR (EPR)
TOPICAL REPORT" (TAC NO. MD0026)
PROJECT NO. 733

1.0 INTRODUCTION AND BACKGROUND

By letter dated November 30, 2006 (NRC's ADAMS Accession Number ML063390039), as supplemented by letters dated May 29, 2007 (ML071500525), and August 15, 2007 (ML072620333), AREVA NP (AREVA) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review proprietary and non-proprietary versions of Topical Report (TR) ANP-10269, Revision 0, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report." AREVA requested that the NRC issue a safety evaluation report which approves the use of the correlation.

Topical Report ANP-10269P, Revision 0 (Reference 1) describes the development of a critical heat flux (CHF) correlation for the fuel geometry of the U.S. EPR fuel design. The fuel assembly for the AREVA's U.S. EPR will utilize high thermal performance (HTP) spacer grids. These grids provide lateral fuel rod support via a flow channel in the rod-to-rod gap. At the outlet (downstream edge) of the grid, the flow through these channels is diverted from the vertical to promote increased thermal mixing. AREVA has developed a CHF correlation specifically for the fuel geometry of the EPR fuel design. This correlation, known as ACH-2, is based solely on an EPR CHF database developed from CHF testing performed at AREVA's Karlstein Thermal Hydraulic Facility in Germany. The correlation was developed specifically for the EPR fuel design important variables of grid spacing, pin pitch, rod and guide tube diameter and heated length.

The functional form of the CHF correlation is empirical and is based solely on experimental observations of the relationship between the measured CHF and the correlation variables. The correlation includes the following variables: pressure, local mass velocity, local quality, axial elevation of CHF, standard BWU (Tong) F Factor, and guide tube outer diameter.

The NRC staff reviewed TR ANP-10269P, Revision 0 and its supplements (References 1, 2, and 3), and its evaluation and findings are documented below.

2.0 REGULATORY EVALUATION

Section 50.36 of Title 10 of the *Code of Federal Regulations* (10 CFR) requires that safety limits be included in the plant-specific technical specifications. Pursuant to 10 CFR Part 50, Appendix A, General Design Criterion (GDC) 10, "Reactor Design," the reactor core and associated coolant, control, and protective systems, are required to be

designed with an appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including anticipated operational occurrences. To ensure compliance with GDC 10, the NRC staff confirmed that the vendor performed the departure from nucleate boiling (DNB) analyses using NRC-approved methodologies as described in NUREG-0800, "Standard Review Plan," Section 4.4.

In addition, Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, Section 34, "Contents of applications; technical information, " requires that safety analysis reports for plant specific designs be submitted that analyze the design and performance of structures, systems, and components provided for the prevention of accidents and the mitigation of the consequences of accidents. As part of the core reload design process, licensees (or vendors) will perform plant specific reload safety evaluations to ensure that their safety analyses remain bounding for the design cycle. To confirm that the analyses remain bounding, licensees will confirm those key inputs to the safety analyses (such as the CHF) are conservative with respect to the initial, as built, design cycle. If key safety analysis parameters are not bounded, a re-analysis or a re-evaluation of the affected transients or accidents will be performed to ensure that the applicable acceptance criteria are satisfied.

The NRC staff's review was based on the evaluation of the technical merit of the submittal and compliance with any applicable regulations associated with reviews of TR and its supplements (Reference 1, 2, and 3).

3.0 TECHNICAL EVALUATION

In nuclear reactor cores, energy is generated by uranium dioxide (or plutonium) fuel pellets enclosed in fuel rods. The energy leaves the fuel rod surface in the form of heat flux, which is removed by the coolant system flow. The normal mode of heat transfer to the coolant at high power densities is nucleate boiling. Nucleate boiling is an efficient mode of heat transfer, with heat transfer coefficients about 50,000 Btu/hr-ft^2-F°. As the coolant temperature increases and its capacity to accept heat from the fuel rod surface and transfer it by bubble detachment to the coolant stream degrades, a continuous layer or film of steam starts to blanket the rod. The steam film insulates the rod and the heat transfer coefficient drops drastically to around 500 Btu/hr- ft^2-F°. This is because the heat transfer mechanism is film boiling, 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 during, film boiling. The heat flux at which the steam film starts to form is termed the CHF or the point of departure from DNB.

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. Therefore, the DNBR is a measure of the thermal margin to film boiling and its associated high temperatures. The greater the DNBR value, the greater the thermal margin. Because the phenomenon of CHF cannot be predicted from first principles, it is measured under laboratory conditions approximating those of a real reactor core. From these experimental measurements, a CHF correlation is developed. This correlation is essentially an empirical regression of the independent variables from the experiments. The method used for the correlation development by AREVA consists of several steps as described below.

The first step in the correlation process is to gather and to certify, as needed, the necessary CHF data. This involves determining the necessary geometric and thermal hydraulic ranges for testing.

The second step in developing a correlation is to establish the level or magnitude of each independent variable for each point of the database (each state point run in each of the tests). There are two classes of independent variables: local thermal hydraulic conditions (e.g., mass velocity and thermodynamic quality), and bundle global conditions (e.g., heated length and grid spacing). While the global values are known, the local conditions within the sub-channels must be calculated based on the measured bundle experimental values of flow, power and system pressure. This task is performed using a thermal-hydraulic computer code such as LYNXT (Reference 4).

The third step is to choose a correlation form that accurately describes the CHF phenomena for the available data (Reference 6). This includes choosing and justifying the independent variables.

The fourth step is to correlate the data, including sorting the data by flow regime and optimization of the correlation coefficients. A sequential optimization technique is normally used (Reference 5), with both a correlation and verification database.

The final step in developing a correlation is to calculate a 95/95 design limit (Reference 7) and to verify that the correlation describes the CHF phenomena accurately and without bias over its entire database. The verification process includes visual and numerical testing of all independent variables for bias.

The staff finds the method employed by AREVA for the correlation development acceptable.

3.1 DATABASE

Critical heat flux test data were taken at the AREVA's Karstein thermal hydraulic facility (KATHY). In the summer of 2006, the NRC staff observed the data collection at KATHY for the purpose of developing the ACH-2 CHF correlation for the U.S. EPR.

AREVA states that since the ACH-2 correlation is the first U.S. pressurized-water reactor application based on KATHY's data, it was necessary to demonstrate the acceptability, through qualification, of using the KATHY facility for PWR CHF data. This qualification was composed of a comparison of CHF performance measured in the KATHY facility and the Columbia University's heat transfer research facility (HTRF) for the same fuel design. AREVA's test geometry is provided in Reference 1. The test results indicate that there is no independent variable bias for either test over the entire test range, and confirms that KATHY CHF data is qualified for use in CHF correlation development. Reference 1 addresses the development and basis for the ACH-2 CHF correlation as a conservative predictor of the CHF performance of the EPR high thermal performance spacer grid. ACH-2 was developed from test data using distinct test geometries shown in Table 2.1 of Reference 1. This database includes data for heated lengths, unit cell and guide tube geometry and both cosine and uniform axial flux shapes.

AREVA indicated that the original EPR CHF test program was designed to produce a specific CHF correlation with applicability over and beyond the entire range of operating conditions of the U.S. EPR. Individual tests cover the local condition variables of pressure (P), mass velocity (G), and thermodynamic quality at CHF (X). Separate individual tests were also needed to establish geometry factors (unit cell and guide tube) and non-uniform AFS heat addition effects.

The non-uniform AFS data was limited to a heated specified length in Reference 1. Subsequent to the submittal of Reference 1, AREVA NP performed additional CHF testing for the length of the U.S. EPR design (14 ft) for the purpose of confirming the adequacy of the ACH-2 CHF correlation and its CHF design limit. The results and their applicability to the ACH-2 CHF correlation and departure from nucleate boiling ratio design limit (DNBRL) are evaluated by AREVA in Reference 2.

AREVA's original development of the ACH-2 CHF correlation (Reference 1) included several conservative provisions, one of which was a 0.05 increase in the application design limit. In order to remove the 0.05 application DL penalty, AREVA provided additional CHF test data (Reference 2) that confirmed the applicability of the ACH-2 CHF correlation for the U.S. EPR fuel.

Based on the NRC observation of the test data collection at KATHY, the staff finds that the CHF testing was conducted in an acceptable manner and in accordance with the test procedures. The staff agrees that the additional data provided by AREVA (Reference 2) justifies removal of the 0.05 increase in the application design limit.

3.2 SUITABILITY OF THE DATABASE

The staff reviewed all the test data points (Reference 2, Table S.5-2) that were used in the ACH-2 CHF correlation development and validation. The test data were grouped into several common groups for assessing the group statistics. A DNBRL value for each group is determined using both Owen (Reference 8) and Somerville (Reference 9) methods. Table S.5-2 (Reference 2) shows the statistics associated with various grouping of the CHF data, including the ACH-2 database from Reference 1.

Standard statistical tests were performed (References 1 and 2) to determine if all or selected data groups belong to the same population in order to be combined for the evaluation of the 95/95 DNBR tolerance limit. In addition, scatter plots were generated for each variable in the correlation to examine the correlation for trends or regions of non-conservatism. The Measured/Predicted CHF ratio was plotted as a function of the local mass velocity, the system pressure, the local quality, the axial location of CHF, and the non-uniform shape (Tong) F factor.

The NRC staff examined these plots and determined that no trends or regions of non-conservatism were evident, and determined that the results were typical.

3.3 CHF CORRELATION

AREVA NP has developed a CHF correlation specifically for the fuel geometry of the EPR fuel design. This correlation, known as ACH-2, is based solely on an EPR CHF database developed from CHF testing performed at AREVA's Karlstein Thermal Hydraulic Facility in Germany. The

correlation was developed specifically for the EPR fuel design important variables. Reference 1 describes the CHF correlation in terms of: standard BWU (Tong) F Factor, natural log of pressure, mass velocity, thermodynamic quality fraction at CHF, axial elevation of CHF, and guide tube outer diameter. The correlation coefficients were based on a subset of the total test data, referred to as the correlation database.

The NRC staff has reviewed the methodology and its application, and found that the methodology is acceptable. In addition, the staff has traveled to Germany to observe data collection at KATHY which it found to be acceptable. Therefore, the NRC staff finds there is reasonable assurance that the database used to develop the ACH-2 CHF correlations for U.S. EPR was based on quality data representative of the design and that the statistical treatment of the database was based on widely recognized statistical methods (Reference 7).

4.0 CONCLUSION

The NRC staff has reviewed the subject reports (References 1 and 2) and the responses to the NRC staff RAIs (Reference 3), and found that the justification for the database and the methodology used for the proposed ACH-2 CHF correlation for the U.S. EPR are acceptable because: 1) an acceptable methodology and DNBR design limits (Reference 7) are used, and 2) at a minimum a 95 percent probability with 95 percent confidence (95/95) exists that a departure from nucleate boiling will not occur.

