ANP-10298NPA
Revision 0

ACE/ATRIUM 10XM Critical Power Correlation

March 2010

AREVA NP Inc.

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Revision 0
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Critical Power Correlation

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Revision 0

ACE/ATRIUM 10XM Critical Power Correlation

 ARC-10-10-011
received 3/22/10

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

March 11, 2010

Mr. Ronnie L. Gardner, Manager
Site Operations and Regulatory Affairs
AREVA NP Inc.
3315 Old Forest Road
Lynchburg, VA 24501

SUBJECT: FINAL SAFETY EVALUATION FOR AREVA NP, INC. TOPICAL REPORT ANP-10298P, REVISION 0, ACE/ATRIUM 10XM CRITICAL POWER CORRELATION (TAC NO. ME0344)

Dear Mr. Gardner:

By letter dated December 29, 2008, AREVA submitted Topical Report (TR) ANP-10298P, Revision 0, "ACE/ATRIUM 10XM Critical Power Correlation," to the U.S. Nuclear Regulatory Commission (NRC) staff. By letter dated December 23, 2009, an NRC draft safety evaluation (SE) regarding our approval of TR ANP-10298P, Revision 0, was provided for your review and comments. By letter dated January 8, 2010, AREVA commented on the draft SE. The NRC staff's disposition of AREVA comments on the draft SE are discussed in the attachment to the final SE enclosed with this letter.

The NRC staff has found that TR ANP-10298P, Revision 0, is acceptable for referencing in licensing applications for boiling water reactors to the extent specified and under the limitations delineated in the TR and in the enclosed final SE. The final 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 license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that AREVA publish accepted proprietary and non-proprietary versions of this TR within three months of receipt of this letter. The accepted versions shall incorporate this letter and the enclosed final SE after the title page. Also, they 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.

Document transmitted herewith contains sensitive unclassified information. When separated from enclosures, this document is decontrolled.

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

Sincerely,

Thomas B. Blount

Thomas B. Blount, Deputy Director
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 728

Enclosures:
1: Non-Proprietary Final SE
2: Proprietary Final SE

FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT ANP-10298P, REVISION 0

"ACE/ATRIUM 10XM CRITICAL POWER CORRELATION"

AREVA NP, INC.

PROJECT NO. 728

1.0 INTRODUCTION AND BACKGROUND

By letter dated December 29, 2008, AREVA NP, Inc. (AREVA) submitted to the U.S. Nuclear Regulatory Commission (NRC) a request for NRC approval of Topical Report (TR) ANP-10298P, Revision 0, "ACE/ATRIUM 10XM Critical Power Correlation." The TR describes a new correlation developed by AREVA to predict the critical power for boiling water reactors (BWRs). This correlation uses the same mechanistic model of dryout used in the ACE/ATRIUM 10 Critical Power Correlation which is currently used to evaluate critical power for BWRs containing ATRIUM-10 fuel.

TR ANP-10298P, Revision 0 (Reference 1), describes a new correlation developed by AREVA to predict the critical power for BWRs. The new correlation (ACE/ATRIUM 10XM) will be used to ensure that reactors using AREVA ACE/ATRIUM 10XM fuel remain within required safety limits during steady state operation and anticipated operational occurrences. The new correlation provides a mechanistic treatment for fluid conditions within the reactor fuel bundles and is expected to more accurately predict the critical power. Based on the NRC staff's initial review of TR ANP-10298P, Revision 0, and an audit conducted at AREVA's Richland Facility, the NRC staff issued a number of requests for additional information (RAIs). The RAIs and the AREVA responses are contained in References 3 and 4.

2.0 REGULATORY EVALUATION

In its review of TR ANP-10298P, Revision 0, the NRC staff utilized the guidance of Standard Review Plan (SRP) - 4.4, "Thermal and Hydraulic Design." SRP 4.4 implements the requirements of General Design Criterion (GDC) - 10 which is found in Appendix A, Section 50 of Title 10 of the *Code of Federal Regulations.* GDC-10 requires the following:

> The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits

are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.

The guidance from SRP 4.4 which is applicable to the review of TR ANP-10298P, Revision 0, is Acceptance Criterion 1.b, which states that for correlations used to predict critical power, the limiting (minimum) value should be established so that at least 99.9 percent of the fuel rods in the core will not be expected to experience departure from nucleate boiling or boiling transition during normal operation or anticipated operational occurrences.

3.0 TECHNICAL EVALUATION

The critical power for operation of a water cooled reactor is the power below which boiling transition will not occur. Boiling transition is defined as a sudden drop in heat transfer due to the change in boiling mechanisms and is indicated by a temperature excursion of the heated surface. It has been the practice of the NRC staff to associate the occurrence of boiling transition at the surface of the nuclear fuel with failure of the fuel at that location in the core.

The mechanism for the occurrence of boiling transition is dependant on the conditions within the coolant channel. In the low quality region, boiling transition is associated with heat flux very large in magnitude, such that the intense boiling causes steam bubbles to be crowded near the surface of the fuel. This bubble crowding prevents additional liquid from reaching the surface so that the fuel surface is blanketed with steam and heat transfer is markedly reduced. This type of boiling transition is generally associated with pressurized water reactors.

The second mechanism for the occurrence of boiling transition occurs in high quality regions and is generally associated with BWRs. At the upper elevations of the core during operation of a BWR, the flow pattern within the coolant channels is expected to be annular with a liquid film at the fuel surface and steam or a mixture of steam and liquid droplets within the interior of the channel. If the heat generation is sufficient to cause dryout of the liquid film or to cause entrainment of the liquid film into the droplet field, a sudden temperature increase associated with boiling transition will occur.

The ACE/ATRIUM 10XM critical power correlation predicts the channel power associated with dryout of the liquid film. The phenomena of entrainment of the liquid film into the droplet field, deposition of droplets into the liquid film and evaporation from the heated fuel surface are all treated in the model. The solution is obtained by integrating the conservation equations affecting the three fields (liquid film, droplets and vapor) starting from the core inlet. Thus axial power distributions are taken into account so that the axial location of dryout as well as the channel power which will produce dryout can be determined. Previous BWR critical power correlations including the Siemens Power Corporation B (SPCB) correlation evaluated average channel conditions using the average channel quality. In evaluating average channel conditions, the liquid film at the fuel surface can not be readily distinguished from the liquid in the droplet field. Such correlations are derived for a specific axial power shape and must be modified to predict the critical power for other axial power shapes. The location for dryout of the liquid film is not readily predicted by correlations based on average channel conditions.

Although the ACE/ATRIUM 10XM correlation follows the course of the three fields up a reactor core channel, the formulation remains a correlation since many of the phenomena are determined using empirical constants which are fit to channel dryout data. Phenomena which have been incorporated into ACE/ATRIUM 10XM using empirical constants include the effect of non-uniform azimuthal power for the rods of a fuel bundle, the affect of part length and water rods, and the effect of turbulent mixing downstream of the fuel element spacer grids.

3.1 ACE/ATRIUM 10XM Database

The ACE/ATRIUM 10XM database is comprised of a large number of steady-state data points taken on different test assemblies. The rod axial power shapes of the tests were peak-to-average chopped cosine and peak-to-average upskew and downskew power profiles. The database was compiled from tests performed exclusively at the AREVA thermal hydraulic test facility located in Karlstein, Germany (KATHY). The AREVA correlation development guideline, an AREVA internal document, was followed in the development of this correlation. In accordance with the criteria set forth in this procedure, the database was randomly divided into a defining data set (a data set used to develop the correlation), and a validation data set (a data set used to validate the correlation).

Transient tests were performed on an ACE/ATRIUM 10XM test assembly using three different power profiles and these were included as a part of the correlation validation set. The dryout tests were designed to cover the range of conditions present in an operating BWR fuel assembly. As a result, the database and correlation address the effects due to operating pressure, mass flow rate, inlet subcooling, axial power profile, and local peaking.

The ACE/ATRIUM 10XM critical power correlation has been used to predict the critical power for each steady state data point in the database. The experimental critical power ratio (ECPR) determined for each test point is used along with the standard deviation of the ECPR as the basis to determine the ability of the correlation to predict the onset of dryout. Comparison of the calculated to the measured critical power for the ACE/ATRIUM 10XM correlation is shown in Figure 2-1 of Reference 1.

The dryout test assemblies are constructed to model full size ACE/ATRIUM 10XM fuel. The assembly consists of heater rods that are directly heated by electric current which is passed through the rod surface. The thickness of the heater wall determines the power of the rod relative to other rods in the test assembly. Heater wall thicknesses are varied up the length of the rods so that axial power profiles may be modeled. Thermocouples are located on the highest powered rods at locations below the spacer grids where dryout is expected to occur.

The database for the ACE/ATRIUM 10XM fuel design contains data for coolant flow rates, inlet subcooling, and pressure variation. Different axial power shapes were evaluated. Part-length rods were included and were given the same power shape as full-length rods with the power shape truncated for the part-length rods.

3.1.1 Dryout Testing of the ACE/ATRIUM 10XM Fuel Bundle -- Comparison of Production Bundle to the Tested Bundle

For all critical power testing (by all vendors), the production assembly is simulated, using electrically heated rods in place of actual fuel rods. The part of the assembly that affects the critical power lies between the beginning of heated length and the end of heated length.

Within the heated length, the production assembly has an internal water canister. This component draws flow from the assembly inlet at a location below the heated length, and discharges its flow at a location above the end of heated length. From the perspective of critical power, the geometry of the assembly between the beginning and end of the heated length is reproduced in both spacers.

The spacers within the heated length of the test assembly preserve the characteristic rod to rod spacing that is essential to the critical power performance. The rod bearing surface of the supports used for holding the fuel rods in place in a production spacer may be shaped into a dimpled design or into a spring shaped design, as shown in Figure 9-1 of Reference 1. The production spacer uses a combination of support shapes in which approximately half of the supports are shaped into a spring design and half are shaped into a dimple design. The tested spacer in the KATHY test loop used supports in which the rod bearing surfaces were all shaped in a dimple design in order to withstand the strong magnetic forces arising from the large electric currents used in the heater rods. The modification in the tested spacer was necessary to prevent displacement resulting in non-conservative dryout performance of the peripheral fuel rods. These magnetic forces are not present in the actual core of a reactor.

The primary influence that the spacer has on the dryout performance is due to the mixing vanes. It has been the experience of AREVA and other vendors, that other spacer features, such as spacer strip thickness and weld nugget size, have no influence on critical heat flux (CHF) or critical power. Thus the influence of the rod supports is very minor in comparison to the swirl vanes. The critical power is not expected to be affected by the use of different types of rod supports provided the projected area of those supports is the same as that of the ones that were replaced. Since both support designs present exactly the same cross sectional area to the path of the flow in a rodded spacer, any influence they would have is expected to be equivalent. To confirm that the two rod support designs have no impact on the dryout performance, AREVA conducted an additional series of test in which a test spacer was carefully designed in which spring shaped supports were included at locations where the direction of the magnetic forces would not work to crush the springs and at locations where the magnetic forces would be minimal. The results of this test were then analyzed to see if there was any difference in the ability of the ACE/ATRIUM 10XM correlation to predict these results compared to the defining and validating data set tests.

The results of the test results are presented in Table 9-1 along with the ACE/ATRIUM 10XM (Reference 1) predictions. The results of the test indicate that the ACE/ATRIUM 10XM correlation predicts the measured results with a mean ECPR and a standard deviation entirely consistent with the predictions from the all dimple spacer tests as shown in Table 9-2. The comparisons of the ACE/ATRIUM 10XM production spacer predictions to the measured results were found to be indistinguishable from the results seen for the tested spacer.

To support the review process of this submittal, the NRC staff conducted an audit that focused on the analysis performed by AREVA to demonstrate the thermal hydraulic similarity between the "tested" spacer and the "production" spacer for the latest fuel design ACE/ATRIUM 10XM (Reference 5).

The purpose of this audit was to evaluate the multi-level analysis conducted by the vendor to demonstrate that the production spacer does not impact detrimentally the performance of the fuel and to confirm that the production spacer design does not affect dry-out. At the completion of the audit, the NRC staff concluded that AREVA had demonstrated qualitatively and quantitatively, via numerous calculations and computational fluid dynamics calculational simulations (Reference 3), that the minor difference between the two spacers does not impact dryout. The reason for this is that minor difference in the design to the production spacer is far away from the mixing vanes which are the main contributor to dry-out performance. The NRC staff agrees that this approach is acceptable.

3.2 ACE/ATRIUM 10XM Correlation

The single phase subcooled flow at the inlet of a BWR fuel assembly rapidly transitions through bubbly flow to annular flow. In the Minimum Critical Power Ratio limiting fuel assemblies, much of the active length of the fuel assembly is in annular flow. A liquid film on the rod and a steam-water mixture in the center region characterizes the annular flow regime. As the flow progressed upward, the water film changes. Evaporation, entrainment, and water droplets are deposited onto the liquid film. A rapid temperature excursion occurs when the cooling effectiveness of the liquid film is lost. The loss of this liquid film is variously termed dryout, boiling transition, and CHF.

The ACE/ATRIUM 10XM correlation, like its predecessor the ACE/ATRIUM-10 correlation (Reference 2), is a correlation based on a model of annular flow and dryout. The phenomena of entrainment, deposition, and evaporation are treated in the model. As applied to the BWR fuel assembly, the model also includes treatment of spacers and the effects of rod local radial peaking. A detailed step-by-step derivation of the ACE/ATRIUM 10XM critical power correlation form is provided in Reference 1, Appendix A.