The NRC staff has found that the ACH-2 CHF correlation for the U.S. EPR TR (Reference 1) and its supplement (Reference 2) are acceptable for referencing in licensing applications for EPR pressurized-water reactors with HTP spacer grid designs, to the extent specified and under the limitations delineated in the TR with a range of applicability given below. The staff's acceptance applies only to material provided in the subject TR and its supplements.

Fuel Design Limitations of the ACH-2 CHF Correlation:
The local conditions ranges and Fuel design limitations of the ACH-2 CHF correlation are as follows:

Local Conditions Ranges:
Pressure: 284 to 2565 psia
Mass Velocity: 0.945 to 3.164 Mlb/hr-ft ^{2}
Thermodynamic Quality at CHF: less than 37%

Fuel Design Limitations:
Spacer Grid Type: AREVA NP EPR HTP
Grid Spacing: 18.5 to 20.0 inches
Fuel Rod OD: 0.374 inches
Guide Tube OD: 0.490 inches
Fuel Rod Pitch: 0.496 inches

Application:
Code: LYNXT (Reference 4)
DNBRL: 1.25

5.0 REFERENCES

1. The ACH-2 CHF Correlation for the U.S. EPR Topical Report (ANP-10269P, Revision 0), dated November 2006 (AREVA Proprietary).

2. The ACH-2 CHF Correlation for the U. S. EPR Topical Report Supplement (ANP-10269P, Revision 0, Supplement), dated August 2007(AREVA Proprietary).

3. Letter from R. L. Gardner (AREVA) to NRC, dated May 29, 2007, Response to a Request for Additional Information Regarding ANP-10269P, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report" (TAC No. MD0026).

4. J. H. Jones, "LYNXT Core Transient Thermal Hydraulic Program," BAW-10156A, Rev. 01, August 1993.

5. D. A. Farnsworth, "Linearization and Sequential Optimization of Nonlinear Empirical Equations," Proceedings of the International Topical Meeting on Advances in Mathematics, Computations and Reactor Physics (Vol. 2), May 1991.

6. "USNRC Standard Review Plan," NUREG-0800.

7. "USNRC: Applying Statistics," Dan Lurie, February 1994.

8. D. B. Owen, "Factors for One-Sided Tolerance Limits and For Variables Sampling Plans," Sandia Corporation Monograph (SRC-607), March 1963.

9. Paul N. Somerville, "Tables for Obtaining Non-Parametric Tolerance Limits," Annals of Mathematical Statistics, Vol. 29, No. 2, pp. 599-601, June 1958.

Principal contributor: Fred M. Forsaty

Date: December 5, 2007

AREVA

November 30, 2006
NRC:06:053

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Request for Review and Approval of ANP-10269P, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report"

AREVA NP Inc. (AREVA NP) requests the NRC's review and approval of the enclosed topical report ANP-10269P Revision 0, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report." AREVA NP developed this CHF correlation specifically for the fuel geometry of the U.S. EPR fuel design. This topical report describes the correlation's development, database, and resulting application design limit and applicability ranges.

AREVA NP requests that the NRC issue a Safety Evaluation which approves the use of the correlation. AREVA NP plans to reference the approved version of the report in its Design Control Document for the U.S. EPR. Therefore, AREVA NP requests that the NRC complete its review of the topical report by November 2007.

AREVA NP considers some of the material contained in the topical report to be proprietary. As required by 10 CFR 2.390(b), an affidavit is enclosed to support the withholding of the information from public disclosure. Proprietary and non-proprietary versions of the topical report are provided on the enclosed CDs.

Ms. Sandra M. Sloan, Regulatory Affairs Manager for New Plants Deployment, remains the point of contact with the NRC for U.S. EPR licensing activities. She may be reached by telephone at 434-832-2369 or by e-mail at sandra.sloan@areva.com.

Sincerely,

Ronnie L. Gardner

Ronnie L. Gardner, Manager
Site Operations and Regulatory Affairs
AREVA NP Inc.

Enclosures

cc: L. Burkhart
G. Tesfaye
Project 733

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AFFIDAVIT

COMMONWEALTH OF VIRGINIA)
) ss.
CITY OF LYNCHBURG)

1. My name is Gayle F. Elliott. I am Manager, Product Licensing, for AREVA NP Inc. (AREVA NP) and as such I am authorized to execute this Affidavit.

2. I am familiar with the criteria applied by AREVA NP to determine whether certain AREVA NP information is proprietary. I am familiar with the policies established by AREVA NP to ensure the proper application of these criteria.

3. I am familiar with the AREVA NP topical report ANP-10269P, Revision 0, entitled "The ACH-2 CHF Correlation for the U.S. EPR," dated November 2006 and referred to herein as "Document." Information contained in this Document has been classified by AREVA NP as proprietary in accordance with the policies established by AREVA NP for the control and protection of proprietary and confidential information.

4. This Document contains information of a proprietary and confidential nature and is of the type customarily held in confidence by AREVA NP and not made available to the public. Based on my experience, I am aware that other companies regard information of the kind contained in this Document as proprietary and confidential.

5. This Document has been made available to the U S. Nuclear Regulatory Commission in confidence with the request that the information contained in this Document be withheld from public disclosure. The request for withholding of proprietary information is made in accordance with 10 CFR 2.390. The information for which

withholding from disclosure is requested qualifies under 10 CFR 2.390(a)(4) "Trade secrets and commercial or financial information".

6. The following criteria are customarily applied by AREVA NP to determine whether information should be classified as proprietary:

(a) The information reveals details of AREVA NP's research and development plans and programs or their results.

(b) Use of the information by a competitor would permit the competitor to significantly reduce its expenditures, in time or resources, to design, produce, or market a similar product or service.

(c) The information includes test data or analytical techniques concerning a process, methodology, or component, the application of which results in a competitive advantage for AREVA NP.

(d) The information reveals certain distinguishing aspects of a process, methodology, or component, the exclusive use of which provides a competitive advantage for AREVA NP in product optimization or marketability.

(e) The information is vital to a competitive advantage held by AREVA NP, would be helpful to competitors to AREVA NP, and would likely cause substantial harm to the competitive position of AREVA NP.

The information in the Document is considered proprietary for the reasons set forth in paragraphs 6(b), 6(c) and 6(d) above.

7. In accordance with AREVA NP's policies governing the protection and control of information, proprietary information contained in this Document have been made available, on a limited basis, to others outside AREVA NP only as required and under suitable agreement providing for nondisclosure and limited use of the information.

8. AREVA NP policy requires that proprietary information be kept in a secured file or area and distributed on a need-to-know basis.

9. The foregoing statements are true and correct to the best of my knowledge, information, and belief.

SUBSCRIBED before me on this 29th
day of November, 2006.

Danita R. Kidd
NOTARY PUBLIC, COMMONWEALTH OF VIRGINIA
MY COMMISSION EXPIRES: 12/31/08

nrc-ic-07-022

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

May 2, 2007

Ronnie L. Gardner, Manager
Site Operations and Regulatory Affairs
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SUBJECT: REQUEST FOR ADDITIONAL INFORMATION REGARDING ANP-10269P, "THE ACH-2 CHF CORRELATION FOR THE U.S. EPR TOPICAL REPORT," (TAC MD0026)

Dear Mr. Gardner:

By letter dated November 30, 2006 (ML063390039), AREVA NP submitted for U.S. Nuclear Regulatory Commission (NRC) staff review Topical Report ANP-10269P, Revision 0, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report" (ML063390043). The NRC staff has reviewed the application and has determined that additional information is required. Our request for additional information is contained in the enclosure to this letter.

A draft of the additional information requested was provided to you on April 9, 2007 (ML071140314), and discussed with your staff on April 17, 2007. Your staff has agreed that your response would be provided by June 1, 2007.

If you have any questions regarding this matter, I may be reached at 301-415-3361.

Sincerely,

Getachew Tesfaye, Project Manager
EPR Projects Branch 1
Division of New Reactor Licensing
Office of New Reactors

Project 733

Enclosure:
Request for Additional Information

cc w/encl: See next page

REQUEST FOR ADDITIONAL INFORMATION (RAI)

REGARDING ANP-10269P, "THE ACH-2 CHF CORRELATION

FOR THE U.S. EPR TOPICAL REPORT," (TAC MD0026)

PROJECT NUMBER 733

RAI 1. In Figure 6-6 (on Page 6-11), the measured dependent variable is plotted against the value predicted by the correlation. What percentage of these data points are specific to the U.S. EPR plant? Please provide Figure 6-6 with only the 14 foot fuel data base.

RAI 2. On page 7-3, you gave an example of the application of the ACH-2 CHF correlation to the statepoint conditions which you showed in Figure 7-1. Please explain how the DNBR value was calculated, and list all the uncertainties.

RAI 3. In Appendix A, you provided the raw bundle conditions test data for the U.S. EPR tests and the two tests supporting the facility qualification. What percentage of the data points are specific to the U.S. EPR plant? What would a CHF correlation look like if only the data base for the 14 foot fuel is used?

RAI 4. Please identify the range (pressure, mass flux, quality, fuel rod diameter, grid spacing guide tube diameter) where the CHF correlation is valid.

RAI 5. How would the CHF or the DNBR be referenced in the Technical Specifications and its bases?

RAI 6. How does the intended average core burnup impact the CHF and the DNBR?

RAI 7. Provide list of computer codes that AREVA is planning to use to calculate the CHF and DNBR.

Enclosure

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May 29, 2007
NRC:07:021

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Response to a Request for Additional Information Regarding ANP-10269P, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report" (TAC No. MD0026)

Ref. 1: Letter, Ronnie L. Gardner (AREVA NP Inc.) to Document Control Desk (NRC), "Request for Review and Approval of ANP-10269P, 'The ACH-2 CHF Correlation for the U.S. EPR Topical Report'," NRC: 06:053, November 30, 2006.

Ref. 2: Letter, Getachew Tesfaye (NRC) to Ronnie L. Gardner (AREVA NP Inc.), "Request for Additional Information Regarding ANP-10269P, 'The ACH-2 CHF Correlation for the U.S. EPR Topical Report,' (TAC No. MD0026)," May 2, 2007.

AREVA NP Inc. (AREVA NP) requested the NRC's review and approval of topical report ANP-10269P Revision 0 in Reference 1. A request for additional information (RAI) was provided by the NRC in Reference 2. The response to this RAI is provided in Attachment A enclosed with this letter.