3.2.1 Determination of Empirical Constants

The physical phenomena affecting dryout of the liquid film on a fuel rod surface are described in the ACE/ATRIUM 10XM methodology by equations containing a number of empirical constants. Similarly to the ATRIUM-10 correlation development, the ACE/ATRIUM 10XM contains 3 types of constants: non-linear constants, linear constants and additive constants. The NRC staff requested that AREVA provide additional information during the audit review (Reference 5), describing the methodology by which the empirical constants were determined. AREVA described the iterative process by which the correlation was fit to the defining data base.

The non-linear constants account for grid spacer heat transfer enhancement, onset of annular flow and entrainment of the liquid film. They were selected so as to provide the best result in following the trend of the data.

De-entrainment of droplets while in the annular flow regime is described in an equation using linear constants. These were determined using a linear least square best fit.

Additive constants are included with the rod assembly local peaking constants (K-factors) so that the predicted critical power will match the experimental critical power. An initial K-factor is determined for each rod from the local rod peaking pattern using methodology which the NRC staff previously reviewed and approved in Reference 2. The final K-factor which includes the additive constant is used to compute the critical power. The final additive constant for each rod is determined from and averaged over the set of peaking patterns for which that rod is limiting. The iteration is repeated until a convergent solution is obtained.

Based on the data from the defining data set, AREVA determined the standard deviation of ACE/ATRIUM 10XM in predicting fuel rod dryout. The standard deviation is used in

Monte Carlo evaluations to determine the safety limit. An acceptable safety limit is achieved when it is shown that at least 99.9 percent of the fuel rods in the core will not be expected to experience dryout during normal operation or anticipated operational occurrences. This is in accordance with the guidance from SRP-4.4 Acceptance Criterion 1.b. The NRC staff agrees that this approach is acceptable and conservative.

3.3 ACE/ATRIUM 10XM Defining and Validating Data Bases

3.3.1 Operational Range

The ACE/ATRIUM 10XM correlation can be used to accurately predict assembly critical power for the ACE/ATRIUM 10XM fuel design. The correlation provides an accurate prediction of the limiting rod. The impact of local spacer effects and assembly geometry on critical power is accounted for by two different sets of parameters. The first is a set of constants, one constant for each rod in the assembly, called additive constants. The second set of parameters provides for modeling of design specific to the ACE/ATRIUM 10XM within the critical power correlation. For comparison of correlation predictions to experimental data, an ECPR is defined as the ratio of the calculated critical power to the measured critical power. The ECPR distribution associated with ACE/ATRIUM 10XM is adequately represented with a normal distribution. The range of applicability of the ACE/ATRIUM 10XM correlation is provided below and in Table 2-1 of Reference 1.

TABLE 2-1 Range of Applicability

[

]

The ACE/ATRIUM 10XM database is comprised of a very large number of steady-state and some transient data points taken on numerous different test assemblies. The database was compiled data gathered for different power profiles from tests performed exclusively at the KATHY test facility.

The correlation development was based on AREVA's in house procedure guidelines. In accordance with the criteria set forth in this procedure, the database was randomly divided into a defining data set and a validation data set.

Approximately [ ] percent of the total database was set aside as the validating set of data. The remaining [ ] percent form the defining data set and were used to develop the critical power correlation. In addition, transient tests were performed on an ACE/ATRIUM 10XM test assembly using the above mentioned power profiles, and these were included as a part of the correlation validation set. In partitioning the data, AREVA placed the entire high inlet subcooling data points in the validating data set in order to test the accuracy of ACE/ATRIUM 10XM when extrapolated in subcooling regions. The correlation was shown to still be accurate when extrapolated. The data analysis showed that the critical power is linear with subcooling, therefore extension of the correlation a few degrees to zero subcooling is justified. The dryout tests were designed to cover the range of conditions present in an operating BWR fuel assembly. As a result, the database and correlation address the effects due to operating pressure, mass flow rate, inlet subcooling, axial power profile, and local peaking. The ACE/ATRIUM 10XM database is described in more detail in Section 4 of Reference 1.

3.3.2 ACE/ATRIUM 10XM Comparison to the Database

The ACE/ATRIUM 10XM critical power correlation has been used to predict the critical power for each steady state data point in the database. The ECPR determined for each test point is used along with the standard deviation of the ECPR as the basis for determining the ability of the correlation to predict the onset of dryout. Comparison of the calculated to the measured critical power for the ACE/ATRIUM -10XM is shown in Figure 2-1 of Reference 1.

The ACE/ATRIUM 10XM correlation statistics were reexamined using the validating data set. The standard deviation of the validating data set is slightly higher than the standard deviation of the defining data. Close agreement with the data is still shown. The accuracy of the correlation in predicting dryout elevation is slightly better for the validating data set than for the defining data set. Using both sets of data a combined standard deviation for the ACE/ATRIUM 10XM was determined which can be used in the Monte Carlo evaluations to determine the safety limit. The dryout elevation prediction feature, imbedded in both the ACE/ATRIUM-10 and the ACE/ATRIUM 10XM, is not used except to gain confidence that the correlation is correctly modeling the physical phenomena of fuel rod dryout.

3.3.3 Other Issues Arising out of the Audit Evaluation

The range of reactor core conditions for which AREVA proposes to utilize the ACE/ATRIUM 10XM correlation extend slightly outside the range of the tested data. The NRC staff discussed these extensions with the AREVA staff and requested justification for the extensions (Reference 2). The extensions involve a), the upper and lower limit for mass flow rate, b), the upper and lower limit for sub-cooling and c), the maximum rod local peaking limit. For the upper limit on mass flow rate and the upper limit on inlet sub-cooling the extension is very small and allows the ACE/ATRIUM 10XM correlation to be used within the range of data uncertainty. This is acceptable to the NRC staff. AREVA provided technical arguments in support of the position that to extend the ACE/ATRIUM 10XM to low flow rates is conservative, (Reference 1 and 2). The ACE/ATRIUM 10XM correlation was shown to predict a critical power approaching zero for very low flow rates.

AREVA pointed out in their December 2008 submittal that in the validation process, the correlation was shown to be accurate when extended in the direction of greater sub-cooling. The NRC staff agrees that the accuracy of the ACE/ATRIUM-10XM correlation has been shown to be relatively insensitive to inlet sub-cooling, so that the ACE/ATRIUM-10XM correlation may be extended to a saturated inlet condition.

AREVA also requested in the December 2008 submittal to extend the maximum range of local radial power peaking from [ ] to [ ]. The local radial power peaking of the rods is an input to the ACE/ATRIUM 10XM correlation formulation. Inaccuracies would appear as changes in the additive constant. AREVA demonstrated that for a range of power peaks, the changes in the additive constant were small and within the range of the additive constant uncertainty. The NRC staff, therefore, agrees that the ACE/ATRIUM 10XM correlation may be extended to a maximum local radial rod peaking of [ ].

3.3.4 Comparisons of the ACE/ATRIUM 10XM Correlation Calculations to Transient Critical Power Data

AREVA, in an effort to demonstrate the conservative aspect of the ACE/ATRIUM 10XM correlation critical power predictions, proceeded to subject the ACE/ATRIUM 10XM correlation simulation to two transients, load rejection and loss of flow events. Although applying steady-state critical power correlations to transients is considered conservative, (See RAI responses, References 3 and 4), the ACE/ATRIUM 10XM correlation is a best fit correlation and for a given steady-state condition shown to be in boiling transition by test, the correlation may under or over predict a boiling transition state within the range of defined uncertainties. Thus, during transient test conditions, dryout may not always be conservatively predicted, but well within defined uncertainties of the data.

Review of the results presented in Chapter 7 of Reference 1, shows that with the exception of four test points out of a large number of tests, the calculated time to boiling transition is less than or equal to the measured time to boiling transition. See Table 7-9 of Reference 1.

4.0 LIMITATIONS AND CONDITIONS

Based on the forgoing considerations, the NRC staff concludes that the use of ACE/ATRIUM 10XM as described in References 1 and 2 is acceptable for plant safety analyses provided that the following conditions are met:

1. Since ACE/ATRIUM-10XM was developed from test assemblies designed to simulate ACE/ATRIUM-10XM fuel, the methodology may only be used to perform evaluations for fuel of that type without further justification.

2. ACE/ATRIUM-10XM should not be used outside its range of applicability defined by the range of the test data from which it was developed and the additional justifications provided by AREVA in this submittal. This range is listed in Table 2.1 of Reference 1.

5.0 CONCLUSION

The NRC staff has found that ANP-10298P, Revision 0, is acceptable for referencing in licensing applications for boiling water reactors to the extent specified and under the limitations and conditions delineated in the TR and this safety evaluation (SE). This SE defines the basis for acceptance of the TR.

6.0 REFERENCES

1. ANP-10298P, "ACE/ATRIUM-10XM Critical Power Correlation," AREVA, December 29, 2008.

2. ANP-10249PA, Revision 0, "ACE/ATRIUM-10 Critical Power Correlation," AREVA, August 2007.

3. Response to a Request for Additional Information Regarding ANP-10298 (P), "ACE/ATRIUM 10XM Critical Power Correlation," NRC 09:089, August 18, 2009.

4. Response to a Request for Additional Information Regarding ANP-10298 (P), "ACE/ATRIUM 10XM Critical Power Correlation," NRC 09:097, September 16, 2009.

5. AREVA Audit Trip Report, May 10 - 15, 2009, ADAMS Accession No. ML0923705740.

Principle Contributor: A. Attard

Date:

RESOLUTION OF AREVA NP, INC. (AREVA)

COMMENTS ON DRAFT SAFETY EVALUATION FOR TOPICAL REPORT (TR)

ANP-10298P, REVISION 0

"ACE/ATRIUM 10XM CRITICAL POWER CORRELATION"

By letter dated January 8, 2010 (ADAMS Accession No. ML100120175), AREVA provided one (1) correction, to the draft safety evaluation (SE) for TR ANP-10298P, and four (4) notations of proprietary markings. The following is the NRC staff's resolution of these corrections and comments:

1. Page 1, Lines 25-27: Delete sentence: "The correlation described in the topical report ANP-10249PA continues to apply to ATRIUM-10 fuel." The correlation described in ANP-10298P applies to ATRIUM-10XM fuel, it does not replace the correlation described in ANP-10249PA. The removal of this incorrect sentence does not change the meaning of the paragraph.

   NRC Resolution for Comment 1 on Draft SE:

   The staff reviewed the AREVA recommendation and found it acceptable.

2. Page 6, Lines 26-27, 37-38; Page 8, Line 2; Page 8, Line 7: Noted as AREVA proprietary information.

   NRC Resolution for Comment 2 on Draft SE:

   The staff reviewed the AREVA recommendation and found it acceptable.

ATTACHMENT

AREVA

December 29, 2008
NRC:08:100

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

Request for Review and Approval of ANP-10298P, Revision 0, "ACE/ATRIUM 10XM Critical Power Correlation"

AREVA NP Inc. (AREVA NP) requests the NRC's review and approval for referencing in licensing action ANP-10298P, Revision 0, "ACE/ATRIUM 10XM Critical Power Correlation."

Proprietary and nonproprietary versions of the topical report are enclosed.

AREVA NP considers some of the material contained in the 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.

If you have any questions related to this submittal, please contact Mr. Alan B. Meginnis, Product Licensing Manager at 509-375-8266 or by e-mail at alan.meginnis@areva.com.

Sincerely,

Ronnie L. Gardner

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

Enclosure

cc: H.D. Cruz
Project 728

AREVA NP INC.
An AREVA and Siemens company

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rom: Holly Cruz [mailto:Holly.Cruz@nrc.gov]
nt: Tuesday, March 31, 2009 1:16 PM
: ELLIOTT Gayle F (AREVA NP INC)
Cc: KEHELEY Thomas H (AREVA NP INC); PRUITT Douglas W (AREVA NP INC); MEGINNIS Alan B (AREVA NP INC); Anthony Attard
Subject: Preliminary "Draft" RAIs for AREVA TR ANP-10298 ACE/ATRIUM 10XM

Good afternoon,

Please find the attached preliminary copy of RAIs for AREVA TR ANP-10298, ACE Critical Power Correlation for ATRIUM 10XM. Please note that as this is a draft copy, editorial changes may take place as the package circulates through our concurrence process. If you have any questions, please contact me at 301-415-1053.

Thanks for your help,

Holly Cruz, Project Manager
Special Projects Branch (PSPB)
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Phone: (301) 415-1053
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U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Request for Additional Information (RAIs) for the ACE/ATRIUM-10XM Correlation

Statistical Concerns

1. In the December 2008 submittal for the ACE/ATRIUM 10XM correlation, 2309 data points were collected for 24 different assemblies. These data points were taken to represent corner-to-corner coverage of the expected normal and transient operational space of the correlation. In chapter 9 of the same submittal, it is revealed that the actual spacer of the production assembly uses a combination spring/dimple rod bearing surface instead of a total dimple load bearing surface. To demonstrate that the spring/dimple spacer behaves consistently with that of total dimple design, additional tests were conducted. However, only sixty data points were taken. It is not clear to the staff as to how these 60 points can be considered representative of the normal and transient operational range of the correlation. Justify the use of 60 points as an experimental design to provided adequate corner- to-corner coverage of all applicable input parameters, as well as providing appropriate statistical basis for a sound correlation and additive constant uncertainties.

   In addition, in regulatory space, the staff has not regulated based on similarity. Test data from fuel type A cannot be used as a data base for fuel type B, regardless of the similarity.

2. Produce a correlation coefficient (Pearson) between in put variables and CPR in a format similar to the table below:

Input parameter	Production bundle (n = 60)	Tested bundle (n = 1845)
Exit pressure		
Inlet subcooling		
Inlet mass		
Power		

3. Reproduce Figure 6-1 through 6-6 and superimpose the 60 production bundles point or indicate where these 60 point would have fitted in.

4 Reproduce Table 6-1 and Tables 6-2 through 6-6 with the counterpart production bundle statistics given in parentheses.

5. Provide a statistical analysis showing that the average CPR for the production bundles(versus the tested bundles) is at least as good as that of the tested bundles. Show detailed calculation.

6. Provide statistics showing that the CPR uncertainty for the production bundles is no larger than that of the tested bundles.

7. Repeat the last comparisons (items 5 and 6) for each of the following mass flow application bins (binning is made by classification given in table 6-3): 0.175, 0.025, 0.050, 0.075, 0.100, 0.125, 0.150.

AREVA

June 11, 2009
NRC:09:066

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

Response to a Draft Request for Additional Information Regarding ANP-10298(P), "ACE/ATRIUM 10XM Critical Power Correlation"

Ref. 1: Letter, Ronnie L Gardner (AREVA NP Inc.) to Document Control Desk (NRC), Request for Review and Approval of ANP-10298P, Revision 0, "ACE/ATRIUM 10XM Critical Power Correlation", NRC: 08:100, December 29, 2008.

Ref. 2: Email, Holly C. Cruz (NRC) to Gayle F. Elliott (AREVA NP Inc.) "Preliminary 'Draft' RAIs for AREVA TR ANP-10298 ACE/ATRIUM 10XM," March 31, 2009.

AREVA NP Inc. (AREVA NP) requested the NRC's review and approval of the topical report ANP-10298(P) in Reference 1. The NRC provided a draft request for additional information (RAI) regarding this topical report in Reference 2. The response to questions 2 through 7 of this request are enclosed with this letter as an attachment. The response to question 1 will be submitted to the NRC following the QA review of the supporting calculations.

AREVA NP considers some of the material contained in the attachments 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 RAI responses are provided.

If you have any questions related to this submittal, please contact Mr. Alan B. Meginnis, Product Licensing Manager by telephone at 509-375-8266 or by e-mail at alan.meginnis@areva.com.

Sincerely,

Ronnie L. Gardner

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

Enclosures

cc: H. D. Cruz
R. Subbaratnam
Project 728

An AREVA and Siemens company

ANP-10298Q1NP

Revision 0

ACE/ATRIUM 10XM Critical Power Correlation – RAI's

June 2009

AREVA

ACE/ATRIUM 10XM
Critical Power Correlation – RAI's

Abstract

Responses to RAI questions 2 through 7 with regard to the ACE/ATRIUM 10XM Critical Power Correlation are provided by this document.

Nature of Changes

Item	Page	Description and Justification
1.	All	This is a new document.

Contents

This document contains a total of 41 pages.

Tables

Figures

Nomenclature

Acronym	Definition
CPR	Critical Power Ratio, defined to be the critical power divided by the power of the assembly.
ECPR	Experimental Critical Power Ratio, defined to be the ACE/ATRIUM 10XM calculated critical power divided by the experimentally measured critical power
RAI	Request for additional information

1.0 Introduction

This document provides responses to initial requests for additional information regarding the ACE/ATRIUM 10XM[1], AREVA NP Inc.[2] critical power correlation for the boiling water reactor ATRIUM 10XM fuel design.

[1] ATRIUM is a trademark of AREVA NP Inc. an AREVA and Siemens company registered in the United States and various other countries.

[2] AREVA NP Inc. is an AREVA and Siemens company.

2.0 RAI Question 1

In the December 2008 submittal for the ACE/ATRIUM 10XM correlation, 2309 data points were collected for 24 different assemblies. These data points were taken to represent corner-to-corner coverage of the expected normal and transient operational space of the correlation. In chapter 9 of the same submittal, it is revealed that the actual spacer of the production assembly uses a combination spring/dimple rod bearing surface instead of a total dimple load bearing surface. To demonstrate that the spring/dimple spacer behaves consistently with that of total dimple design, additional tests were conducted. However, only sixty data points were taken. It is not clear to the staff as to how these 60 points can be considered representative of the normal and transient operational range of the correlation. Justify the use of 60 points as an experimental design to provided adequate corner- to-corner coverage of all applicable input parameters, as well as providing appropriate statistical basis for a sound correlation and additive constant uncertainties.

Response:

The response to Question 1 is in preparation and will be submitted at a later date.

3.0 RAI Question 2

Produce a correlation coefficient (Pearson) between input variables and CPR in a format similar to the table below:

Input parameter	Production bundle [ ]	Tested bundle [ ]
Exit pressure		
Inlet subcooling		
Inlet mass		
Power		

Response

The Pearons Coefficients are shown in Q1-6-13. Because questions request information to be added to some of the existing tables, the Table numbering in Reference 1 is retained with a Q1 prefix. New tables will receive new sequential numbers. As shown in the Table, the Pearson Coefficients that are requested are consistent between the validation test STS 112 and the original test STS 109.1A as well as the remainder of the test body.

Table Q1-6-13 Pearson Coefficients

4.0 RAI Question 3

Reproduce Figure 6-1 through 6-6 and superimpose the 60 production bundle points or indicate where these 60 points would have fitted in.

Response

The Figures 6-1 through 6-6 are reproduced in Figures Q1-6-1 through Q1-6-6 and show the validation test data points superimposed on the correlation data base.

Figure Q1-6-1 Calculated vs Measured Critical Power (Defining and STS 112)

Figure Q1-6-2 ECPR as a Function of Mass Flow Rate (Defining and STS 112)

Figure Q1-6-3 ECPR as a Function of Pressure (Defining and STS 112)

Figure Q1-6-4 ECPR as a Function of Inlet Subcooling (Defining and STS 112)

Figure Q1-6-5 ECPR as a Function of Axial Power Shape (Defining and STS 112)

Figure Q1-6-6 ECPR as a Function of K-Factor (Defining and STS 112)

5.0 RAI Question 4

Reproduce Table 6-1 and Tables 6-2 through 6-6 with the counterpart production bundle statistics given in parentheses.

Response

The comparable statistics have been added as requested to the Reference 1 Tables.

Table Q1-6-1 Overall Statistics (Defining)

[redacted]

Table Q1-6-2 Higher Moments of ECPR Mean (Defining)

[redacted]

Table Q1-6-3 Statistics by Binned Mass Flow Rate (Defining)

Table Q1-6-4 Statistics by Binned Pressure (Defining)

Table Q1-6-5 Statistics by Binned Inlet Subcooling (Defining)

Table Q1-6-6 Statistics by Axial Power Shape (Defining)

6.0 RAI Question 5

Provide a statistical analysis showing that the average CPR for the production bundles (versus the tested bundles) is at least as good as that of the tested bundles. Show detailed calculation.

Response:

Statistical methods such as found in Reference 2 provide the characterization sought.

7.0 RAI Question 6

Provide statistics showing that the CPR uncertainty for the production bundles is no larger than that of the tested bundles.

Response:

Statistical methods such as found in Reference 2 provide the characterization sought.

8.0 RAI Question 7

Repeat the last comparisons (items 5 and 6) for each of the following mass flow application bins (binning is made by classification given in table 6-3): 0.0175, 0.025, 0.050, 0.075, 0.100, 0.125, 0.150.

Response:

Statistical methods such as found in Reference 2 provide the characterization sought.

9.0 Summary Table for RAI Questions 5, 6, and 7

Table Q1-6-14 Response Matrix for RAI Questions 5, 6, and 7

The conclusions affirm that the validation test behaves the same as the correlation tests.

10.0 References

1. ANP-10298P ACE/ATRIUM 10XM Critical Power Correlation, December 2008.

2. Experimental Statistics, Handbook 91, M.G. Natrella, 1966 printing, National Bureau of Standards, U.S. Government Printing Office.

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

July 9, 2009

Mr. Ronnie L. Gardner, Manager
Site Operations and Regulatory Affairs
AREVA NP, Inc.
3315 Old Forest Road
Lynchburg, VA 24501

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION RE: AREVA NP, INC. TOPICAL REPORT ANP-10298P, REVISION 0, "ACE/ATRIUM 10XM CRITICAL POWER CORRELATION." (TAC NO. ME0344)

Dear Mr. Gardner:

By letter dated December 29, 2008, (Agencywide Documents Access and Management System Accession No. ML090050026), AREVA NP, INC. (AREVA) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review Topical Report ANP-10298P, Revision 0, "ACE/ATRIUM 10XM Critical Power Correlation."

Upon review of the information provided, the NRC staff has determined that additional information is needed to complete the review and is included as enclosure to this letter. The NRC staff requests that AREVA provide the response within 30 days from the date of this letter.

If you have any questions regarding the enclosed request for additional information, please contact me at 301-415-1478.

Sincerely,

Ram Subbaratnam, Project Manager
Special Projects Branch
Division of Policy and Rulemaking
Office of Nuclear Reactor Regulation

Project No. 728

Enclosure:
RAI

OFFICE OF NUCLEAR REACTOR REGULATION

REQUEST FOR ADDITIONAL INFORMATION

TOPICAL REPORT-10298P

"ACE/ATRIUM 10XM CRITICAL POWER CORRELATION," REVISION 0

AREVA NP, INC.

PROJECT NO. 728

1. Figure 3-2 shows part-length rods (PLR) adjacent to the water hole. Were any PLR driven into dry-out? Could these rods be driven into dry-out during normal operation or transient events? Will they ever be located in a limiting location in a bundle?

2. The second paragraph on page 5-2 alludes to the importance of spacer location, spacer deposition enhancement factors, and spacer coefficient, on dry-out, assembly power, etc. Are all these parameters impacted by the spacer design?

3. Page 5-5, following equation 5.5, it is stated that the parameter, L_s, is now a variable in the ATRIUM 10XM design. Provide additional information regarding this parameter. i.e., is the variability of this parameter utilized to obtain optimum spacer separation?

4. Table 6-8 on page 6-18 has columns that need further clarification. Please be prepared to elaborate. For example, there are wide variations between the values for the ATRIUM-10XM and the ATRIUM 10. In addition, the paragraph below the Table on the same page, states that these parameters are generally smaller for the ATRIUM-10XM than they are for the ATRIUM 10 design, but no explanation is given as to why. Please explain.

5. Figures 5-12 through 5-15 address the chopped cosine power profile. Are there similar plots for other power profiles?

6. Page 7-17, Section 7.5 addresses the issue of "Inlet-sub-coolant" bounds. In this section, reference is made to the inclusion inlet sub-coolant data and to the reference of exclusion of data. Please be prepared to discuss and provide additional clarification to this section on a qualitative and quantitative technical basis.

7. Page 7-18, the first paragraph in this section states that, it is an accepted industry standard in Boiling Water Reactor (BWR) transient methodology that steady-state developed dry-out correlations are conservative when predicting transient behavior. Please provide reference(s) to this end.

8. Page 7-19, section 7.5, the second paragraph from the bottom alludes to the prediction of boiling transition by the ACE/ATRIUM-10XM correlation. The paragraph also alludes

ENCLOSURE

to the same correlation under and over predicting the boiling transition state within the range of "defined uncertainties". What are these ranges of defined uncertainties? How are they defined? Why are they defined as such?

9. Page 8-1, the last paragraph addresses axial power profiles tested. Has the AREVA staff investigated double-hump power profile prediction with the ACE/ATRIUM-10XM correlation?

<u>Statistical Concerns</u>

1. Page 2-3, Table 2-1: Range of Applicability, the ranges of the parameters are lower than those presented in Table 4-2 for the development range. Please explain.

2. Page 6-2, Figure 6-1 (repeated Page 2-3, Figure 2-1). The prediction becomes less precise at higher critical power. Explain and show boundaries of this prediction. Also, what are the characteristics of the 4 (or 5) points at the very top of the chart (critical power about 15)?

3. Page 6-26, claims that "no trend is observed" for Figure 6-2. Yet, in almost every individual test (pages 6-27 through 6-37) there is a hint of a pattern.

    a. Provide technical justification for the various trends in these series of plots.

    b. Is it possible that combining the tests camouflages such trends?

    c. Also, provide similar plots for pressure and inlet sub-coolant.

4. Page 7-3, the first sentence of the 2nd paragraph states that no significant bias exists with respect to the dry-out spacer elevation. How does one determine bias in this case?

5. Page 7-10, first paragraph: Why was the level of significance chosen at the 1percent level?

    a. Pages 2-1, (last 3 lines), and pages 7-17 and 7-18, allude to the exclusion of high inlet data being included in the defining data base of the correlation. Why resort to extrapolation when you have the data covering the operational range of the correlation?

    b. Figures 7-4 and 7-12 indicate that the behavior of the ECPR with Inlet sub-coolant for the 0.100Mlb/h is not as linearly behaved as that for the 0.05Mlb/h. Please provide technical justification for the discrepancy in behavior.

6. As mentioned in the opening paragraph of Chapter 2, the impact of local spacer effects and assembly geometry on critical power is very important. To fully assess the impact of

spacer design on CHF, sufficient statistics must be collected to enable one to perform statistical analysis. As such, justify the use of only 60 points as an experimental design data base to provided adequate "cover-to-cover", (i.e., normal and transient), range of all applicable input parameters: mass, pressure, subcooling and power.

AREVA

August 18, 2009
NRC:09:089

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

Response to a Draft Request for Additional Information Regarding ANP-10298(P), "ACE/ATRIUM 10XM Critical Power Correlation"

Ref. 1: Letter, Ronnie L Gardner (AREVA NP Inc.) to Document Control Desk (NRC), "Request for Review and Approval of ANP-10298P, Revision 0, 'ACE/ATRIUM 10XM Critical Power Correlation'," NRC:08:100, December 29, 2008.

Ref. 2: Email, Holly C. Cruz (NRC) to Gayle F. Elliott (AREVA NP Inc.) "Preliminary 'Draft' RAIs for AREVA TR ANP-10298 ACE/ATRIUM 10XM," March 31, 2009.