AREVA NP considers some of the material contained in the enclosed document to be proprietary. As required by 10 CFR 2.390(b), an affidavit is enclosed to support the withholding of the information from public disclosure. Proprietary and non-proprietary versions of the attached are provided.

If you have any questions related to this submittal, please contact Ms. Sandra M. Sloan, Regulatory Affairs Manager for New Plants Deployment. She may be reached by telephone at 434-832-2369 or by e-mail at sandra.sloan@areva.com.

Sincerely,

Ronnie L. Gardner

Ronnie L. Gardner, Manager
Site Operations and Regulatory Affairs
AREVA NP Inc.

Enclosures

cc: L. J. Burkhart
G. Tesfaye
Project 733

AFFIDAVIT

COMMONWEALTH OF VIRGINIA)
) ss.
CITY OF LYNCHBURG)

1. My name is Gayle F. Elliott. I am Manager, Product Licensing, for AREVA NP Inc. (AREVA NP) and as such I am authorized to execute this Affidavit.

2. I am familiar with the criteria applied by AREVA NP to determine whether certain AREVA NP information is proprietary. I am familiar with the policies established by AREVA NP to ensure the proper application of these criteria.

3. I am familiar with the AREVA NP information contained in the Enclosure to Letter Number NRC:07:021, "Response to a Request for Additional Information Regarding ANP-10269P, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report," dated May 29, 2007 and referred to herein as "Document." Information contained in this Document has been classified by AREVA NP as proprietary in accordance with the policies established by AREVA NP for the control and protection of proprietary and confidential information.

4. This Document contains information of a proprietary and confidential nature and is of the type customarily held in confidence by AREVA NP and not made available to the public. Based on my experience, I am aware that other companies regard information of the kind contained in this Document as proprietary and confidential.

5. This Document has been made available to the U.S. Nuclear Regulatory Commission in confidence with the request that the information contained in this Document be withheld from public disclosure. The request for withholding of proprietary information is made in accordance with 10 CFR 2.390. The information for which withholding from disclosure is

requested qualifies under 10 CFR 2.390(a)(4) "Trade secrets and commercial or financial information."

6. The following criteria are customarily applied by AREVA NP to determine whether information should be classified as proprietary:

(a) The information reveals details of AREVA NP's research and development plans and programs or their results.

(b) Use of the information by a competitor would permit the competitor to significantly reduce its expenditures, in time or resources, to design, produce, or market a similar product or service.

(c) The information includes test data or analytical techniques concerning a process, methodology, or component, the application of which results in a competitive advantage for AREVA NP.

(d) The information reveals certain distinguishing aspects of a process, methodology, or component, the exclusive use of which provides a competitive advantage for AREVA NP in product optimization or marketability.

(e) The information is vital to a competitive advantage held by AREVA NP, would be helpful to competitors to AREVA NP, and would likely cause substantial harm to the competitive position of AREVA NP.

The information in the Document is considered proprietary for the reasons set forth in paragraphs 6(b) and 6(c) above.

7. In accordance with AREVA NP's policies governing the protection and control of information, proprietary information contained in this Document have been made available, on a limited basis, to others outside AREVA NP only as required and under suitable agreement providing for nondisclosure and limited use of the information.

8. AREVA NP policy requires that proprietary information be kept in a secured file or area and distributed on a need-to-know basis.

9. The foregoing statements are true and correct to the best of my knowledge, information, and belief.

SUBSCRIBED before me this 29th

day of May, 2007.

Sherry L. McFaden
NOTARY PUBLIC, COMMONWEALTH OF VIRGINIA
MY COMMISSION EXPIRES: 10/31/10

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION (RAI)

REGARDING ANP-10269P, "THE ACH-2 CHF CORRELATION

FOR THE U.S. EPR TOPICAL REPORT," (TAC MD0026)

PROJECT NUMBER 733

RAI 1: *In Figure 6-6 (on Page 6-11), the measured dependent variable is plotted against the value predicted by the correlation. What percentage of these data points are specific to the U.S. EPR plant. Please provide Figure 6-6 with only the 14 foot fuel data base.*

Response 1: Approximately **[ ]** percent of the ACH-2 data base is from the 14 foot tests (**[ ]** total data). The equivalent to Figure 6-6 with only the 14 foot data is shown in Figure 1.

Figure 1

Measured CHF versus Predicted CHF for the 14 Foot Data Only

[ ]

RAI 2: *On page 7-3, you gave an example of the application of the ACH-2 CHF correlation to the statepoint conditions which you showed in Figure 7-1. Please explain how the DNBR value was calculated, and list all the uncertainties.*

Response 2: For topical report Figure 7-1 a single LYNXT model was used to generate the local conditions of P, G and X versus elevation for a specific CHF test data point (25041.01). The LYNXT model simulated the CHF test geometry of a 5x5 array with a central guide tube.

The ACH-2 CHF correlation was used with these local conditions and the test bundle geometry to calculate the CHF (Q_{CHF}) at each elevation for each subchannel/heater rod combination. The DNBR at each axial position is the local Q_{CHF} divided by the actual heat flux (Q_{Actual}) at that elevation.

$$DNBR = Q_{CHF} / Q_{Actual}$$

Since the LYNXT model and predicted coolant conditions are a representation of an actual CHF test data point used in correlation development and since each statepoint in the test is forced to a detected CHF, the minimum DNBR is very close to 1.0. (A perfect correlation would result in a minimum DNBR of 1.0 for all of its CHF test data points, resulting in no scatter.) Another example of the calculated DNBR value is shown in Figure 2 for the limiting time during a loss of flow event. In this case, the minimum DNBR was computed to be 1.434 at an elevation of approximately 92% up the heated length of the fuel rod. The example shows the minimum DNBR to be greater than the 1.30 (Contingency) Design Limit using the ACH-2 correlation. The DNBR margin for this transient case is 13.4 DNB points, where 1 DNB point = 0.01.

Figure 2

[ ]

As to the uncertainties, every geometric and test variable has its own uncertainty. The CHF correlation development process captures the impact of these uncertainties in the Design Limit DNBR (DNBRL). Thus in Section 7.1 of the topical report the DNBRL is calculated with the overall uncertainty of the combined tests (the standard deviation of [ ] percent of the CHF value calculated by the correlation).

When the ACH-2 CHF correlation is applied in reload analyses with the LYNXT code to simulate the in-reactor conditions, the uncertainties associated with core power, core RCS flow rate, core bypass, radial peaking, hot channel factors, etc. are explicitly modeled to determine the local coolant conditions and the surface (actual) heat flux.

RAI 3: *In Appendix A, you provided the raw bundle conditions test data for the U.S. EPR tests and the two tests supporting the facility qualification. What percentage of the data points are specific to the U.S. EPR plant. What would a CHF correlation look like if only the data base for the 14 foot fuel is used.*

Response 3: In a general sense, all of the supplied CHF test data for the ACH-2 correlation are applicable to the U.S. EPR because the mixing grid and cross-sectional geometry are of the U.S. EPR design and only differ from this design in heated length. However, in a strict sense, the two 14 foot tests most accurately represent the U.S. EPR fuel design geometry.

A CHF correlation, based only on the 14 foot data, would differ somewhat from the ACH-2 form out of necessity. There would be, of course, [

]. Other than [ ] a 14 foot CHF correlation would be quite similar to the ACH-2 correlation. Its base form would be

[ ]

i.e. [ ] terms (of the equation on Page 5-1 of the topical report).

The coefficients would be different, from those of ACH-2, because they would be optimized on a different data base.

RAI 4: *Please identify the range (pressure, mass flux, quality, fuel rod diameter, grid spacing guide tube diameter) where the CHF correlation is valid.*

Response 4: On page 8-1 of the topical report, the ACH-2 correlation validity ranges for these parameters are included in the specified applicability ranges for Local Conditions, Fuel Design and Application.

Local Conditions

- Pressure: 284 to 2565 psia
- Mass Velocity: 0.945 to 3.164 Mlb/hr-ft^2
- Thermodynamic Quality at CHF: less than 37%

Fuel Design

- Spacer Grid Type: AREVA NP EPR HTP
- Grid Spacing: 18.5 to 20.0 inches
- Fuel Rod OD: 0.374 inches
- Guide Tube OD: 0.490 inches
- Fuel Rod Pitch: 0.496 inches

Application

- Code: LYNXT

RAI 5: *How would the CHF or the DNBR be referenced in the Technical Specifications and its bases?*

Response 5: In Section 2.0 of plant Technical Specifications, the CHF correlation, used for demonstrating acceptable core protection from departure from nucleate boiling, is defined as well as the CHF Design Limit for the correlation. In the case of the U.S. EPR plant Technical Specifications, the ACH-2 correlation would be identified along with the ACH-2 Correlation Design Limit of **[ ]** (if so approved by the NRC) and the ANP-10269(P)(A) topical report would be included in the list of approved topical reports for analysis application. The Technical Specification Bases would provide more details associated with the ACH-2 correlation that would be extracted from the topical report.

RAI 6: *How does the intended average core burnup impact the CHF and the DNBR?*

Response 6: The average core burnup does not impact the calculated CHF directly because it is not a variable in the ACH-2 correlation. However, in reload analysis application, the core and assembly burnup do affect the radial and axial power distributions (used to compute the Actual Heat Flux and local coolant conditions) in the core. Since the DNBR is the ratio of Calculated CHF to Actual Heat Flux, core and assembly burnup can indirectly affect the DNBR through its influence on radial and axial power distributions.

RAI 7: *Provide list of computer codes that AREVA is planning to use to calculate the CHF and DNBR.*

Response 7

BAW-10156P-A, Revision 1, *LYNXT Core Transient Thermal-Hydraulics Program*, August 1993.

End of RAI, additional information provided below.

AREVA has identified two typographical errors in the submitted topical report ANP-10269(P). Below are shown the corrections that will be included in the release of the NRC approved version of ANP-10269(P).

Correction 1: Page 2-3, table. The number of data for CHF test FCF40 should be shown as [ ].

Correction 2: Page 5-1, equation for the F-factor. A minus sign is missing from the exponent in the denominator. The equation should be as follows.

[ ]

AREVA

August 15, 2007
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Washington, D.C. 20555-0001

Supplement to ANP-10269P, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report" (TAC No. MD0026)

Ref. 1: Letter, Ronnie L. Gardner (AREVA NP Inc.) to Document Control Desk (NRC), "Request for Review and Approval of ANP-10269P, 'The ACH-2 CHF Correlation for the U.S. EPR Topical Report'," NRC: 06:053, November 30, 2006.