Ref. 3: Letter, Ronnie L Gardner (AREVA NP Inc.) to Document Control Desk (NRC), "Response to a Draft Request for Additional Information Regarding ANP-10298(P), 'ACE/ATRIUM 10XM Critical Power Correlation'," NRC:09:066, June 11, 2009.

AREVA NP Inc. (AREVA NP) requested the NRC's review and approval of the topical report ANP-10298(P) in Reference 1. The NRC provided a draft request for additional information (RAI) regarding this topical report in Reference 2. The response to questions 2 through 7 of this request were provided in Reference 3. The response to question 1 is submitted to the NRC in this transmittal.

AREVA NP considers some of the material contained in the attachments 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 RAI responses are provided.

If you have any questions related to this submittal, please contact Mr. Alan B. Meginnis, Product Licensing Manager by telephone at 509-375-8266 or by e-mail at alan.meginnis@areva.com.

Sincerely,

Ronnie L. Gardner

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

Enclosures

cc: H. D. Cruz
Project 728

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ANP-10298Q1NP
Revision 0

ACE/ATRIUM 10XM Critical Power Correlation – RAI's

June 2009

AREVA

ACE/ATRIUM 10XM
Critical Power Correlation – RAI's

Abstract

Responses to Round 1 RAI question 1 with regard to the ACE/ATRIUM 10XM Critical Power Correlation is provided by this document.

Nature of Changes

Item	Page	Description and Justification
1.	All	This is a new document.

Contents

This document contains a total of 49 pages.

Tables

Figures

Nomenclature

Acronym	Definition
CFD	Computational Fluid Dynamics.
CPR	Critical Power Ratio, defined to be the critical power divided by the power of the assembly.
ECPR	Experimental Critical Power Ratio, defined to be the ACE/ATRIUM 10XM calculated critical power divided by the experimentally measured critical power
RAI	Request for additional information

1.0 Introduction

This document provides a response to the first question of the initial request for additional information regarding the ACE/ATRIUM 10XM[1], AREVA NP Inc.[2] critical power correlation for the boiling water reactor ATRIUM 10XM fuel design.

[1] ATRIUM is a trademark of AREVA NP Inc. an AREVA and Siemens company registered in the United States and various other countries.

[2] AREVA NP Inc. is an AREVA and Siemens company.

2.0 RAI Question 1

In the December 2008 submittal for the ACE/ATRIUM 10XM correlation, [ ] data points were collected for [ ] different assemblies. These data points were taken to represent corner-to-corner coverage of the expected normal and transient operational space of the correlation. In chapter 9 of the same submittal, it is revealed that the actual spacer of the production assembly uses a combination spring/dimple rod bearing surface instead of a total dimple load bearing surface. To demonstrate that the spring/dimple spacer behaves consistently with that of total dimple design, additional tests were conducted. However, only [ ] data points were taken. It is not clear to the staff as to how these [ ] points can be considered representative of the normal and transient operational range of the correlation. Justify the use of [ ] points as an experimental design to provided adequate corner-to-corner coverage of all applicable input parameters, as well as providing appropriate statistical basis for a sound correlation and additive constant uncertainties.

Response:

It is the position of AREVA NP that the tested spacer and the production spacer are "thermal-hydraulically" the same in critical power performance. This position is based on:

- Basis for the spacer design and experience on factors affecting critical power performance, (see discussion beginning on page 3)
- Use CFD to develop appropriate subchannel loss coefficients (see discussion beginning on page 4)
- Evaluation of the effect of spring and simple supports with RINGS showing no significant difference, (see discussion beginning on page 4)
- Evaluation of the effect of spring and dimple supports with single phase and two phase CFD (STAR CD), showing no significant difference, (see discussion beginning on page 9)
- Experimental comparison of two spacers with significantly different rod supports showing no significant differences, (see discussion beginning on page 16)
- Experimental comparison of two spacers with simple change in rod support showing no significant differences, (see discussion beginning on page 21)
- Test STS-112.1, of a spacer containing both springs and dimples, that showed no significant difference compared to STS-109.1A (see discussion beginning on page 30).

These points are described in the subsections that follow.

2.1 *Basis for Spacer Design*

The design of the ATRIUM 10XM spacer evolved from the ULTRAFLOW spacer used in the ATRIUM 10 test program. [

]

While every rod in the assembly remains supported on two sides by dimples and on two sides by springs, the dimples are no longer all oriented toward the geometric center of the assembly. This departure from previous designs (to improve fuel reliability) had to be addressed in the critical power testing.

Critical power tests are difficult to perform and require tremendous amounts of power. In the KATHY loop, direct current (DC) resistance heating of the rod surface is used to simulate the nuclear heating of the rods. The use of high electrical currents in the test assembly creates significant magnetic forces that cause the rods to be pulled toward the center of the assembly. (NOTE: These magnetic forces do not exist in the reactor). This force is several times higher than the force needed to collapse the springs used in the spacer. In previous designs, the dimples in the spacer were oriented in such a way that the spacer held the rods in the correct position when the test assembly was subjected to the magnetic forces. Unfortunately, testing of unmodified ATRIUM 10XM production spacers cannot be performed because the prototypical geometry would not be preserved (the magnetic forces would collapse the support springs and the rods would move out of position and the measured performance would no longer represent the performance of the production assembly in the reactor).

In order to perform the critical power tests and maintain prototypical geometry, it was necessary to replace the springs in the production spacer with dimples. This change was considered to be insignificant because [

]

[ ], which are the primary components within the spacer that affect the critical power performance.

2.2 *CFD Evaluation of Loss Coefficients*

As part of the 'due diligence' of the ATRIUM 10XM design of the grid spacer, Computational Fluid Dynamics (CFD) was used to examine the pressure loss coefficients between subchannels with all springs and subchannels with all dimples (Figure 2-1). The normal RINGS calculation procedure is to calculate [ ] so the normal calculation procedure could not be used. Therefore, CFD was used to determine the loss coefficient of an all spring and an all dimple subchannel.

The CFD model was built using hexahedral mesh with a cell size of [ ]. The boundary conditions were base on saturated liquid at 69 bar (1000 psi) and a nominal inlet flow. The loss coefficient was determined by taking the volume averaged pressure at the inlet to the spacer and the volume averaged pressure at the exit of the spacer. The calculation was then performed using:

$$\xi = \frac{2\Delta P}{\rho V^2}$$

The resulting loss coefficients are:

2.3 *RINGS Evaluation of Spring and Dimple Subchannels*

Subchannel calculations were then performed using the subchannel loss coefficients modified to account for the results from the CFD calculations to assess whether the critical power for the bundle with the all dimple test spacer is equivalent to the critical power for a production spacer.

Figure 2-2 shows the calculation model for the all dimple spacer while Figure 2-3 shows the model for the production spacer.

Several radial and axial profiles were considered in the evaluation. Test STS-107.1 (see Figure 8–14 of Reference 1) with a down skew power profile, test STS-109.1A (see Figure 8–42 of Reference 1) with a chopped cosine power profile, and test STS-111.3 (see Figure 8–83 of Reference 1) with an upskew profile were selected for subchannel evaluation. The calculations included a flow range of [ ].

The difference in critical power ratio, $CPR_D - CPR_P$, is shown in Table 2-1. The subscript D denotes all dimple spacer (the tested bundle) and subscript P denotes the production spacer with the correct arrangement of springs and dimples.

A more accurate subchannel analysis is achieved by iterating on power to identify the power at which the subchannel calculated CPR is 1.000. An example of this is accomplished by considering only the cosine test and only the 69 bar (1000 psi) data. The iteration on power for both the dimpled test bundle and the production test bundle can then be used to obtain pseudo critical power ratios where a pseudo critical power ratio is the iterated power divided by the measured power of the dimpled test bundle. The difference between the values of the dimpled test spacer CPR and the production spacer calculated CPR is then averaged with the result shown in Table 2-2.

The averaged difference between the all dimple and the production spacer is less than [ ].

From the above analyses, one concludes that the effect of the difference in loss coefficients is small. The effect of the dimple and/or spring arrangements may have a slight local modification of flow but that difference is less than the accuracy of the models used in the subchannel code.

Table 2-1. Subchannel Differences in CPR

Table 2-2. Converged Subchannel Analysis Results at 69 bar

Figure 2-1. Spring/Dimple Arrangement

Figure 2-2. All Dimple Test Spacer

Figure 2-3. Production Spacer

2.4 *CFD Evaluation of Flow Patterns*

It has been proposed that a horse shoe vortex caused by high velocity vapor under a spacer could be the cause of premature dryout (Reference 3). To determine if the spring could result in this condition a 2x2 subchannel mesh was developed (see Figure 2-4) and then analyzed using CFD calculations.

The CFD mesh was built to the same standards as those built for the pressure drop calculations. This resulted in a mesh size of 0.3 x 0.3 x 0.3 mm with a 0.07 mm extrusion layer. The boundary conditions are based on [ ]. The inlet velocity is set to [ ].

The resulting velocity profiles are shown below. Figure 2-5 shows a section of the model comparing the velocity vectors between the springs and dimples.

A closer view of the spring region (Figure 2-6) shows there is no horseshoe vortex resulting from the flow around spring/rod contact.

Closer views of the dimple region (Figure 2-7 and Figure 2-8) show there is no horseshoe vortex resulting from the flow around dimple/rod contact.

The purpose of this analysis is to check the flows around the springs and dimples. As stated, the springs and dimples do not have a significantly different flow pattern near the rods. No horseshoe vortex is set up by either the springs or the dimples. Therefore, there should be no change in dryout performance based on the change in flow patterns around the springs and dimples.

In addition, this model shows that the flow pattern of the springs and dimples have no impact on [

] One way to look at that was with a section/clipped sweep. This was made into a movie using a panel composed of 50 individual figures in a GIF format. These were put into Microsoft's Movie Maker as individual frames and then combined as a video. The resulting video is

Figure 2-4. 2x2 Mesh With Both Springs and Dimples

Figure 2-5. Spring and Dimple Flow Patterns

Figure 2-6. Closer View of Flow Around Spring

Figure 2-7. Flow Around a Dimple

Figure 2-8. Detailed View of Flow Around a Dimple

2.5 *Experimental Comparison of Two Spacers With Different Rod Supports*

As part of a new product development program, new spacer concepts have been explored with significantly different rod support structures [ ]. Some of these concept spacers were tested in 5x5 arrays with a cosine axial power shape to measure differences in critical power. Examinations of the results of these tests provide an assessment of the impact that rod supports have on the critical power performance of a spacer. The first or reference spacer examined represents the AH62/18 spacer that is the basis for the ATRIUM 10XM testing. This is shown in Figure 2-9. It was tested in STS-100.

The second spacer (designated AH-67) has a completely different rod support design, as shown in Figure 2-10. [ ] are the same on the two spacers. As observed in the side views of the spacers, the rod support design is quite different. [ ]

The two tests are compared in Figure 2-11. The critical power is plotted against the inlet subcooling at each mass flow rate for the two tests. Both tests were performed at 69 bar (1000 psi) pressure. The overall difference in performance between the tests is [ ] as shown in Table 2-3. Within the uncertainty of the test measurement, the performance is the same.

To summarize, the differences between the spacers tested in STS-100 and STS-102 are much larger than the differences between the test spacer and the production spacer in the ATRIUM 10XM design yet critical power performance is nearly equal. Significant changes to the rod support structure do not significantly change the critical power.

Table 2-3. STS-100 and STS-102 Performance Comparison

Figure 2-9. AH 62/18 Spacer (Test STS-100)

Figure 2-10. AH 67 Spacer (Test STS-102)

Figure 2-11. Comparison of STS-102 to STS-100 Critical Power

2.6 *Experimental Comparison of Two Spacers With Changes to the Rod Supports*

The spring used in the PWR AFA2 spacer (shown in Figure 2-12) was modified to reduce the pressure loss. The width of the spring was reduced from [ ], a reduction of about [ ]. The new spacer, designated AFA3Glr, is shown in Figure 2-13. The reference critical power test K1100 was repeated with the modified spacer as test K1400. These were 5x5 KATHY tests using a uniform axial power shape.

The data from these tests are compared in Figure 2-14 through Figure 2-21. Each Figure represents a single pressure class, ranging from 20 bar (300 psi) to 165 bar (2400 psi). Comparable points in the test matrix (those with similar mass flux, pressure, and inlet temperature) are compared, point-by-point, to calculate a percent difference in critical power. No corrections are made for the slight variations in mass flux, pressure, or inlet temperature. The overall performance difference is [ ] as shown in Table 2-4 and Table 2-5.

The performance difference as a function of pressure is provided in Table 2-4. The performance difference as a function of mass flux is shown in Table 2-5. At each pressure, and each mass flux, the difference in performance between the two tests is less than or comparable to the experimental uncertainty. Variation (standard deviation) is examined in Table 2-6. For all of the data in the point-by-point comparison, the standard deviation is [ ]. If one considers only data which are near the BWR range of applicability in pressure, the standard deviation is [ ]. If the data are further restricted to those mass fluxes near the BWR range of applicability, the standard deviation becomes [ ].

It is acknowledged that in addition to the spring width, the method of shimming the spacers in the test channel was changed between the tests (compare side views of Figure 2-12 and Figure 2-13) so the comparison is not a clean one. The edges are well away from the part of the spacer where the critical heat flux is observed and are not considered significant. The physical differences between these two spacers are larger than the differences between the ATRIUM 10XM test spacer and the ATRIUM 10XM production spacer. Unlike the ATRIUM 10XM spacers, the spring redesign in the AFA2 spacer [ ]. Yet the change in performance is not significant. Here again, the changes made to the spacer are larger than those between the ATRIUM 10XM production spacer and the ATRIUM 10XM tested spacer yet the critical power performance is relatively unaffected by the change.

Table 2-4. Critical Power of K1400 Relative to K1100 By Pressure

Table 2-5. Critical Power of K1400 Relative to K1100 by Mass Flux

Table 2-6. Standard Deviation of Difference in Critical Power

[ ]

Figure 2-12. AFA2 5x5 Test Spacer (K1100)

Figure 2-13. AFA3GIr 5x5 Test Spacer (K1400)

Figure 2-14. Critical Power of K1100 and K1400 (20 bar)

Figure 2-15. Critical Power of K1100 and K1400 (40 bar)

Figure 2-16. Critical Power of K1100 and K1400 (60 bar)

Figure 2-17. Critical Power of K1100 and K1400 (80 bar)

Figure 2-18. Critical Power of K1100 and K1400 (100 bar)

Figure 2-19. Critical Power of K1100 and K1400 (125 bar)

Figure 2-20. Critical Power of K1100 and K1400 (145 bar)

Figure 2-21. Critical Power of K1100 and K1400 (165 bar)

2.7 *Test STS-112.1*

A photograph of the production spacer is shown in Figure 2-22 with the view in the direction of the flow. Rod stubs are inserted in a part of the spacer to show the positions of the dimples and springs with rods inserted. A photograph of the test spacer used for the ATRIUM 10XM critical power tests is shown in Figure 2-23, again with rod stubs inserted. Comparing these two figures shows that [ ].

Test STS-112.1 was designed to confirm that replacing the springs in the test spacer with dimples would have no effect on critical power. A special spacer was constructed that contained both springs and dimples. The arrangement of springs and dimples was such that in most positions the dimples point toward the center of the assembly.

There were some constraints. We started with a prototypical ATRIUM 10XM spacer. The outer strip could not be easily changed; therefore the dimples in the outer strip remained unchanged. In the interior positions, both springs and dimples were used; the dimples were placed in positions that support the rod against the magnetic forces (described on page 3). This is shown for nearly all rod positions in Figure 2-24. A section of the STS-112.1 test spacer is shown in Figure 2-25. Although it has a mixture of springs and dimples, it has [ ].

The peaking pattern was carefully chosen. The tested rod positions were [ ] and their symmetric counterparts, rod positions [ ]. In selected positions [ ] springs were applied even though there is a component of the magnetic force that was applied to the spring. This allowed the subchannels around these positions to be bordered mostly by springs. Springs placed in these positions saw a little over 8 degrees of angle with respect to the magnetic force (as shown in Figure 2-24). In this test at the two selected positions, the fraction of the force applied to the springs was about [ ] of the total force; the remainder of the force was restrained by the adjacent dimples.

The peaking pattern in STS-112 was the same as tested in STS-109. In order to provide a direct data-to-data comparison, the cosine axial power shape was used (no comparable test was performed in either downskew or upskew).

The test was performed at 69 bar (1000 psi) with a range of mass flow rates ranging from [ ]. In order to make sure that the behavior was consistent across different pressures, some points at 41 bar (600 psi) and some points at 97 bar (1400 psi) were also collected. Once sufficient data was collected to show that the performance was the same, there was no point in collecting additional data (these tests are very expensive to perform, and this test, in particular, carried a significant risk of damaging the test hardware).

Direct data comparison between STS-112.1 and STS-109.1 is provided in Figure 2-26 to Figure 2-28. The difference in performance between the measurements is provided as a function of pressure and mass flow rate in Table 2-7. The overall difference is [ ]. This difference is shown to be insignificant in the responses to Round 1 RAI questions 2 through 7 (Reference 2). It should further be noted that that the uncertainty of the correlation is [ ] (standard deviation) but that the additive constant uncertainty used in the safety limit calculation is [

]

The conclusion from STS-112.1 is consistent with the conclusion provided in the comparisons shown in the sections above – using dimples in place of springs in the test spacer does not affect the critical power.

Table 2-7. Comparison of STS-112.1 to STS-109.1 by Pressure and Flow

Figure 2-22. Section of AH62/14 Spacer (Production)

Figure 2-23. Section of AH62/18 Spacer (Dimples Replace Springs)

Figure 2-24. Arrangement of Springs/Dimples on STS-112 Spacer

Figure 2-25. Section of AH62/22 Spacer (With Springs and Dimples)

Figure 2-26. Comparison of STS-112.1 to STS-109.1 (69 bar)

Figure 2-27. Comparison of STS-112.1 to STS-109.1 (97 bar)

Figure 2-28. Comparison of STS-112.1 to STS-109.1 (41 bar)

2.8 *Conclusion*

To reiterate, the AREVA NP position is that the tested spacer and the production spacer are "thermal-hydraulically" the same for critical power performance. It has been shown, by subchannel analysis, by CFD analysis, and by experiment, that the rod supports have no impact on the critical power of the test assembly. It was further shown, through testing of an ATRIUM 10XM production spacer with a modified arrangement of springs and dimples, that the performance is the same.

In chapter 9 of the topical report, and in RAI responses 2 through 7, it is further shown that there is no significant difference in either the mean or the standard deviation of the STS-112 data relative to the tested spacer.

Based on these evaluations, it is concluded that the critical power data collected in the ATRIUM 10XM test program applies directly to the production spacer that will be placed in the reactor.

3.0 References

1. ANP-10298P ACE/ATRIUM 10XM Critical Power Correlation, December 2008.

2. "ACE/ATRIUM 10XM Critical Power Correlation – RAI's," AREVA NP Inc. Report No. ANP-10298Q1P, Revision 0, June 2009.

3. R. T. Lahey, Jr., and F. J. Moody. "The Thermal-hydraulics of a Boiling Water Reactor." 1977.

AREVA

September 16, 2009
NRC:09:097

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

Response to a Request for Additional Information Regarding ANP-10298(P), "ACE/ATRIUM 10XM Critical Power Correlation"

Ref. 1: Letter, Ronnie L Gardner (AREVA NP Inc.) to Document Control Desk (NRC), Request for Review and Approval of ANP-10298P, Revision 0, "ACE/ATRIUM 10XM Critical Power Correlation", NRC: 08:100, December 29, 2008.

Ref. 2: Email, Holly C. Cruz (NRC) to Gayle F. Elliott (AREVA NP Inc.) "Preliminary 'Draft' RAIs for AREVA TR ANP-10298 ACE/ATRIUM 10XM," March 31, 2009.

Ref. 3: Letter Ronnie L Gardner (AREVA NP Inc.) to Document Control Desk (NRC), Response to a Draft Request for Additional Information Regarding ANP-10298(P), "ACE/ATRIUM 10XM Critical Power Correlation", NRC:09:066, June 11, 2009.

Ref. 4: Letter Ronnie L Gardner (AREVA NP Inc.) to Document Control Desk (NRC), Response to a Draft Request for Additional Information Regarding ANP-10298(P), "ACE/ATRIUM 10XM Critical Power Correlation", NRC:09:089, August 19, 2009.

Ref. 5: Letter, Ram Subbaratnam (NRC), to Ronnie L Gardner (AREVA NP Inc.), "Request for Additional Information RE: AREVA NP Inc. Topical Report ANP-10289P, Revision 0, 'ACE/ATRIUM 10XM Critical Power Correlation'," (TAC NO. ME0344), July 9, 2009.

AREVA NP Inc. (AREVA NP) requested the NRC's review and approval of the topical report ANP-10298(P) in Reference 1. The NRC provided a draft Request for Additional Information (RAI) regarding this topical report in Reference 2. The responses to the Reference 2 draft RAI were provided to the NRC in References 3 and 4. The NRC provided an additional RAI to AREVA in Reference 5. The attachments to this letter present the responses to the Reference 5 RAI.

AREVA NP considers some of the material contained in the attachments 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 RAI responses are provided.

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If you have any questions related to this submittal, please contact Mr. Alan B. Meginnis, Product Licensing Manager by telephone at 509-375-8266 or by e-mail at alan.meginnis@areva.com.

Sincerely,

Ronnie L. Gardner

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

Enclosures

cc: H. Cruz
Project 728

An AREVA and Siemens company

ANP-10298Q3NP
Revision 0

ACE/ATRIUM 10XM Critical Power Correlation – RAI's

September 2009

AREVA

ACE/ATRIUM 10XM
Critical Power Correlation – RAI's

AREVA NP Inc.

Abstract

Responses to second round RAI questions 1 through 10 and statistical questions 1 through 6 with regard to the ACE/ATRIUM 10XM Critical Power Correlation are provided by this document.

Nature of Changes

Item	Page	Description and Justification
1.	All	This is a new document.

Contents

This document contains a total of 62 pages.

Figures

Nomenclature

Acronym	Definition
CPR	Critical Power Ratio, defined to be the critical power divided by the power of the assembly.
ECPR	Experimental Critical Power Ratio, defined to be the ACE/ATRIUM 10XM calculated critical power divided by the experimentally measured critical power
RAI	Request for additional information

1.0 Introduction

In December 2008, AREVA NP, Inc. submitted the ACE/ATRIUM 10XM critical power correlation topical report (Reference 1). This document provides responses to the request for additional information (Reference 2) regarding the ACE/ATRIUM 10XM[1], AREVA NP Inc.[2] critical power correlation for the boiling water reactor ATRIUM 10XM fuel design.

[1] ATRIUM is a trademark of AREVA NP Inc. an AREVA and Siemens company registered in the United States and various other countries.

[2] AREVA NP Inc. is an AREVA and Siemens company.

2.0 Round 2 RAI Question 1

Figure 3-2 shows part-length rods (PLR) adjacent to the water hole. Were any PLR driven into dryout? Could these rods be driven into dry-out during normal operation or transient events? Will they ever be located in a limiting position in the bundle?

Response

The PLR's were not peaked in the tests. [

]

3.0 Round 2 RAI Question 2

The second paragraph on page 5-2 alludes to the importance of spacer location, spacer deposition enhancement factors, and spacer coefficient, on dry-out, assembly power, etc. Are all these parameters impacted by the spacer design?

Response

The parameters appear in the ACE correlation model equation, including the constitutive relations. Some parameters are directly related to the spacer design, [ ]. Others are indirectly related. It should be kept in mind that the correlation is an assembly correlation, using assembly conditions – not a subchannel correlation. This means that changing the rod diameter, or changing the number or locations of part length rods in the design can affect the other parameters. Changing the spacer pitch can also impact other parameters because it is an assembly correlation.

4.0 Round 2 RAI Question 3

On page 5-5, following equation 5.5, it is stated that the parameter, L_S, is now a variable in the ATRIUM 10XM design. Provide additional information regarding this parameter, i.e., is the variability of this parameter utilized to obtain optimum spacer separation?

Response

[

]

Neither the ACE/ATRIUM-10, nor the ACE/ATRIUM 10XM correlations were used to determine or optimize the spacer pitch used in the ATRIUM 10XM design.

5.0 Round 2 RAI Question 4

Table 6-8 on page 6-18 has columns that need further clarification. Please be prepared to elaborate. For example, there are wide variations between the values for the ATRIUM-10XM and the ATRIUM 10. In addition, the paragraph below the Table on the same page, states that these parameters are generally smaller for the ATRIUM-10XM than they are for the ATRIUM 10 design, but no explanation is given as to why. Please explain.

Response:

There are two parts to this question. For the first part, refer to page 6-12 of the topical report for how each parameter in columns of Table 6-8 on page 6-18 is calculated. Except for the independent variable in the first column, each of the Tables 6-3 through 6-7 has the same structure with the same columns as Table 6-8.

For the second part, the discussion in the topical regarding parameters being generally smaller for ATRIUM-10XM than for the ATRIUM 10 design is found on page 5-8 of the topical report.
[

]

[

]

6.0 Round 2 RAI Question 5

Figures 5-12 through 5-15 address the chopped cosine power profile. Are there similar plots for other power profiles?

Response:

[

]

Figure 6-1. ACE/ATRIUM 10XM Critical Power vs Pressure (Upskew)

Figure 6-3. ACE/ATRIUM 10XM Critical Power vs Inlet Subcooling (Upskew)

Figure 6-5. ACE/ATRIUM 10XM Critical Power vs Pressure (Downskew)

Figure 6-7. ACE/ATRIUM 10XM Critical Power vs Inlet Subcooling (Downskew)

7.0 Round 2 RAI Question 6

On page 7-17, Section 7.5 addresses the issue of "inlet-sub-coolant" bounds. In this section, reference is made to the inclusion inlet subcoolant data and to the reference of exclusion of data. Please be prepared to discuss and provide additional clarification to this section based on a qualitative and quantitative technical basis.

Response:

The treatment of the data follows the same procedure used in the ACE/ATRIUM-10 correlation (Reference 3, pages 5-17 and 5-18). The very high inlet subcooling data (data above 85 Btu/lb) were all placed in the validating data set. By placing these data in the validating data set, and fitting the correlation to a narrower range of data in inlet subcooling, it is possible, after the correlation is developed, to show that it can be extrapolated in inlet subcooling.

It should be remembered that [

] By showing that the correlation can extrapolate in inlet subcooling, the lower limit on inlet subcooling can be set to zero and the high inlet subcooling limit can be set to the limit of the data, extended slightly by the experimental uncertainty.

Note that the additive constant uncertainty calculation is based on the combined data set, defining plus validating.

8.0 Round 2 RAI Question 7

On page 7-18, the first paragraph in this section states that, it is an accepted industry standard in Boiling Water Reactor (BWR) transient methodology that steady-state developed dry-out correlations are conservative when predicting transient behavior. Please provide reference(s) to this end.

Response:

NUREG/CR-0056 "Critical Heat Flux Under Transient Conditions: A Literature Survey," by J. C. M. Leung

- Chapter IIA addresses use of steady-state correlations.
- Page 11: "Comparison with flow and power transient experiments indicated that the prediction was quite conservative."