AREVA NP Inc. (AREVA NP) requested the NRC's review and approval of topical report ANP-10269P, "The ACH-2 CHF Correlation for the U.S. EPR Topical Report," in Reference 1. The development of this correlation included several conservative provisions, one of which was a 0.05 increase in the application Design Limit. This supplement provides additional critical heat flux (CHF) test data to confirm the applicability of the ACH-2 CHF correlation for the U.S. EPR fuel and to justify the removal of the 0.05 increase in the application Design Limit.

A proprietary and non-proprietary version of the Supplement to ANP-10269P entitled, "The CHF Testing and Analysis of a U.S. EPR 14 Foot Non-Uniform Axial Power Shape" are enclosed on CDs.

AREVA NP considers some of the material contained in the enclosed document to be proprietary. As required by 10 CFR 2.390(b), an affidavit is enclosed to support the withholding of the information from public disclosure.

If you have any questions related to this submittal, please contact Ms. Sandra M. Sloan, Regulatory Affairs Manager for New Plants Deployment. She may be reached by telephone at 434-832-2369 or by e-mail at sandra.sloan@areva.com.

Sincerely,

Ronnie L. Gardner

Ronnie L. Gardner, Manager
Site Operations and Corporate Regulatory Affairs
AREVA NP Inc.

Enclosures

cc: L. J. Burkhart
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2. I am familiar with the criteria applied by AREVA NP to determine whether certain AREVA NP information is proprietary. I am familiar with the policies established by AREVA NP to ensure the proper application of these criteria.

3. I am familiar with the AREVA NP proprietary information contained in ANP-10269P, Revision 0, Supplement, "The CHF Testing and Analysis of a U.S. EPR 14 Foot Non-Uniform Axial Power Shape," dated August 2007 and referred to herein as "Document." Information contained in this Document has been classified by AREVA NP as proprietary in accordance with the policies established by AREVA NP for the control and protection of proprietary and confidential information.

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8. AREVA NP policy requires that proprietary information be kept in a secured file or area and distributed on a need-to-know basis.

9. The foregoing statements are true and correct to the best of my knowledge, information, and belief.

SUBSCRIBED before me this 14th

day of August, 2007.

Sherry L. McFaden
NOTARY PUBLIC, COMMONWEALTH OF VIRGINIA
MY COMMISSION EXPIRES: 10/31/10
Reg. # 7079129

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OF
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NOTARY PUBLIC

AREVA

ANP-10269NP
Revision 0
Supplement

The ACH-2 CHF Correlation for the U.S. EPR
Topical Report Supplement

by

D. A. Farnsworth

R. L. Harne

The CHF Testing and Analysis of
a U.S. EPR 14 Foot Non-Uniform Axial Power Shape

August 2007

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ABSTRACT

The fuel assembly for the AREVA NP's U.S. Evolutionary Pressurized Water Reactor (EPR) will utilize High Thermal Performance (HTP) spacer grids. These grids provide lateral fuel rod support via a flow channel in the rod-to-rod gap. At the outlet (downstream edge) of the grid, the flow through these channels is diverted from the vertical to promote increased thermal mixing.

AREVA NP has developed a Critical Heat Flux (CHF) correlation specifically for the fuel geometry of the EPR fuel design. This correlation, known as ACH-2, is based solely on an EPR CHF database developed from CHF testing performed at AREVA's Karlstein Thermal Hydraulic Facility in Germany. The correlation was developed for the EPR fuel design's specific important variables of grid spacing, pin pitch, rod and guide tube diameter and heated length.

The development of the ACH-2 CHF correlation included several conservative provisions, one of which was a 0.05 increase in the application Design Limit. This supplement provides additional CHF test data to confirm the applicability of the ACH-2 CHF correlation for the U.S. EPR fuel and to justify the removal of the 0.05 increase in the application Design Limit.

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Nomenclature

Acronym	Definition
95/95	95% probability / 95% confidence
AFS	Axial Flux Shape
CHF	Critical Heat Flux
DNBRL	Departure from Nucleate Boiling Ratio Design Limit
G	Mass Velocity
HTP	High Thermal Performance
KATHY	KArlstein Thermal Hydraulic FacilitY
M/P	Measured to Predicted

S.1.0 INTRODUCTION

The development of the ACH-2 CHF correlation in ANP-10269P (Reference 1) included several conservative provisions, one of which was a 0.05 increase in the application Design Limit. This supplement provides additional CHF test data to confirm the applicability of the ACH-2 CHF correlation for the U.S. EPR fuel and to justify the removal of the 0.05 increase in the application Design Limit.

Reference 1 addresses the development and basis for the ACH-2 CHF correlation as a conservative predictor of the CHF performance of the EPR High Thermal Performance (HTP) spacer grid. ACH-2 was developed from test data using eight distinct test geometries as seen in Table 2.1 of Reference 1. This data base includes data for [ ], unit cell and guide tube geometry and both cosine and uniform axial flux shapes. The local conditions ranges and fuel design limitations of the ACH-2 CHF correlation are as follows:

Local Conditions Ranges:

Pressure: 284 to 2565 psia

Mass Velocity: 0.945 to 3.164 Mlb/hr-ft^2

Thermodynamic Quality at CHF: less than 37%

Fuel Design Limitations:

Spacer Grid Type: AREVA NP EPR HTP

Grid Spacing: 18.5 to 20.0 inches

Fuel Rod OD: 0.374 inches

Guide Tube OD: 0.490 inches

Fuel Rod Pitch: 0.496 inches

The non-uniform axial heat flux shape (AFS) data was [

] The Standard BWU (Tong) F Factor, defined in Section 5.1 of Reference 1, adjusts the ACH-2 CHF correlation for non-uniform axial heat addition. It was adapted directly from Reference 2 and is based on [ ] distinct flux shapes shown in Figure 4.1 of Reference 1. Subsequent to the submittal of Reference 1, AREVA NP performed additional CHF testing of a [

] for the length of the U.S. EPR design (14 ft) for the purpose of confirming the adequacy of the ACH-2 CHF correlation and its CHF design limit.

The 14 foot heater rods for [

].

The results of these additional tests were evaluated with the ACH-2 correlation. These results and their implications for the ACH-2 CHF correlation and departure from nucleate boiling ratio design limit (DNBRL) applicability are addressed in this supplement.

S.2.0 TEST SECTION GEOMETRY

In the additional CHF testing, the cross-sectional geometries for the [ ] were identical to the eight baseline tests as described in Section 3.2 of Reference 1. Both the [ ] axial flux shapes have maximum peaks of [ ] as shown in Figure S.2-1. The normalized lengths are shown in Figure S.2-2. The grid spacing is identical in each EPR HTP test section [ ]

Figure S.2-1: EPR [ ] Axial Flux Shapes

[ ]

Figure S.2-2: EPR [ ] Axial Flux Shapes

[ ]

S.3.0 ADDITIONAL DATA

The 14 foot non-uniform APS tests were performed at the AREVA Karlstein Thermal Hydraulic Facility (KATHY), as were the other EPR HTP CHF tests described in Reference 1. A standard test matrix was planned and executed for each 14 foot non-uniform APS test. [

]

The initial phase of the [

]

The bundle condition data for the 14 foot [ ] tests are provided in Table S.A-1. The results and local conditions for each individual test point are listed in Table S.A-2.

S.4.0 ANALYSIS AND RESULTS

The data from tests [ ] have been examined and compared to the predicted performance using the ACH-2 CHF correlation, defined in Section 5.0 of Reference 1. Table S.4-1 provides the ACH-2 CHF correlation performance for both tests.

Table S.4-1: ACH-2 CHF Correlation Performance for Additional CHF Tests

[ ]

Visual demonstrations of applicability of the 14 foot [ ] data are presented in bias plots (with trend lines included) in Figures S.4-1 through S.4-4 for pressure, mass velocity, thermodynamic quality at CHF, and axial elevation of CHF. Figure S.4-5 is a non-typical bias plot of measured to predicted (M/P) CHF versus the magnitude of the Standard BWU F Factor for each point. The absence of bias (as shown by the flat trend line) in Figure S.4-5 confirms that the originally chosen F Factor coefficients from Reference 2 are valid for the 14 foot [ ]. Finally, Figure S.4-6 shows the measured versus predicted heat flux with [ ] limit lines corresponding to the limit lines shown in Figure 6-6 of Reference 1. The 14 foot [ ] data supports the conclusion that the ACH-2 CHF correlation is conservative.

Figure S.4-1: Measured to Predicted CHF versus Pressure 14 Foot [ ] Data

[ ]

Figure S.4-2: Measured to Predicted CHF versus Mass Velocity 14 Foot [ ] Data

[ ]

Figure S.4-3: Measured to Predicted CHF versus Thermodynamic Quality 14 Foot [ ] Data

[ ]

Figure S.4-4: Measured to Predicted CHF versus Axial Location of CHF 14 Foot [ ] Data

[ ]

Figure S.4-5: Measured to Predicted CHF versus AREVA (Tong) F Factor 14 Foot [ ] Data

[ ]

Figure S.4-6: Measured CHF to Predicted CHF 14 Foot [ ] Data

[ ]

S.5.0 STATISTICS AND DNBRL VALUES FOR VARIOUS GROUPINGS

During the development of the ACH-2 CHF correlation, the final data base consisted of **[ ]** These outliers were highly conservative in M/P ratio. The uncorrelated data **[ ]**. In total, there were **[ ]** outliers within the final data base of Reference 1 and the two additional CHF tests. The outliers are shown in Table S.5-1.

Table S.5-1: Outliers Excluded from the Correlation Development and Performance Comparison

[ ]

After the exclusion of the **[ ]** outliers, a total of **[ ]** U.S. EPR HTP CHF data remain.

The data were grouped into several common groups for assessing the group statistics. A DNBRL value for each group is determined using both Owen (Reference 3) and Sommerville (Reference 4) methods in the same manner as used in Reference 1.

Owen DNBRL (assumes normal or near normal distribution)

In Owen theory the standard deviation of the M/P distribution is adjusted upwards to account for the number of degrees of freedom of the optimized correlation.

Where:

S = standard deviation of the M/P distribution

N = number of data in the correlation data base

nc = number of undetermined coefficients in the correlation

Ndf = N – 1 – nc

$$(S_{limit})^2 = (S)^2 * Ndf / (N-1)$$

Then:

$$DNBRL = 1 / (M/P - K_{95/95/N} * S_{limit})$$

Where:

K = the 95/95 one-sided Factor for one-sided Tolerance Limits.

Sommerville DNBRL (any distribution, no normality requirements)

DNBRL = Inverse of the Nth ranked M/P value.

Where N is determined by the table in Reference 4 and is dependent on the number of data in the group and the desired protection and confidence. Again, the 95/95 protection and confidence is used.

Table S.5-2 shows the statistics associated with various groupings of CHF data, including the ACH-2 data base from Reference 1. Note that none of the groupings have a DNBRL larger than the [ ] Sommerville DNBRL from Reference 1 for the ACH-2 data base.