Collier and Thome, "Convective Boiling and Condensation, 3rd Ed." 1994.

- Section 9.6.2, page 405, addresses critical heat flux under transient conditions. Use of instantaneous nodal values of the parameters were used in steady-state CHF correlation, with predicted time of CHF occurring earlier than measured time to CHF. This indicates conservatism.

9.0 Round 2 RAI Question 8

Page 7-19, section 7.5,, the second paragraph from the bottom alludes to the prediction of boiling transition by the ACE/ATRIUM-10XM correlation. The paragraph also alludes to the same correlation under and over predicting the boiling transition state within the range of "defined uncertainties". What are these ranges of defined uncertainties? How are they defined? And why are they defined as such?

Response:

The uncertainty in the ACE/ATRIUM 10XM critical power correlation is [

].

For the transient analysis, [

]

10.0 Round 2 RAI Question 9

Page 8-1, the last paragraph addresses axial power profiles tested. Has the AREVA staff investigated double-hump power profile prediction with the ACE/ATRIUM-10XM correlation?

Response:

Yes. A study comparable to that performed in Reference 3 for extreme axial power shapes (outside of those tested) was performed. This study includes a double hump axial power shape. For the double hump axial power shape, the ACE/ATRIUM 10XM correlation prediction was compared to the RINGS prediction. The ECPR was [

]

11.0 Round 2 RAI Question 10

During a dryout testing program, some data points are repeated to ensure that test parameters and components have not drifted during the current test session and/or recently completed test sessions.

(a) Provide description of how AREVA performs/conducts repeatable points and associated uncertainties,

(b) What criteria is used to accept or reject repeated data points?

(c) Regarding STS-112.1, the bundle with the spacer containing both springs and dimples, for all the data points that were repeated, provide the uncertainties associated with the repeated points,

(d) How do these uncertainties compare to those uncertainties associated with the other tests conducted with this same fuel?

Response:

Part (a)

During the critical power testing, repeat points are taken to provide quantifiable evidence that the assembly performance has not changed since the original point was taken. [

]

Generally, in a test [

]

The possibility of systematic errors also exists [

]

When the data are selected for correlation, they are examined to determine the repeatability. The repeatability is determined by test series. These are compared to see if significant changes to loop behavior occurred over the time frame of conducting the critical power correlation licensing tests.

[

]

Part (b)

The criterion for acceptable repeatability with raw data is [ ]. If a repeat point differs from the original value by more than [ ], it indicates that there may be something wrong with the test. Procedurally, the testing must be stopped and the cause of the problem determined.

Part (c)

The replicate uncertainty for test STS-112.1 is [ ] .

Part (d)

The replicate uncertainty for the critical power tests used in the development of the ATRIUM 10XM critical power correlation ranged from [ ] with an overall mean of [ ] . The replicate uncertainty for test STS-112.1 is consistent with the observations from the other tests.

12.0 Round 2 Statistical RAI Question 1

On page 2-3, Table 2-1: Range of Applicability, the ranges of the parameters are lower than those presented in Table 4-2 for the development range. Please explain.

Response:

<u>Mass flow lower limit:</u>

The lower limit is justified based on the topical report discussion of Figure 5-21, page 5-32 of ANP-10298P which shows that [ ].

<u>Inlet subcooling lower limit:</u>

[ ]

<u>Pressure lower limit:</u>

The correlation is developed with a data range of between [ ]. The lower limit is [ ]. Section 8.3, page 8-106 discusses the low pressure data and Table 8-3, page 8-107 demonstrates the [ ].

13.0 Round 2 Statistical RAI Question 2

Page 6-2, Figure 6-1 (repeated page 2-3, Figure 2-1). Prediction becomes less precise at higher power. Explain and show boundaries of this prediction. Also, what are the characteristics of the 4 (or 5) points at the very top of the chart (critical power about 15)?

Response:

Figure 13-1 below is a duplicate of Figure 6-1 from Reference 1 with the prediction boundary lines included. This figure shows no significant variation in the precision of the predictions as a function of the critical power. The absolute difference in critical power may appear larger at the high power conditions, but on a relative basis, they are within the range of precision found at other power levels.

With respect to 5 of the data points at the very top of the chart, these high power points are runs 156.1, 156.2, 156.3, 156.4, and 156.41 from STS-107.3. These are low pressure points at high flow and fall within the tolerance limit for this test set (see Table 6-8 on page 6-18). They are however part of the group of 90 data points that do lie outside the tolerance limit for the overall defining data set (as seen in the bottom line in Table 6-8).

Figure 13-1. Calculated vs. Measured Critical Power

14.0 Round 2 Statistical RAI Question 3

Page 6-26, claims that "no trend is observed" for Figure 6-2. Yet, in almost every individual test (pages 6-27 through 6-37) there is a hint of a pattern.

(a) Provide technical justification for the various trends in these series of plots.

(b) Is it possible that combining the tests camouflages such trends?

(c) Also, provide similar plots for pressure and inlet subcoolant.

Response:

Parts (a) and (b)

The observed trends in ECPR as a function of mass flow rate by test are similar to those observed in all of the critical power/critical heat flux correlations, including (but not limited to) ANFB (Reference 4), ANFB-10 (Reference 5), SPCB (Reference 6), and ACE/ATRIUM-10 (Reference 3). These kinds of small trends also exist in Critical Quality/Boiling Length (XL type) correlations.

It is important to realize that the ACE/ATRIUM 10XM is a bundle correlation. It is designed to be a best estimate fit to the design specific experimental data over the entire range of conditions and for all the tested rod locations. Thus, by definition, the correlation will reflect the average behavior of all the tested rods. Indeed, the small trends observed in the various tests will be averaged out in the overall bundle behavior.

The variations seen in the different tests do result in increasing the uncertainty associated with the correlation. Specifically, they impact the ECPR uncertainty and more importantly, the additive constant uncertainty. The additive constant uncertainty is impacted by both the within test and between test variations in ECPR.

Part (c)

The plots were provided of the ECPR as a function of mass flow rate by test because mass flow rate is the most significant parameter affecting the critical power. Plots are provided below as a function of pressure [ ] and as a function of inlet subcooling [ ] for each test. Similar trends or observations can be made that were already revealed in the plots of ECPR versus mass flow rate for each test.

15.0 Round 2 Statistical RAI Question 4

Page 7-3, the first sentence of the 2nd paragraph states that no significant bias exists with respect to the dry-out spacer elevation. How does one determine bias in this case?

Response:

Section 7-3 (on page 7-7), the first sentence of the 2nd paragraph states that no significant bias exists with respect to dry-out spacer elevation. Figure 7-7 on page 7-8 provides a qualitative indication of distribution elevation prediction accuracy according to the spacer. [

] Therefore, there is no significant bias with respect to the spacer where dryout was observed.

16.0 Round 2 Statistical RAI Question 5

Page 7-10, first paragraph. Why was the level of significance chosen at the 1 percent level?

Response:

Section 7.4, page 7-10 states that the significance level is a result of application of Lilliefors test for normality. The 1% value was used by Lilliefors in his paper "On the Kologorov-Smirnov Test for Normality With Mean and Variance Unknown," Journal of the American Statistical Association, Vol. 62, June 1967.

The corresponding histogram presented in Figure 7-10 and expected value for normal distribution shown in Figure 7-11 provide additional credibility to accepting the validation data set as coming from a normal distribution.

17.0 Round 2 Statistical RAI Question 5a

Pages 2-1 (last 3 lines), and pages 7-17 and 7-18, allude to the exclusion of high inlet subcooling data being included in the defining data base of the correlation. Why resort to extrapolation when you have the data covering the operational range?

Response:

AREVA NP, Inc. would like to apply the ACE/ATRIUM 10XM correlation with inlet subcooling as low as 0 Btu/lb. It is not possible to test with inlet subcoolings this low in the KATHY loop because cavitation would occur in the pump. Therefore, a small extrapolation is needed.

Section 7.5 presents the rationale that by leaving the high subcooling data in the validation set that the extrapolation to high subcooling shows that the correlation is properly founded and that the correlation robustness with respect to inlet subcooling was demonstrated. Thus, it shows that the correlation can be accurately extrapolated in inlet enthalpy.

18.0 Round 2 Statistical RAI Question 5b

Figures 7-4 and 7-12 indicate that the behavior of the ECPR with inlet sub-coolant for the 0.100 Mlb/h is not as linearly behaved as that for the 0.05 Mlb/h. Please provide a technical justification for the discrepancy in behavior.

Response:

The observation is correct. However, the significance of the observation must consider the scale being used. For example, if the critical power data are plotted and fit to a line (Figure 18-1), the critical power data are observed to be approximately linear with inlet subcooling. If the ACE/ATRIUM 10XM correlation is used to calculate the critical power and the resulting predictions are fit to a line (Figure 18-2), the correlation is observed to be approximately linear with inlet subcooling. The scale being used magnifies small or insignificant differences.

If the 0.10 Mlb/h data are examined more closely, it is observed that the lower inlet subcooling data were collected on May 15, 2008. The higher inlet subcooling were collected on May 21, 2008. Figure 18-3 shows the 0.10 Mlb/h data from Figure 18-1 segregated by date collected. It is observed that the slopes of the lines are slightly different. This is what causes the observed curvature. Unfortunately, this variation in the test data is one of the factors which contribute to higher correlation uncertainty.

Figure 18-1. High Inlet Subcooling Data From STS-111.2

Figure 18-2. ACE/ATRIUM 10XM Critical Power (1000 psi; STS-111.2)

Figure 18-3. Measurements by Date (1000 psia; 0.10 Mlb/h)

19.0 Round 2 Statistical RAI Question 6

As mentioned in the opening paragraph of Chapter 2, the impact of local spacer effects and assembly geometry on critical power is very important. To fully assess the impact of spacer design on CHF, sufficient statistics must be collected to enable one to perform statistical analysis. As such, justify the use of only 60 points as an experimental design data base to provided adequate "cover-to-cover", (i.e. normal and transient), range of all applicable input parameters: mass, pressure, subcooling, and power.

Response:

The part that test STS-112.1 played in the justification of the tested design applicability to the production design is fully described in Round 1 RAI 1 (see Reference 7, pages 29 – 30). It was described that the test was expensive, and carried a significant risk of hardware damage. Once sufficient data was collected to conclude that there was no significant difference in critical power performance, the test was stopped.

20.0 References

1. "ACE/ATRIUM 10XM Critical Power Correlation," AREVA NP Inc. Report No. ANP-10298P December 2008.

2. "Request for Additional Information Re: AREVA NP, Inc. Topical Report ANP-10298P, Revision 0, 'ACE/ATRIUM 10XM Critical Power Correlation.' (TAC No. ME0344)" NRC Letter to Ronnie L. Gardner, July 9, 2009.

3. "ACE/ATRIUM-10 Critical Power Correlation," AREVA NP, Inc. Report No. ANP-10249PA, August 2007.

4. "ANFB Critical Power Correlation," Advanced Nuclear Fuels Report No. ANF-1125(P)(A) and Supplements 1 and 2, April 1990.

5. "ANFB-10 Critical Power Correlation," Siemens Power Report No. EMF-1997(P)(A), July 1998.

6. "SPCB Critical Power Correlation," Framatome ANP Report No. EMF-2209(P)(A), Revision 2, September 2003.

7. "ACE/ATRIUM 10XM Critical Power Correlation – RAI's," AREVA NP Inc. Report No. ANP-10298Q2P, August 2009.

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ANP-10298NP
Revision 0

ACE/ATRIUM 10XM Critical Power Correlation

December 2008

AREVA

ACE/ATRIUM 10XM
Critical Power Correlation

Abstract

A critical power correlation for the ATRIUM 10XM fuel design is described. This correlation uses the same mechanistic model of dryout used in the ACE/ATRIUM-10 correlation. It provides an accurate prediction of the critical power [ ]

Nature of Changes

Item	Page	Description and Justification
1.	All	This is a new document.

Contents

This document contains a total of 254 pages.

Tables

Figures

Nomenclature

Acronym	Definition
AOO	Anticipated Operational Occurrence
BOHL	Beginning of Heat Length
BWR	Boiling Water Reactor
CHF	Critical Heat Flux
CPR	Critical Power Ratio, defined to be the critical power divided by the power of the assembly.
DC	Direct Current
ECPR	Experimental Critical Power Ratio, defined to be the ACE/ATRIUM 10XM calculated critical power divided by the experimentally measured critical power
EOHL	End of Heated Length
LOCA	Loss of Coolant Accident
LRNB	Load Reject with No Bypass
MCPR	Minimum Critical Power Ratio
PLHR	Part Length Heater Rod

1.0 Introduction

This document describes the ACE/ATRIUM 10XM[1], AREVA NP Inc.[2] critical power correlation for the boiling water reactor (BWR) ATRIUM 10XM fuel design. This correlation is designed for application to steady-state design analysis, core monitoring, transient anticipated operational occurrences (AOO's), transient accidents, LOCA, and instability analysis for the ATRIUM 10XM fuel design.

The starting point for this correlation is the ACE/ATRIUM-10 correlation which is a licensed BWR CPR correlation for the ATRIUM 10 fuel design. The ACE/ATRIUM-10 correlation is described in Reference 1 and consists of a theoretical model that describes the point of maximal heat transfer in boiling, sometimes termed critical heat flux, boiling transition, or dryout. This theoretical model is constructed using [

] Both the ACE/ATRIUM-10 and the ACE/ATRIUM 10XM correlations share this same basic form of the correlation.

The differences in the two correlations arise from the physical differences between the ATRIUM 10 and the ATRIUM 10XM fuel bundle designs. The primary differences between the two bundle designs [

]. The ATRIUM 10XM design [

]. A more detailed description of the differences between the two bundle designs is provided in Section 3.

1 ATRIUM is a trademark of AREVA NP Inc. an AREVA and Siemens company registered in the United States and various other countries.

2 AREVA NP Inc. is an AREVA and Siemens company.

The critical power test data for both fuel bundle designs were collected at the AREVA Karlstein Test Facility. A comparison of the critical power databases used for the development of the two correlations is provided in Section 4. A complete description of the ATRIUM 10XM database is provided in Section 8.

2.0 Summary

The ACE/ATRIUM 10XM correlation can be used to accurately predict assembly critical power [ ] for the ATRIUM 10XM fuel design. The correlation provides an accurate prediction of the limiting rod. The impact of local spacer effects and assembly geometry on critical power is accounted for by two different sets of parameters. The first is a set of constants, one constant for each rod in the assembly, called additive constants, and these are presented in Table 5-2 for the ATRIUM 10XM design. The second set of parameters provides [ ].

For comparison of correlation predictions to experimental data, an experimental critical power ratio (ECPR) is defined as the ratio of the calculated critical power to the measured critical power. The ECPR distribution associated with ACE/ATRIUM 10XM is adequately represented with a normal distribution using an overall mean of [ ]. The range of applicability is provided in Table 2-1.

2.1 *ACE/ATRIUM 10XM Database*

The ACE/ATRIUM 10XM database is comprised of [ ] steady-state data points taken on [ ] different test assemblies. The rod axial power shapes of the tests were [ ] peak-to-average chopped cosine and [ ] peak-to-average upskew and downskew. The database was compiled from tests performed exclusively at the AREVA thermal hydraulic test facility located in Karlstein, Germany.

The [ ], was followed in the development of this correlation. In accordance with the criteria set forth in this procedure, the database was randomly divided into a defining data set and a validation data set. Approximately [ ] were set aside as the validating set of data. The remaining [ ] form the defining data set and were used to develop the critical power correlation. [ ]. In addition, transient tests were performed on an ATRIUM 10XM test assembly using [ ] and these were included as a part of the correlation validation set.

The dryout tests were designed to cover the range of conditions present in an operating BWR fuel assembly. As a result, the database and correlation address the effects due to operating pressure, mass flow rate, inlet subcooling, axial power profile, and local peaking. The ATRIUM 10XM database is described in more detail in Section 4.

2.2 *ACE/ATRIUM 10XM Comparison to the Database*

The ACE/ATRIUM 10XM critical power correlation has been used to predict the critical power for each steady state data point in the database. The ECPR determined for each test point is used along with the standard deviation of the ECPR [ ] as the basis to determine the ability of the correlation to predict the onset of dryout. Comparison of the calculated to the measured critical power for ATRIUM 10XM is shown in Figure 2-1.

Table 2-1 Range of Applicability

Figure 2-1 Comparison of Calculated to Measured Critical Power Data

---

1 Throughout this document, comparisons will be made to the ACE/ATRIUM-10 correlation. This document applies solely to the ACE/ATRIUM 10XM correlation. The approved ACE/ATRIUM-10 correlation is described in Reference 1.

3.0 Comparison of ATRIUM 10XM and ATRIUM 10 Fuel Designs

The ATRIUM 10 XM and the ATRIUM 10 fuel design share a common 3x3 water channel and 91 fuel rod locations. The primary differences between the two designs [ ] The ATRIUM 10XM design [ ]. The axial features of the two test bundle designs can be compared in Figure 3-1.

The ATRIUM 10XM design contains [ ] The different configurations are shown in Figures 3-2 and 3-3 for the ATRIUM 10XM and ATRIUM 10 designs, respectively.

The production ATRIUM 10XM design [ ] A summary comparing the pertinent bundle parameters between the two fuel designs is provided in Table 3-1.

Table 3-1 ATRIUM 10 / ATRIUM 10XM Test Bundle Comparison

Figure 3-1 ATRIUM 10 / ATRIUM 10XM Test Bundle Axial Comparison

Figure 3-2 ATRIUM 10XM PLR Locations

Figure 3-3 ATRIUM 10 PLR Locations

4.0 Comparison of ATRIUM 10 and ATRIUM 10XM Databases

The dryout tests were conducted over the range of conditions present in an operating BWR fuel assembly and the coverage of the operating conditions was very similar between the two test assembly designs. However, more than [ ] were taken for the ATRIUM 10XM test assembly. A comparison of the two different databases is provided in Table 4-1 and a summary of the operating ranges covered by the two databases is provided in Table 4-2.

Table 4-1 Database Comparison

Table 4-2 Range of Data for Correlation Development

5.0 ACE/ATRIUM 10XM Correlation

The single phase subcooled flow at the inlet of a BWR fuel assembly rapidly transitions through bubbly flow to annular flow. In the Minimum Critical Power Ratio (MCPR) limiting fuel assemblies, much of the active length of the fuel assembly is in annular flow. A liquid film on the rod and a steam-water mixture in the center region characterizes the annular flow regime. As the flow progresses upward, [ ]. A rapid temperature excursion occurs when the cooling effectiveness of the liquid film is lost. The loss of this liquid film is variously termed dryout, boiling transition, and critical heat flux (CHF).

The ACE/ATRIUM 10XM correlation, like its predecessor, the ACE/ATRIUM-10 correlation (Reference 1) is a correlation based on [ ]. A detailed step-by-step derivation of the ACE/ATRIUM 10XM critical power correlation form is provided in Reference 1, Appendix A. The correlation is based on [ ]

6.0 Assessment of ACE/ATRIUM 10XM With Defining Data Set Critical Power

The performance of the ACE/ATRIUM 10XM critical power correlation compared to the defining data set is provided in this section. The following topics are presented:

- ECPR trend plots comparing the critical power to the defining data set as a whole (Section 6.1)
- [ ] performance (Section 6.2)
- Statistical analysis by single variable subset, test subset, and in some cases two variable subsets of the defining data set (Section 6.3)
- ECPR as a function of mass flow rate by test (Section 6.4)
- Additive constant statistical distribution (Section 6.5)

6.1 *Overall Critical Power and ECPR Behavior (Defining)*

The ACE/ATRIUM 10XM correlation is compared to measured data with respect to critical power, mass flow rate, pressure, inlet subcooling, axial power shape, and K-Factor to examine overall trends.

The correlation predicted critical power is plotted against the measured critical power in Figure 6-1. The data fall in a narrow, well-defined band about the expected value, consistent with the overall standard deviation. No trends are evident.

Figure 6-2 shows the ECPR as a function of mass flow rate. Mass flow rate is the most significant parameter in the critical power correlation. Examination of the data shows that no trend is evident. A trend line representing a linear least squares fit of the ECPR as a function of mass flow rate is shown on the plot, confirming that no significant trends with mass flow rate exist.

The ECPR is plotted as a function of pressure in Figure 6-3. The data show no significant trends in pressure. Figure 6-4 shows the ECPR as a function of the inlet subcooling. There is no apparent trend with inlet subcooling. The ECPR is plotted as a function of axial power shape in Figure 6-5. There is no apparent trend with axial power shape. Figure 6-6 shows the ECPR as a function of K-Factor. There is no apparent trend with K-Factor.

Figure 6-1 Calculated vs. Measured Critical Power (Defining)

Figure 6-2 ECPR as Function of Mass Flow Rate (Defining)

Figure 6-3 ECPR as Function of Pressure (Defining)

Figure 6-4 ECPR as Function of Inlet Subcooling (Defining)

Figure 6-5 ECPR as Function of Axial Power Shape (Defining)

Figure 6-6 ECPR as Function of K-Factor (Defining)

6.2 [ ]

[

]

[

]

Figure 6-7 [ ]

Figure 6-8 [ ]

Figure 6-9 [ ]

6.3 *ACE/ATRIUM 10XM Statistical Analysis of Defining Data Set*

Overall statistics of the fit of the ACE/ATRIUM 10XM correlation fit to the defining data set are provided in Table 6-1. [

] are in excellent agreement with the experimental data.

Higher moments for the ACE/ATRIUM 10XM correlation analysis of ECPR are computed. Reference 7 provides the relationships for computing the higher order moments about the mean. The second moment about the mean is calculated

$$m_2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{6.1}$$

The third moment about the mean is calculated

$$m_3 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^3 \tag{6.2}$$

The fourth moment about the mean is calculated

$$m_4 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^4 \tag{6.3}$$

A measure of skewness is given by

$$\sqrt{\beta_1} = \frac{m_3}{m_2^{1.5}} \tag{6.4}$$

A measure of kurtosis is given by

$$\beta_2 = \frac{m_4}{m_2^2} \tag{6.5}$$

These statistics, computed for the ECPR from the ACE/ATRIUM 10XM correlation, are summarized in Table 6-2. [ ] The distributional character of the ACE/ATRIUM 10XM critical power ratios are shown in Figure 6-10 and Figure 6-11. Figure 6-10 is a histogram of the frequency of occurrence of ECPR while

Figure 6-11 shows that the distribution [

]

The number of degrees of freedom [

] The conclusion is that the correlation has not been over-fit.

Table 6-1 Overall Statistics (Defining)

Table 6-2 Higher Moments of ECPR Mean (Defining)

Figure 6-10 Frequency Distribution of ECPR (Defining)

Figure 6-11 Expected Value for Normal Distribution of ECPR (Defining)

6.3.1 Statistics by Single Variable Subsets

The key variables determining the critical power are the mass flow rate, pressure, inlet subcooling, axial power shape, and K-Factor. The ECPR data are examined by binning each independent variable to quantitatively determine if there are significant trends.

[

] The columns in the table contain the following information:

- The first column in the table identifies the flow rate.
- The second column identifies the number of data points within the flow rate bin.
- The third column contains the mean ECPR of the flow rate bin.
- The fourth column contains the standard deviation in ECPR for the flow rate bin.

- The ninth column shows the maximum value of the ECPR of the flow rate bin.
- The tenth column shows the number of data points in the flow rate bin that are above the ECPR 95/95 limit.
- The eleventh column shows the percent of the data points in the flow rate bin that lie below the 95/95 limit.

There is no trend in ECPR with mass flow rate. The standard deviation of ECPR is slightly [

] shows that there are no significant numbers of outliers at these higher mass flow rates.

The ECPR is examined as a function of binned pressure in Table 6-4. There is no significant trend in ECPR. The standard deviation shows slightly higher standard deviations at low pressure and at high pressure. [

] This result suggests that the observed slightly higher standard deviation is insignificant.

The ECPR is examined as a function of binned inlet subcooling in Table 6-5. There is no significant trend in ECPR. The standard deviation of the lowest and highest inlet subcooling data is slightly higher than for the other data. [

] This result suggests that the observed slightly higher standard deviation is insignificant.

The ECPR is examined as a function of axial power shape in Table 6-6. There is no significant trend with ECPR. [

] This result suggests that the observed slightly higher standard deviation is insignificant.

The ECPR is examined as a function of K-Factor in Table 6-7. There is no significant trend with either ECPR or standard deviation.

Table 6-3 Statistics by Binned Mass Flow Rate (Defining)

Table 6-4 Statistics by Binned Pressure (Defining)

Table 6-6 Statistics by Axial Power Shape (Defining)

Table 6-7 Statistics by Binned K-Factor (Defining)

6.3.2 Statistics by Test

The descriptive statistics for the overall data can be examined by several subgroups of data. Mean, standard deviation, and number of data are presented. The correlation predictions are compared to the defining data set in Table 6-8.

The conclusion is that the defining data set, as a whole and by individual test, confirms the fit of the critical power correlation to the defining data set.

Table 6-8 Statistics by Test (Defining)

6.3.3 Statistics by Subgroups of Two Variables

The next group of statistics examines the correlation behavior by paired statistics. The defining data set is large enough to permit the examination of data by paired statistics in mean and standard deviation. However, care should be taken in interpreting these statistics because the size of the data samples in some paired statistic bins is small.

Table 6-9 provides statistics by subgroups of test and mass flow rate. There are no significant trends in the ACE/ATRIUM 10XM correlation with respect to the paired variables mass flow rate and test peaking pattern.

Table 6-10 provides statistics by subgroups of mass flow rate and pressure. [

]

Table 6-11 provides statistics by subgroups of mass flow rate and inlet subcooling. [

]

[

] Therefore, there are no significant trends apparent in either the ECPR or the standard deviation in ECPR.

The paired statistics in ECPR support the conclusion that not only are the overall statistics acceptable, but subsets in key measured variables are also acceptable.

Table 6-9 Statistics by Test and Mass Flow Rate (Defining)

Table 6-9 Statistics by Test and Mass Flow Rate (Defining) (Continued)

Table 6-10 Statistics by Mass Flow Rate and Pressure (Defining)

Table 6-11 Statistics by Mass Flow Rate and Inlet Subcooling (Defining)

Table 6-12 Statistics by Inlet Subcooling and Pressure (Defining)

6.4 *ECPR - Mass Flow Plots*

The mass flow rate is the most significant variable in determining the critical power of the fuel assembly. For this reason, the ECPR of each test is plotted as a function of mass flow rate. The overall view of ECPR versus mass flow is shown in Figure 6-2 and no trend is observed.

[

]

6.5 *Additive Constants*

A residual additive constant for each state point can be obtained by subtracting the final additive constant from the test state point additive constant calculated as the difference between the experimental K-Factor and the theoretical K-Factor for the limiting rod. A frequency plot of these residuals in additive constant for the defining data set is provided in Figure 6-34.