Table S.5-2: Statistics and Design Limits for Various Groupings

S.6.0 DISCUSSION AND CONCLUSION

During the development of the ACH-2 CHF correlation and design limit for Reference 1, two major conservatisms were implemented. First, three CHF tests were conservatively omitted from the correlation optimization. As addressed in Section 4.4 of Reference 1, [

]

Subsequent testing showed that the 14 foot [

]

Although there is a technical basis for the [

], AREVA NP concludes it is acceptable to retain the present conservative ACH-2 CHF correlation coefficients. AREVA also concludes it is justifiable to remove the DNBRL conservative increase, [ ], and to restore the DNBRL to 1.25 as supported by the 14 foot non-uniform data. Additional support for the later conclusion is presented in Table S.5-2, where none of the resulting DNBRL values exceeds [ ], confirming the conclusion that the original 1.25 DNBRL in Reference 1 is valid. The measured CHF versus predicted CHF performance for the original [ ] data, shown in Figure 6-6 of Reference 1, are shown in Figure S.6-1 with the +/-25% limits.

Based on the evidence presented in this supplement, the ranges and limitations of the ACH-2 CHF correlation would be maintained from Reference 1 with the exception of the Design Limit which would be 1.25 as shown in Table S.6-1.

Table S.6-1: Ranges and Limitations of the ACH-2 CHF Correlation

Local Conditions:

- Pressure: 284 to 2565 psia
- Mass Velocity: 0.945 to 3.164 Mlb/hr-ft^2
- Thermodynamic Quality at CHF: less than 37%

Fuel Design:

- Spacer Grid Type: AREVA NP EPR HTP
- Grid Spacing: 18.5 to 20.0 inches
- Fuel Rod OD: 0.374 inches
- Guide Tube OD: 0.490 inches
- Fuel Rod Pitch: 0.496 inches

Application:

- Code: LYNXT
- DNBRL: 1.25

Figure S.6-1: Measured CHF versus Predicted CHF for ACH-2

[ ]

S.7.0 REFERENCES

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4. Paul N. Somerville, "Tables for Obtaining Non-Parametric Tolerance Limits," Annals of Mathematical Statistics, Vol. 29, No. 2, pp. 599-601, June 1958.

Appendix S.A

Bundle Conditions Data and Local Conditions Results with ACH-2 for the 14 Foot [ ] Tests

General Notes:

[ ]

Parameter Units

P - psia, G - Mlb/hr sq-ft, T - F, Zchf - inches, q" - Mbtu/hr sq-ft
Pm - Mpa, Gm - t/hr-m^2 , Tm - C, Zm - meters, qm" - Mw/hr-m^2

Table S.A-1: Bundle Conditions Data for the 14 Foot [ ] Tests

[ ]

Table S.A-1: Bundle Conditions Data for the 14 Foot [ ] Tests (cont'd)

Table S.A-1: Bundle Conditions Data for the 14 Foot [ ] Tests (cont'd)

[ ]

Table S.A-1: Bundle Conditions Data for the 14 Foot [ ] Tests (cont'd)

Table S.A-1: Bundle Conditions Data for the 14 Foot [ ] Tests (cont'd)

[ ]

Table S.A-2: Local Condition Results with ACH-2 for the 14 Foot [ ] Tests

Table S.A-2: Local Condition Results with ACH-2 for the 14 Foot [ ] Tests (cont'd)

Table S.A-2: Local Condition Results with ACH-2 for the 14 Foot [ ] Tests (cont'd)

Table S.A-2: Local Condition Results with ACH-2 for the 14 Foot [ ] Tests (cont'd)

Table S.A-2: Local Condition Results with ACH-2 for the 14 Foot [ ] Tests (cont'd)

[ ]

ANP-10269NP
Revision 0

The ACH-2 CHF Correlation for the U.S. EPR

Topical Report

by

D. A. Farnsworth

R. L. Harne

November 2006

AREVA NP Inc.

Non-Proprietary

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ABSTRACT

The fuel assembly for the AREVA NP's U.S. Evolutionary Pressurized Water Reactor (EPR) will utilize High Thermal Performance (HTP) spacer grids. These grids provide lateral fuel rod support via a flow channel in the rod-to-rod gap. At the outlet (downstream edge) of the grid, the flow through these channels is diverted from the vertical to promote increased thermal mixing.

AREVA NP has developed a CHF correlation specifically for the fuel geometry of the EPR fuel design. This correlation, known as ACH-2, is based solely on an EPR CHF database developed from CHF testing performed at AREVA's Karlstein Thermal Hydraulic Facility in Germany . The correlation was developed for the EPR fuel design's specific important variables of grid spacing, pin pitch, rod and guide tube diameter and heated length. This report describes the correlation's development, database, and resulting application design limit and applicability ranges.

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Nomenclature

Acronym	Definition
95/95	95% probability / 95% confidence
AFS	Axial Flux Shape
CHF	Critical Heat Flux
D_{GT}	Guide Tube Outer Diameter
DNB	Departure from Nucleate Boiling
DNBR	Departure from Nucleate Boiling Ratio
DNBRL	Departure from Nucleate Boiling Ratio Design Limit
EPR	Evolutionary Power Reactor
G	Mass Velocity
GT	Guide Tube
HMP	High Mechanical Performance
HTP	High Thermal Performance
HTRF	Heat Transfer Research Facility
ln (P)	Natural Log of Pressure, psia
KATHY	Karlstein Thermal Hydraulic Facility
M/P	Measured to Predicted
OD	Outer Diameter
P	Pressure
Q_{CHF}	Predicted Critical Heat Flux
Q_{actual}	Actual Heat Flux
TC	Thermocouple
UC	Unit Cell
X	Thermodynamic Quality at CHF
Z_{CHF}	Axial Elevation of CHF

1.0 INTRODUCTION

1.1 *Background*

In nuclear reactor cores, energy is generated by uranium dioxide fuel pellets enclosed in fuel rods. The energy leaves the fuel rod surface in the form of heat flux, which is removed by the coolant system flow. The normal mode of heat transfer to the coolant at high power densities is nucleate boiling. Nucleate boiling is an efficient mode of heat transfer, with heat transfer coefficients about 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 or film of steam starts to blanket the rod. The steam film insulates the rod and the heat transfer coefficient drops drastically to around 500 Btu/hr-ft^2-F. This is because the heat transfer mechanism is film boiling, 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 during, film boiling. The heat flux at which the steam film starts to form is termed the Critical Heat Flux (CHF) or the point of Departure from Nucleate Boiling (DNB).

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. Therefore, the DNBR is a measure of the thermal margin to film boiling and its associated high temperatures. The greater the DNBR value, the greater the thermal margin.

The CHF cannot be predicted from first principles, so it is empirically correlated as a function of the local thermal-hydraulic conditions, the geometry and the power distribution measured in experiments. CHF test data are typically obtained from experiments under steady state conditions. It is common practice, based on test evidence, to assume the CHF, during a transient situation, will be exceeded when the local instantaneous conditions are equivalent to those causing its occurrence under steady-state conditions as discussed in Reference 17. Because 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, consistent with the specified acceptable fuel design limit discussed in Reference 1. A calculated DNBR value greater than this design limit ensures that there is, at a minimum, a 95% probability with 95% confidence (95/95) that a departure from nucleate boiling will not occur.

AREVA NP has developed and continues to use numerous CHF correlations for its fuel assemblies. One of these correlations, the High Thermal Performance (HTP) correlation (Reference 2) was developed for the HTP spacer grid application and was based on the general geometry of the HTP spacer grid design across a range of geometric conditions. Although the EPR fuel design utilizes the HTP spacer grid design, the ACH-2 CHF correlation was developed specifically for the EPR fuel design's grid spacing, pin pitch, fuel rod diameter, guide tube diameter and heated length. This report describes the development and verification of the ACH-2 CHF correlation.

1.2 *Methodology*

Because the phenomenon of CHF cannot be predicted from first principles, it is measured under laboratory conditions approximating those of a real reactor core. From these experimental measurements, a CHF correlation is developed. This correlation is essentially an empirical regression of the independent variables from the experiments. The method used for the correlation development is discussed below and is consistent with the AREVA NP in-house guideline in Reference 3.

The first step in the correlation process is to gather and to certify, as needed, the necessary CHF data. This involves determining the necessary geometric and thermal-hydraulic ranges for testing.

The second step in developing a correlation is to establish the level or magnitude of each independent variable for each point of the data base (each statepoint run in each of the tests). There are two classes of independent variables: local thermal hydraulic conditions (e.g., mass velocity and thermodynamic quality), and bundle global

conditions (e.g., heated length and grid spacing). While the global values are known, the local conditions within the subchannels must be calculated based on the measured bundle experimental values of flow, power and system pressure. This task is performed using a thermal-hydraulic computer code such as LYNXT (Reference 7).

The third step is to choose a correlation form that accurately describes the CHF phenomena for the available data. This includes choosing and justifying the independent variables.

The fourth step is to correlate the data, including sorting the data by flow regime and optimization of the correlation coefficients. A sequential optimization technique is normally used (Reference 4), with both a correlation and verification data base (Reference 3).

The final step in developing a correlation is to calculate a 95/95 design limit (Reference 1) and to verify that the correlation describes the CHF phenomena accurately and without bias over its entire data base. The verification process includes visual and numerical testing of all independent variables for bias.

2.0 SOURCES OF DATA

The fuel assembly in AREVA NP's U.S. EPR will utilize HTP spacer grids. These grids provide lateral fuel rod support via a flow channel in the rod-to-rod gap (see Figure 2-1). At the outlet (downstream edge) of the grid, the flow through these channels is diverted from the vertical to promote increased thermal mixing in the adjacent subchannels.

This HTP spacer grid design is used in many domestic and foreign applications. The existing CHF correlation for these applications was based on a series of tests at the Columbia University Heat Transfer Research Facility (HTRF). These tests represented one-at-a-time proof tests for a specific HTP spacer grid geometry.

Because the overall design of the AREVA NP EPR fuel assembly was not specifically represented in the HTRF tests at Columbia University, AREVA NP embarked on a new HTP testing program specific to the AREVA NP EPR HTP grid and fuel assembly design. AREVA's facility in Karlstein was used for this testing program. The Karlstein facility is known as KATHY (KArlstein Thermal-Hydraulic FacilitY).

2.1 *Testing Facility*

The KATHY test facility is similar to the Columbia HTRF. The main difference is that KATHY utilizes a pressurizer for pressure control, and the HTRF utilized a feed and bleed design for pressure control. The KATHY loop is illustrated in Figure 2-2.