[ ]

Figure 6-34 Distribution of Additive Constant Residuals

7.0 ACE/ATRIUM 10XM Correlation Validation

The development of the ACE/ATRIUM 10XM correlation required that the database be divided into two sets, one for correlation development and the other for correlation validation. When the correlation development was complete, the defining data set was used to verify that the correlation had a proper fit to the data. In this section, the validation data set is applied to examine the behavior of the ACE/ATRIUM 10XM critical power correlation.

The ACE/ATRIUM 10XM critical power correlation was further validated by comparing its prediction with the measurements made for transient critical power tests.

This section covers the following topics:

- Overall statistical performance of the validating data set, with comparison to defining data set and combined data set (Section 7.1).
- ECPR trend plots comparing the critical power to the validating data set as a whole (Section 7.2)
- [ ]
- Statistical analysis by single variable subsets (Section 7.4)
- Validation of [ ] (Section 7.5)
- ACE/ATRIUM 10XM critical power correlation benchmark to transient test data (Section 7.6)

7.1 *Overall Statistical Performance*

The overall statistics of the correlation are presented in the following table:

[

]

The standard deviation of the defining and validating data sets is the same. [

] The differences are insignificant. On the basis of these statistics, the ACE/ATRIUM 10XM critical power correlation is in excellent agreement with the validating data set and with the combined data set.

7.2 *Overall ECPR Trends*

One of the requirements imposed on the correlation is that there are no significant trends in the correlation with measured variables. Therefore, the key experimental variables are plotted against the ECPR to examine trend behavior.

The calculated critical power is plotted against the measured critical power of the validating data set in Figure 7-1. The data fall in a narrow, well-defined band about the expected value, consistent with the overall standard deviation. No trends are evident.

The ECPR as a function of inlet mass flow rate is shown in Figure 7-2. Mass flow rate is the most significant variable in the critical power correlation. A trend line representing a linear least square fit of the ECPR with mass flow rate is shown on the plot confirming that no trends exist.

The ECPR as a function of pressure is shown in Figure 7-3. The data show no trends with pressure.

The ECPR as a function of inlet subcooling is shown in Figure 7-4. A trend line representing a linear least square fit of the ECPR with inlet subcooling is shown on the plot confirming that no significant trends exist.

The ECPR as a function of axial power shape is shown in Figure 7-5. There is no apparent trend with axial power shape.

The ECPR as a function of K-Factor is shown in Figure 7-6. There is no significant trend with K-Factor.

On the basis of the observed trends in the validating data set, the ACE/ATRIUM 10XM critical power correlation is in excellent agreement with the experimental data and exhibits no significant trends.

Figure 7-1 Calculated vs. Measured Critical Power (Validating)

Figure 7-2 ECPR as Function of Mass Flow Rate (Validating)

Figure 7-3 ECPR as Function of Pressure (Validating)

Figure 7-4 ECPR as Function of Inlet Subcooling (Validating)

Figure 7-5 ECPR as Function of Axial Power Shape (Validating)

Figure 7-6 ECPR as Function of K-Factor (Validating)

7.3 [ ]

[

]

Figure 7-7 [ ]

Figure 7-8 [ ]

Figure 7-9 [ ]

7.4 *Statistical Analysis*

The frequency distribution of ECPR for the validating data set is shown in Figure 7-10. [

]

The validating data set is binned by mass flow rate in Table 7-1. There is no trend in ECPR with mass flow rate. [

] shows that there are no significant numbers of outliers at these higher mass flow rates. This result suggests that the observed slightly higher standard deviation is insignificant.

The validating data set is binned by pressure in Table 7-2. There is no significant trend in ECPR. The standard deviation shows slightly higher standard deviations at low pressure and at high pressure. However, [

] shows that there are no significant numbers of outliers at low and high pressures. This result suggests that the observed slightly higher standard deviation is insignificant.

The validating data set is binned by inlet subcooling in Table 7-3. There is no significant trend in ECPR. The standard deviation of the lowest and highest inlet subcooling data is slightly higher than for the other data. However, [

] shows that there are no significant numbers of outliers at low and high inlet subcoolings. This result suggests that the observed slightly higher standard deviation is insignificant.

Similar statistical examinations are performed for the axial power shape, in Table 7-4. There is no significant trend with ECPR. The standard deviation of the upskew and downskew shapes is slightly higher than the cosine shape. However, [

]

outliers for either upskew or downskew. This result suggests that the observed slightly higher standard deviation is insignificant.

The ECPR is binned as a function of K-Factor in Table 7-5. No significant trends are observed in the ECPR.

The results by test can be examined to determine if the correlation predicts the ECPR for each test treated as a subset of the population. The calculated results are provided in Table 7-6. The structure of the table and the entries are the same as those described in Section 6.3.

The conclusion is that the validating data set, as a whole, by important variables and by individual test, confirm the applicability of the critical power correlation to the population.

Table 7-1 ECPR Binned by Mass Flow Rate (Validating)

Table 7-2 ECPR Binned by Pressure (Validating)

Table 7-3 ECPR Binned by Inlet Subcooling (Validating)

Table 7-4 ECPR Binned by Axial Power Shape (Validating)

Table 7-5 ECPR Binned by K-Factor (Validating)

Table 7-6 Statistics by Test (Validating)

Figure 7-10 Frequency Distribution of ECPR (Validating)

Figure 7-11 Expected Value for Normal Distribution of ECPR (Validating)

7.5 *[ ] Bounds*

[

]

Figure 7-12 [ ]

7.6 *Evaluation of Transient Critical Power Data*

An industry accepted standard in BWR transient methodology is that steady-state dryout correlations are conservative for use in transient methodology. Transient dryout tests [ ] were performed to reconfirm this for ATRIUM 10XM when using the ACE/ATRIUM 10XM critical power correlation.

The limiting transient tests of interest are simulated load rejection without bypass (LRNB) events that consist of power and pressure ramps and flow decay; and simulated loss of flow events that consist of flow decay and power decay. The power, pressure, and flow were all controlled by a function generator. The forcing functions were programmed to produce the transient rod surface heat flux typical of the various events. Figure 7-13 shows the forcing function characteristics for a typical LRNB test and Figure 7-14 shows the comparable forcing function characteristics for a typical loss of flow event.

A total of [ ] ATRIUM 10XM LRNB and loss of flow transients were run which were either measured or predicted to have dryout. An additional [ ] of these transients were run which were neither measured nor predicted to go into dryout. By comparison, a total of [ ] transient tests were used in the evaluation of the ACE/ATRIUM-10 correlation. Of these [ ] transient critical power tests, [

] Table 7-7 summarizes initial state conditions for all the transient tests.

The AREVA NP transient thermal hydraulic code XCOBRA-T (References 10 and 11), was used to predict the transient test results using the ACE/ATRIUM 10XM critical power correlation. The test power forcing function provides the boundary condition of power, which is modeled in XCOBRA-T [

]

The [ ] transient tests modeling the ATRIUM 10XM geometry in simulated LRNB or loss of flow events were first evaluated assuming all the [

]. These results are summarized in Table 7-8. [

]

[

]

The same [

]

The same [

]

Table 7-7 Transient Initial Conditions

Table 7-7 Transient Initial Conditions (continued)

Table 7-7 Transient Initial Conditions (continued)

Table 7-8 XCOBRA-T Transient Dryout Results, [

]

**Table 7-8 XCOBRA-T Transient Dryout Results, [
] (continued)**

**Table 7-8 XCOBRA-T Transient Dryout Results, [
] (continued)**

**Table 7-9 XCOBRA-T [
]**

Table 7-10 XCOBRA-T Transient Dryout Results [ ]

**Table 7-10 XCOBRA-T Transient Dryout Results [
] (continued)**

**Table 7-10 XCOBRA-T Transient Dryout Results [
] (continued)**

**Table 7-11 XCOBRA-T [
]**

Figure 7-13 Typical LRNB Transient Forcing Function

Figure 7-14 Typical Loss of Flow Transient Forcing Function

8.0 ACE/ATRIUM 10XM Database

The ACE/ATRIUM 10XM database contains [ ] to validate the correlation. All data were taken at the AREVA NP KATHY thermal hydraulic test facility located in Karlstein, Germany. Descriptions of the test facility and the electrically heated test assembly are described in Section 8 of Reference 1.

8.1 *Test Strategy*

The development of a dryout correlation requires the acquisition of a database that covers the application domain with a sufficient number of data points with an acceptable uncertainty and proven repeatability. Radial peaking, axial power profile, pressure, flow, and inlet subcooling were all considered in developing the testing strategy to ensure that the application domain is adequately covered.

8.1.1 Radial Peaking Profiles

The usual practice is for the local peaking of the test rods to vary between [ ] occasionally. Because the purpose of the variation in local peaking is to determine the dryout characteristics of a particular rod position, no effort is made to simulate any particular neutronic design.

The testing program takes advantage of the symmetry of the test assembly. The ATRIUM 10XM has half-assembly symmetry along the main diagonal. Figure 8-1 shows all the peaked locations and the tests in which they were peaked. Note that rod location 34 did achieve dryout in test 107.1 and Rod 74 achieved dryout in test 108.5. Thus, all full length rod locations within the bundle were peaked, achieved dryout, or can be covered via symmetry considerations.

8.1.2 Axial Power Profile

Three axial power profiles were tested during the ATRIUM 10XM dryout test series. The STS-108, STS-109, and STS-110 series were performed with a [ ] peak to average chopped cosine axial. The STS-107 series was performed with a [ ] peak to average downskew axial, and the STS-105 and STS-111 series was performed with a [ ] peak to average upskew axial power profile. Note that test series STS-106 was a PWR test and not part of the

ATRIUM 10XM test series. Table 8-1 summarizes the type of each test and number of data points in each test.

The test rod axial power shapes are shown in Figure 8-2 (downskew), Figure 8-3 (cosine), and Figure 8-4 (upskew). For the part length rods, the axial power shape is composed of the full length rod shape (external skin) combined with the heat contribution from the inner copper conductor.

Dryout occurs only after the peak of an axial power profile. [

]

Table 8-1 Dryout Test Data

Figure 8-1 ATRIUM 10XM Database Summary by Rod Position

Figure 8-2 Downskew Test Rod Axial Power Shapes

Figure 8-3 Cosine Test Rod Axial Power Shapes

Figure 8-4 Upskew Test Rod Axial Power Shapes

8.1.3 Test Design

The methodology developed for performing dryout testing is fairly standard. The testing is performed by setting pressure and flow. The inlet subcooling is then set and the power is slowly increased until dryout is achieved. The inlet subcooling is then decreased or increased and the process is repeated. After one flow condition is tested, the flow is reset to the desired rate and the entire process is repeated. After all inlet subcoolings and flows are tested, the pressure is changed and testing continued.

Because the dryout test results are somewhat ordered, most errors in the test are immediately evident. When the flow is set, the critical power will vary directly with the inlet subcooling. The slope of the line increases as the flow increases. This is seen in any of the plots at the end of this section. During the test series for each day, some test points are repeated to ensure reproducibility.

8.2 *ACE/ATRIUM 10XM Data*

The database for ACE/ATRIUM 10XM contains [ ] peaking patterns performed on test sections with cosine, upskew, and downskew axial power profiles for the ATRIUM 10XM design. The correlation database contains [ ] data points taken over the range of applicability of the ACE/ATRIUM 10XM correlation. Of the [ ] data points, [ ] form the information used during the correlation process and [ ] data points validate the correlation. Table 8-2 contains the measured and calculated critical power ratio of the combined data sets. [ ] present the dryout test peaking patterns and their associated inlet subcooling versus critical power plots for both the test data and the ACE/ATRIUM 10XM predictions.

Table 8-2 ACE/ATRIUM 10XM Data and Analysis Results

Table 8-2 ACE/ATRIUM 10XM Data and Analysis Results (continued)

Table 8-2 ACE/ATRIUM 10XM Data and Analysis Results (continued)

Table 8-2 ACE/ATRIUM 10XM Data and Analysis Results (continued)

Table 8-2 ACE/ATRIUM 10XM Data and Analysis Results (continued)

Table 8-2 ACE/ATRIUM 10XM Data and Analysis Results (continued)

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Table 8-2 ACE/ATRIUM 10XM Data and Analysis Results (continued)

Table 8-2 ACE/ATRIUM 10XM Data and Analysis Results (continued)

Table 8-2 ACE/ATRIUM 10XM Data and Analysis Results (continued)

8.3 [ ]

[

]

Table 8-3 [ ]

9.0 Comparison of Production Bundle to the Tested Bundle

For all critical power testing (by all vendors), the production assembly is simulated, using electrically heated rods in place of fueled rods. The part of the assembly that affects the critical power lies between the beginning of heated length and the end of heated length. The lower tie plate and upper tie plate have no effect on the critical power and are not included in the test assembly.

Within the heated length, the production assembly has an internal water canister. This component draws flow from the assembly inlet at a location below the heated length, and discharges its flow at a location above the end of heated length. [

]

From the perspective of critical power, the geometry of the assembly between the beginning and end of the heated length is reproduced. [

] The pitch between rods is 0.510 in.

The part length rods in the test assembly have the same length from the beginning of heated length to the end of the part length rod. [

] Although the heating is different, the geometry observed by the flow field remains correct.

[

]

[

]

[

]

Table 9-1 STS-112.1 Results

Table 9-1 STS-112.1 Results (Continued)

Table 9-2 Statistical Results by Test

Figure 9-1 Graphical Representation of the Spacer Supports

Figure 9-2 Spacer Subchannel Flow Representation

Figure 9-3 Combination Spring and Dimple Spacer

10.0 References

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8. [ ]

9. [ ]

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12. [ ]

13. [ ]

Appendix A List of Symbols

Symbol	Description	Units

Symbol	Description	Units

Symbol	Description	Units

Symbol	Description	Units

Symbol	Description	Units

Symbol	Description	Units

Symbol	Description	Units