2.1.1 *Loop Characteristics*

The test vessel is designed to 2680 psia and 680 °F temperature and pressure limits. The 300 kW pressurizer has a volume of one cubic meter and a design pressure and temperature consistent with the test vessel. The circulation pump has a design pressure of 3050 psi and a design temperature of 698 °F. The circulation pump has a maximum pump head of 160 psi and a maximum volumetric flow of 634 gpm. The loop's electrical power supply has a maximum (gross) power of 15 MWe and a maximum current of 83 kA at 180 V DC. This DC power is achieved using four thyristor controlled rectifiers. KATHY has electro-hydraulic control valves with an opening and closing time of one second.

2.1.2 *Instrumentation*

The inlet temperature is measured at the test vessel inlet by two independent, calibrated temperature transducers. The outlet temperature is measured by three temperature transducers. The absolute system pressure is measured by two pressure transducers at the outlet of the test section (flow channel). The current is measured by four high precision fast response shunts. At least one heater rod is equipped with voltage taps across the heated length. As a backup, the voltage between the busbars is measured.

2.1.3 *Data Acquisition System*

The signals of the loop instrumentation to digital converter are sampled and stored on hard disk: 256 analog input and 32 digital input channels are available.

The sample rate per channel is 20 Hz. Four computers monitor the test. One computer controls the acquisition and data flow; the other three display and visualize selected channels, especially the thermocouples (TCs) during CHF tests. The evaluation software is used to transfer the measured values into physical values (e.g., pressure, temperature and mass flow).

2.2 *Qualification of the KATHY CHF Data*

Because the ACH-2 correlation will be the first U.S. PWR application based on KATHY data, it is necessary to demonstrate the acceptability, through qualification, of using the KATHY facility for PWR CHF data. This qualification is composed of a comparison of CHF performance measured in the KATHY facility and the Columbia University HTRF for the same fuel design.

[

] The HTRF test (performed in 1998) is designated as Test FCF40. The KATHY test (performed in 2004) is designated as Test K2100. The test section geometry for the qualification tests is provided in Table 3-2.

The measured test data (Appendix A) was reduced to local conditions (see Section 3.0). A simple quadratic surface fit with cross products in pressure, mass velocity and quality

at CHF was performed on the combined local condition data set. The individual results are shown in Appendix E.

The overall results on a measured-to-predicted (M/P) basis were:

[ ]

[A standard t test was performed on these results and showed a t statistic of 1.076. The critical t statistic at the .05 confidence level was 1.661] (Reference 5). This indicates there is no statistical difference in test results. Standard scatter plots of the independent variables in Figure 2-3, and Figure 2-4 and Figure 2-5 show that there is no independent variable bias for either test over the entire test range. These results confirm that KATHY CHF data is qualified for use in CHF correlation development.

2.3 *EPR Geometry*

The EPR fuel assembly has a 0.496 inch rod pitch, a 0.374 inch fuel rod diameter, a 0.490 inch guide tube diameter, and a heated length of 165.3 inches. The fuel design contains High Mechanical Performance (HMP) non-mixing end grids and eight intermediate HTP grids. The uppermost three spans between the HTP mixing grids have a pitch of 18.5 inches while the lower four spans have a 20.0 inch pitch. Figure 2-6 illustrates the HTP mixing design features.

2.4 *U.S. EPR CHF Test Program*

The original EPR CHF test program was designed to produce a specific CHF correlation with applicability over and beyond the entire range of operating conditions of the U.S. EPR. Individual tests cover the local condition variables of pressure (P), mass velocity (G), and thermodynamic quality at CHF (X). Separate individual tests were also needed to establish geometry factors (unit cell and guide tube) and non-uniform AFS heat addition effects.

A basic assumption, which required simple verification, was that there was no heated length effect. During the testing program, it was discovered that this assumption could not be demonstrated with a single test at a different heated length **[ ]** than the baseline tests **[ ]**. Consequently, three tests were added **[ ]**.

The U.S. EPR CHF test program is described below. The overall test geometry was:

- Pin Pitch: 0.496 inch
- Heater Rod Outer Diameter: 0.374 inch
- Guide Tube Outer Diameter: 0.490 inch
- Spacer Grid Pitch: **[ ]**
- Heated Length: **[ ]**

[ ]

The CHF test matrix supporting this report is shown in Table 2-1. The matrix of individual tests provides a total of nine, one at a time parameter changes:

[ ]

The range of local conditions of the [ ] test data points from eight geometries is:

[ ]

Table 2-1 Individual Tests in the U.S. EPR CHF Test Program

[ ]

Figure 2-1 U.S. EPR HTP Mixing Grid Design Features

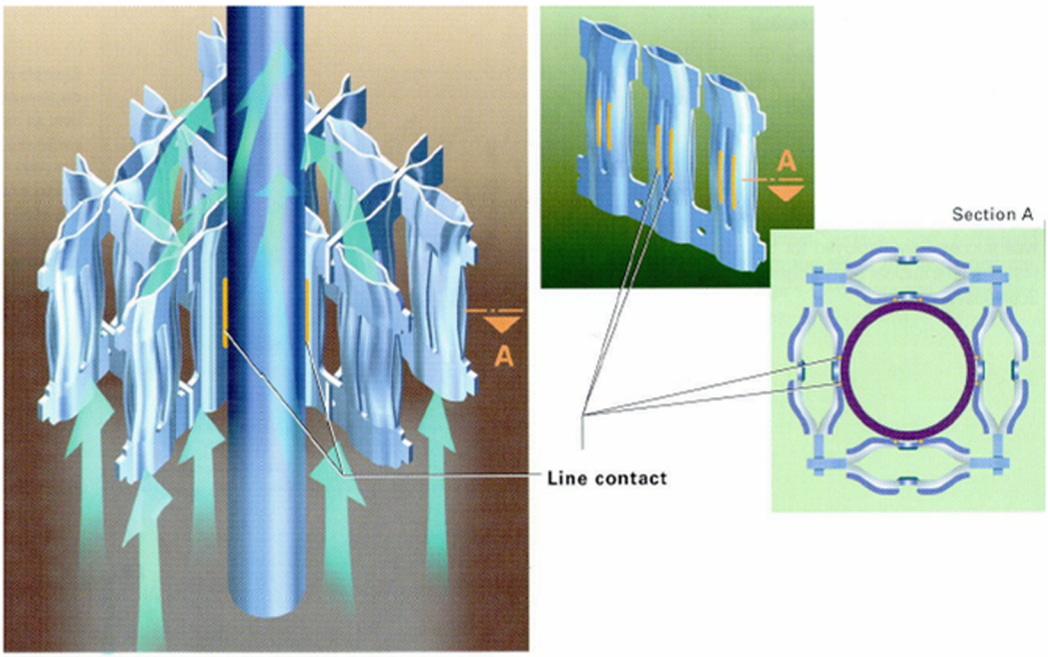


Figure 2-2 KATHY Heat Transfer Research Facility

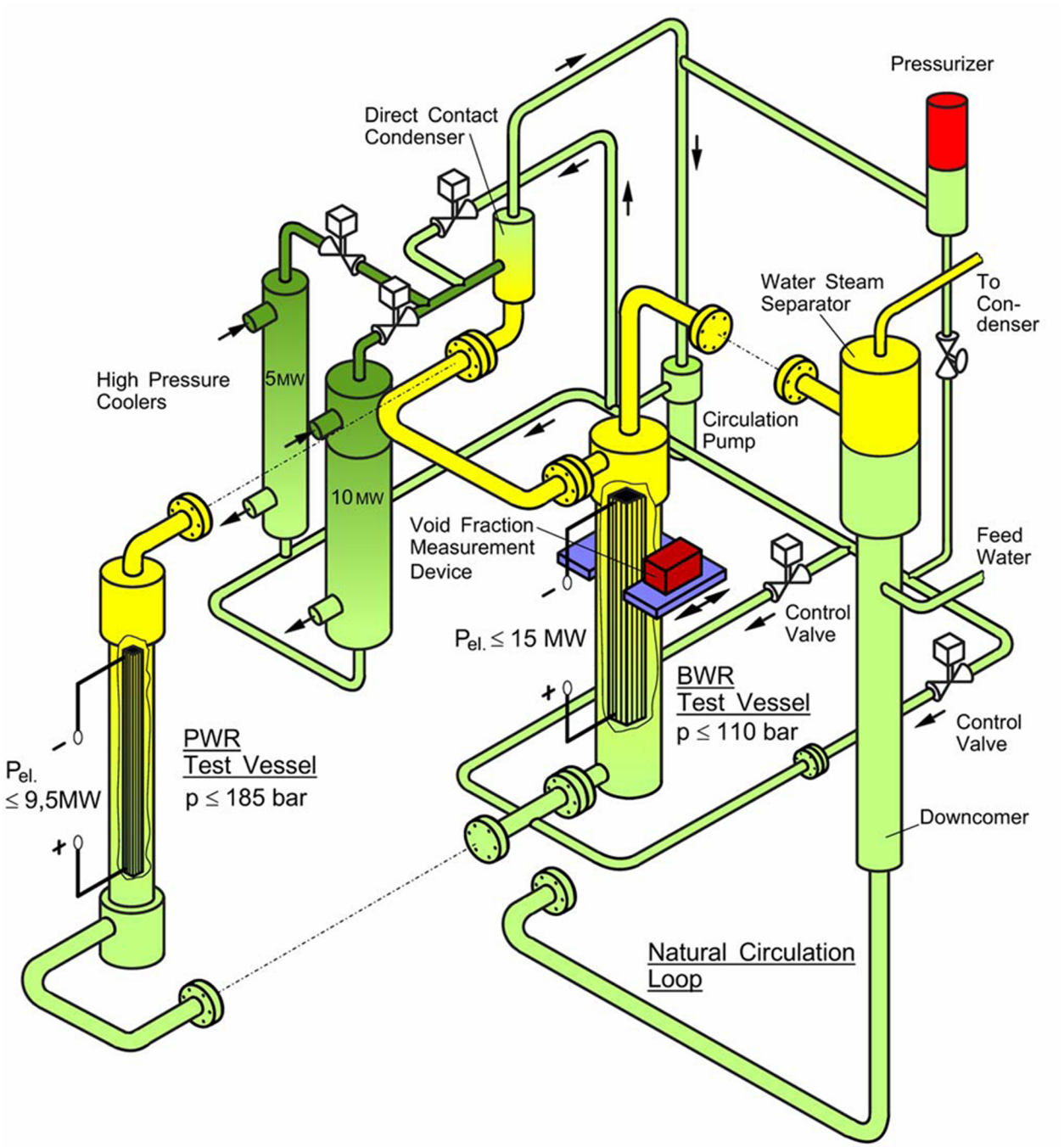


Figure 2-3 M/P CHF versus Mass Velocity for KATHY and Columbia AFA-2G Tests

[ ]

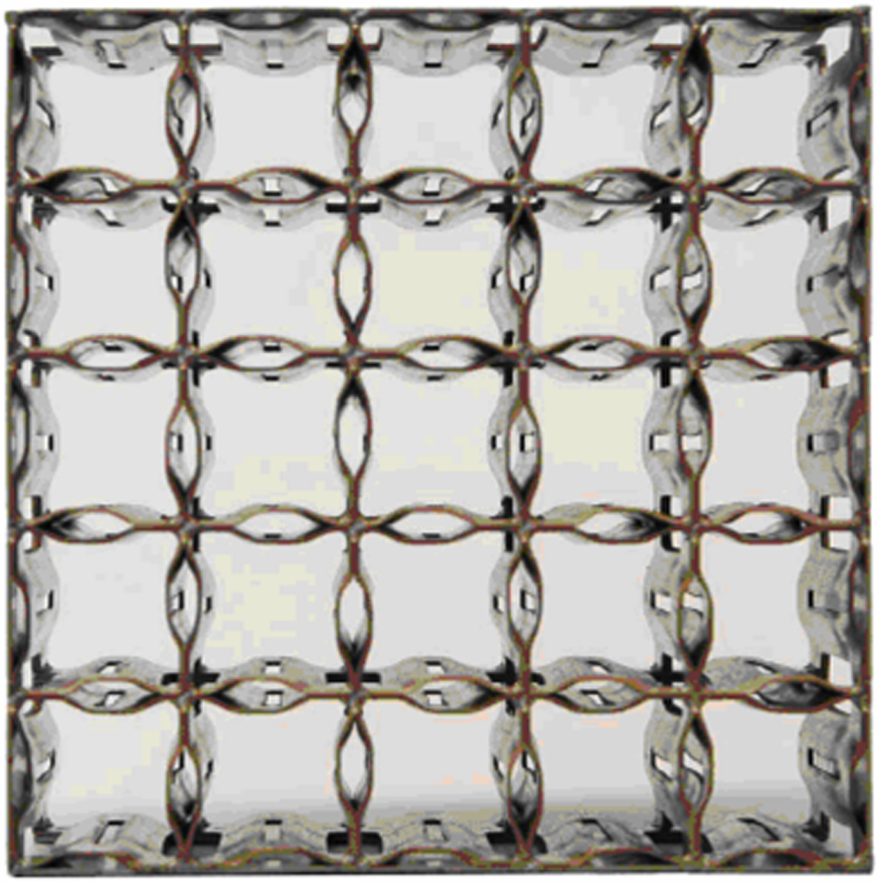
Figure 2-4 M/P CHF versus Pressure for KATHY and Columbia AFA-2G Tests

[ ]

Figure 2-5 M/P CHF versus Quality for KATHY and Columbia AFA-2G Tests

[ ]

Figure 2-6 U.S. EPR HTP CHF Test Grid (Unit Cell)



3.0 DATA ANALYSIS

3.1 *Local Condition Analysis*

In order to correlate CHF, the physical value of each independent variable must be established for every point of the data base (each statepoint run in each of the tests). There are two classes of independent variables:

1) the local thermal hydraulic conditions at the axial location of CHF (pressure “P”, mass velocity “G”, and thermodynamic quality “X”)
2) the bundle global conditions (e.g., heated length, pin pitch, rod diameter, and axial flux shape) that are necessary to model each test.

While the global conditions are known for each separate test geometry, the local conditions within the subchannels must be calculated based on the measured bundle experimental values of power, flow, inlet temperature and system pressure.

The local thermal hydraulic conditions for the correlation were determined using the LYNXT thermal hydraulic computer code (Reference 7). The use of the LYNXT code (an AREVA NP derivative of the COBRA code) required geometric modeling, which includes axial and radial heat input distributions, and input of the measured experimental bundle values of pressure, flow, power and inlet temperature. The resulting set of local and global conditions for each data point forms the data base from which to correlate CHF.

3.2 *Test Section Geometry*

All CHF tests were performed using a 5x5 rod array with a **[ ]** shroud. In all cases, the pin pitch was 0.496 inches and the heated rod diameter was 0.374 inches. The guide tube tests had an unheated 0.490 inch diameter ceramic rod as the center rod. The inner nine (eight for guide tube) heater rods were peaked **[ ]** above the remaining heater rods.

Table 3-1 shows the test geometries for the various CHF tests.

Figure 3-1 shows the cosine axial flux shapes used in EPR CHF tests K2300, K2301 and K2500, as well as the facility qualification tests K2100 (KATHY) and FCF40 (Columbia HTRF).

3.3 *Test Data*

The raw bundle conditions test data are provided in Appendix A for the U.S. EPR tests and the two tests supporting the facility qualification. The data consists of system pressure, inlet mass velocity, inlet temperature, bundle average heat flux values and axial location of primary burnout detection for each statepoint condition.

3.4 *Resulting Local Conditions*

The local conditions for individual test data have been evaluated with the LYNXT code and the ACH-2 CHF correlation and are shown along with the M/P results in Appendix B for the correlation data base, in Appendix C for the outliers and in Appendix D for the uncorrelated tests as defined in Section 6.0.

Table 3-1 Test Section Geometry U.S. EPR CHF Test Program

Table 3-2 Test Section Geometry for the Facility Qualification Tests

Figure 3-1 Axial Flux Factor versus Elevation U.S. EPR HTP and Columbia Rods

[ ]

4.0 CORRELATION FORM

4.1 *Independent Variables*

The first step in optimization of a CHF correlation is to identify the independent variables that determine the level of experimentally detected CHF. The pressure, mass velocity, and quality (P, G, X) local conditions are the primary independent variables in most CHF correlations. A modifier for non-uniform axial heat input is typically necessary (usually in the form of the Tong F factor) to yield an acceptable CHF correlation. Candidates that are considered for the other independent variables, usually geometric in nature, included grid spacing, length to CHF (or total heated length), and a cold wall term (e.g., guide tube diameter or wetted perimeter ratio).

The process for determining the form for the ACH-2 correlation considered various combinations of each of the possible independent variables.

[

]

The independent variables determined to be important in correlating the CHF capability of the U.S. EPR HTP spacer grid were found to be the local conditions of P, G and X and the geometric conditions of length to CHF (Z_{CHF}) and the guide tube outer diameter (D_{GT}).

4.2 *Correlation Form*

[

]

4.3 *The Tong F Factor*

The uniform CHF is usually modified for non-uniform axial heat input by use of a Tong F factor. In Reference 10, the coefficients of the Tong F factor were optimized for an AREVA NP mixing vane grid CHF correlation. These coefficients were confirmed as appropriate for additional AREVA NP CHF correlations in References 6 and 11. This optimization was based on the non-uniform heat addition effects of the BWU data base (six distinct axial flux shapes as shown in Figure 4-1). The BWU coefficients were used with the Tong F factor in the ACH-2 correlation.

4.4 *Tests for Optimization*

Numerous preliminary optimizations were performed to determine an appropriate and conservative data base for final optimization. The first observation was that the inclusion of the lower mass velocity data (~0.5Mlb/hr-ft^2), resulted in a less precise correlation. Because of this fact and that these mass velocities are well below the lower limit mass velocity needed for present core DNB analysis, they were excluded from the final data base for optimization.

[

]

The data base selected for optimization of the correlation included the following five tests:

[ ]

4.5 *Optimization and Verification*

[

]

Figure 4-1 Axial Flux Shape Basis for the Non-Uniform F Factor

[ ]

5.0 THE ACH-2 CHF CORRELATION

5.1 *The Correlation*

The uniform critical heat flux for the ACH-2 correlation is defined as

[ ]

where:

F = Standard BWU (Tong) F Factor
$Q_{uniform}$ = Predicted uniform CHF, MBtu/hr-ft^2
Q_{CHF} = Predicted CHF, MBtu/hr-ft^2
ln (P) = natural log of pressure, psia
G = mass velocity, Mlb/hr-ft^2
X = thermodynamic quality fraction at CHF
Z_{CHF} = axial elevation of CHF, inches
D_{GT}: guide tube outer diameter, inches

The critical heat flux is

$$Q_{CHF} = Q_{uniform} / F$$

where:

[ ]

and:

q''_{av} = rod average heat flux, Btu/hr-ft^2

$\phi(z)$ = local to average heat flux ratio

q''_l = local heat flux, Btu/hr-ft^2

z = axial location, inches

The coefficients of the correlation and their t ratios are shown in Table 5-1.

5.2 *Trends of the Correlation*

Figure 5-1, Figure 5-2, Figure 5-3 and Figure 5-4 show the trends of the correlation over wide ranges of four of the independent variables (G, X, ZCHF and P respectively). Figure 5-5 shows the property value relationship necessary for Figure 5-4.

Two observations apply to each of the trends. First, there are no discontinuities; second, the trends are in the expected direction. This second observation is discussed further.

In Figure 5-1 (Mass Velocity), the negative trend of CHF with increasing mass velocity at the lower pressures and higher qualities (specifically the P = **[ ]**, X = **[ ]**) shows that the ACH-2 correlation can correctly evaluate data in the inverse flow regime. In many previous correlations (References 2, 10, 11 and 12), data in the inverse flow regime would not correlate without a change of coefficients and were usually omitted from the correlation data base.

In Figure 5-2 (Quality), the rate of the decrease in CHF with increasing quality is dependent on the pressure-mass velocity region.

Although its significance increases with decreasing pressure and increasing quality, Figure 5-3 (Elevation) shows that Z_{CHF} is a relatively minor correlating variable. In Figure 5-4 (Pressure at Constant Enthalpy), it is observed that CHF always increases with pressure. Note that if the quality relationship with pressure at constant enthalpy shown in Figure 5-5 was not used, and quality was held constant with changing pressure, CHF would unrealistically decrease with increasing pressure in some regions.

However, it is not possible to change pressure and maintain a constant quality because the energy in the coolant, the enthalpy, does not change with a simple pressure change.

Table 5-1 Coefficients of the ACH-2 CHF Correlation

[ ]

F (Tong) Factor

[ ]

Cross products X3*X4, X3*X5 and X4*X5 were eliminated.

R^2 = 0.9293D+00, Xmtp = 0.9999D+00, Cmtp = 0.0934D+00

X1 = ln(P), natural log of Pressure, psia
X2 = G, mass velocity, Mlb/hr-ft^2
X3 = X, thermodynamic quality at CHF
X4 = Z_{CHF}, axial elevation of CHF, inches
X5 = D_{GT}, guide tube diameter, inches

Figure 5-1 Calculated CHF versus Mass Velocity

[ ]

Figure 5-2 Calculated CHF versus Quality

[ ]

Figure 5-3 Calculated CHF versus Elevation

[ ]

Figure 5-4 Calculated CHF versus Pressure

[ ]

Figure 5-5 Thermodynamic Quality versus Pressure (Constant Enthalpy)

[ ]

6.0 CORRELATION VERIFICATION

The statistics of the correlation are presented in Table 6-1 and Table 6-2 for various groupings (e.g., optimization, verification, and individual tests).

6.1 *Correlation and Verification Data Bases*

The results of a standard t test between the Optimization Group and the Verification Group substantiates that there is no statistical difference between these two data bases, **[ ]**, using Reference 5. Therefore, the groups were combined to form the Application Group.

6.2 *Individual and Grouped Results*

The low pressure data (less than 1000 psia) were added to the Application Group resulting in the Final Correlation Group.

The ACH-2 correlation was then applied to the three test geometries not used in correlation development (Uncorrelated Test Group – see discussion in Section 4.4, Tests for Optimization). The results are shown as a group in Table 6-1 and as individual tests in Table 6-2. The mean M/P CHF values of each of these groups are substantially greater than 1.0. These means verify that the correlation data base (with a mean of **[ ]**) is conservative and appropriate for EPR CHF application.

Examination of the CHF performance of the individual tests in the Application Group in Table 6-2 shows that the ACH-2 correlation is conservative for non-uniform heat addition (mean M/P CHF of **[ ]** for the K2300/K2301 cosine data) and that it is also slightly conservative for the **[ ]** tests (mean M/P CHF values of **[ ]** for K3100 and K3200 respectively).

Figure 6-1 shows the histogram of M/P CHF values for the ACH-2 CHF correlation. As seen by the overlay of the normal distribution (Reference 5), the distribution has a fairly high value of kurtosis (a higher number of data than expected very close to the mean), but otherwise is a good representation of the expected normality of results.

6.3 *Bias Tests for the ACH-2 CHF Correlation*

A requirement of any acceptable CHF correlation is that it does not exhibit any bias regarding the independent variables. That is, the M/P performance over the full range of its variables does not have a significant slope. There are two standard ways to test this requirement: visually through scatter plots, and mathematically by fitting a linear regression in M/P CHF versus the variable of interest.

Figure 6-2, Figure 6-3, Figure 6-4 and Figure 6-5 are scatter plots for the independent variables of pressure, mass velocity, quality at CHF and elevation of CHF, respectively. These figures illustrate that there is no significant bias or slope with any of these variables. These results are verified in Table 6-3, Table 6-4, Table 6-5 and Table 6-6 where the P, G, X, Z_{CHF} linear regression Correlation Coefficients (R^2) are **[ ]** respectively (i.e., all less than one percent correlated). An R^2 value near zero indicates that there is no significant correlation with that variable. A linear regression against the guide tube diameter variable, D_{GT}, as shown in Table 6-7, also confirms that no bias exists, with a R^2 value of **[ ]**.

In Figure 6-6, the measured dependent variable is plotted against the value predicted by the correlation. The data points are scattered along a 45 degree angle. This is verified in Table 6-8 where the correlation coefficient is **[ ]**. (In this case, an R^2 value of 1.00 would indicate perfect correlation.)

Table 6-1 ACH-2 CHF Correlation Performance by Correlation Group

(Individual Results for the various groups are shown in Appendix B and Appendix D)

Table 6-2 ACH-2 CHF Correlation Performance by Test Section

Figure 6-1 Histogram of M/P CHF Values

[ ]

Figure 6-2 M/P CHF versus Pressure

[ ]

Figure 6-3 M/P CHF versus Mass Velocity

[ ]

Figure 6-4 M/P CHF versus Quality at CHF

[ ]

Figure 6-5 M/P CHF versus CHF Elevation

[ ]

Figure 6-6 Measured CHF versus Predicted CHF

[ ]

7.0 DESIGN LIMITS AND SAMPLE APPLICATIONS

7.1 *Design Limit DNBR*

The design limit departure from nucleate boiling ratio (DNBRL) is normally calculated to protect 95 percent of the hot pins in the core with 95 percent confidence from departure from nucleate boiling, or CHF, as discussed in Reference 1. Depending on the M/P distribution and its statistics, either Owen (Reference 13) or Sommerville (Reference 14) one-sided tolerance theory is used to determine this DNBRL.

Because of the unique nature of the ACH-2 correlation and its data base, the DNBRL was calculated using both Owen and Sommerville. Using the larger of the two resulting DNBRL values, the protection levels (both in excess of the normal 95 percent level) were recalculated to estimate the additional measure of conservatism added to the ACH-2 CHF correlation.

7.1.1 *Owen*

In Owen theory (Reference 13), which applies to a normal distribution, the standard deviation of the M/P distribution is adjusted upwards to account for the number of degrees of freedom of the optimized correlation.

Where:

S = standard deviation of the M/P distribution

N = number of data in the correlation data base

nc = number of undetermined coefficients in the correlation

$Ndf = N - 1 - nc$

$(S_{limit})^2 = (S)^2 * (N-1) / Ndf$

Then,

$$DNBRL = 1 / (M/P - K_{95/95/N} * S_{limit})$$

[ ]

using Reference 13. Therefore,

DNBRL = **[ ]** (based on Owen).

7.1.2 *Sommerville*

Sommerville theory (Reference 14) applies to any non-parametric distribution (e.g., one which will not pass the standard D prime test, References 15 and 16, for normality). Here the limit is calculated by determining how far into the sorted list of M/P values a specified protection and confidence is located. This number of data is a function of the protection, confidence and number of data in the correlation. For the 95/95 criteria discussed above, the specified value is **[ ]**. Sorting the M/P distribution results in an M/P value of **[ ]**. Therefore,

DNBRL = **[ ]** (Sommerville).

7.2 *Contingency Design Limit*

The ACH-2 correlation has been shown to be conservative with the three test series not used in the Final Correlation Group data base. That is, their inclusion would have raised the actual level of predicted CHF. Additionally, AREVA NP has conservatively raised the design limit to:

DNBRL = 1.300 (applied to ACH-2 correlation)

The protection levels using both theories at the DNBRL value of 1.300 are:

- Sommerville, **[ ]**
- Owen, **[ ]**

Therefore, a protection level well above the normal 95 percent is achieved by the combination of the use of the 1.300 design limit and the conservative omission of the three tests whose inclusion would have raised the level of the ACH-2 CHF correlation.

7.3 *Sample Application*

An example of the application of the ACH-2 CHF correlation to the statepoint conditions for data point 25401 is shown in Figure 7-1. This figure shows all of the determining parameters for a typical CHF data point. The minimum DNBR is slightly higher than

1.0. For a perfect correlation, the minimum DNBR at the detected location of burnout would be exactly 1.0 every time.

Figure 7-1 Correlation Application Example

[ ]

8.0 SUMMARY AND CONCLUSIONS

The linear regressions and scatter plots of Section 6.0 verify that there is no statistically or visually significant bias in the ACH-2 correlation performance against any of its variables. The plots of dependent variable trends over a wide range of its independent variables (Section 5.0) demonstrate that the ACH-2 CHF correlation exhibits no discontinuities or unexplained physical results. Finally, a conservative Design Limit DNBR has been defined (Section 7.0).

The conclusion that the ACH-2 CHF correlation adequately and conservatively describes the CHF performance of the EPR HTP spacer grid and is appropriate for core DNBR safety analysis is supported by the evaluations.

The ranges and limitations of the ACH-2 CHF correlation are:

Local Conditions

- Pressure: 284 to 2565 psia
- Mass Velocity: 0.945 to 3.164 Mlb/hr-ft^2
- Thermodynamic Quality at CHF: less than 37%

Fuel Design

- Spacer Grid Type: AREVA NP EPR HTP
- Grid Spacing: 18.5 to 20.0 inches
- Fuel Rod OD: 0.374 inches
- Guide Tube OD: 0.490 inches
- Fuel Rod Pitch: 0.496 inches

Application

- Code: LYNXT
- DNBR Design Limit: 1.30

9.0 REFERENCES

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Appendix A

CHF Bundle Conditions Data

General Notes:

Parameter Units

P - psia, G - Mlb/hr-ft^2, T - F, Zchf - inches, q" - Mbtu/hr-ft^2
Pm - Mpa, Gm - t/hr-m^2 , Tm - C, Zm - meters, qm" - Mw/hr-m^2

ID	P	G	T	Zchf	q"	Pm	Gm	Tm	Zm	qm"

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

P - psia, G - Mlb/hr-sq ft, T - F, Zchf - inches, q” - Mbtu/hr-sq ft
Pm - Mpa, Gm - t/hr-sq m, Tm - C, Zm - meters, q” - Mw/hr-sq m

ID	P	G	T	Zchf	q”	Pm	Gm	Tm	Zm	qm”

ID	P	G	T	Zchf	q″	Pm	Gm	Tm	Zm	qm″

Appendix B

Local Condition Results for the ACH-2 Data Base

The data in this section are divided into three groups to support the analyses of Section 6 (Statistical Verification of the ACH-2 CHF Correlation):

- Correlation Group [ ]
- Verification Group]
- Low Pressure data [ ]

Correlation Group [ ]

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

Verification Group [(168 data)]

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

Low Pressure data [ ]

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

Appendix C

Local Condition Results for the ACH-2 Outliers

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

Appendix D
Local Condition Results with ACH-2 for the Uncorrelated Tests

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

ID	M/P	P	G	X	Zchf	Dgt	Qmeas	Qpred	F
		psia	Mlb/hr-f^2		inches	inches	MBtu/hr-ft^2		

Appendix E
Local Condition Results for the KATHY Qualification Tests

ID	M/P	Qmeas	P	G	X	Zchf	F	Hin
		Btu/hr-ft^2	psia	lbm/hr-f^2		inches		Btu/lbm

ID	M/P	Qmeas	P	G	X	Zchf	F	Hin
		Btu/hr-ft^2	psia	lbm/hr-f^2		inches		Btu/lbm

ID	M/P	Qmeas	P	G	X	Zchf	F	Hin
		Btu/hr-ft^2	psia	lbm/hr-f^2		inches		Btu/lbm

List of Changes for ANP-10269NP-A

Section	Page	Change Description
2.2	2-3	In table on page, Test FCF40, changed data from **[ ]** to **[ ]**
5.1	5-1	In second equation on page, added minus sign before K of the denominator
7.1.1	7-1	Changed $(S_{limit})^2 = (S)^2 * Ndf / (N-1)$ to $(N-1) / Ndf$ And Changed **[** **]**